Tools for End-to-end Analysis, Calibration and Troubleshooting of Synchrophasor Systems

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Abstract—**The data quality issues in synchrophasor systems are quite complex and require new test methodology and tools to detect and mitigate the causes of bad data. This paper presents an approach for end-to-end testing of synchrophasor systems based on nested testing of the system components. It also introduces a portable device capable of performing calibration and troubleshooting tests on synchrophasor systems, from the components installed in substations to the ones installed in control centers. The capability to analyze each system component separately, one at a time, allows locating as well as characterizing data quality deterioration causes or any design anomalies very accurately. After the system components are tested, based on the obtained troubleshooting information, a comprehensive end-to-end calibration can be performed.**

Index Terms—**Synchronized Phasor Measurement, Phasor Measurement Unit, Phasor Data Concentrator, Wide Area Measurements, System Testing, Cyber-Physical systems**

I. INTRODUCTION

With an ever-increasing population and demand for energy, the need for continuous operation, safety and reliability of the power grid have made it one of the most critical infrastructures of the modern era. Events like the North America blackout on Aug. 14, 2003 [1] show just how vulnerable a power system is. The investments spurred by the American Recovery and Reinvestment Act of 2009 [2] helped wide utilization of the most accurate measurement devices deployed in the recent past, namely Phasor Measurement Units (PMUs). When integrated into synchrophasor system solutions, various applications utilizing such measurements, enabled groundbreaking progress in analysis and monitoring of power systems. With reporting rates of up to 120 samples per second, it is more than 100 times faster than the existing Supervisory Control and Data Acquisition (SCADA) technology and provides unprecedented insights and visibility into the integrity of continuous power system operation. This has led to an increase of PMU deployments in the field by a factor of ten [3] in the past decade. This enhancement is supplementing the legacy Energy Management System (EMS) used in the control centers of Independent System Operators (ISOs), Transmission Owners (TOs) and Regional Transmission Organizations (RTOs) throughout the United States [4]-[6]. In recent years, the technology is also gaining importance in Europe as well as China, India and Brazil [7]-[11].

The value of synchrophasor technology due to Global Positioning System (GPS) and Global Navigation Satellite System (GNSS) time aligned input waveform sampling, and consequently time stamping, becomes especially apparent in large interconnected grids. Synchrophasor streams [12]-[14] gathered by PMUs and phasor data concentrators (PDCs) and made available to end-user applications deployed in control centers are responsible for providing control strategies to improving reliability and resilience in power systems [15]-[18].

Maintaining data integrity and reliability throughout a synchrophasor system is critically important. Commissioning a system as well as scheduling and performing periodic maintenance tests to ensure the system performance is retained within expected limits, is highly desirable [19], [20]. If a system is suspected to be compromised, which may occur due to intentional intrusions, random failures, or a poorly calibrated device setup affecting the GPS clocks [21]-[23], PMUs, PDCs, and communication links [24], troubleshooting can be performed using the same methodology as for commissioning and periodic maintenance tests. As examples, references [25], [26] show the impact of compromised system components on end-use applications. Literature review suggests two efforts to be of exceptional importance to power system operators and maintenance personnel: 1. Evaluating impacts of disturbances on synchrophasor end-use applications; 2. Detecting and locating malfunctions and failures in a synchrophasor system.

The global market shows a variety of developments and deployments of PMUs and PDCs. The performance evaluation for synchrophasor systems implements the well-defined standardized type test [27] and related guides [28]-[31].

This paper focuses on specification of nested testing for end-to-end evaluation and analysis of Synchrophasor systems as part of commissioning, periodic maintenance or troubleshooting tests, which is not defined by the existing standards. It also describes methodologies, test plans, hardware and software implementation for application testing, which is not readily used in practice today. Combined, nested and application testing are the paper distinct contribution, since they

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allow more comprehensive system and application integrity assessment than any other known approach.

