Synchrophasor Technology: The Boom of Investments and Information Flow from North America to Latin America

David Elizondo, Member, IEEE, R. Matthew Gardner, Member, IEEE, Ramón Leon, Senior Member, IEEE.

Abstract—The Smart Grid Investment Grants (SGIG) by the USA federal government at the transmission level are focused primarily on synchrophasor technology and bring an adequate platform to initiate the paradigm shift from SCADA-based real time monitoring at 5 to 10 seconds updating rate to synchrophasor-based real time monitoring at 30-60 samples per second updating rate. The current projects in the USA are marking the initial state of a transition for synchrophasor applications towards its integration to the EMS at the control center. This paper initiates with an overview of the main synchrophasor technology applications based on current projects in the USA. One specific synchrophasor project, currently executed by a joint effort between Virginia Tech, Dominion and Quanta Technology is described in detail including specific synchrophasor applications and future plans. An update of the synchrophasor technology applications being implemented by XM in Colombia are discussed in detail. The paper presents alternatives in which information and expertise may flow between utilities in the USA as well as to other utilities which have experience and/or plans with synchrophasor technology in Latin America.

Keywords—Synchrophasor Technology applications, PMUs, Three phase state estimator, Smart Grid.

I. INTRODUCTION

The Smart Grid Investment Grants (SGIG) by the USA federal government at the transmission level are focused primarily on synchrophasor technology [1]. These big monetary investments, in the order of several hundreds of dollars, bring an adequate platform to initiate the paradigm shift from SCADA-based real time monitoring at the 5 to 10 seconds updating rate to synchrophasor-based, real time monitoring, at the 30-60 samples per second updating rate.

Historically, one of the first uses and applications of synchrophasor technology has been post mortem disturbance analysis for transmission related events and the visualization of synchrophasor related information was generally done outside the Energy Management System (EMS) or the control center environment. The historical development of the heart of synchrophasor technology, the Phasor Measurement Unit (PMU), which evolved after developments of transmission relaying applications, supports the fact that the first uses of the synchrophasor technology were at the transmission level [2-3].

Analysis of the main SGIG synchrophasor related projects, indicate that the center of gravity for synchrophasor applications is moving towards the integration of this technology to the EMS at the control center. Based on a number of the current major synchrophasor technology projects in the USA [4], the typical model includes an Independent System Operator (ISO) or Regional Transmission Operator (RTO) which operates a control center to take the lead and work in collaboration with the transmission owners (TO’s) to define the PMU technology solution for the electric power system footprint that they are responsible for.

The SGIG monetary investments are providing the fuel to mobilize electric power utilities, technology providers, consultants, and other actors to shape the US electric power industry and the PMU technology is finding its natural environment at the control center. While the transmission environment was certainly the origin of the PMU technology applications, and will continue to be used there, trends indicate that the near future of synchrophasor technology applications is moving towards the EMS and the control center.

Following recommendations of the 2003 US blackout [5], the main synchrophasor technology applications are centered towards situational awareness and the real time monitoring of large geographical areas of the electric power system. The real time monitoring of large geographical areas of the electric power system with the use of synchrophasor technology brings new information to the control center environment and a substantial increase in the granularity of the information which could be up 150 times more.

While the synchrophasor technology platform is adequate for more accurate real time monitoring and brings significant benefits, it also brings additional burdens to the control center.
environment and power system operators in the form of the amount of information and new type of information.

The objective of this paper is to present an overview of a number of the synchrophasor technology applications based on current projects in the USA with a focus of the new information and increased granularity of information to be available at the control center. The paper also presents alternatives in which information and expertise may flow between utilities in the USA as well as to other utilities which have experience and/or plans in the synchrophasor technology in Latin America.

In order to achieve the objectives listed above, Section II of the paper provides a high level overview of a selected number of synchrophasor technology based projects currently ongoing in the USA with a focus on the planned synchrophasor applications in which new and increased granularity of information is integrated to the control center. Section III presents one project currently executed by a joint effort between Virginia Tech, Dominion and Quanta Technology. The synchrophasor applications are presented from the perspective of the new and increased granularity of information. Section IV describes the synchrophasor technology initiatives by XM, the grid operator in Colombia. Finally the conclusions are summarized in Section V in which a number of the technology transfer alternatives are discussed.

II. OVERVIEW OF SYNCHROPHASOR TECHNOLOGY PROJECTS IN THE USA

A summary of the monetary investments for a number of SGIG synchrophasor projects is presented in Table 1 [4].

