Phasor Measurement Units Applications Prioritization Based on Wide-Area Disturbance Events

Leydi T. Zora

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science

In

Electrical Engineering

Jaime De La Ree Lopez, Chair

Virgilio Centeno

Arun Phadke

December 10, 2014
Blacksburg, VA

Keywords: Synchrophasors, PMUs, roadmap, PMU prioritization, wide area measurement events.

Phasor Measurement Units Applications Prioritization Based on Wide-Area Disturbance Events

Leydi T. Zora

Abstract

Synchrophasor Measurement Units (PMUs) are devices that can not only measure but also time stamp voltage, current, frequency, among others. PMUs take these synchronized measurements as fast as 60 times per second; compared with the traditional 2-4 second SCADA measurements, PMUs bring a much clear and real-time picture of what is happening in the power system. PMUs have been increasingly deployed across transmission power grids worldwide. In the USA this is primarily done by utilities through projects sponsored mainly by SIGS and Smart Grid grants. There are different applications that synchrophasors can provide, including off-line and real-time applications. However, due to budget constraints, technology development and characteristics specific to each system, not all applications are equally suitable and essential for all electric power systems. This thesis provides a method for PMU applications prioritization based on the analysis and results of wide area disturbance events.

Acknowledgements

First, I would like to acknowledge my committee chair, Dr. Jaime De la Ree and my mentor Dr. David Elizondo for his support throughout my thesis development. Without their expert guidance and advice, this thesis would not have been possible. I am grateful to Quanta Technology for giving me the opportunity to work with them with this project sponsored by USTDA, and to XM Colombia for providing me the bases for this study. I am very grateful I was able to contribute to the successful development of this USTDA sponsored project and to develop my thesis work based on the work done. For their technical advice during this research, I acknowledge the following engineers and technical experts – Santiago Mesa Jaramillo and Dr. David Elizondo. Finally, I am grateful to all my loved ones, specially my mom, for their encouragement throughout my graduate studies.

Contents

List of Figures

List of Tables

1 Introduction

The idea of PMUs was introduced since the 1980's, but the need for their deployment was not recognized until the industry saw how these devices could help in the analysis and mitigation of the occurrence of major blackouts in the power systems.

Synchrophasor Measurement Units (PMUs) are devices that can measure, time stamp voltage, current, frequency, among others. PMUs take these synchronized measurements as fast as 60 times per second; compared with the traditional 2-4 second SCADA measurements, PMUs create a much clear and real-time picture of what is happening in the power system. PMUs have been increasingly deployed across transmission power grids worldwide. In the USA this is primarily done by utilities through projects sponsored mainly by SIGS and Smart Grid grants.

Synchrophasors can be used for applications which provide state estimation, post-mortem analysis, islanding, fault location, PTs and CTs calibration, model calibration, voltage and frequency monitoring, among others. PMUs help improve the observability and monitoring, analysis and control of their system. At this point in time, PMUs applications can provide observability and monitoring, whereas control is a feature that will be accessible as technology evolves and this technology is fully adopted.

Synchrophasors provide the operators PMU measurement-based analytics that augment the traditional model-based energy management analytics and monitor, analyze and control grid behavior [1]. They do not just provide improved situational awareness, but more importantly, actionable information. It is important for operators to be able to fix problems, not just know about them.

Wide area disturbance events occur mainly when the system faces outages that cause it to operate under stressed conditions, or close to its limits because system and equipment have been removed without sufficient levels of adjustment, when there is not enough load shedding, or proper isolation of the fault causing cascading of events and more severe consequences in the system [2].

There is no single solution to prevent power system events and blackouts, but synchrophasors applications can help to mitigate the impact of wider area disturbances events. It is important to take into account that each system is unique and has different vulnerable operating conditions, and as a result, possible faults and cascading events.

The development and deployment of PMUs and PMU-Based applications such as monitoring, protection and controls is a task that requires financial commitment, system studies, gathering of information from field engineers and acceptance from the complete organization. A starting point of this endeavor would benefit from a list of applications that would prioritize the benefits and impact of each proposed application into the power system based on prior contingencies and experiences from past events. The benefits could include, but not limited to, model calibration, preventive maintenance, advanced protection schemes, SIPS, etc.

Based on the occurrence of wide area disturbance events in the Colombian system, the need for PMU-based applications and a way to prioritize the synchrophasor applications for the deployment and development of this technology in their system based on their budget investments and level technology acquired/developed, as well as focus on the need of prevention and mitigation of the power system faults and blackouts, and ultimately reduction of economic losses by reducing the time with unserved energy.

1.1 Objective

For the deployment of a technology and its applications, certain budget, installations, training, and possibly other technologies are needed. This thesis work came from the need identified in some systems which are in the initial stage of adoption of synchrophasor technology and need guidelines and a source, or a method to determine which applications to start implementing in their system according to the technology available, the training needed, and the financial constrains in order to have a better idea of the limits of their system, mitigate disturbances or cascading events, and time of unserved energy.

This thesis will analyze the records of specific wide area disturbance events experienced by the Colombian transmission system. This thesis also presents PMU applications found during the literature search that suit the needs of the system that was used on this study. From the results obtained in the wide area disturbance analysis, this thesis proposes a methodology for PMU applications prioritization where a mapping of the applications with the events analysis is done in order to identify the applications that could help the system to prevent or mitigate the magnitude of the event. This work was performed targeting an applicable methodology for PMU applications prioritization and roadmap development guidelines for systems where synchrophasor technology is being deployed.

2 Literature Review

This literature review was based on the work performed for Quanta Technology for the Intelligent Supervision and Advanced Control Center project for XM Colombia. The information in this section presents the relevant information found in each source of the literature review of PMU applications in North America.

2.1 Synchrophasor Technology in North America

2.1.1 Application of synchrophasors for improving reliability (RAPIR) [20]

Phasor data applications can be grouped into three categories, as follows:

1. To improve system planning and analysis. (e.g., power system performance base-lining, model validation and event analysis).
2. Applications to support real-time grid operations for wide area visualization, and increase situational awareness.
3. Response-based control applications that use real-time wide area information to take automated control actions on the power system.

A number of the applications within the three categories mentioned are described below:

1. Wide-area situational awareness

Wide-area synchronized measurements for wide-area visualization was one of the key lessons learned from cascading outages that occurred in the Western Interconnection in 1996 and the Eastern Interconnection in 2003. Utilities and grid operators have developed in-house tools for wide-area visualization using wide-area synchronized data.

2. Frequency stability monitoring and trending

As system frequency is a key indicator of the load-resource balance, the size of the frequency deviation is well correlated with the size of generation loss. System frequency is also a good indicator of integrity of an interconnection during system events involving separation or islanding. The operator can identify islands and system separation points by looking at the bus frequencies across the entire interconnection.

3. Power oscillations

The detection of power system oscillations and ambient grid damping are among the key applications that require the high-speed data that SCADA does not provide, but PMUs do. Based on [20]: “Low-frequency oscillations occur when an individual or group of generators swing against other generators operating synchronously on the same system, caused by power transfers and high-speed, automatic turbine controls attempting to maintain an exact frequency. Low frequency oscillations are common on most power systems due to either power swings or faults”. Synchrophasor data bus frequency, angles, line loading and voltage are critical to detect potential and actual oscillations within the bulk power system. “Inter area oscillations can be seen by examining bus voltages and frequencies, so most methods of oscillation detection are applied to the path or flow gate.” [20].

4. Alarming and setting system operating limits

A number of studies of disturbances have shown that relative phase angles in the USA system strongly correlate with overall system stress and the system susceptibility to inter-area oscillations. The rate of change of the phase angle difference is an important indicator of growing system stress. The rate of change was a precursor for the 2003 Northeast blackout and the 2008 Florida blackout; this can be used as the basis for operator alarms. One goal for a phasor data situational awareness and trending tool is to have it trend phase angles against phase angle limits. Further research and base lining is needed to fully develop this capability.

5. State estimation

“Snapshots of data from PMUs can be integrated into an orthogonal state estimator by feeding PMU measurements (e.g., voltage and current) directly into the state estimator measurement vector and the Jacobian matrix it uses to solve the network.”[20].

6. Phasor data use for planning

As synchrophasor deployment and analysis improves, the understanding of power system performance and system models will also improve. Planning is very important for system reliability, below are some phasor data uses for planning:

7. Base-lining power system performance

Analysis with extensive records of phasor measurements across a large region, covering a wide variety of loads, equipment status, and other system conditions is necessary to associate system performance, and identify and understand phase angles under a variety of system conditions. PMU data is used to structure power system simulations to predict how system performance relates to the phase angles under large disturbance events.

8. Event analysis

The time-stamped synchronized nature of the data provided by PMUs provides us with a high-resolution-simultaneous-picture of the state of the system. This data is essential for disturbance event analysis and sequence event reconstruction.

9. Static system model calibration and validation

Synchrophasors can provide high-speed observations of system conditions allowing model calibration, better understanding of system operations, model data and algorithm error identification and model fine-tuning.

10. Dynamic system model calibration and validation

Realistic models are very important to ensure reliable and economic power system operations. System planning and operating decisions are based on simulations of the dynamic behavior of the power system. When system models are inaccurate or over-optimistic, they can lead operators to make decision that stress the system and eventually produce power outages whereas if the model is pessimistic, the economic generation dispatch will be affected.

11. Power plant model validation

This application has been one of the most successful applications of synchrophasors. Disturbance monitoring allows verification of the generator model performance.

12. Special protection schemes (SPS)

Synchrophasor data can be used to design and test SPS and islanding. With the increase of synchrophasors deployments and its technology improvement, it will be possible to use real-time phasor data that shows the location and causes of system stress where SPS can be applied.

13. Primary frequency response

It is important to have an adequate primary frequency control for reliable operation of an interconnected powered system. Some utilities use synchrophasor data to assess the primary frequency response by analyzing generator trip-out events.

One of the main utilizations of synchrophasors is to help deliver real-time tools that improve system operators' situational awareness. System reliability will improve as the deployment of synchrophasors increases and the collection and delivery of system condition data is improved with more dedicated high-speed communications.

Synchrophasors can be used to monitor, predict and manage frequency and voltage on the bulk power system. System voltage trending at key load centers and bulk transmission busses is one of the most promising near-term synchrophasor applications.

By monitoring system voltage using phasor measurements of voltage profile, voltage sensitivities, and MVAR margins, power system operators are able to watch voltage levels in real-time, while a trending application would provide an early indication of voltage instability vulnerability. The voltage trending and reactive reserve monitors are already mature applications.

Another use of synchrophasor measurements is for the improvement of system models for on-line and off-line network analysis. This use helps to evaluate system security and to have the capacity to withstand expected contingencies. In order to achieve this, interconnections have to have reliable, robust and secure synchrophasor data measurements, data gathering system as well as highly available, robust, and dependable analysis applications. Operators' training and support processes for the use of advanced technologies is key for the success of this technology.

In order to effectively perform wide-area situational awareness analysis, effective visualization is critical. In China, Quebec, Brazil, Europe and Eastern and Western Interconnections of North America synchrophasors are being used for wide-area measurement systems (WAMS).

"Synchrophasor technology has the potential to greatly improve operators' ability to conduct real time grid operations and detect and respond to potential disturbances." [20].

Some advantages of synchrophasor measurements are presented below:

1. Wide-area visibility and situational awareness.
2. Static and dynamic models at the system level and for individual grid assets (e.g., power plants).
3. Design of special protection schemes (SPS)/ remedial action schemes (RAS), and other system controls using local and wide-area control signals.
4. Dynamic security assessment.
5. Decision support systems to readjust the grid to improve operational security and flexibility.