After an introduction to the developed test methodology of end-to-end and nested testing in Section II, Section III describes the hardware/software implementation. Methodology and results from the evaluation capable of identifying system malfunctions, intrusions or failures in synchrophasor systems and applications, are presented in Sections IV and V respectively.

II. Test Methodology for Detecting and Locating Synchrophasor System Malfunctions

A. *Possible Sources of Failure*

System malfunctions can occur due to various reasons, some of which are aging of equipment, drift of internal clock, incorrect settings or human error, malicious attacks, outdated calibration, timing intrusion, etc. The incidence of any such scenarios will lead to deterioration of data quality and disrupt data integrity. The fault surface includes a multitude of device internal and external components that, for the sake of practicality in this paper, are only considered down to the device level as shown Fig. 1.

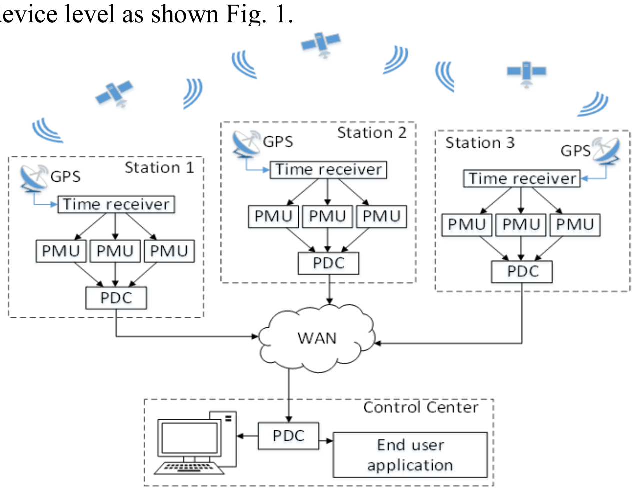

Figure 1: Example of Synchrophasor System Components.

B. *Malfunction Detection and Evaluation Using End-to-end testing*

Should the need arise to re-evaluate a synchrophasor system's integrity, be it due to suspected malfunction or as a scheduled maintenance procedure, possible system failure may be detected using an end-to-end testing procedure.

The concept of end-to-end testing used in this paper is to inject known waveforms, i.e. type and application waveforms (see section II.E), into a system and compare the output synchrophasor stream to a reference calculated from the known input. The system under test can be considered as a "black box", see Fig. 2. One of the most crucial points in this approach is to ensure the time stamping of the signal reference is synchronized with an absolute time reference, most commonly GPS/GNSS. This allows one to generate and compare the introduced test waveforms and data streams to the actual system performance.

In the case of type testing, the final evaluation is performed based on the Total Vector Error (TVE) [12]:

$$TVE(n) = \sqrt{\frac{\left(\left(\hat{X}_r(n)-X_r(n)\right)^2+\left(\hat{X}_i(n)-X_i(n)\right)^2\right)}{\left(X_r(n)\right)^2+\left(X_i(n)\right)^2}} \quad (1)$$

Where $\hat{X}_r(n)$ and $\hat{X}_i(n)$ are the sequences of estimates given by the unit under test, and $X_r(n)$ and $X_i(n)$ are the sequences of theoretical values of the input signal at the instants of time (n) assigned by the unit to those values.

The calculated TVE value provides insight into a system's accuracy. The TVE will show if a system is compromised based on pre-set threshold values. The classification thresholds can either be estimated based on accumulated maximum thresholds of individual components, or determined as part of the commissioning process, which may improve test sensitivity.