<table>
<thead>
<tr>
<th>Ref</th>
<th>Entity</th>
<th>Investment in MUSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WECC (BPA, PG&amp;E, SCE, and others)</td>
<td>108</td>
</tr>
<tr>
<td>2</td>
<td>NYISO</td>
<td>76</td>
</tr>
<tr>
<td>3</td>
<td>PJM</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>Midwest ISO</td>
<td>35</td>
</tr>
<tr>
<td>5</td>
<td>ATC</td>
<td>28</td>
</tr>
<tr>
<td>6</td>
<td>Entergy</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
<td>ISO New England</td>
<td>9</td>
</tr>
<tr>
<td>8</td>
<td>Duke Energy</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>Midwest Energy</td>
<td>1.5</td>
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<tr>
<td></td>
<td></td>
<td><strong>315.5</strong></td>
</tr>
</tbody>
</table>

As we can see from Table 1, there are about 9 projects in the USA related to synchrophasor technology with a total monetary investment in the order of 316 millions of dollars. These projects are generally multiyear projects that initiated in 2009 and are currently on going at the time of this paper. Within the 108 MUSD for the WECC project, 47 are allocated to PG&E, 20 to BPA, 4 to SCE, and the rest to other entities within the WECC. The current list of PMU installations in the USA is shown in Figure 1.

Figure 1: Location of Phasor Measurement Units in North American Power Grid. Source NERC 2010.

A. Brief project descriptions and main applications

PG&E is in the process of deployment of large-scale synchrophasor measurement system to enhance EMS and Grid visualization to implement in three years. The project entails the deployment of a PG&E-wide, open, flexible, interoperable, secure, and expandable phasor monitoring network that are enhancement to PG&E’s existing monitoring systems.

A number of the main synchrophasor applications for the PG&E project and the functions within the applications are listed in Table 2 based on [6].

<table>
<thead>
<tr>
<th>Ref</th>
<th>Synchrophasor Application</th>
<th>Functions within the application</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Situational Awareness, Visualization and Alarming for Electric Transmission Operators</td>
<td>Unbalanced power applications, Abnormal angles, Abnormal voltages, Line overloads, Dynamics oscillations (small-signal oscillation) monitoring, System restoration</td>
</tr>
<tr>
<td>2</td>
<td>Enhanced Energy Management Systems and State Estimation for current EMS users</td>
<td>Add synchrophasor measurements to existing SE measurements.</td>
</tr>
<tr>
<td>3</td>
<td>Post-Disturbance Event Analysis for Planners and Engineers</td>
<td>Substation level data analysis and System level event analysis</td>
</tr>
<tr>
<td>4</td>
<td>Distributed State Estimation</td>
<td>Executed at the substation level.</td>
</tr>
</tbody>
</table>

As we can see from Table 2, the synchrophasor applications include traditional ones like post disturbance analysis for planners and engineers at the substation and system level. Other more novel applications include the distributed state estimation and the incorporation of synchrophasor measurements into the current state estimation routine of the EMS. The information resulting from the Situational Awareness, Visualization and Alarming application may be seen as new information with increased granularity to be available at the control center to the operators.
NYISO PMU project is planned to enhance the reliability and efficiency of the New York state power grid by the deployment of a phasor measurement unit (PMU) network and capacitor banks that will be used to expand wide-area situational awareness and coordination of voltage across the state transmission grid.

A number of the main synchrophasor applications for the NYISO project and the functions within the applications are listed in Table 3 based on [7].

### Table 3: Selected Synchrophasor Applications for NYISO project.

<table>
<thead>
<tr>
<th>Ref</th>
<th>Synchrophasor Application</th>
<th>Functions within the application</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wide Area Situational Awareness</td>
<td>Monitoring of key system variables such as: Voltage Phase Angle, Interface MW Flow Local and Interarea Frequency Oscillation, Voltage Magnitude, Frequency, among others.</td>
</tr>
<tr>
<td>2</td>
<td>PMU Assisted State Estimator</td>
<td>Add synchrophasor measurements to existing SE measurements.</td>
</tr>
<tr>
<td>3</td>
<td>Post Disturbance Analysis</td>
<td>Post mortem application</td>
</tr>
<tr>
<td>4</td>
<td>Monitoring of Proximity to Voltage Collapse</td>
<td>Assure system security during high power flow transfers</td>
</tr>
<tr>
<td>5</td>
<td>Calibration of Dynamic System Models</td>
<td>Fine tuning generator controls to match with system performance</td>
</tr>
</tbody>
</table>

As we can see from Table 3, the project includes traditional applications such as post disturbance analysis. Other more novel applications include the calibration of dynamic system models and the PMU assisted state estimator. The information resulting from the wide area situational awareness application may be seen as new information with increased granularity to be available at the control center to the operators.