2.1.2 NASPI and Synchrophasor technology progress [21]

Synchrophasor measurements have different applications. Some of them are off-line and some others are for real time applications. According to the "NASPI and Synchrophasor technology progress report", control rooms in NYISO, ISO-NE, WECC, BPA, ERCOT, MISO, and PJM plan to use synchrophasor data to perform:

1. Wide-area view with dynamic and trending assessments
2. Operator dashboards with aggregated alerts into single display
3. Shared screens across multiple control rooms
4. Integration of PMU data with EMS and other data sources

Figure 2-1 shows a map with the synchrophasor deployment in the North American power grid based on information up to Oct 17, 2013.

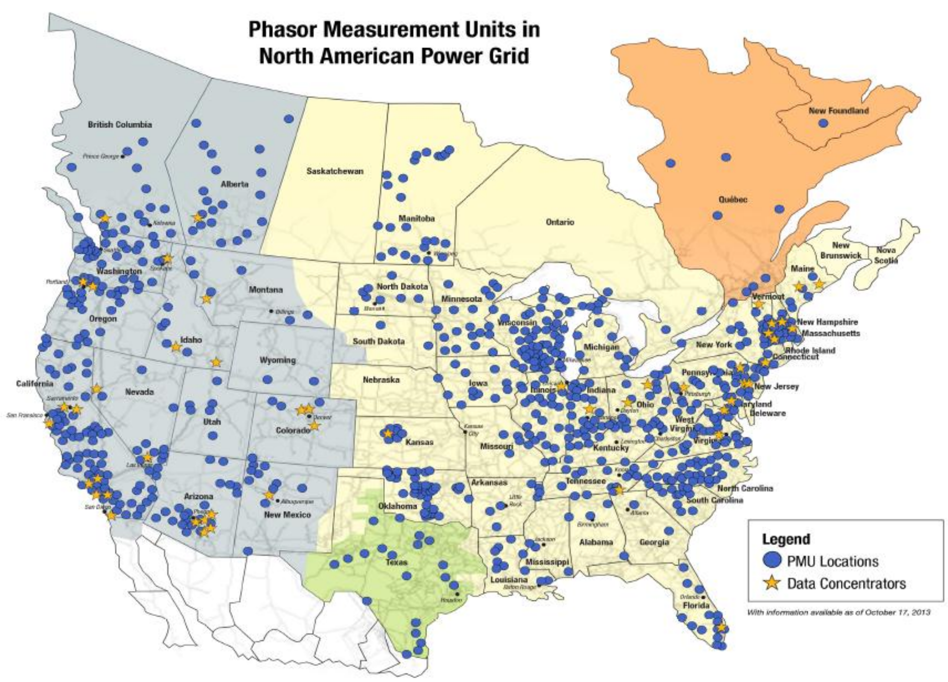

Figure 2-1: PMU deployment in North America, 2013. [21]. Silverstein, Alison. "NASPI and Synchrophasor technology progress". NERC OC-PC Meetings, December, 2013. PDF file. Used under fair use, 2014.

Some of the synchrophasor uses include, wide-area visualizations, oscillation detection, event detection analysis and response, angle difference monitoring, island detection, operator training, state estimation improvements, fault location analysis, back-up for EMS and AGS. A number of the uses mentioned are expanded next:

1. Wide-area visualization and situational awareness:

Some places like WECC, PJM, CAISO, BPA, MISO, ERCOT, and FPL have implemented it or are planning to do so. Wide-area situational awareness includes: wide-area visualization with dynamic and trending assessments, operators' visualization of alerts and system monitoring, shared screens across multiple rooms, integration of PMU with EMS and other data sources.

2. Oscillation detection:

Oscillation detection has been implemented in BPA since end of 2013. It includes the scan of voltages, power and frequency at interconnections power plants. Alarms are set to alert the operators when an oscillation is detected. BPA has displays available for problem drill-down, and engineering support applications for base-lining and alarm thresholds. "Oscillation detection and analysis is the premier application of PMU technology" - Vickie Van Zandt (WECC staff).

3. State estimation:

PJM, WECC, BPA, ISO-NE, Dominion, Duke Carolinas, and NYSIO use or soon will be using synchrophasor data into state estimator. Validation of state estimator is available at FPL and ATC, among others. Duke is working on the implementation of state estimator with only PMU data.

4. Phase angle monitoring:

In WECC, PJM, CAISO, BPA, MISO, ERCOT, and FPL, real-time phase angle monitoring and angle difference displays are being used.

5. Voltage stability monitoring and control:

ISO-NE, WECC, CAISO, MISO, NYISO, OG&E, among others, use or soon will be using synchrophasor data for voltage stability monitoring. SCE is using synchrophasor data with automation to diminish repetitive tasks for operators and improve system quality and utilization. Also their local substation voltage control uses local PMU measurements. SCE is also planning to implement multi-level hierarchical voltage control transmission network.

Different utilities and RTOs are planning to implement other operational uses of PMU data. The list below shows the name and the use of the synchrophasor data.

a. PG&E:
    - Disturbance and equipment miss-operation analysis.
    - Fault location using VAR flows.
    - Failing equipment identification.

a. Duke Energy:
    - Identified oscillations affecting a nuclear unit as caused by near-by hydro unit
    - Analyzed voltage dips created by generator AVR misbehavior, that couldn't be seen by SCADA.

b. ATC:
    - Determine causes of grid disturbances so operators can answer customer questions about faults and PQ.

c. ERCOT:
    - Uses PMU data to verify load response to demand response calls.

d. WECC, CAISO, BPA:
    - Model validation studies of disturbance events.

In addition, some of the synchrophasor uses are Off-line. This uses include, model validation, oscillation detection, frequency analysis, management of transmission, disturbance analysis, identification of miss operating equipment, reply of grid events. Some of the uses mentioned are expanded next:

6. Model validation

Model validation includes state estimator validation, and power plant validation under MOD standards (NERC). PMUs data allows displaying clear fault and unit response which gives the user the possibility to validate generator models and control operations as well as detection and response to plant oscillations.

a. NYPA: SVC unit, MarcySTATCOM
b. BPA: 10+Yrs using PMUs for generator model validation
c. ISO-NE: HVDC unit

7. Analyze oscillatory modes and events

WECC, BPA, ISO-NE, ERCOT, PJM, CAISO, FPL, Duke Carolinas, and others are currently using PMU data for this operation.

8. Management of transmission amount

Synchrophasor data and analytics can be used for real-time line ratings, congestion management, major transmission paths could benefit from this analysis.

9. Instrument transformer calibration

Current and voltage transformers can be calibrated using PMU data to improve fault location, and understanding of the power system performance. Dominion is implementing this.

2.1.3 PJM Synchrophasor Roadmap [22]

Some lessons learned from PJM synchrophasor project. Some of the challenges for the road map and recommendations are presented next.

1. Data validation, detection and elimination or correction of bad data will be difficult since there is not enough data to consider eliminating some of it.
2. Developing reliable applications that can withstand loss of a few data points is difficult with scarce data.

3. For generator and load model development and verifications, large amounts of synchrophasor data are needed at generator and load buses.
4. The installation of more synchrophasor measurement devices is recommended.

- Only a few generators and load buses have PMUs. There are not large amount of PMU measurement points.
- Install PMUs at all new generator interconnections or upgrades of larger than 75 MVA
- Install PMUs at points with major regional Transmission Expansion Planning (RTEP)

PJM Synchrophasor project consisted in the implementation of a robust data collection network and the development of PMUs in 81 of its high-voltage substations. This project was performed between PJM and 12 transmission owners (TOs). Figure 2-2 shows the system overview of the PMU deployment for PJM.

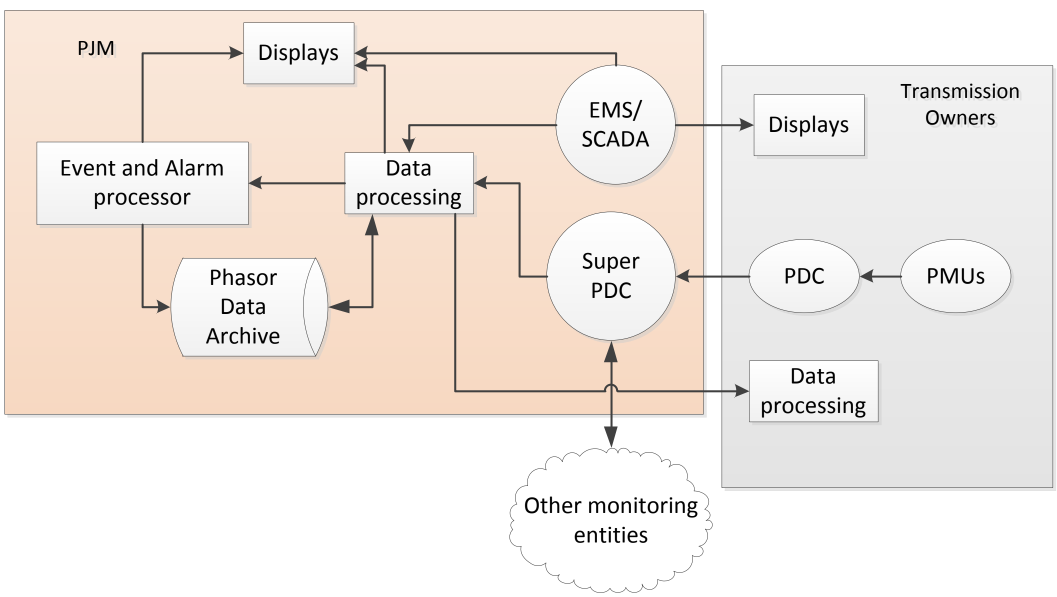

Figure 2-2: PJM Synchrophasor Deployment [22]. Synchrophasor Roadmap. SOS Meeting, 01 March, 2012.

Figure 2-3 presents a table with the implementation roadmap, where the requirements and risks classified as low, medium, and high; against the business benefits which are also classified as low, medium and high.

Synchrophasor Application Prioritization for Implementation Roadmap

Implementation Requirements and Risks				
	High	Special protection system design; System operation limits evaluation and design.		Transient stability monitor
	Medium	Renewable resources output monitoring and alarm; Fault location	Controlled system separation; System restoration; Real-time transfer limits; Real-time reactive power and voltage control	Voltage stability monitoring and alarming; Oscillation detection
	Low	Frequency monitoring	Grid stress	Improve accuracy of state estimation; System model calibration and validation; Post event analysis
		Low	**Medium**	**High**
		Business Benefits		

Defer | Long Term | Medium Term | Short Term

Figure 2-3: Application assessment. "Project Specific Deployment." SmartGrid. U.S Department of Energy. Web. 25 Feb, 2014.<www.smartgrid.gov/recovery_act/deployment_status/project_specific_deployment>.

2.1.4 Project Specific Deployment (Recovery Act Smart Grid Programs) [23].

The American Recovery and Reinvestment Act of 2009 provided funding for smart grid projects through several distinct programs. Some programs are Projects funded through the Smart Grid Investment Grant (SGIG) and the Smart Grid Demonstration program (SGDP). Below is a list and a high level description of some of the projects related with synchrophasor technology reported by the recipients of the Recovery Act funding. Figure 2-4 shows the number of PMUs that have been deployed in the U.S as a result of the SGIG program.