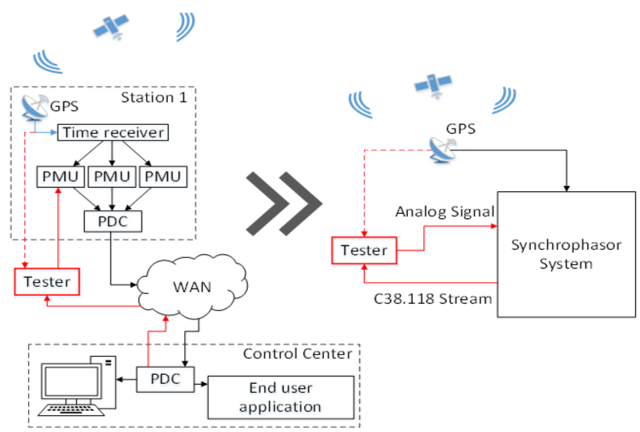

Figure 2: Blackbox Representation for Testing Purpose.

C. *Malfunction Location using a Nested Testing Approach*

The concept introduced in this paper uses a bottom-up approach (see Fig. 3). Starting with evaluating the integrity of the timing source, in each test iteration, additional equipment is included into the test loop until all elements are verified. A malfunction is detected as soon as the integrity evaluation of the subsystem under test fails to meet the requirements. The malfunction can then be allocated to the last part that was included into the test loop.

This method will capture any malfunctions or intrusions that affect the data quality as well as integrity of the overall system including the timing source. Misalignments or attacks upstream of the timing receiver, i.e. GPS signal source, cannot be detected.

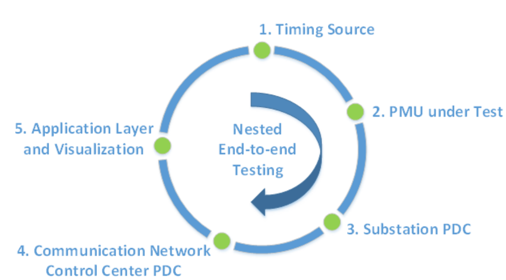

Figure 3: Nested Testing Approach.

D. *Timing Source Evaluation*

The timing source evaluation differs from all other components, as it does not use generated analog test signals. It is based on comparison of standardized timing signals, i.e. GPS input and IRIG-B or 1PPS output of the clock receiver, as shown in Fig. 4. Misalignment of the output, detected using a field test set, indicates an erroneous timing system.

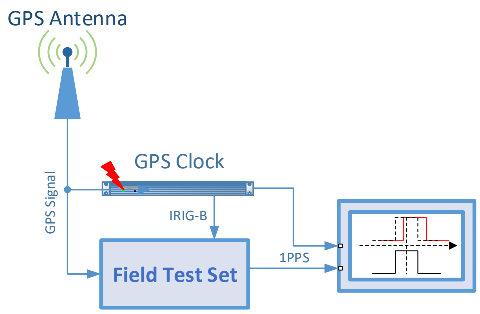

Figure 4: Time Module Test Setup Showing an Intrusion.

E. *Type and Application Test waveforms*

Type and application waveforms may both be used for detecting and locating errors in synchrophasor systems. Type waveforms are standardized and used to evaluate the design of PMUs [12], [13]. Application waveforms are corresponding to a simulated or measured scenario that is very specific to a certain location and topology of a power system and will yield expected results in the end-user application. Both methods use the knowledge of the input signal characteristics to calculate the output deviation from the expected reference.

1) *Type Test Waveforms*

Type test waveforms are defined in the IEEE standard [12], as well as its amendment [13]. The purpose of this standard is to define operational TVE range for PMUs. Any deviations outside of this range may be classified as different error categories.

The test procedure includes synchronously playing back type test waveforms to the PMU under test, looping back the synchrophasor data stream and comparing it to the known input signal reference. Once the PMU passed the test, one or multiple PDCs may be included into the nested testing loop. The setup for this evaluation is shown in Fig. 5 and 6, respectively.

