Life Cycle Management Tools for Synchrophasor Systems: Why We Need Them and What They Should Entail

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Abstract: A synchrophasor system solution generally incorporates precise timing sources, Phasor Measurement Units (PMUs), Phasor Data Concentrators (PDCs), communication network and phasor based applications. Even though all components may pass the laboratory tests, there is no guaranty that everything will work properly together after installation and deployment in the field. To preserve an acceptable level of service quality, the system components need to be tested keeping in mind different stages of the deployment. This paper discusses various aspects of a comprehensive life-cycle management model for Synchrophasor technology, ranging from the component to the overall end-to-end system level, and rigorous procedures for testing and evaluating such mission critical systems. In this effort, a unique PMU calibration lab is constructed to execute standardized PMU acceptance tests according to IEEE and IEC standards, such as the IEEE C37.118.1a among others. Field end-to-end calibrator is introduced using an accurate reference PMU called "Gold PMU" to perform field acceptance and periodic maintenance tests utilizing the nested testing concept. To illustrate the value of synchrophasor life-cycle management tools, use cases for state estimation and fault location application end-to-end tests are implemented to evaluate impact of accuracy deterioration and component failure on the performance of the synchrophasor system.

Keywords: Calibration tests, field end-to-end testing, life-cycle management, phasor data concentrator, phasor measurement unit, synchrophasor system.

1. INTRODUCTION

Deployment of Phasor Measurement Units (PMUs) and PMU-based Intelligent Electronic Devices (IEDs) over last 30 years has facilitated an understanding of modern power systems through high-resolution and precision observation. PMUs now serve as the backbone of various critical applications in electric industry such as State Estimation, Fault Detection, Remedial Actions, and Wide Area Monitoring [Singh (2011)]. Over time, issues such as the use of different synchrophasor estimation methods in various PMU products offering inconsistent accuracy, as well as difficulties in integration of proprietary software and hardware features of different products from different vendors are hindering the wide implementation of synchrophasor technology [Martin (2007)]. To ensure the system robust operation and reliable performance, testing tools must be developed to certify PMUs and perform field end-to-end tests during the system life cycle management evaluation stages: acceptance, commissioning, maintenance, troubleshooting, interoperability compliance, etc.

Multiple efforts have resulted in standards and guides for PMU testing and calibration. Since 2005, standardized testing and evaluation for PMU static and dynamic performance have been proposed. IEEE C37.118.1-2011 standard defines performance requirements for synchrophasor measurement. In 2014, this standard was revised, where some tests were removed and some of the requirements were relaxed because none of the PMUs available at that time in the market could comply with the standard. Testing procedures and requirements for the test equipment, such as timing reference, signal source, calibration device, and environmental conditions, are given in IEEE Synchrophasor Measurement Test Suite Specification (TSS) document published by IEEE Conformity Assessment Program (ICAP). TSS provides a suite of unambiguous test procedures in accordance with the Smart Grid Interoperability Panel (SGIP) Recommendations contained in the Interoperability Process Reference Manual [Gunther (2014)]. IEEE C37.118.2-2011 standard covers the requirements for the PMU data transfer in power systems. IEEE C37.242 document provides guidance for synchronization, calibration, testing, and installation of PMUs applied in power system protection and control. Testing procedures for the Phasor Data Concentrators (PDCs) are given in the IEEE C37.244 Guide for Phasor Data Concentrators Requirements for Power System Protection, Control, and Monitoring. Several organizations have been developing PMU test systems in accordance with these standards. Synchro-Metrology lab was built at NIST in 2006 [Stenbakken (2006)], and has developed static and dynamic test systems in [Stenbakken (2007a)] and [Stenbakken (2007b, 2008)], respectively. Recently, Fluke Company has promoted a commercial PMU calibration system, which complies with IEEE C37.118.1-2011 [Fluke (2011)].