Figure 2-4: PMUs Installed and Operational as of Dec 2013 [24]. "Deployment Status." SmartGrid. U.S Department of Energy. Web. 25 Feb, 2014. <www.smartgrid.gov/recovery_act/deployment_status>. Used under fair use, 2014.

1. Western Electricity Coordinating Council (Western Interconnection Synchrophasor Program)

The Western Electricity Coordinating Council (WECC) and eight of its member transmission owners are deploying synchrophasor devices throughout the U.S. portion of the Western Interconnection. For this project, the deployment of PMUs, PDCs, communication systems, information technology infrastructure and advanced transmission software applications was required.

The main objectives of this project are:

a. Improve electric system reliability and restoration procedures
b. Prevent the cascading of outages to other regions.
c. Improve grid operators' visibility of bulk power system conditions in almost real-time.
d. Enable earlier detection of problems that could cause system instability
e. Facilitate sharing of information with neighboring control areas.
f. Access to better system operating information which also allows:
    - Power system models improvement
    - Analysis tools improvements
    - Improvement in reliability and operating of the power system.

2. PJM Interconnection, LLC (PJM Synchrophasor technology deployment project)

This project is formed by PJM Interconnection (PJM) and twelve of its member transmission owners. This project is a complement for the exciting deployed technology in their system in order to provide information technology infrastructure and wide-area coverage and motoring, thus helping the development for additional applications. This project consists on the deployment of synchrophasor measurement devices in 81 of its high-voltage substations and the implementation of a robust data collection network.

3. Midwest Independent Transmission System Operator (Midwest ISO synchrophasor deployment project)

The Midwest Independent Transmission System Operator (Midwest ISO) is deploying synchrophasor technology across its system. This project deploys phasor measurement units (PMUs), phasor data concentrators, and advanced transmission software applications.

4. ISO-New England (synchrophasor infrastructure and data utilization (SIDU) in the ISO New England transmission region)

ISO-New England (ISO-NE) and seven of its transmission owners are installing synchrophasor, phasor data concentrator (PDC) devices, communication infrastructure, and new applications across the six states in the New England control area.

The main objectives of this project are:

a. Improve electric system reliability and restoration procedures.
b. Prevent the cascading of outages to other regions.
c. Enhance monitoring capabilities
d. Increase situational awareness
e. Determines real-time grid stability margins.
f. Improve grid operators' visibility of bulk power system conditions in almost real-time.
g. Enable earlier detection of problems that could cause system instability
h. Facilitate information sharing with neighboring control areas.

i. Access to better system operating information which also allows:

- Power system models improvement
- Analysis tools improvements
- Improvement in reliability and operating of the power system.

5. Entergy Services, Inc. (Deployment and Integration of synchrophasor technology)

Entergy's Deployment and Integration of Synchrophasor Technology project is deploying phasor measurement units (PMUs), phasor data concentrators (PDCs), and state of the art decision support tools across Louisiana, Mississippi, Arkansas, and non-ERCOT portions of east Texas. The main objectives of this project are:

a. Improve grid operators' visibility of bulk power system conditions in almost real-time.
b. Enable earlier detection of problems that could cause system instability
c. Facilitate information sharing with neighboring control areas
d. Training and education for the operations and engineering groups to implement these advanced tools.

6. American Transmission Company (Phasor measurement unit project)

American Transmission Company's (ATC) Phasor Measurement Unit Project is deploying synchrophasor technologies across the company's Wisconsin service area. ATC plan is to use synchrophasor technology for monitoring. The project expands the collection of synchrophasor data throughout ATC's transmission system from 25 substations to 73 substations by project completion. The main objectives of this project are:

a. Improve electric system reliability and restoration.
b. Prevent the cascading of outages to other regions.
c. Improve grid operators' visibility of bulk power system conditions in almost real-time.
d. Enable earlier detection of problems that could cause system instability
e. Facilitate information sharing with neighboring control areas

Some advanced transmission applications that ATC is implementing for the synchrophasor system are:

a. Angle/frequency monitoring
    - Provides operators and engineers detailed information about grid conditions and power flows.
b. Post-mortem analysis
    - Enables operators and engineers to analyze disturbances and large scale system events.
    - Allows improvement of future system models and operations.
c. State estimation
    - Improvement of accuracy of power systems models for planning and operations.
d. Steady-state model benchmarking
    - Improvement of accuracy of power systems models for planning and operations.

7. Duke Energy Carolinas, LLC (PMU deployment in the Carolinas with communication Esystem modernization)

Duke energy Carolinas, LLC (Duke) phasor measurement unit deployment in the Carolinas with communication system modernization project consist in the upgrade of existing serial-based communications infrastructure, installation of PMUs and phasor data concentrators, and update to the existing energy management systems, along with visualization software. Fifty-one substations across the Carolinas, at the 230KV and 500 KV levels, are targeted to have the communications upgrade and approximately two PMUs planned per substation.

The deployment of this technology will enhance:

a. Situational awareness for grid operators
b. Visualization of the transmission system
c. Management of the transmission system
d. Reliability and grid operations.

2.1.5 ISO New England Completes Synchrophasor Deployment [25]

ISO-NE and the regional transmission owners installed about 80 PMUs at 40 substations in New England. Also, phasor data concentrators (PDCs) at the ISO and 7 transmission owners, communication infrastructure to support PMU data streaming from the substations to the transmission owners (TOs) and then to the ISO. A number of PMU applications were also installed as part of the Synchrophasor Infrastructure and Data Utilization (SIDU) project.

ISO-NE is now able to monitor system dynamics, execute fast and accurate post-event analysis, and validation and improvement of power system models. ISO-NE will try to find applications to determine potential integration of PMU data in the operation of the power system. With these deployments, it is expected to improve reliability with new restoration capabilities, better situational awareness, and faster response to real time system events.

2.1.6 Innovation leader: MISO uses real-time synchrophasor technologies to enhance reliability [26]

The incorporation of synchrophasor technology into real-time operations has advantages and some of them are shown below:

a. Increase situational awareness of grid activity to grid operators.
b. Grid modernization.
c. Provide unprecedented data on situations that could affect reliability.
d. Ability to see ongoing system conditions.
e. Enhance ability to simulate and troubleshoot bulk power systems.
f. View vital current and voltage measurements at any point where PMUs are placed.

MISO developed an enhanced Real-Time Display (eRTD), a feature for Control Room displays, which gives a two-way visualization of real-time grid activity allowing participating TOs to see the same displays of grid activity as MISO control room operators.

2.1.7 Eastern Interconnection Phase Angle Base Lining Study [27]

Some advantages of phase angle base lining with PMUs are:

1. Phasor measurements provide the capability to monitor phase angle differences in real-time helping to indicate wide area system stress.
2. Angle differences can be correlated with power flows and state estimators and also indicate system stress.

An example of a screen shot of the results for 35selected angle pairs can be found at [27]

The objective of this study was to develop a methodology for base lining using data from different ISOs and to establish angle difference ranges for use in real-time operations.

In order to perform the study based on the angle base-lining, data from state estimator solutions and stressed power flow cases was used to:

1. Analyze phase angle difference.
2. Analyze other power system metrics.
3. Establish baseline for performance.
4. Utilize results to establish benchmarks and norms for use by operators.

Some challenges faced during this project were:

1. Operators monitor power flows at specific interchange points (power flows may not be a good measure of wide area system stress).
2. The data from ISOs is in different formats.

Data Time Periods Not Consistent - data coordination and merging have been difficult.

2.1.8 Real-Time Voltage Stability Monitoring [28]

The hybrid approach to voltage stability assessment consist on voltage stability based on measurements and based on models to help identify potential problems and to evaluate the power system respectively.

1. “Measurement-based” voltage stability identify potential problems:

    a. Voltage profile & sensitivities
    b. Monitor available reactive power levels
    c. Singular value decomposition
    d. Real-time voltage instability indicator (RVII)

2. “Model-based” voltage stability evaluate:

    a. MW/MVAR margins
    b. Weak network elements
    c. Voltage stability assessment (VSA) from state estimation contingency analysis.
    d. Corrective actions
    e. Model validation
    f. Track the relative distance from voltage instability continually in real time.

3. Real-time voltage instability indicator gives fast real-time voltage instability detection, independent of state estimation. It can be easily combined with other methods (reactive power monitoring, model–based contingency analysis). It gives the ability to process data from different sources and takes advantage of available PMUs. It is simple to implement in control center tools and local IEDs allowing operator tools to increase situational awareness and local automated actions. Figure 2-5 shows monitoring control strategies based on RVII.

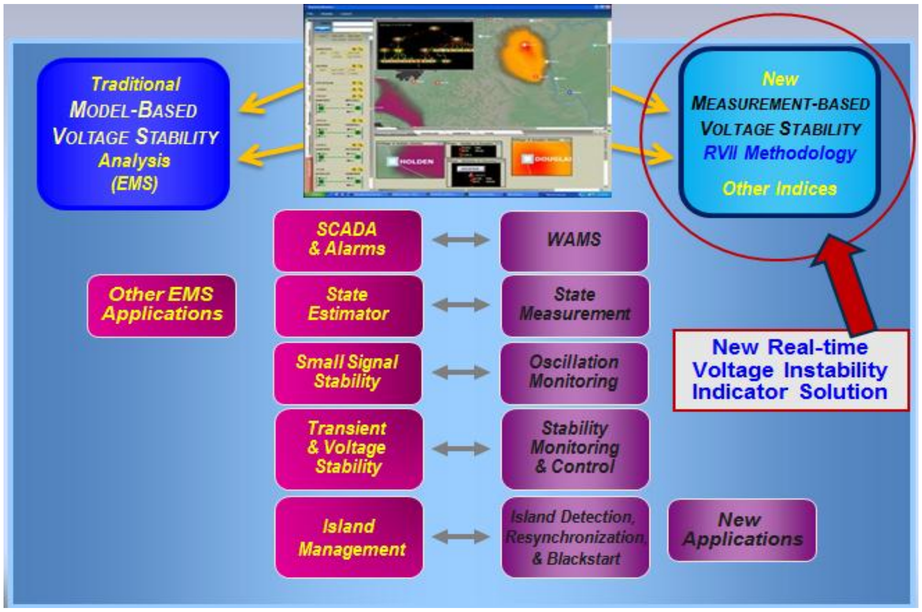

Figure 2-5: Design monitoring control strategies based on RVII, [28]. Damir Novosel. (2013). Real-Time Voltage Stability Monitoring. JSIS Meeting, Tempe, AZ, USA, January 15-17. Used under fair use 2014.

2.1.9 New technology can improve electric power system efficiency and reliability [29]

Some off-line uses for synchrophasor data include:

a. Electric system models for use in real-time operations and planning.
b. Disturbance analysis
c. Forensic investigation

Some on-line uses for synchrophasor data include:

a. Enhance situational awareness
b. Prevent transmission system failures
c. Isolate grid problems
d. Develop automated responses to system disruptions (needs more research)
e. Identify and correct mismatch between supply and demand, or a breakdown in synchronization

Some lessons learned from previous blackouts in the U.S are:

a. Develop methods to improve storage, analysis, and distribution of large amounts of data.
b. Better understanding of the grid behavior from high-speed phasor data.
c. Make software applications fully usable.

"(NASPI) reports there are about 500 networked PMUs installed. NASPI expects that approximately 1,000 PMUs will be in place and networked by the end of 2014, a timeline associated with the Department of Energy's Smart Grid Investment Grant" [29].