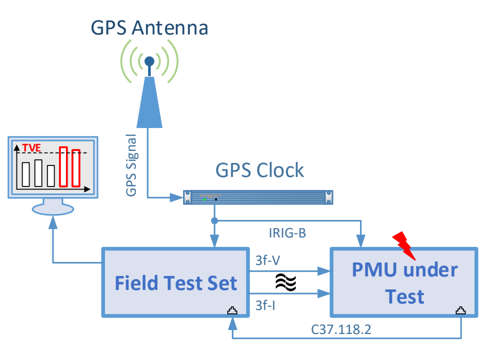

Figure 5: PMU Test Setup with Intrusion.

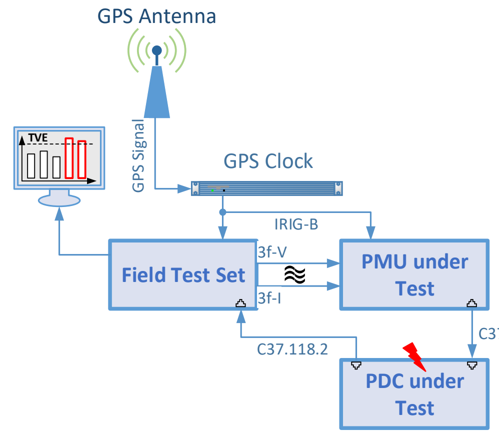

Figure 6: PDC Test Setup with Intrusion.

2) *Application Test Waveforms*

Application test waveforms have no generic definition and depend on individual events and topologies in power systems. These waveforms may be simulated or measured in an actual system and typically correspond to a certain system event that affects a specific behavior in one of the end-user applications in a control center. As an example, replaying waveforms corresponding to a specific fault scenario to a fault location application running in the control center should return the known fault location. If the data is affected by any malfunction symptoms in the loop, the location may deviate from the expected value, which allows error classification. The test loop schematic of a fault location application is shown in Fig. 7.

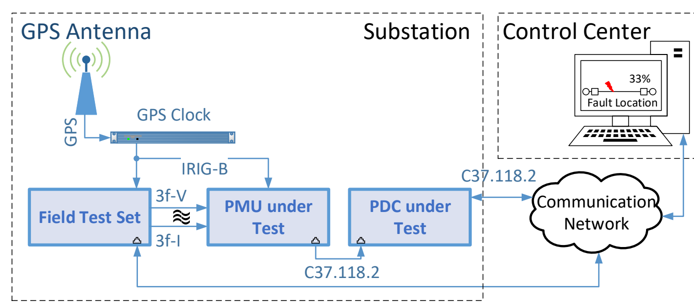

Figure 7: Application Test Setup.

III. DESIGN AND IMPLEMENTATION OF TEST EQUIPMENT

A. *Field Test Set*

The Field Test Set is based on the modular compactRIO (cRIO) design from National Instruments. For the simulations and measurements in this paper, a cRIO 9082 is used in combination with the following modular cards:

- NI 9263 – Analog Waveform Output
- NI 9567 – GPS/GNSS Receiver
- NI 9402 – Digital In/Outputs (IRIG-B)

The hardware is embedded in a NI 9919 enclosure, as shown in Fig. 8. The cRIO modules are internally wired and all external connections are made via the back panel or the ribbon cable connectors leading out of the enclosure.

Figure 8: Field Test Set Hardware.

B. *Test Environment*

All testing in this paper fully exploits the small signal capability of the Field Test Set (FTS) and the PMUs under test. The generated waveforms are small signal voltages (<1V), that are transferred to the internal PMU connectors via ribbon cables. This strategically circumvents any impact caused by amplifiers and auxiliary transformers in the test loop.

This form of testing not only avoids the impact caused by additional equipment, but also reduces the size and weight of the test equipment needed for field-testing. This allows the Field Test Set to be used as a portable analysis tool for existing synchrophasor applications.

C. *System Calibration*

The methodology introduced in Section II can also be applied to perform an initial system calibration during commissioning. 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.