Testing and certification lab for device and end-to-end testing of synchrophasor systems is established at Texas A&M University, which meets the widely accepted International Organization for Standardization/ International Electrotechnical Commission (ISO/IEC) 17025 and ISO/IEC Guide 65 (recently revised as ISO 17065:2012) international standards for certification of test laboratory and certification-body management systems, respectively. Most recently, the idea of "Gold PMU", which is a highly accurate PMU empowered by carefully devised synchrophasor algorithms, is proposed to be incorporated in PMU testing procedure [Qian (2016)]. The concept of end-to-end testing has been established in literature [Meinhardt (2008); Apostolov (2012, 2014); Turner (2013)]. An example of such end-to-end testing of protection system and fault clearing system is discussed in [Apostolov (2012); Turner (2013)] where the overall engineering process of system study, protection concept, design, purchase, build, and installation is described.

This paper is organized as follows. Section 2 covers the concept of life cycle management. Section 3 describes the use of newly developed testing tools through description of various tests: calibration of PMUs in the lab, and end-to-end evaluation of the synchrophasor system in the field. The same section describes the use of the reference PMU called "Gold PMU" to perform field acceptance and periodic maintenance and troubleshooting tests utilizing the nested testing concept. To build more insight into the life-cycle management tools, two application use cases to preform end-to-end testing of the synchrophasor system are also described in this section. Section 4 presents the conclusions, and References follow.

2. LIFE CYCLE MANAGEMENT

The synchrophasor infrastructure is a mission critical system introduced to improve monitoring, control and protection performance of the power grid and is expected to operate reliably each time it is called upon. A possibility that the system components have some random failures or do not meet certain performance prescribed by standards is, hence, a realistic scenario, particularly when the system is being initially commissioned or deployed in service for a long time (see Fig. 1). The "bathtub curve" in Fig. 1 illustrates typical equipment failure behavior over its life-cycle. The curve actually maps the rate of infant mortality failures of equipment at the early commissioning stages, the rate of random failures during the equipment useful life-span, and eventually the rate of wear and tear failures when the equipment designed lifetime is exceeded [Klutke (2003)]. Having a rigorous procedure and adequate tools to test different aspects of the hardware and software design, from the component to the overall system level, and over different time spans is the only way to assure a

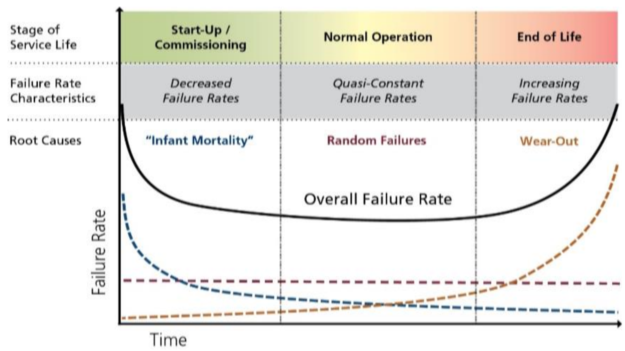

Fig. 1. Bathtub curve of a product/equipment over its life-cycle

robust and reliable operation of the mission-critical systems. Systematic life-cycle management practices are needed to achieve that goal. While there are several life-cycle models for the equipment and complex systems, the strategic question is which model best fits the project. Waterfall model, iterative/incremental model, closed-loop model and spiral model are among the well-known life-cycle management models [Basu (2015); Hundal (2001); Myers (1999)]. The suggested life-cycle model for the synchrophasor systems is a risk-reduction oriented "spiral" model as demonstrated in Fig. 2.

