Life-Cycle Management of Mission-Critical Systems through Certification, Commissioning, In-Service Maintenance, Remote Testing, and Risk Assessment

Final Project Report

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Power Systems Engineering Research Center
Empowering Minds to Engineer
the Future Electric Energy System

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Power Systems Engineering Research Center

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Executive Summary

The overall research problem was to develop various tools and, methodologies to support life cycle management of mission-critical systems. The mission critical systems are represented with synchrophasor solutions, as well as the special protection schemes. The various evaluation stages included certification, commissioning, in-service maintenance, remote testing, and risk assessment. The tools have been developed for both laboratory and field-testing. The evaluation procedure assumed testing of individual components, as well as end-to-end system testing. With the developed tools, end-users will be able to maintain the system through the life-cycle from the initial selection of the system components and commissioning to the use throughout its life-time.

The project activities resulted in a PMU calibration lab developed at all participating universities, and other tools being developed as follows: a) Field test device and test protocols for device and system commissioning, acceptance, and in-service tests (M. Kezunovic, Texas A&M University), b) End-to-end remote testing of PMU and RAS (A. Srivastava and D. Bakken, WSU), c) PMU/MU Characterization and data validation via Substation Dynamic State Estimation, (Sakis Meliopoulos, GaTech), and d) Prototype algorithms and visualization for PMU data error identification and oscillation analysis (T. Overbye, Texas A&M University). The various tools have been tested mostly in the lab environment, and in some instances, actual utility data was used. The extension of this project in the future would be to use such tools and methodologies in specific utility applications.

Part I: Development of Field Test Devices and Test Protocols for Device and System Commissioning, Acceptance, and In-Service Tests

In this part of the study we focused on development of the various testing and evaluation tools to meet the acceptance and commissioning of the synchrophasor systems. The research method was to gradually proceed with testing various components starting from PMUs, then adding the communication channel, and PDCs, and finally adding an application for a complete end-to-end test. This approach was designated as "nested testing" approach. To facilitate such evaluation, we engaged in three developments: PMU field calibrator, "Gold PMU", and Fault Location assessment procedure. Besides that, we develop a PMU test and evaluation setup that may be used for future certification of PMU products.

The implication of our work is in the ability of end-users to utilize such devices and methodologies in evaluating performance of their synchrophasor system and its components. Such a capability was not readily available in the past resulting in inability of the end-user to verify performance of their synchrophasor system, particularly in the case when system components are showing some malfunction or even failure. The PMU certification lab may be used to evaluate future purchases and make sure they meet the IEEE standards. The Gold PMU may be used to verify that a commercial PMU meets its in-service performance requirements by comparing the outputs from an installed PMU and Gold PMU installed in parallel. To create test inputs for in-service evaluation of synchrophasor systems, the field calibrator has automated waveform replay features allowing the test plan to be executed automatically. The Fault Location application is used to illustrate how all the mentioned tools may be used to perform an in-service evaluation of performance of an application.

The next step in this research would be to utilize the mentioned tools extensively for utility uses and develop user manuals for the utilization.

Part II: End-to-End Remote Testing of PMU and RAS

In addition to testing phasor measurement units before deployment following IEEE Test Suite Specification (TSS), it is important to test and validate PMU and associated real time critical applications in field. The proposed "PMU Performance Analyzer (PPA)" is capable of testing the PMU's in field by integrating it with middleware called Erkios. The PPA is a software application that makes PMU testing effortless and highly accurate. It is capable of analyzing the performance of a PMU (under test) during steady state and dynamic conditions as specified in the IEEE Standard and guidelines. The PPA may also include some tests that are not in the standard based on utility specific requirements.

Erkios is developed with an objective to provide a solution for remote PMU testing and in-field testing of RAS. Erkios is a middleware framework and utilizes a number of fault-tolerance techniques to provide in-field testing of PMU and Remedial Action Scheme (RAS).