2.1.10 PJM Synchrophasor Technology Deployment Data Network & Applications [30]

The purpose of this PJM project is to deploy data network and applications in order to be able to connect the following applications to a PDC in any level in the synchrophasor system.

a. Situational awareness
b. Decision support
c. Real-time analysis (SE/CA)
d. Planning
e. Automated control

Figure 2-6 shows a diagram of the list above:

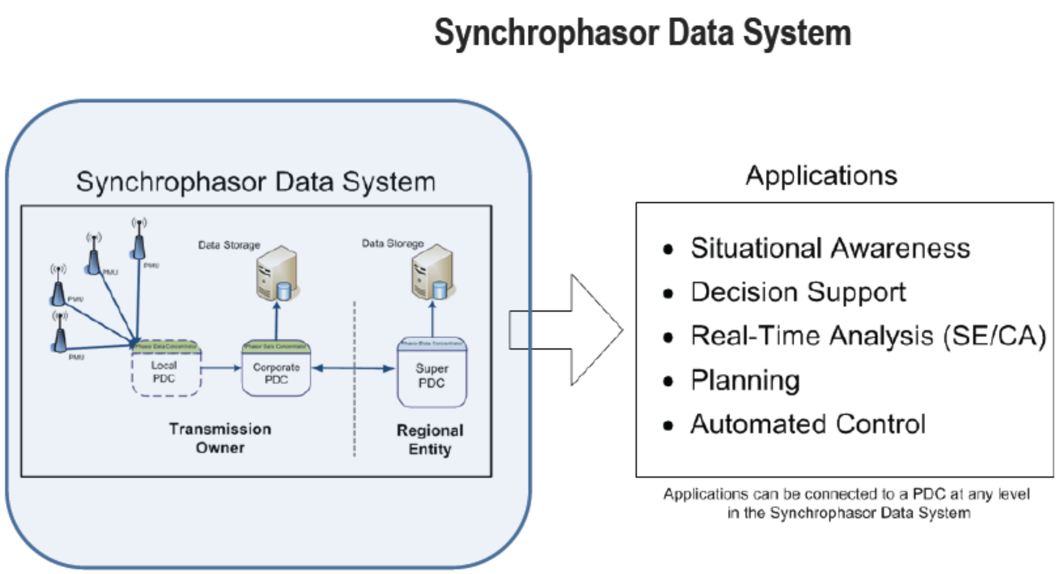

Figure 2-6: Synchrophasor data system in PJM. Patel, Mahendra. "PJM Synchrophasor Technology Deployment Data Network & Applications". Applied Solutions, PJM. PDF file Used under fair use, 2014.

The following information presents applications to implement with synchrophasor data.

1. The System architecture includes the architecture, design and communication of the system. There should be a reliable performance between PMU/PDC equipment, ensure that the

architecture is capable of accepting more PMUs and changes in the database size and format.

2. Synchrophasor security framework has some benefits for the power system. Some of them are:

- Detection
- Response
- Mitigation
- Correction
- Restoration

3. Model validation includes modeling of lines, transformers, generators, and loads.
4. Oscillations detection: for this application a prototype screen of a mode meter is shown in reference [30]., a display of a time plot of a critical signal, the spectral energy, and oscillation frequencies and damping (alarm included) can be found.

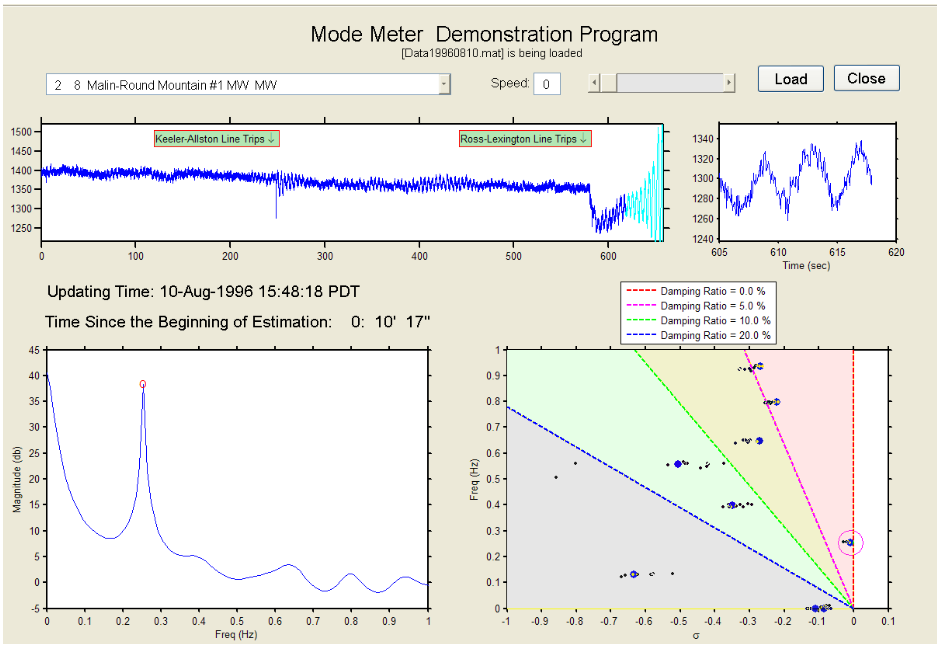

Figure 2-7: Oscillations detection: Mode meter [30]. Patel, Mahendra. "PJM Synchrophasor Technology Deployment Data Network & Applications". Applied Solutions, PJM. PDF file. Used under fair use, 2014.

5. Visualization tools are important to have at the control room, since it allows operators to see the "big picture" of the system behavior. A number of visualizations include:

a. Dashboard
b. Voltage sensitivity display
c. Interconnection wide view

6. Statistical analysis for this project consist of plots showing the daily angle differences for on-peak and off-peak data.
7. Wide-area situational awareness use PMU data to give the current system state. The goal is to be able to determine where the edge is, and how close to the edge can the system still operate reliably.
8. Base lining studies based on synchrophasor measurements are required to understand the behavior of the system.
9. Other analysis and developments that can be done with synchrophasors data are:

a. On-line data validation
b. Voltage stability controls for synchrophasor state estimation
c. Data mining, pattern recognition, and decision trees for decision support are need for transient stability controls.

Some of the challenges and lessons learned from this project are listed next:

a. Establish test criteria to use at installation
b. Ensure data quality at TO PDC before sending data.
c. Lack of situational awareness contributed many wide-area disturbances
d. TO installation schedule changes
e. Multiple vendors hardware and software in use
f. Data quality and availability
g. Coordination of all project stakeholders TOs, Vendors, ISO/RTOs, DOE
h. Ensuring the architecture is scalable
i. Storage capacity
j. Data exchange with other RTO/ISO’s

The goal is to have a redundant network like the one shown in Figure 2-8.

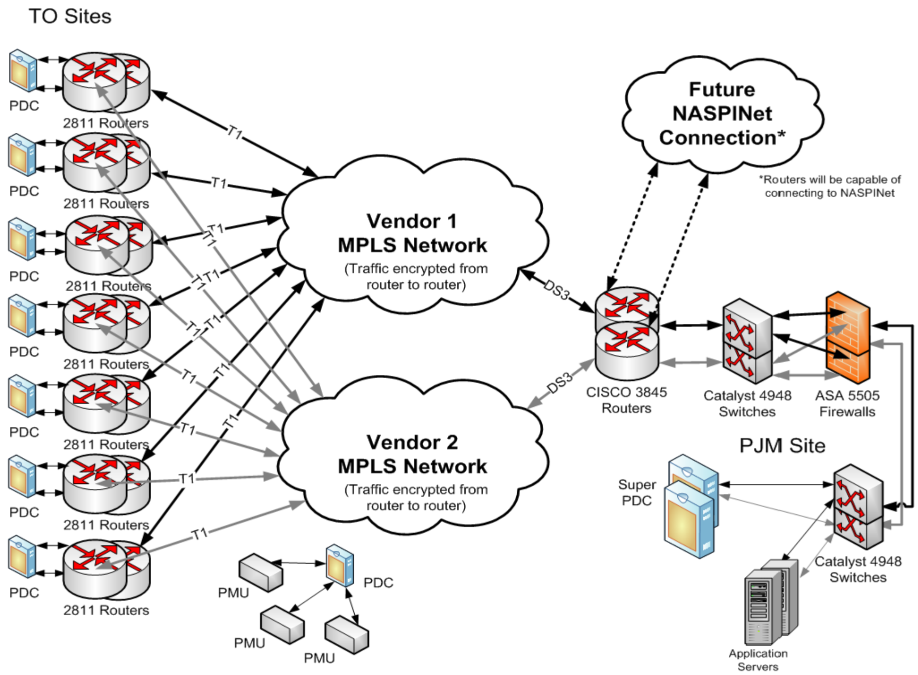

Figure 2-8: Synchrophasor redundant network [30]. Patel, Mahendra. "PJM Synchrophasor Technology Deployment Data Network & Applications". Applied Solutions, PJM. PDF file . Used under fair use, 2014.

2.1.11 NASPI Overview [31]

Synchrophasor technology has several applications, on-line and off-line. In order to implement some applications, there is a "maturation process" that should be done. One of them is focusing and facilitating base lining and trending of the system (e.g. oscillation detection). Another aspect is to try to find solutions to the early identification of the challenges that the project has, as well as the different groups that need to work together for the implementation. Some of these challenges are listed next:

1. Develop and test PMU device specifications, interoperability, and communications network design
2. PMU placement
3. End-to-end data flow and quality
4. Develop requirements for "production-grade" systems
5. Key software infrastructure
6. Enhance applications value and operator and user training

Another set of lessons learned from synchrophasor technology implementation is the deployment challenges. Some of these challenges are:

1. Application maturity
2. Training
3. Cyber security
4. Interoperability
5. Reliability of the measurement technology
6. Robustness of the supporting architecture
7. Data sharing challenges
8. Network and data quality
9. Adaptability of the system

Security of synchrophasors is important and R&D is being done by different programs. Some of the things to consider in synchrophasor security are:

1. Synchrophasors will require physical and cyber security.
2. Synchrophasor systems will coexist with other bulk electricity system (BES) cyber infrastructure and will have similar dependencies on common communications and network elements
3. System designers and owners are leveraging emerging cyber-security standards and technologies
4. Currently available phasor applications require further data analysis, software refinement and operational validation to be fully effective
5. Due to nature of continuous, high-volume data flows, new technology will likely be required for measurement, communications, and applications.

2.1.12 Grid Operations – program 39 [32]

The increase of computational efficiency of control room applications and increase of the resolution of the calculations has had a lot to do with the implementation of synchrophasor data to enhance situational awareness and decision support tools, which allow operators to reliably and economically operate the system when failures or stress is detected.

Reactive power support, base lining, system stability, system management and aid through extreme event occurrence are needs that EPRI's Grid Operations research program is studying.

Operations and Utilizations:

The main objective of this program is to develop practical systems and computational techniques that take advantage of the synchrophasor data in a real-time environment to enhance situational awareness and control capabilities when the system is unstable.

Actual voltage stability analysis technologies are based on what-if simulations to anticipate potential voltage instabilities and know how to act accordingly. The increase of PMU deployment helps toward the goal of performing voltage stability analysis in real-time. The integration of measurement-based and simulation-based studies is an item that still needs more R&D to better monitor and control the system.

In the next three years, the U.S will have a total of more than 1000 PMUs deployed with the help for smart grids investment grants and demonstration projects funded. This is a big step in the right direction to develop practical systems and computational techniques to effectively apply PMUs for online monitoring and control of the power system.