Fig. 2. The spiral life-cycle management model

The spiral model depicted in Fig. 2, is a comprehensive life cycle model which addresses very nature of the synchrophasor systems, which consist of multiple components provided by different vendors. Because of such nature, the expectation is that various components will deteriorate or be upgraded at different times requiring the life cycle process to unfold in a "spiral" fashion indefinitely repeating the cycles with each new change. In a spiral life-cycle model, each cycle is initiated with the specification of the following [Myers (1999)]:

- The main objectives of the (portion of the) system such as its performance, functionality, ability to accommodate any specific desirable change, etc.;
- The alternatives for implementation of the (portion of the) system such as design A, design B, reuse, buy etc.;
- The other constraints related to alternatives' application such as imposed cost, schedule and interfaces.

The unfolding spiral life-cycle model ensures the acceptable performance of the overall system by continuously testing the facilities and amending the shortages and/or new requirements. With the proposed tools within the suggested spiral life-cycle management model adapted to the synchrophasor landscape, the users of such mission-critical systems will be able to perform life-cycle long testing and maintenance procedures, which are essential for sustained wide use of such systems in real world. In the example of the synchrophasor systems, the life cycle procedures will cover:

- Equipment (PMU, PDC, etc.) calibration and certification before purchase
- System commissioning, and commissioning of any upgrades using standard test procedures
- Periodic field maintenance testing and calibration as well as testing and troubleshooting on demand

- Continuous checking of software for bugs and hidden failures using periodic tests
- Operator awareness of any system quality of service deteriorations detected by the proposed tools

The calibration and certification tests assure desirable performance of the equipment at the time of purchase. The commissioning tests allow both substation measurement equipment and system-wide solution to be deployed and verified in the field before the production use. This set of tools also contains operator-aimed displays that convey the stages of the tests and provide an assurance that the tests are performed comprehensively and successfully. Periodic field tests for in-service maintenance over the life-cycle of the mission critical system operation allow assessment of the deterioration of the quality of service performance over extended period of system use. Automated triggers are generated when anomalies occur to alert the personnel to engage in field calibration and performance verification. Software tools to enable remote testing and detection of failures in the devices and related data management architecture are needed for such purpose. The tools can automatically be triggered and executed on demand to collect data for remote testing. The solution needs to include on-line analysis of input data stream to spot any deviations in the measured data that may lead to conclusions about potential system malfunctioning.

3. TESTING TOOLS

3.1. PMU Testing

PMU test platform is developed to verify the performance of PMU device exposed to type-tests. The tests can be generally categorized into steady state or dynamic tests as specified in the IEEE C37.118.1a, as shown in Table I. Steady-state conditions are defined as magnitude, frequency, and phase sweep of the test signal and all influence quantities being fixed for the period of the test. Dynamic tests are devised to account for the dynamic signal changes that a PMU would face when applied in real -world power grid. As shown in Fig. 3, PMU test system consists of signal generator, timing reference, power amplifier, data collector and analysis tools. Timing reference provides GPS information so that the entire system is synchronized and time-stamped. Test signals are generated from a signal generator according to test types specified by the IEEE TSS document. The theoretical synchrophasor reference can be, hence, used for the comparison, then followed by analysis and documentation of the test results.

Table I. PMU Test Categories

Steady State Tests	Voltage/Current magnitude sweeping test
	Voltage/Current angle sweeping test
	Frequency sweeping test
	Harmonic distortion test
	Out-of-band interference test
Dynamic State Tests	Measurement bandwidth test
	Frequency ramp test
	Magnitude/Angle step test