The first step in building such a tool is to set up a testbed that emulates the real-world scenario so that the tool can be validated. Development and integration of real time testbed with Erkios to facilitate cyber-physical simulation of end-to-end in-field testing of PMU and RAS are presented here. The testbed involves a real time power system simulator that has the capability to integrate with power system sensors and controllers in a closed loop. Also, the testbed has the communication channels and data flow closer to real world scenario.

This project resulted in updated PPA and Erkios software for remote PMU and RAS testing as well as a cyber-physical testbed to test and validate the developed tools.

Part III: PMU/MU Characterization and Data Validation via Substation Dynamic State Estimation

Present day PMU and Merging Unit (MU) technologies offer the capability for better, accurate and faster monitoring of the power system. The data generated from these systems are utilized by many applications. These technologies are complex, and many things can cause deterioration of the performance of these systems. However, data from relays, PMUs, MUs, FDRs, and in general any IED in the substation are treated as separate entities without any tools to test their cross correlation and in general to provide automated checking of the validity of the data. If for some reason gaps and errors are generated in the data, these gaps/errors remain and propagate to higher level devices. Furthermore, if any physical anomalies occur (such as a blown fuse, a damaged wire, etc.) they will affect the quality and validity of the data, yet there is no mechanism to determine the root cause of these anomalies.

This project integrated technologies developed under previous projects into an integrated physical-and-protection co-model and analysis software that performs the following: (a) validate all data coming out of all relays, PMUs, and in general IEDs via the distributed state estimator, (b) detect anomalies and identify the root cause of these anomalies (hidden failures such as blown fuses, cut wires, etc. or human errors such as incorrect entry of system parameters such as CT and VT ratios, incorrect instrument transformer connection (delta/wye), etc.), (c) in case of temporary loss of data, it creates the missing data from the state estimator and inserts the estimated data into the stream, and (d) it provides the validated data and the substation state up stream for further utilization, such as construction of the system wide real time model at the control center. These objectives have been achieved by a two parts process: (a) construction of a laboratory for the purpose of fully characterizing the individual components of the system, i.e. PMUs, merging units, digital fault recorders, etc. and (b) by constructing a laboratory that comprises the protective relaying scheme of a small substation, the substation automation infrastructure and a simulator to drive the system for the purpose of managing the data, identifying bad data and correcting bad data before the data are send upstream.

A field demonstration of the developed methods was planned. Specifically, the plan is to demonstrate these methods on the MARCY substation. Due to construction delays at MARCY substation, it was not possible to complete the demonstration before the end of the project. We do plan to complete this part of the project after the official completion of the project. Specifically, the required hardware at the substation for this demonstration will be installed in fall 2018 during a planned outage for the substation. Shortly after we plan to install the software at MARCY and test them in the field.

The work of this project will have substantial impact on future research activities. The developed methods and software will be critical components for many applications in the substation and control center. For example, we presently are extending these methods to be part of the protection and control system in the substation by making sure that all relays receive validated data. This application will solve a perennial problem in protection. Specifically, occasionally hidden failures occur in the instrumentation and data acquisition systems resulting in sending erroneous data to the relays and causing relay mis-operations. The data validation methods of this project can identify the hidden failures and correct data this avoiding relay mis-operations.

Another direction is to use the methods develop in this project to form the basic infrastructure of the next generation management systems. Note that a basic problem at control center operations is the accurate knowledge of the system in real time. The developed methods and software provide the validated data and model of each substation at speeds not possible before, specifically once per cycle. The validated data and validated real time model of each substation can be sent to the control center where the validated real time model of the entire system can be constructed by assembling the validated substation models at the same instant of time. This task can be achieved once per cycle. Thus, the control center can have the validated real time model of the entire system once per cycle and with a delay as short as much requires to stream the data from each substation, typically milliseconds. All the applications can now run on a validated real time model. In addition, the speed and accuracy open up a number of new applications such as full state feedback control of many fast responding resources in the power system such as universal power flow controller and other FACTS devises.