### III. Detailed Description of a Synchrophasor Technology Project in the USA: Dominion Virginia Power

Dominion Virginia Power, a US-based utility, is planning to monitor, in real time, three-phase current imbalances in the transmission infrastructure with synchrophasor technology. This monitoring is made possible with the use of synchrophasors monitored in three phases. The essence of the project is the development of a purely synchrophasor-based tracking three-phase state estimator. The project has also developed transducer calibration techniques, analysis and visualization tools, and synchrophasor-based islanding detection capabilities for the Dominion Virginia Power extra high voltage transmission network.

#### A. Project Description

Dominion’s EHV transmission network and other utilities can exhibit unbalanced flows under certain operating conditions. These conditions are suboptimal for generators on or near the EHV infrastructure. Synchrophasors, with the help of a three-phase estimator, offer a unique tool for tracking the behavior of unbalanced flows and developing corrective strategies for excessive negative sequence current flows or islanding conditions. In most cases, islands are formed as a consequence of catastrophic events. The proposed three-phase estimator can also be used to detect and track islanding conditions in the Dominion Virginia Power system. Phase I of the project established a study system model and analytical techniques were developed for a tracking three-phase state estimator. In Phase II, a plan was developed and executed to deploy PMUs in the substations and a PDC in the control center. Phase III is focused on simulating the behavior of the applications as the central data concentration facilities are built-out and the balance of the field devices (PMUs) are deployed.

#### B. Main Applications

This project has three main applications: three-phase state estimation, transducer calibration, and islanding detection. Both transducer calibration and islanding detection are tied to the backbone of the three-phase synchrophasor state estimator.

Using a three-phase pi-equivalent, the bus voltage on adjacent buses can be computed from the three-phase line currents. An integer programming problem will be solved to determine an optimum phased placement strategy at each stage and resulting in a minimum set of synchrophasors by end of Phase III. Unlike the traditional state estimator, this estimator is based upon the solution of a linear equation and hence no iterations are needed. As soon as the measurements are obtained, the estimate is obtained by matrix multiplication. The matrix that converts the measurements to the state estimate is constant as long as the bus structure does not change. It can be computed off-line, and stored for real time use. This conversion matrix can be altered as more measurements are added to the system.

Previous work by the Virginia Tech team has discovered a method for on-line calibration of all current and voltage transformers with the help of data collected during daily load cycles. This process can be repeated as frequently as desired, and has shown excellent performance in simulation studies.

The method takes advantage of the known calibration of a few instrument transformers, usually potential transformers connected to EHV buses. It is assumed that a synchrophasor is connected to that bus, and to several other buses which have capacitive voltage transformers (CVTs) which need to be calibrated. In a staged calibration process, light load conditions are used to calculate calibration factors for the CVTs, and heavy load conditions help calibrate the current transformers. In practice, several heavy and light load measurement sets are needed to solve an over-determined set of equations for the unknown calibration constants for all instrument transformers. This technique has been modified and tested for calibrating three-phase instrument transformers.

Finally, if dramatic events cause a separation of the monitored system into two or more pieces it would be best if the estimator could determine the islands and correct the estimator. The correction is in the estimate of the state itself and in obtaining the appropriate conversion matrices for each island. If this can be done, then the estimates of the states of the islands will be useful in reconnecting the islands to each other. Given the number of possible islands that can be formed in a small system is limited, detecting islands is only slightly more complicated than detecting bad data. While the number of possible islands in large systems is too large to make such a
claim it seems likely to be true for Dominion Virginia Power’s EHV system. This islanding application has been developed to detect islands in three major areas of concern within the Dominion network. The application is currently being tested and will eventually be deployed alongside the synchrophasor state estimator.

C. Opportunities and Challenges

While this project is full of opportunity to access and visualize new information, challenges remain. Synchrophasors provide a new look to conventional data and add a parameter never before seen on a wide area, phase angle. No doubt challenges will arise in the areas of engineer and operator training. Some of these challenges may be the addition of new information to the operator such as three phase voltages and sequence domain quantities.