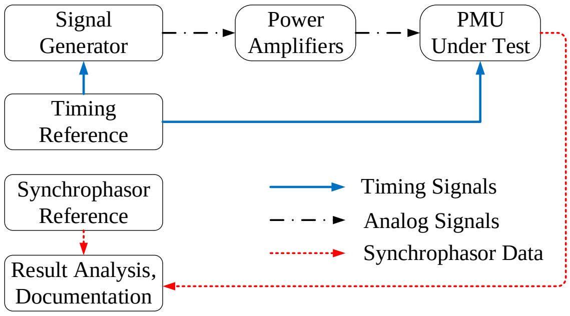

Fig. 3. Structure of PMU test system

The PMU test and calibration platform is implemented using National Instrument (NI) hardware as shown in Fig. 4. The entire system consists of the PXI virtual instrument system, an FPGA module to generate the required waveforms, and an amplifier to generate 3-phase voltage and current signals feeding the PMU device under test. Measurements from the tested PMU are acquired through Ethernet communication ports, analyzed, and reports are generated using the NI LabVIEW software package. In the IEEE C37.118.1 standard three different metrics for the PMU performance evaluation have been defined, Total Vector Error (TVE), Frequency Error (FE) and error in measuring Rate of Change of Frequency (ROCOF). TVE includes error in estimating signal magnitude and phase angle and the maximum allowed value is equal to 1%. Depending on the type of the test and the reporting rate of the tested PMU, maximum values of the FE and RFE can vary. Testing outcome of the PMU device will be a "pass", but only in case that all measurement errors are within the desirable limits. Example results of several steady state and dynamic tests on a given PMU are demonstrated in Fig. 5. As one can see, while the PMU under test has been in compliance with some standard performance requirements and passed several type-tests (e.g., frequency sweeping and harmonic distortion) in accordance with the desirable limits, the results from the PMU calibration lab illustrates the failure of some other tests (e.g., frequency ramp) which may impose a significant risk to the desirable performance of the tested PMU for a certain end-use application. Main reason for the failure during the PMU performance evaluation is the mathematical property of the algorithm for the phasor estimation that is used in a given measuring device. Moreover, hardware implementation can also introduce some level of the uncertainties and the measuring error.