2.1.13 North American Synchrophasor Initiative, Report of Task Force on Testing and Certification [33]

As part of the American Recovery and Reinvestment Act (ARRA), PMUs and the necessary infrastructure to gather data and develop reliability applications are being deployed in more than 850 substations. In addition to large-scale deployment of the synchrophasor technology in the United States, China, India, countries in the European grid, Russia, Australia, Brazil, and Indonesia have initiated projects focused on wide-area monitoring using synchrophasor technology. The majority of these devices are planning to follow the Institute of Electrical and Electronics (IEEE) standard C37.188-2005. With the large installed base using the 2005 standard's data transmission protocol, the new C37.118.2 data transmission standard maintained backward compatibility to provide continued support with some improvements over the 2005 version.

An important point to take into account for synchrophasor deployment is that the devices available from various vendors should be interoperable, so that the end users have compatible data. The protocols and formats are as important as the synchrophasor, frequency, rate of change of frequency (ROCOF) from the devices that need to have certain accuracy range.

It is key to plan how the system expansion will evolve and to know the phasor measurement suite of products to make sure the system meets the future interoperability requirements.

To make sure the system meets future interoperability requirements, one must anticipate how the future expansion of the system may unfold. However, the key component of the system is the phasor measurement suite of products. Figure 2-9 shows the end-to-end data flow in a typical synchrophasor system.

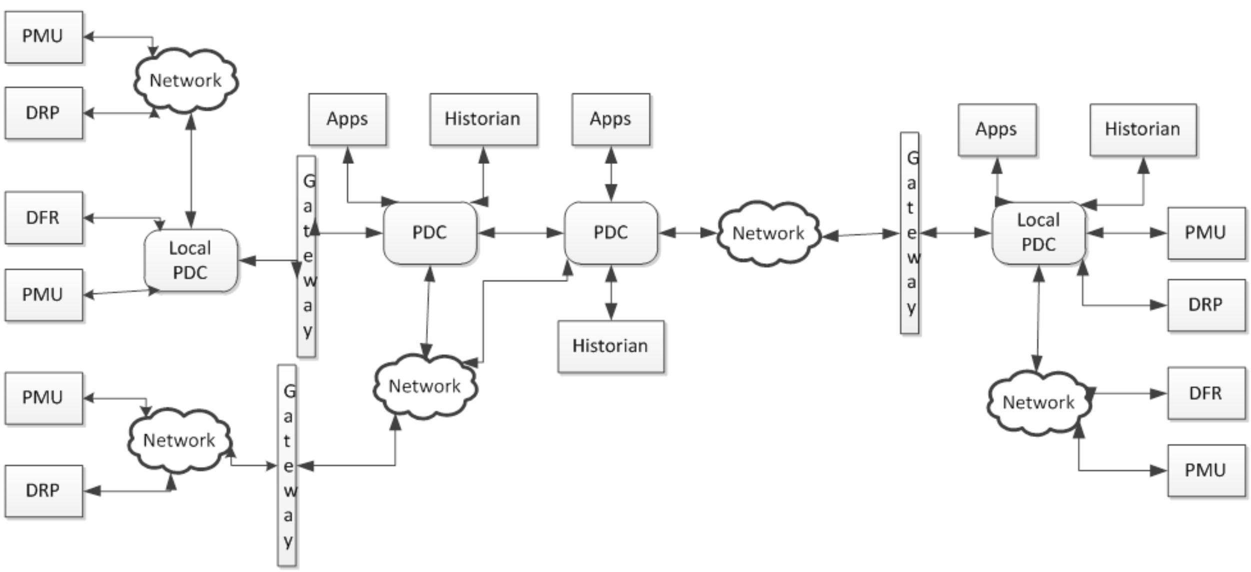

Figure 2-9: Typical End-to-End Synchrophasor Wide-Area Measurement, Protection and Control System and its Components [33]. NASPI Report of Task Force on Testing and Certification". NASPI TF, Report on PMU testing and certification, Oct 17, 2013. PDF file.

2.1.14 Considerations for the Application of Synchrophasors to Predict Voltage Instability [34]

From the R&D demonstration project installed by Long Island Power Authority, it was concluded that phase angle difference gives important information about the total power transmitted. It is very important to know the system so that when analyzing the collected data, it can be associated with the phase angle data since changes in the system configuration change the phase angle of the power transmitted.

Synchrophasors were used to predict voltage instability in the Long Island system. This section lists some of the lessons learned from this experience.

1. Setting up the communications is a challenging task that takes a lot of time. It requires collaboration between communication groups.
2. In order to distribute data in real time to multiple users, details of the firewall configuration have to be determined.
3. It is important to be able to connect to and from different types of communication media. So, accommodation of different types of communications should be built into a synchrophasor system from the ground up.
4. To mitigate communications and system security problems, the “stakeholders” in the project should be involved early in the design process.
5. The system design should have enough flexibility to meet the needs of different users including: Data-base formats, training, display options are topics that can be established in the first project phases.
6. It is important to find a way to use SCADA inputs of the system topology so that the impedance is known at the same time that the PMUs measure the voltage angles.

2.1.15 North American Synchrophasor Initiative –FPL [35]

The Energy Smart Florida (ESF) project consisted in the deployment of 45 PMUs at 13 transmission stations, phasor data concentrators (PDCs), and communication networks. Some of the expected improvements from the synchrophasor implementation are:

1. Wide-area situational awareness for system operators
2. More reliable analysis for detection of system margins
3. Phasor monitoring to determine stress points of the transmission system.
4. Detection and mitigation for islanded sections of the system.
5. Post-disturbance analysis capability

6. Enables visualization of PMU data for system operations to be incorporated into the energy management system (EMS)
7. State estimation (SE) improvement in EMS
8. EMS applications more accurate helps overcome modeling delays

The implementation of an Open Phasor Data Collection also gives benefits, which are listed next:

1. Provide a flexible framework for the collection, processing, concentration and archiving of PMU data.
2. Develop integration of PMU data to interface with EMS state estimator, NASPI project historian.
3. Improve SE in EMS
4. Enables system stress check for small perturbations
5. Enables port-event data analysis

Wide area monitoring tools were implemented to improve situational awareness and system monitoring, have a more comprehensive view of the system conditions that provide alarming and GIS-based visualization, and allow system operators to monitor abnormal grid conditions utilizing PMU data in conjunction with other applications.

The development of voltage stability analysis solutions gives the following benefits listed next:

1. Integration of model-based dynamic security assessment applications
2. Anticipate instability/ system stress
3. Allow the operator to mitigate instabilities
4. Improve visualization of system’s voltage profile
5. Improve analysis of voltage conditions across system

For the implementation of this technology three challenges were identified:

1. Pathway to other operating entities

2. Network installation coordination
3. Coordinating of equipment outages for PMU installation

2.1.16 NASPInet - The Internet for Synchrophasors [37]

The NASPI data infrastructure currently uses a number of devices, mainly PMUs that take power system measurements from stations and substations, and phasor data concentrators (PDCs) which time-align (synchronizes) the data and gives it to applications. PMUs transmit the data to PDCs or other data collection devices which are at either the centralized control center where the data is collected and combined, or in the field. PMUs give a better indication of grid stress, and can be used to provide information to system operators, and to trigger mitigating actions to maintain reliability.

Wide arrays of protocols are currently in use [37]. This leads to a level of management complexity that is not desirable or sustainable across an interconnect-wide deployment. Also, the Super PDC and its associated services are potentially a single point of failure.

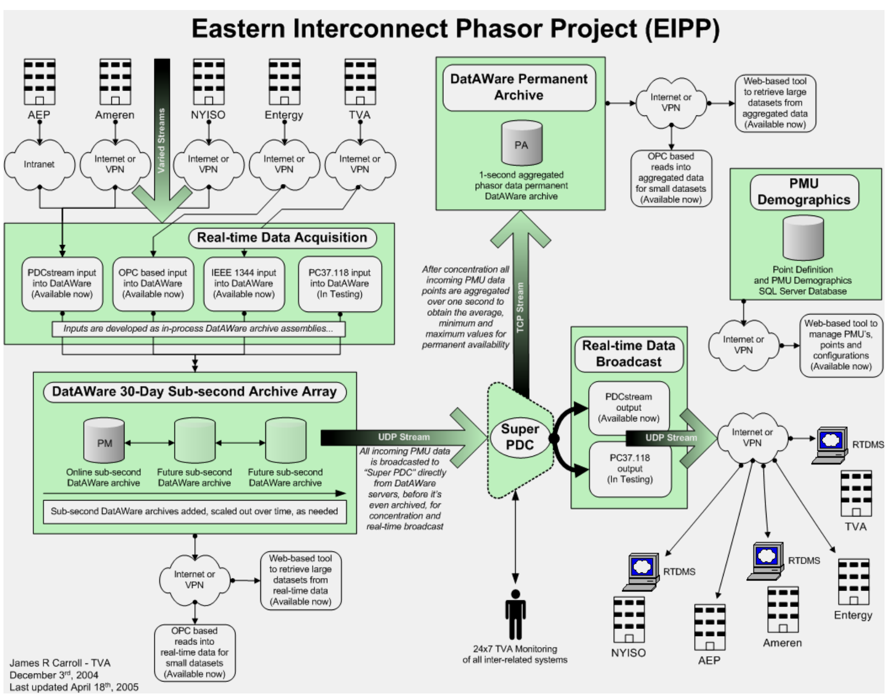

Figure 2-10: Existing super PDC architecture [37]. Paul T. Myrda, Kris Koellner. "NASPInet - The Internet for Synchrophasors" System Sciences, 2010. Proceedings of 43rd Hawaii International Conference on System Sciences. Used under fair use, 2014.

Figure 2-10 shows architecture with multiple nodes and a centralized configuration management service. This architecture does not have the single point failure of the Super PDC since it has all data sent to two connection point servers. This model is better for data archiving; however, there are still some difficulties in the overall system management.

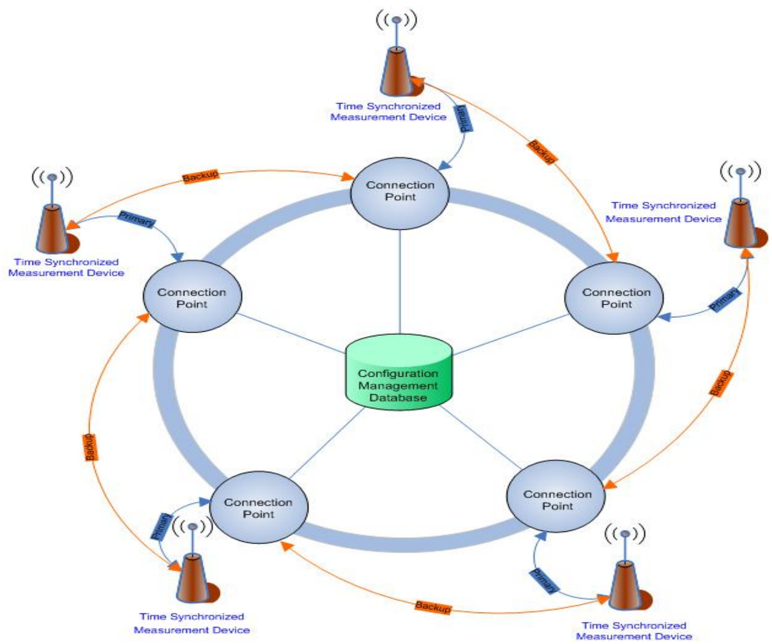

Figure 2-11: generation II System [37]. Paul T. Myrda, Kris Koellner. "NASPInet - The Internet for Synchrophasors" System Sciences, 2010. Proceedings of 43rd Hawaii International Conference on System Sciences. Used under fair use, 2014.