D. Technology Transfer to other utilities

This project is at full momentum at the time of this paper and we expect to have the opportunity to share experiences and lessons learned with other transmission operators that face similar problems.

IV. SYNCHROPHASOR TECHNOLOGY INITIATIVES IN COLOMBIA

A. Project Description

The project for implementing synchrophasor technology in the Colombian power system was motivated by two main drivers, the total blackout of 2007 and the appearance of very low frequency oscillations in 2008.

Initially, the goal of the project was to develop a National Defense System against Large Scale Events for the Colombian power system, seeking to design advanced protection systems able to act upon rare occurrence events. The project’s Spanish name of “Sistema de Respaldonacional ante Eventos de Gran Magnitud” yields its acronym SIRENA [8].

The SIRENA project focused on two lines of work: applications of synchrophasor technology and the implementation of a limited prototype for technology demonstration and test bed. At that point in 2007, the technology was still in the developing stage and therefore, it was decided to embark upon a research effort to achieve the proposed goals. Additionally, in 2008, a series of very low frequency oscillation modes (0.06 Hz) appeared in the Colombian system [9]. XM worked with Psymetrix and installed their Phasor Point PDC in order to use synchrophasor measurement technology to understand the behavior of the power system and to test the actions needed to mitigate problems.

The limited Wide Area Monitoring System (WAMS) prototype is installed in 12 major substations including some of the major generation plants in the system. Figure 2 presents the display of the Phasor Point situational awareness tool, showing the location of the PMUs as arrows representing the relative voltage angle in each substation.

For research and development, the project sought cooperation with universities in Colombia and Brazil. In Colombia, XM is working with Universidad Pontificia Bolivariana (UPB) developing methodologies for power system analysis based on angular behavior and the implementation of algorithms and indices based on the results of the analysis. In Brazil, XM works with Universidad Federal de Santa Catarina (UFSC) developing methods and tools for parameter estimation and validation for generators and their voltage and frequency controllers. Now, as a member of the Electric Power Research Center of Iowa State University, XM will collaborate in upcoming R&D projects based on PMU technology.

The SIRENA project will finish in May 2012, giving way to a new project with a wider scope. The new project seeks to design an Intelligent Supervision and Advanced Control (iSAAC) system, which is envisioned to be the evolution of the current SCADA/EMS system. This is aligned with the trends previously identified in this paper.

B. Main Synchrophasor Technology Applications

The project uses PMU’s from different manufacturers, including an in-house PMU design, developed in order to understand the phasor measurement principles, processes, standards and to test the integration between manufacturers.

The WAMS prototype has PMUs in 12 substations, using mixed TCP/UDP protocol with a data rate of 10 frames per second. This low rate is required due to the fact that initially it was using the corporate WAN. By June 2012, the prototype will have an exclusive communications infrastructure, which will allow at least 30 phasors per second. By the end of 2012 the prototype will have 12 more PMU and in 2013, 15 more will be installed, with a total of 51 PMU expected by the end of 2013.
Given the great importance of oscillatory analysis due to the presence of very low frequency modes of 0.06 Hz observed in the Colombian power system, this application is being supported by a robust monitoring and analysis platform. XM uses Psysmetrix’s Phasor Point as the main control center PDC, providing situational awareness, oscillatory analysis, resynchronization and islanding tools. Also, in collaboration with Iowa State University, parallel research has been conducted for reproducing the observed behavior by the PMUs with an appropriate simulation model [10]. Currently, XM performs daily analysis of the oscillatory behavior of the system using Phasor Point and works with the generators to assess angular and frequency stability under any operational state.

The phasor information architecture also uses Grid Protection Alliance’s OpenPDC for developing new applications based on the ongoing research on methods and algorithms for power system analysis using angular behavior. Additionally, given that Osisoft’s PI is used at the Colombian control center as its main historian tool, the main PDC also provides PMU data to this tool for displaying values and other PMU information in the control room.

In parallel with the prototype, the research effort has demonstrated the feasibility of using the angular behavior of the voltages on the power system to provide early warnings and locational information for large scale events in the power system. The first stage of research demonstrated qualitatively that by only using a combination of voltage magnitude, angle differences and speed of change of angles, it was possible to determine the state of the system and to pinpoint which portion of it is involved. Later, a series of indices were developed using different angular aggregation strategies, demonstrating that it was possible to obtain values that could be used as alarms for critical system states [11-12].