Part IV: Prototype Algorithms and Visualization for PMU Data Error Identification and Oscillation Analysis

An increased scale of power system interconnectivity and size poses challenges for operator visibility of the grid. Fast-measurement and high-reporting devices, known as phasor measurement unit (PMU) devices and used for monitoring grid health at high resolution scales, expand the capabilities for grid data processing and analysis, whose results are then used to increase the awareness level of the power system. A growing interest in the use of these unique devices in large-scale systems prompts the development of newer, robust analysis methods fit enough to capture both local and holistic dynamic features of the system. For example, the integrity testing of huge amounts of data obtained from geo-spatially, distributed grid sensors prior to data usage by critical grid applications, such as stability monitoring, grid disturbance and oscillation monitoring, to assess the state of the system. In this report, the goal is to study mechanisms of PMU device failures, and prototype algorithms and visualizations for data error identification and oscillation analysis. A 2,000-bus synthetic large-scale system is used for the different case studies in this report.

Sections 2 and 3 present PMU device failure mechanism and data error analysis in large scale power systems. respectively Firstly, we ed error propagation models that allows for the study of different mechanisms of time issues associated with PMU device operation, which in turn affect the integrity of reported data measurements. Secondly, we developed an approach to measurement error analysis in large scale grids considering the spatial and temporal variations that could exist among device measurements. In addition, the use of a hybrid, multidimensional scaling (MDS) method is proposed for use to visualize all pairwise measurement error correlations among all buses in a test system. A Matlab user interface tool is developed to aid generation of artificial PMU data errors. Designed using the Matlab GUIDE program, the developed user interface accepts user input for a selected PMU error type. Also, a prototype visualization dashboard display designed in a rapid application development (RAD) studio, and using Delphi programming language, is developed for the presentation of PMU error information in the large-scale system. It uses MDS correlation plots, tables, trend and bar charts to present its information. To migrate these developed tools to an application level would require additional data processing modules (as some of the processes are still being implemented manually) and extensive debugging.

Sections 4 and 5 focus on methods for presenting information pertaining to system oscillation. This information is obtained from the processing of enormous amounts of PMU data measurements obtained from a large-scale power grid. The use of a one-line diagram of the 2,000-bus synthetic Texas system overlaid on a geographic map of Texas, small object representations (known as glyph objects) and a method in vector field visualization are used to visualize large-scale system oscillation information. A wide-area visualization method is intended to present large-scale system dynamics to an engineer in a condensed, easy-to-interpret, holistic view of the system. The proposed visualization method is currently implemented in the PowerWorld simulator software for field visualizations in geomagnetic disturbance (GMD) and oscillation monitoring studies.

In summary, the key contributions/takeaways from this project are:

- The formulation and use of model equations to explain some of the timing issues associated with PMU devices. In addition to other system dynamics, these model equations can be used to generate artificial data for research purposes.
- Assist engineers to better understand unique, PMU-reported data patterns attributable to timing issues in PMU device operation rather than supposedly actual events on the grid. This can help in the interpretation of data discrepancies, and further search for error source if patterns of time errors are observed in the data.

- Development of a hybrid, distributed analysis method to detect erroneous measurements from PMU data obtained from a large-scale power grid. The result of the proposed method shows a 100% accuracy, and greater improvement over a central error analysis method, in the detection of bad PMU data from measurements obtained from several measurement locations in a 2,000-bus, large-scale system.
- Implementation of data-layering techniques and vector field visualizations for the wide-area visualization of oscillation information obtained from the processing of large-scale system PMU data. Condensed and holistic views of system states will provide engineers with a better understanding of system dynamics.

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[2] Christoph Seidl. *A comparison of end-to-end testing techniques for Synchrophasor Systems*, Master’s Thesis. Texas A&M University.

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