In order to provide reliable connections between data suppliers, NASPI and Network Management Task Team (DNMTT) developed the idea that uses Phasor Gateways and wide area Data Bus. From this idea, NASPInet specifications were developed. Figure 2-12 shows an overview of the NASPInet idea.

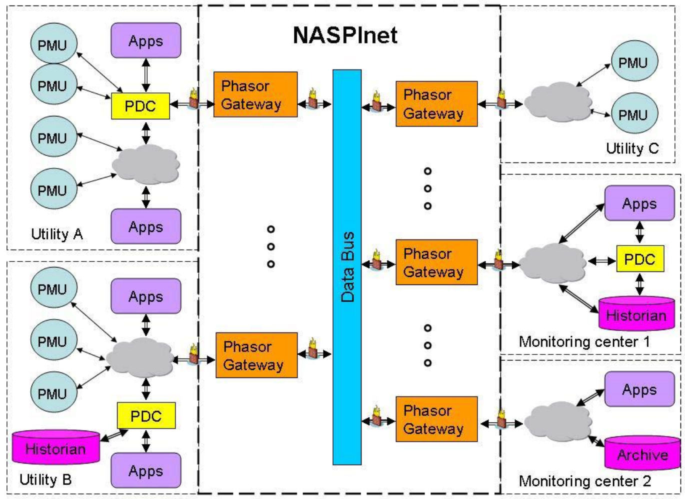

Figure 2-12: NASPInet Overview [38]."Data Bus Technical Specifications for North American Synchro-Phasor Initiative Network (NASPInet)," Yi Hu Project Manager, May 29, 2009. Used under fair use, 2014.

2.1.17 Network Information Gathering and Fusion of PMU Measurements [39]

Lessons learned from synchrophasor R&D

"The synchrophasor technology is emerging as an enabling technology to facilitate both information interaction and energy interaction between providers and customers. It is critical to develop reliable and secure communication systems for synchrophasor data."[39].

NASPI plays a main role in the information management aspect of the deregulation of the power industry where it has moved the operations of power grids from vertically integrated centralized management to coordinated decentralized management.

"A possible approach to security assessment is the "modeless" approach, where Thevenin equivalents as seen by key lines are computed from PMU data and used to estimate the margins to thermal, voltage and angles security violations. With PMU data being the primary a source of creating equivalents, the assessment would be able to track the margins to critical values in real-time". [39].

3 Case Study and Results

This section of the thesis presents a definition of the real-time and off-line applications PMU applications identified throughout the literature review.

3.1 PMU Applications

There are many synchrophasor applications. Ideally a system would deploy all of them and mitigate and prevent many different kinds of events. The reality is that there are budget constraints as well as technology and R&D, so not all applications are ready for deployment and not all are equally necessary for a power system. This section presents different real time applications and their definition.

3.1.1 Real-time Applications

1. Advanced applications

These applications include PMU assisted System Protection Integrity Schemes (SIPS), special protection system (SPS), remedial action schemes (RAS), under voltage load shedding (UV), and out-of-step detection and mitigation.

Unlike conventional protection systems that are applied to protect a specific power system element, SIPS are installed to protect the integrity of the power system or strategic portions of the system. SIPS encompass Special Protection Schemes (SPS), Remedial Action Schemes (RAS) and varieties of other safety nets. These schemes provide countermeasures to slow and/or stop cascading outages caused by several levels of contingencies.

2. Advanced situational awareness

Advanced situational awareness has the goal to combine energy management systems (EMS) and phasor management system which helps the operator in the wide area monitoring and decision making. Early stages of visualization include EMS-only or PMU-only visualization applications where as advanced situational awareness combines both data from EMS and from synchrophasors into an integrated visualization application.

3. Frequency monitoring and control

Frequency monitoring is an application that synchrophasors provide to monitor frequency of specific buses and to indicate when there is generation loss based on frequency deviation. It is important to determine the primary frequency of the system by performing base-lining studies and model calibration. Some of the wide area disturbance events presented in the system had frequency deviations and using PMUs for frequency control will help for the under-frequency load shedding scheme.

4. Oscillation monitoring

Oscillation monitoring of local and inter-area oscillations is one of the applications that SCADA does not provide. The data from synchrophasors for voltages, power and frequency can be analyzed to identify low-frequency oscillations in the system.

Oscillations can be present in various different areas of the power system, due to local conditions, e.g. sub-synchronous resonance in a generating plant, or swings between generators. This application detects the presence of low frequency oscillations due to either of these causes, to estimate the degree of damping, and to support various, user configured input signals to enable operators or analysts to narrow the possible cause of the oscillations and take corrective measures.

This application function can operate in either real-time mode or study mode. In real-time mode, it can detect existence of low frequency oscillations and generate alarms / warnings based on preset amplitude and frequency limits. In the study mode, it can perform spectral analysis on the system and identify various oscillation modes on the historical data.

5. Power flow monitoring

This application is usually a standard part of a wide area monitoring system (WAMS). The user of this application should be able to monitor power flow across the defined transmission interfaces. An interface is defined as a branch or a collection of branches carrying bulk power from one region to another. The application is required to calculate power flow along each line of the interface and add them to arrive at the total interface power flow.

6. Real-time data validation

Data validation helps ensure that applications have data availability, integrity, and arrives on time. In this way, the most common problems can be identified and solutions/directions can be addressed. This application has two main steps; self-validation and crosscheck. Self-validation focuses on PMU related issues (follow IEEE Standard C37.118) and does not require physical meaning of the measurement or the status of the power system. For crosscheck with SCADA/EMS, the focus is on the physical meaning of the measurements and of the power system, by looking at the voltage magnitude and angle, as well as P, Q, and MVA. It takes into account issues with wiring, system elements, and configuration. For high redundancy, a crosscheck with other PMUs would be possible, but it requires more synchrophasor deployments [3, 4]

7. State Estimation (SE)

The traditional state estimator function in a control center today is a suite of three programs solved sequentially: topology processing, state estimation, and bad data detection-identification. The state estimation equations are nonlinear because the inputs are mostly real and reactive power measurements, so the solution requires iterating to reach convergence. Convergence can be hindered by bad data, particularly if there is an error in the network topology. If all the analog measurements were complex currents and voltages (not the case with EMS SCADA data), the state estimation would be linear, thus eliminating the convergence issue.

The State Estimation application can be implemented in several versions:

EMS-based state estimator is the key application in the energy management system (EMS) because the performance of the advanced applications is highly dependent on the state estimator robustness and the quality of the state estimator result. The SE uses real-time analog and status telemetry in order to calculate an estimate of system voltages and MW and MVAR power flows in the entire power system network. Since inexact measurements are used to calculate the complex voltages, the estimate will also be inexact. This introduces the problem of how to devise a “best” estimate for the voltages given the available measurements. It is important to emphasize that the traditional EMS SE does not qualify as a real-time application – it is performed on a periodic basis, with multi-minute intervals.

Phasor- based (linear state estimator), a linear state estimator is possible if the inputs are only complex currents and voltages and if there are enough such measurements to meet observability and redundancy requirements. The linear SE requires PMUs located at all buses that are desired to be monitored by the SCADA/EMS systems. The main limitation in implementation of the linear SE on a wider base is insufficient number of the PMUs installed. To address this issue, presently this type of SE is being considered at voltage levels that are well covered by PMUs (for instance, at 500kV, or 345 kV). However, in the future this problem will be less pronounced, since the PMU technology cost is decreasing

Hybrid (enhanced) state estimator, it has been shown by researchers [5] that by careful placement of PMUs in the system, and using the measurements from them along with the conventional measurements, it is possible to enhance the accuracy and convergence characteristics of the existing EMS based and phasor based state estimators combination. Usually, a weighted least squares (WLS) estimator is used to find the best estimates of the states [6]. In case the system is completely observable by only PMU measurements, a linear estimator can be used to obtain the states. However, such a measurement system will need a large number of PMUs for a large system, which may not be technically and economically feasible in the near future. A ‘hybrid’ state estimator is needed to find the best estimates of the states when the measurement set consists of conventional as well as PMU measurements. There are multiple ways of implementation of the hybrid SE [7].

Distributed state estimator, this is a type of SE conceptually simple and consists of the following components:

Distributed state estimator (DSE) is a phasor-based and real-time application that requires a detailed three-phase substation model (for monitoring all three phases) and at least one PMU device per substation. It enables calculation of the states at each phasor sampling cycle (e.g. sixty times per second). The advantage of the DSE is that there is no information loss since detailed models at substation levels are available, and data traffic is minimized as only the results of the locally calculated (substation level) states are sent to the central control center. A number of the characteristics include:

a. Utilize all available data (relays, DFRs, PMUs, meters, etc.)
b. Utilize a detailed substation model (three-phase, breaker oriented model, including instrumentation channel and data acquisition model)
c. Use “derived” and “virtual” measurements by application of physical law
d. Needs at least one GPS synchronized device (PMU, relay with PMU, etc.) to enable a truly decentralized state estimator

The DSE is defined in terms of model, state, measurement set, and estimation method. The system is represented with a set of differential equations; the dynamic state estimator fits the streaming data to the dynamic model of the system.

8. Voltage stability monitoring

Voltage Stability can be defined as the power system’s ability to maintain voltages at load buses under changing system conditions including fluctuations in load, changes in generation profile and in system topology. At each load bus for each network condition there is a maximum load limit beyond which the bus voltage will collapse, causing under-voltage trips. This application function will assess the margin to voltage collapse by using an equivalent of the portion of the system of interest, and by stressing this equivalent to a point of collapse. Either or both of the following equivalents should be able to be obtained in this application: (a) EMS computed equivalent that is transferred to the synchrophasor side of the system, or (b) an equivalent computed within the application based on the phasor measurements.

The loading limit changes with system conditions. The objective of the voltage stability monitoring application is to provide a real-time assessment of the power system reliability margin with respect to voltage stability for the system configuration for which the equivalent is computed. For example, if a base case equivalent is used this application will return the base case voltage collapse margin. If the method listed above is used to compute the equivalent, and the

EMS provides an equivalent for a contingency, then the voltage collapse margin will be for that contingent configuration.

3.1.2 Off-Line applications

1. Base-lining

The base-lining includes relating power system measurements such as phase angles, path flows, voltages, reactive reserves with the system performance measures for normal operating conditions and its variations over a period of time and during various limiting conditions like thermal limits, proximity to voltage instability or voltage collapse, frequency and damping of oscillations, voltage collapse, transient angular stability, etc.[8]. This kind of analysis will facilitate development of situational awareness tools from wide area measurements. The primary users of the base-lining results are system operators in a control center.

2. Model calibration and validation

Computer simulation models of power systems are needed to facilitate effective and reliable means of planning, designing and operating the bulk power system. One of the major challenges when developing models is developing a subsequent process to calibrate the dynamic models of the power system elements with consideration to more closely simulate the actual system performance. The introduction of phasor data into current model calibration processes provides the opportunity to incorporate more dynamic characteristics into both steady-state and transient stability analysis of the grid system. Incorporating this new data source in a calibration process of current models has the potential for supplying a level of accuracy previously unattainable.

In modeling a large power system, the following categories of models should be developed [9]:

Transmission System Component Model, includes modeling of specific transmission components such as transmission lines, power transformers, mechanically switched shunt capacitors and reactors, FACTS devices, HVDC systems etc.

a. Generating Unit Models: Includes modeling of specific supply resources such as conventional hydro, steam and gas turbines, combined-cycle power plants, wind turbine generators, etc.
b. Dynamic Load Models: Modeling electrical load in the system ranging from light bulbs, small and large induction motors, to large industrial plants.