C. Opportunities and Challenges

The prototype and the research efforts have demonstrated the benefits of PMU technology implementation in the Colombian power system and also identified a clear potential for advanced supervision, protection and control of the power system. The next step is to apply the described results and with the combination of new computing and communication technologies to develop an Intelligent Supervision and Advanced Control (iSAAC) system.

The new project will focus on three main challenges required to be solved in order to successfully implement an advanced supervision and control system. As shown in Figure 3 the challenges involve building an underlying WAMS architecture and infrastructure, the integration with control center functionality, with EMS in particular; and the development of methods and applications for data analysis, protection and control functions, and for improved visualization of the power system state at the control center.

D. Technology transfer/adaptation

As have been discussed previously, the main technology adaptation in the Colombian PMU project is the utilization of Grid Protection Alliance’s OpenPDC. The open source nature of this tool has been greatly helpful for rapid deployment of new implementations of system’s analysis algorithms and novel visualization schemes. As an example, Figure 4 shows the development of a control center tool representing the impedance characteristic of the power grid as seen by a distance relay in one substation with PMU monitoring. This tool could help operators to assess the risk of undesirable additional line trips, following an outage in highly loaded corridors.

The newly proposed iSAAC project will focus more in the technology integration side in order to achieve a highly distributed supervision and control system, using cloud-like communications and new visualization and analysis tools. In this direction, XM have been following closely the proposed NASPINet architecture [13-14], the Open Source Phasor Gateway and the future implementation of IEC 61850 protocol for PMU data, and for out of substation information exchange.

V. Conclusions

This paper presented two synchrophasor projects currently in deployment in the USA along with synchrophasor applications that result in new and increased granularity of information to the power system operators. The project being led by Dominion Virginia Power described the PMU only state estimator which is based upon the solution of a linear
equation and hence no iterations are needed as well as other synchrophasor applications. XM presented its plans to exploit the synchrophasor technology which started with the SIRENA project and now has evolved in the iSAAC project which plans to install a total of 51 PMU by 2013.

While all projects are unique and address different problems in the power system, we can conclude that there is an opportunity to test different approaches to PMU technology implementation given the differences in the industry’s structure in different countries.

Regarding how electric power utilities based in Latin America could benefit from the homogeneous synchrophasor investments in the USA, we could state that the XM experience by participating in industry events like NASPI have help them to gain more information on approaches in implementation and planning for synchrophasor applications. For international interconnections, the synchrophasor technology is key for assessing the security and reliability of the power systems and Latin America based utilities should exploit this technology to leverage from a continent-wide approach for the more complete observation of the electric power system and stimulate the economic progress.

The authors of this paper are fortunate to have had exposure in the inception of the synchrophasor technology and are planning to continue working in synchrophasor based projects in the coming years. As these projects come into fruition, innovative techniques would be needed to deal with the new and increased granularity of information to be available at the control centers, which is part of the author’s future work.

VI. ACKNOWLEDGEMENTS

Part of this material is based upon work supported by the Department of Energy [National Energy Technology Laboratory] under Award Number(s) DE-OE0000118.

VII. REFERENCES


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VIII. BIOGRAPHIES

David Elizondo, PhD., is a Principal Advisor and has more than 17 years of electric power systems experience, 10 years in the USA and 7 years in Mexico. Dr. Elizondo has a broad range of experience in electric power transmission planning and has participated in numerous transmission planning studies for most of the large utilities in the US. Dr. Elizondo has recent experience with the integration of synchrophasor measurement units into the Energy Management Systems of electric power networks. His work has been focused on the development of the visualization tools for the effective utilization and use of the synchrophasor based data to power system operators. Dr. Elizondo is the project manager for the PMU visualization project for Dominion and was responsible for the visualization specification for the NYISO PMU project. Dr. Elizondo earned his Masters and PhD degrees in Electrical Engineering at Virginia Tech and his Mechanical and Electrical Engineering Bachelor degree from the ITESM in Mexico.

Robert Matthew Gardner is a Professional Engineer registered in the Commonwealth of Virginia and an electric transmission planning engineer at Dominion Virginia Power where he is responsible for the company’s synchrophasor deployment and application development strategies. Matthew received his doctorate from Virginia Tech in 2008 where he was a Bradley Fellow collaborating on the efforts to develop a distribution-level solution for the monitoring of the bulk electric power grid.

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