Fig. 4. PMU test platform

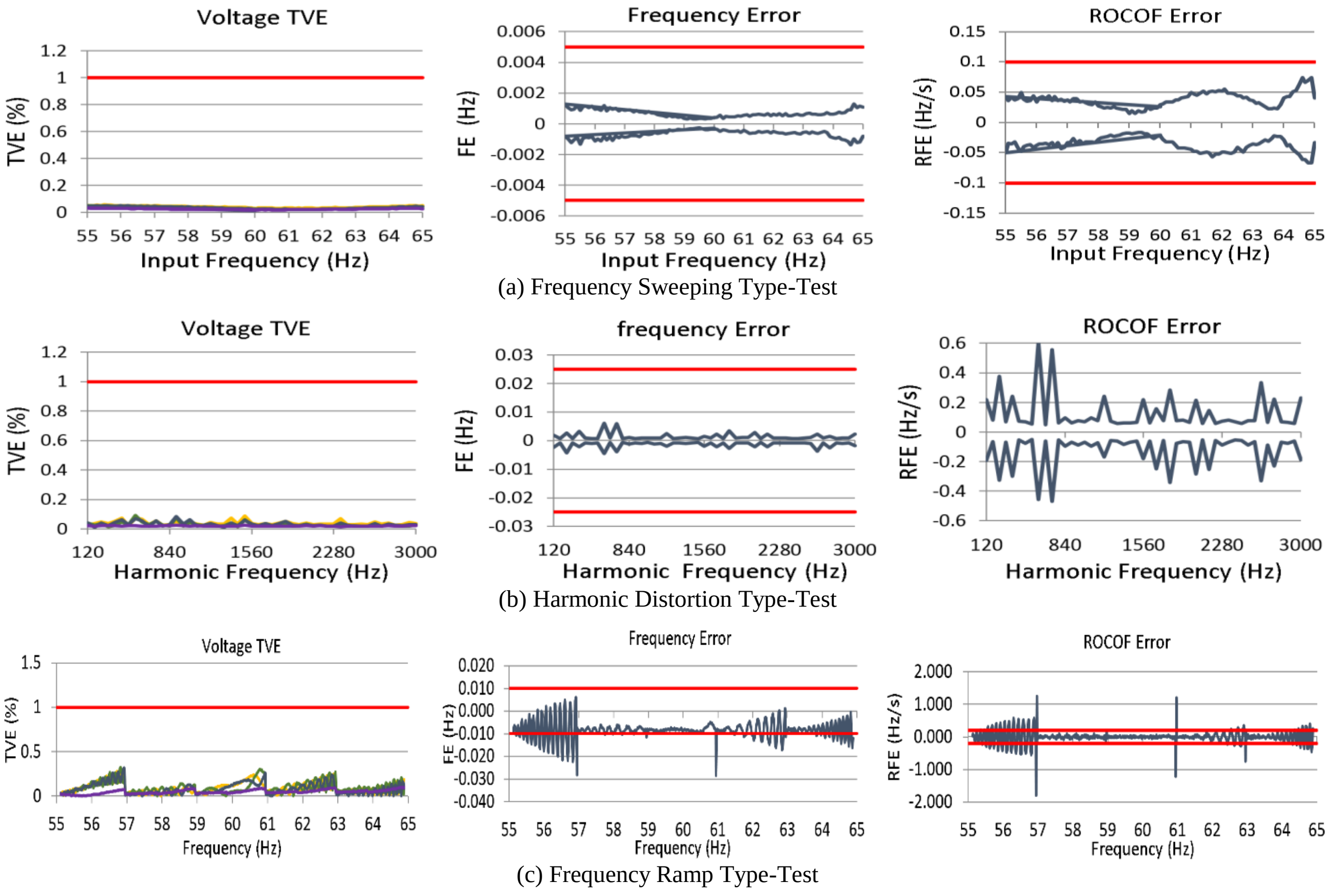

Fig. 5. Sample results of PMU static and dynamic test performance

3.2. Field End-to-end System Testing

As depicted in Fig. 6, the entire synchrophasor system consists of several layers: PMU devices, communication subsystem, PDCs, applications and visualization. A real possibility that the system components do not comply with certain standards, or have some hidden failures once they are connected, does exist. To evaluate synchrophasor system as a complete end-to-end solution, it is necessary to confirm that all pieces work properly once the system is commissioned in the field. Likewise, periodic testing is also desirable after the system has been in service for some time. Field tests are conducted to verify the proper functionality of a PMU at its installed location after it has been commissioned. Reasons for field evaluation include:

- In case of wrong installation, PMU may generate invalid phasor measurements.
- During the validation of PMU in the laboratory environment, it is very hard (practically infeasible) to simulate/produce signal conditions of a real power system.

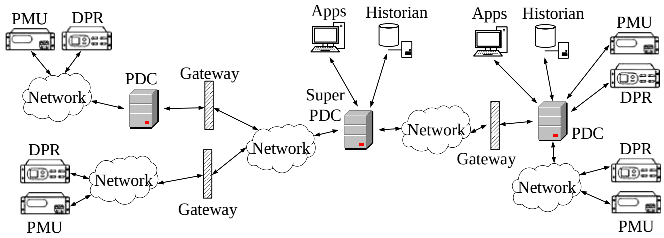

Fig. 6. Synchrophasor system

Field calibration consists of two types of tests: acceptance/commissioning tests and periodic maintenance tests. Field acceptance tests are approached to evaluate synchrophasor system as a complete end-to-end solution. PMU field acceptance test must include routine visual inspection, wiring check, basic functionality check, etc. Periodic maintenance test is conducted to validate the calibration of PMU according to IEEE Std C37.118.1a and enable detecting system abnormalities, if there is any, that should lead to troubleshooting tests. Periodic maintenance test should be run at least once a year or whenever the bad data detection module alarms that there are some problems in the system. In both cases, the test starts from the bottom layer and goes up to the application layer, constituting so-called "nested testing". As depicted in Fig. 7, first in chain for testing is the time reference, then phasor measurement unit, followed with the PDC at the substation with the communication li nk to the PDCs at the various control centers. By including the testing

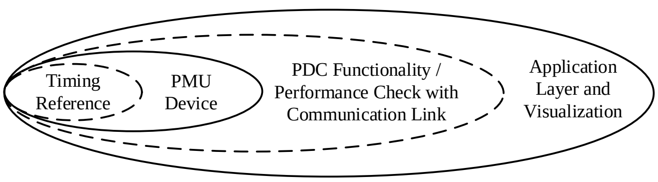

Fig. 7. Block diagram of nested testing

of the application layer, the loop of the end-to-end testing of synchrophasor system is closed.