The focus of the dynamic system model calibration study is to utilize the data collected from the existing and new dynamic data sources (DDS) including Digital Disturbance Recorders (DDRs) and PMUs - as input to calibrate existing dynamic system models.

Calibrating the developed models is a more challenging task than developing the models given the vast nature of transmission systems, large number of variables associated with the models, varying nature of system loads etc. While there is an absolute need to produce generator and load models that closely represent the actual behavior, the amount of efforts needed for calibration should be manageable and within reason.

3. Operator Training Simulator

This is an application aimed to train the power system operator with PMUs similar to EMS based systems have operator training simulators.

4. Post-mortem analysis

This application enables power system planners and engineers to perform quick analysis of power system dynamics and events, and to establish baseline performance triggers and alarm limits. The application is designed to facilitate fast analysis of phasor data from the historical database after a system event occurred. This application should incorporate a variety of state-of-the-art modal estimation algorithms including Prony, Matrix-Pencil, Yule-Walker, N4SID, and HTLS.

A typical post-mortem analysis application should have the following components:

a. Data section, cleanup and merge, which allows the user to define and create data sets for analysis using a variety of pre-processing techniques.

b. Time domain analysis for identification of trends, rate of change, statistics, etc.
c. Spectral analysis to identify, analyze and classify oscillatory modes and their observability patterns under both ambient and post-event conditions
d. Modal analysis, which identifies and analyses small-signal stability characteristics, such as modal frequency, damping, and energy under ambient system conditions;
e. Ringdown analysis for performing modal analysis post-disturbance, which characterizes grid stability and robustness to major disturbances;
f. Tools to export raw data, processed data, and results analysis.

Phasor-based Fault Location is related to analysis of faults and is a subset of Post-Mortem Analysis application. The Fault Location function is inherent (with approximate methods) in distance relays and digital fault recorders and also available off-line with more sophisticated computational algorithms. It will be important to include more sophisticated fault locating algorithms in the real time computations of relays, in which case the algorithm can be enhanced by phasor measurements. The fault locating function has two components: verify the occurrence of the fault, and estimate the location of the fault. They are very important because the fault location can confirm whether a fault has indeed occurred on the line. If used on-line, it can also serve as a relay verification tool for a back-up fault detection algorithm. Both the dependability and security of protection system operation will be improved by incorporating a precise fault location function.

5. Synchrophasor system simulator

In any large-scale system, the performance and functionality of its major components must be tested and validated before system deployment. Ensuring the quality and timely deployment of a large-scale production-grade synchrophasor technology based wide-area monitoring, protection, automation and control (WAMPAC) system, as well as its smooth integration into the system planning, operation and engineering activities requires support of specialized tools for system testing and personnel training.

PMU simulator is a software component that makes a Windows-based PC act as multiple virtual PMUs. Its main purpose is to convert, with or without additional transformations - user provided timed signals into phasors that are sent out using the IEEE C37.118 protocol. The additional transformations, controlled by user inputs, can be used to test various functions of a synchrophasor system. For example, it is possible to delay signals of interest for a controlled amount of time or it is possible to change signal levels by e.g. bringing a signal above its threshold level for a controlled amount of time, and then bringing it back at a specific time; thus allowing efficient testing of the alarm functionality of a WAMS system.

Instead of synthetic input signals, the PMU simulator can use timed signals of voltages and currents obtained from a transient simulation program, such as the PSS/E, power factory or other programs. The timed signals of sufficient duration and the corresponding phasors generated by the PMU simulator can provide a realistic picture of how a system would respond to events of interest such as an out of step condition or a voltage collapse event. This allows tuning of synchrophasor applications or operator training in the use of new applications to be done under controlled, operations-meaningful scenarios, similar to what is done with the existing EMS OTS simulator and the EMS functions.

Another way of testing the currently available and future synchrophasor applications is to use the actual phasor data recorded in a historical data base and use them to playback and analyze events. The phasor data, extracted from the historical data base in ".csv" format can be replayed, or it can be changed to create different "what if" scenarios that would not be available in the actual PMU/PDC data streams.

6. System separation/islanding

This application has been recognized as a possible means for limiting the extent of major outages from cascading events. In effect, this type of scheme preemptively trips electric system elements - lines, generators, loads - to stop the unintentional breakup of the network via cascading events, and leaves the system in a more favorable position for restoration once the cascading outages are contained. This was one of the recommendations in the August 14, 2003 Blackout Final Report by the US-Canada Power System Outage Task Force [10]. Such schemes have been conceptually understood and studied for decades, but are now increasingly feasible with the advent of PMU networks for wide-area monitoring and control.

In order to establish control system separation schemes, it is necessary to conduct a detailed study of the Colombian power system, including both analytical and simulation studies in according with the following requirements:

a. Build upon prior controlled system separation research. A significant amount of analysis has been conducted in the area of controlled system separation by EPRI, NYISO, NYSRC, and NPCC.
b. Identify criteria for triggering system separation. This process needs to identify and develop criteria and appropriate real-time control/protection algorithm(s) that are able to determine the need for separation and the interface(s) where separation should occur. The developed criteria and algorithm(s) should utilize real-time dynamic data and may be deployed at the control center for the purpose of online oscillation monitoring and enabling/disabling the separation function. The study should consider predetermined "fixed" interfaces and explore the feasibility of determining floating or "adaptive" interfaces so as to minimize loss of load due to generation/load imbalances.
c. Identify potential separation points. It is expected that coherent generation groups, which can be identified offline, as well as typical power-flow profiles will be utilized. The separation points should provide for the isolation of each coherent generation group while minimizing generation/load imbalance. The power flow profiles considered in the analysis should include a range of demand levels, generation dispatch patterns, import/export scenarios, and other critical system conditions including post-contingency conditions in accordance with the company's design criteria contingencies and extreme contingencies.
d. Recommend locations for dynamic data sources. The proposed controlled separation schemes should utilize available sources of dynamic data (e.g., digital fault recorders, digital relays, digital transient recorders, sequence of events recorders, phasor measurement units, etc.) to monitor generator oscillation online and determine the timing of controlled separation. Existing dynamic data sources and those being deployed as part of the iSAAC project should be used where possible. The study should also determine additional locations of dynamic data sources to improve performance of the scheme.

e. Identify timing for controlled system separation. Once the need of separation is determined, the timing of separation will be the point in the out of step cycle when the actual command to separate is triggered. The criteria for determining the right timing to trigger separation should be developed in order to minimize the stresses on the system and minimize the potential for equipment damage. The developed criteria may be embedded into separation devices that are installed at potential separation points and can be coordinated using real-time dynamic data sources.
f. Coordinate system separation with under-frequency load shedding (UFLS) program and other remedial actions available. A preliminary validation of the proposed controlled separation schemes through scenario analyses, varying system conditions and originating events should be performed and validated. Validation of the controlled separation schemes can be done by dynamic simulations. It would be useful to perform a study of how to coordinate the separation/islanding with the UFLS program and other remedial actions. The study can focus on separation schemes for two time frames; historical and future.

3.2 Colombian Transmission and Generation System

Colombia's energy sources include several fossil fuel and natural resources. The country has petroleum and coal reserves. Its coal reserves form the largest in South America. Colombia also has large natural gas reserves some of them are still unexploited. Colombia has abundant water resources for hydroelectric power, and is second only to Brazil in hydroelectric potential in Latin America. Hydroelectric sources presently provide most of Colombia's electricity power generation. Demand for energy (petroleum, natural gas, and electricity) is expected to grow 3.5% per year through 2020 [16].

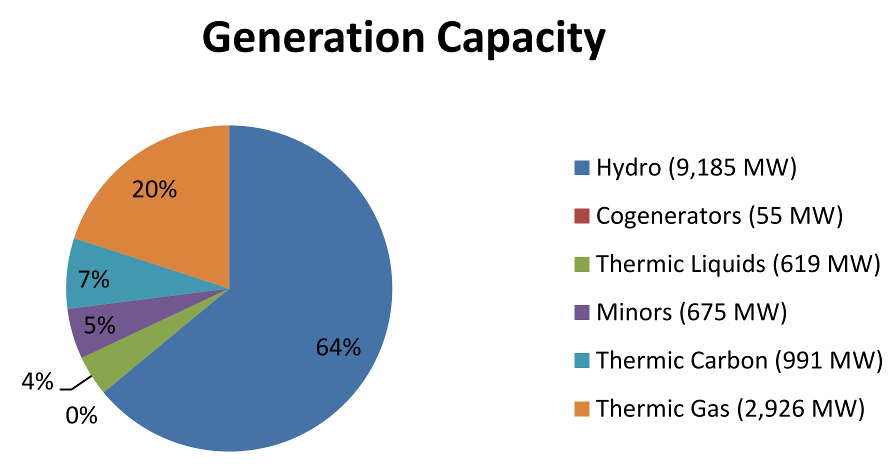

Figure 3-1: Colombian Generation Capacity

Colombian's transmission network has an installed capacity of 14.7 GW in about 24,000 Km of transmission lines at 110 kV or higher. Colombia presents a daily demand of approximately 9.6 GW. The following table shows the Km of transmission lines dedicated to the respective kV level.

Table 3-1. Transmission Network

Voltage Levels (kV)	Length (Km)
110-115	10,137
220-230	11,839
500	2,437
Total	24,404

3.3 XM Colombia

This thesis was based on the case study of the Company of Experts in Markets (XM) Colombia. XM is in charge of delivering services of operation, planning and coordination of the assets of the National Interconnected System (SIN), administration of the electric power commercial settlement system in the Wholesale Market, and settling and clearing of charges for use of the National Interconnected System's grids. XM conducts activities related to operation of electric energy and gas systems, administration of corresponding markets, settling and clearing of charges for use of electric transport networks, administration of financial derivative markets with electric energy and gas as underlying asset, including compensation systems. It also delivers specialized additional services related to the technology and knowledge acquired along the execution of its activities. XM Colombia is also is in charge of the short-term International Electricity Transactions (TIE) with Ecuador that started on March 1, 2003 upon commissioning of the 230kV interconnection line between Jamondino (Colombia) and Pomasqui (Ecuador) substations.[11]

XM developed the National Defense Plan against Large Scale Events (SIRENA) project which consisted of implementation of PMUs, upgrade of telecommunications, distributed computing, new methods for simulation and analysis of power systems [11]. With the PMU deployment and the Wide Area Monitoring Protection and Control (WAMPAC) system conceptual design, the advantage of using this technology for protection and control applications started to be considered. XM defined the combination of these technologies as an Advanced Supervision and Control system. With the installation of the initial WAMS prototype in 12 transmission substations, the PDC and WAMS software tools installed in the control center, XM had the need to move on to the next stage of the project [14].

The Intelligent Supervision and Advanced Control Center (iSAAC) is the next stage and the goal is to use the synchrophasor technology, communications architecture, distributed functionality at the different substations, advanced special protection schemes (SPS), and advanced situational awareness as part of the transition of SCADA to EMS system with the final goal to prevent or mitigate the consequences of large scale event in the Colombian interconnected system. The figure below shows the platform goal for this project. The platform consists of a main control center, super PDC, iSAAC network, local PDCs and PMUs at substations.