IV. Results

A. *Impact Analysis Using Type Tests*

The data shown in Table 1 was acquired using the aforementioned methods and equipment for type testing and location of malfunctions. The following can be observed:

- In normal operation the TVE value is well within the limits defined in the standard and barely deviates from that value.
- In case of a “clock drift”, where the internal clock mechanism falls out of synchronization with the reference time source, the TVE threshold may still be within the standard’s limits, which may implicate a misleading judgment on the systems health. The elevated standard deviation, however, is an indicator for a component malfunction or intrusion. Looking at this in more detail clearly shows the clock drift, see Fig. 9. For that reason, it is advised to commission a system to obtain reference values and determine failure states from normal operation more accurately.
- A case of PDC timing intrusion of ~2ms delay can be determined very clearly by a significantly elevated TVE.

Table 1: Impact Analysis Using Type Tests.

ΔTVE [%]		PMU	PDC	CC-PDC
Normal Operation	Avg	0.373552	0.373552	0.373552
	Std. dev	0.003330	0.003330	0.003330
Clock Drift	Avg	0.540796	0.540796	0.540796
	Std. dev	0.096631	0.096631	0.096631
PDC time intrusion	Avg	0.373552	141.2593	141.2593
	Std. dev	0.003330	0.002866	0.002866

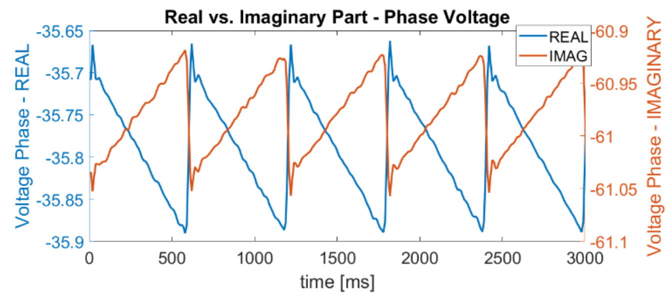

Figure 9: Analysis of Clock Drift.

B. *Impact Evaluation Using Application Tests*

For demonstrating the impact of system malfunctions on an end-user application, a fault location application is used. Fig. 10 shows an evaluation of fault location accuracy depending on time-stamp alignment and magnitude error. These two factors cover a majority of the most common malfunctions like aging of equipment, drift of internal clock, incorrect settings or human error, malicious attacks, outdated calibration, Timing Intrusion, etc. While there is some deviation in the application output caused by magnitude error (or also phase error), it can be observed that timing related issues have a much more severe impact.

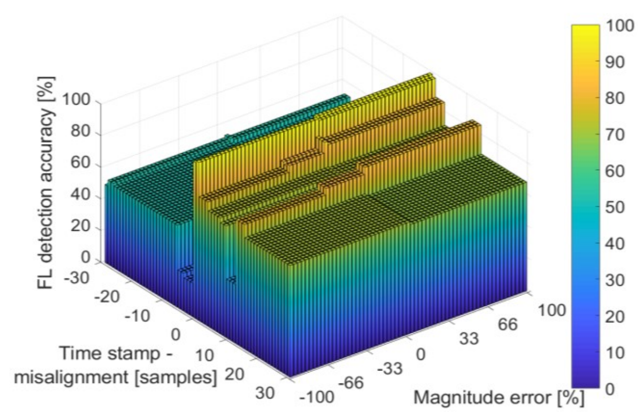

Figure 10: Impact Evaluation on Fault Location.

V. Conclusion

- Synchrophasor system malfunctions can be detected and located very accurately using nested end-to-end testing.

- Small signal testing allows to use the FTS as a portable analysis tool for existing installations
- Malfunctions or attacks that affect the timing system, especially when being reflected in the synchrophasor time-stamp, may have severe impact on the overall system performance.
- It is very important to calibrate a system during commissioning to establish reference thresholds for anomalies with smaller initial impact, as exemplary shown for the clock drift in section IV.A.

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