In this effort, we built a portable field calibrator using NI compact RIO device, as the platform to perform the field acceptance and periodic maintenance tests. The signal generator is developed using the FPGA module to ensure precise and reliable test signals. Instead of using a commercial PMU as the reference PMU, we developed a more accurate algorithm called "Gold PMU" which provides a valid reference for comparison tests under any given measurement condition. A Gold PMU is a PMU device with more accurate phasor estimation algorithm than what is used in a commercial device. As shown in Fig. 8, Gold PMU will be implemented using several elements including:

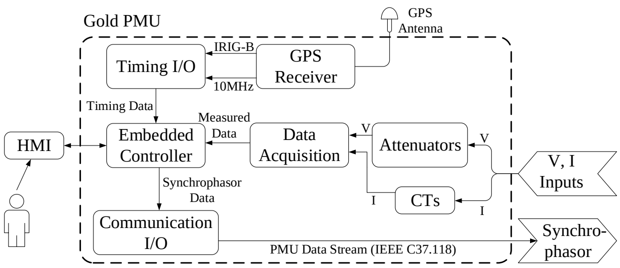

Fig. 8. Structure of Gold PMU

- Timing system, where GPS information is acquired from GPS antenna and GPS receiver, and then decoded and distributed by the timing I/O module of the Gold PMU.
- Data Acquisition, where power system voltage and current signals are attenuated, sampled and digitized for phasor computation.
- Spectral analyzer which will determine composition of the input signal for a pre-defined time interval
- Signal Model Selector, which is in charge of selecting the best phasor estimation algorithm for a given input signal condition
- Communication I/O which streams calculated synchrophasor reference values according to the respective standards.

The structure of the Gold PMU algorithm itself is shown in Fig. 9. In order to guarantee that the Gold PMU has high accuracy under all possible signals from the grid, a signal model selector is designed so that the type of input signal is identified. Then, algorithm with the highest accuracy corresponding to the input signal type is used to perform synchrophasor estimation. By doing so, Gold PMU algorithm design is free from the burden of designing one single method

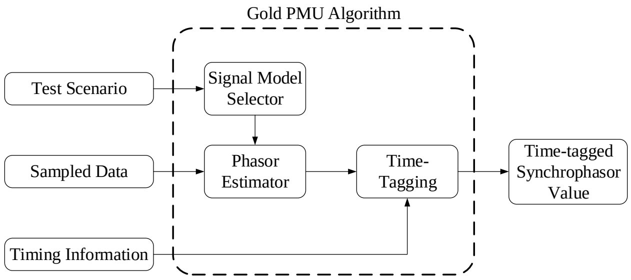

Fig. 9. Structure of proposed algorithm

that is supposed to work for all input signals. The work that has been done so far is a design of an algorithm that utilizes Levenberg-Marquardt method [Qian (2016); Kelley (1999)], whose theoretical accuracy in general can be 1000 times better than the standard PMU requirements. The algorithm utilizes nonlinear signal model so that input signals can be modeled in higher details with parameters of real physical meaning [Qian (2016)]. This algorithm, however, lacks the function of identifying input signal types. The future work would be the construction of signal model selector, and the revision of synchrophasor algorithms to meet requirements of respective input signal types. Merging Gold PMU within field calibrator will allow the user to explore impact of any component in a chain, sensitivity of the system to various failures and reliability of PMU measurements by using the nested test approach.

3.3. Application Testing

Once the lab and commissioning tests are performed to assure that the synchrophasor system elements are intact, a tool which enables end-to-end testing during operation is required since equipment type testing may not verify accuracy of the entire synchrophasor system while it is in-service. Therefore, an application end-to-end test procedure is defined to verify accuracy of the entire synchrophasor system at both element & system levels using nested test approach introduced in pervious section. For instance, Fig. 10 shows a set up for testing two wide area based applications which are chosen to reflect the impact of deploying life-cycle management tool. The two use cases are namely State Estimation and Fault Location which are designed to evaluate performance of synchrophasor systems under normal and abnormal power system conditions respectively.

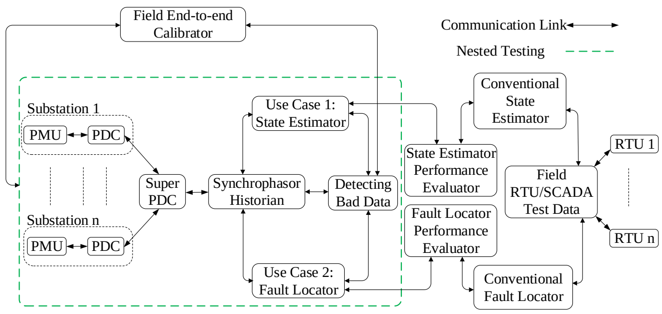

Fig. 10. Structure of proposed test procedure

3.3.1. Use Case 1: State Estimation

Monitoring and control of power system is managed by SCADA system, which collects the measurements in real time from the remote terminal units (RTUs) installed at the substations across the power system. State estimation is widely used as a tool to evaluate the real time power system prevailing conditions [Monticelli (2000)]. Conventional state estimator uses the measurements obtained from RTUs along with network topology processor to determine state variables of the system [Monticelli (1999)]. More recently, the widespread applications of PMUs also bring about beneficial impacts to the state estimation, which includes the improvement in network observability and state estimation accuracy, etc. [Phadke (2008)]. State estimators could suffer divergence under stressed system conditions or as a result of bad input data [Yu (2005)]. Therefore, they can be used as an excellent measure of deterioration caused by quality of service issues with PMU measurements and communication system. As depicted in Fig. 10, once bad data is detected in synchrophasor system, field end-to-end calibrator will be employed to perform nested testing as explained earlier. Therefore, the source of bad data (communication failure, PMU or PDC failure, etc.) is detected and system is maintained to remove causes of deterioration of state estimator output. This use case specifies how to compare performance of conventional state estimator that operates based on RTU/SCADA data with the synchrophasor based state estimator, and how to perform tests using the proposed life-cycle management tool.

3.3.2. Use Case 2: Fault Location

Application of centralized fault location methods for maintenance purposes has increased over the last 20 years. As well known, wide area synchrophasor measurement based fault location methods are highly sensitive to quality of the input data. This application can be used as an excellent measure to understand the application accuracy deterioration caused by deterioration in the quality of service. As shown in Fig. 10, the output bad data detection module is used to trigger field end-to-end calibrator to perform nested testing. Once the source of bad data is detected the system will undergo a maintenance procedure to remove the reasons for the deterioration of the fault location results.

4. CONCLUSIONS

With the aim of providing a comprehensive life-cycle management tool for synchrophasor system, we developed the following:

- A certification lab for device and end-to-end testing of synchrophasor systems capable of performing type and application testing;
- Test and certification equipment for commissioning mission-critical systems supplemented with wide array of hardware and software tools for performance evaluation;
- Field testing and calibration equipment for in-service maintenance and troubleshooting over life-cycle of the mission-critical system operation.
- Initial Gold PMU algorithm to be used as an accurate synchrophasor reference.

5. ACKNOWLEDGEMENTS

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