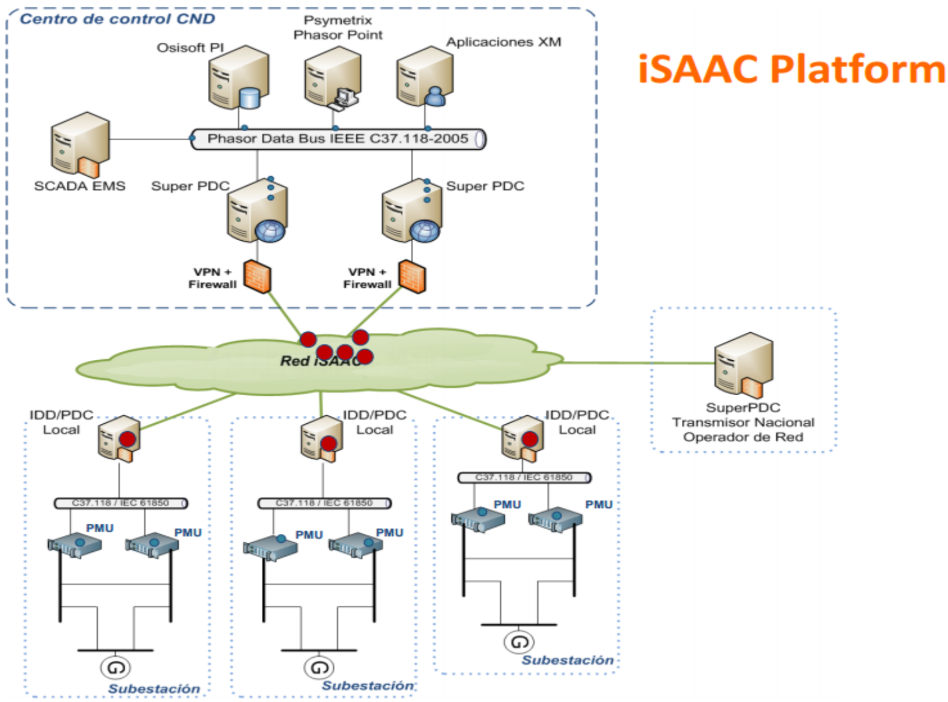

Figure 3-2. iSAAC platform [14]. Leon, R.A; Gomez, J. E., "Colombian National Defense System against Large Scale Events," Power and Energy Society General Meeting, 2011 IEEE , vol., no., pp.1,6, 24-29 July 2011. Used under fair use, 2014.

3.3.1 Geographical location of Events

Figure 3-3 presents the Colombian electric system and the areas were the 10 events used as a basis for the PMU applications prioritization took place. From the figure, three main areas where past events have occurred are identified and for which wide area monitoring and control actions are recommended:

a. 500 kV transmission loop in the vicinity of San Carlos, Porce III and Cerromatoso buses.
b. 230 kV Paraiso, and Torca, substations.
c. 230 kV transmission loop in the vicinity of San Bernandino, Yumbo, Paez and Juanichito buses.
d. 230 kV transmission line Jamondino Pomasqui, Colombia-Ecuador Interconnection.

This information was provided by XM and is part of the material used by Quanta Technology for the development of the project performance evaluation plan for the iSAAC project.

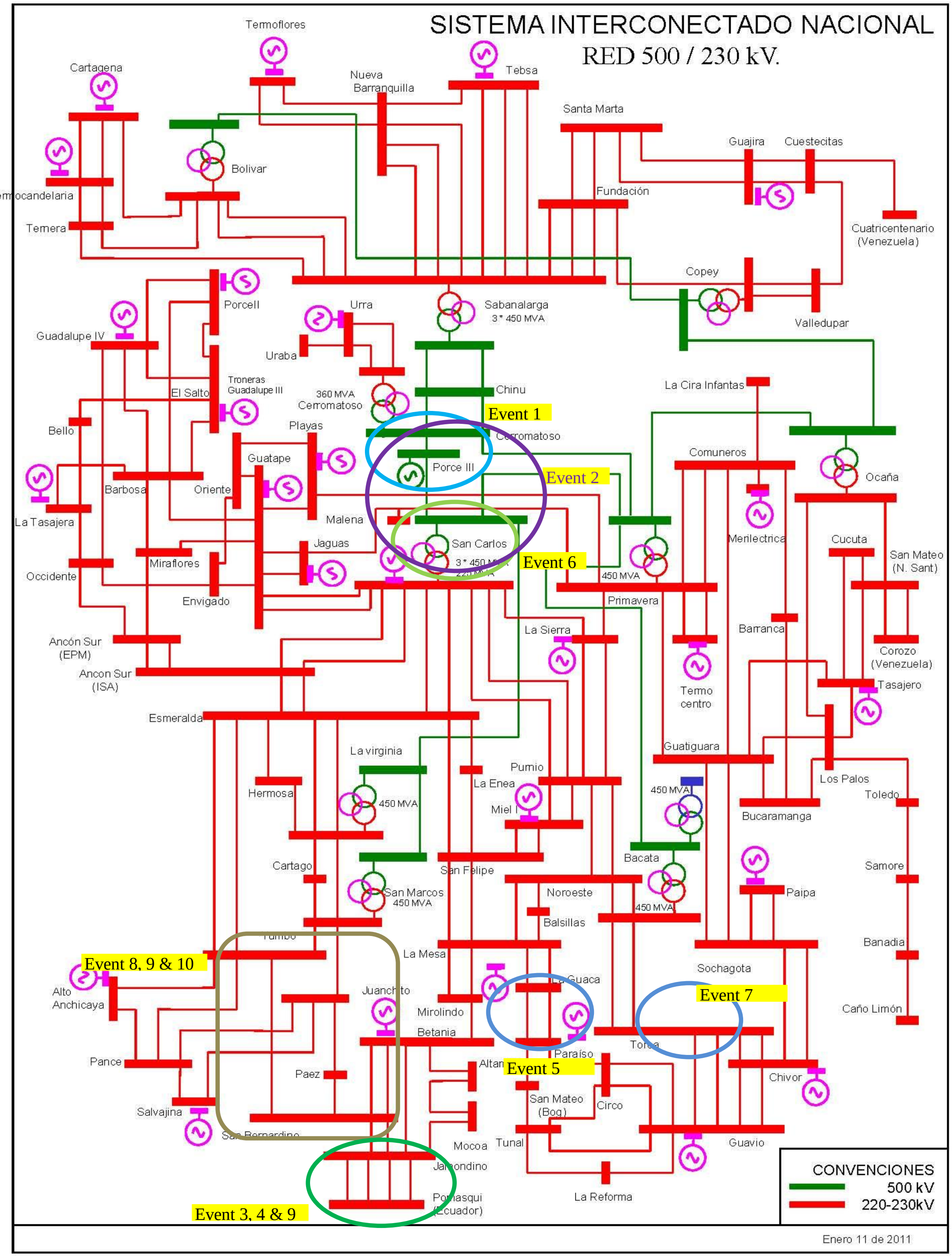
SISTEMA INTERCONECTADO NACIONAL
RED 500 / 230 kV.
Termoflores
Cartagena
Tebsa
Nueva Barranquilla
Santa Marta
Bolivar
Guajira
Cuestecitas
Termocandelaria
Fundación
Ternera
Cuatricentenario (Venezuela)
Copey
Porcell
Urra
Sabanalarga
3 * 450 MVA
Valledupar
Guadalupe IV
Uraba
Troneras Guadalupe III
El Salto
360 MVA
Cerromatoso
Chinu
La Cira Infantas
Event 1
Bello
Playas
Cerromatoso
Comuneros
Guatape
Porce III
Event 2
Ocaña
Barbosa
Oriente
La Tasajera
Malena
Merilectrica
Cucuta
Jaguas
San Carlos
Event 6
San Mateo (N. Sant)
Occidente
Miraflores
450 MVA
Envigado
Primavera
Barranca
La Sierra
Ancón Sur (EPM)
Corozo (Venezuela)
Ancon Sur (ISA)
Termo centro
Tasajero
Esmeralda
Guatiguara
La virginia
Purnio
Los Palos
La Enea
450 MVA
Toledo
Hermosa
450 MVA
Miel I
Bucaramanga
Cartago
San Felipe
Bacata
Samore
San Marcos 450 MVA
Noroeste
Paipa
Balsillas
450 MVA
La Mesa
Banadia
Event 8, 9 & 10
Sochagota
Alto Anchicaya
La Guaca
Event 7
Juanchito
Mirolindo
Caño Limón
Betania
Paraíso
Torca
Pance
Event 5
Chivor
Paez
San Mateo (Bog)
Circo
Salvajina
Mocoa
Tunal
Guavio
Jamondino
Pomasqui (Ecuador)
La Reforma
Event 3, 4 & 9
CONVENCIONES
500 kV
220-230kV
Enero 11 de 2011

Figure 3-3: Geographical location of events (Source XM), [14]. Leon, R.A; Gomez, J. E., "Colombian National Defense System against Large Scale Events," Power and Energy Society General Meeting, 2011 IEEE , vol., no., pp.1,6, 24-29 July 2011. Used under fair use, 2014.

3.4 Ranking criteria for PMU applications

In order to prioritize the PMU applications for a specific system, this thesis proposes to rank the applications using wide area measurements as a start point. The following table presents the list of the PMU applications that have been described in detail in Section 3.1.

Table 3-2: Identified PMU Application

No.	Applications
	Real-time Applications
1	Advanced applications
2	Advanced Situation Awareness (ASA) (includes EMS and phasor management system)
3	Frequency monitoring and control
4	Oscillation monitoring
5	Power flow monitoring
6	Real Time Data Validation
7	State Estimation
8	Voltage stability monitoring
	Off-Line Applications
9	Base-Lining
10	Model Calibration and Validation
11	Operator training simulator
12	Post-mortem Event Analysis
13	Synchrophasor system simulator
14	System separation/Islanding

Based on the analysis of wide area disturbances events of a specific system, a diagnostic of how synchrophasor could be applicable to mitigate the same kinds of events in the future were determined. These generic applications were mapped with the synchrophasor applications described above that has either been deployed or are being contemplated for deployment within the industry. The following sub-sections explain further all the criteria used for prioritization of synchrophasor applications.

As explained in the previous sections, there are different PMU applications, and not all the systems have the same need of each one of the applications due to the nature of the different power system grids. This section proposes three criteria to identify and prioritize the need of synchrophasor applications:

- Power system need.
- Application readiness for deployment
- Additional effort required to implement the application.

Figure 3-4 shows the three factors used for the prioritization of PMU-based applications for a power system.

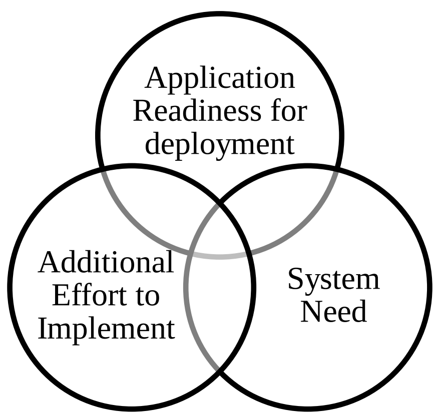

Figure 3-4: Venn diagram of criteria for PMU applications prioritization.

Power System need:

System need was identified as the most important criteria since it is unique to a system. The score based for System Need is defined as follows:

1. Score of 1: Low. Helps but not with the mitigation of the main weaknesses of the system.
2. Score of 2: Medium. Helpful to have but not necessary.
3. Score of 3: High priority. Critical application that could greatly help to mitigate system events.

The importance of synchrophasor applications with respect to the power system need was defined based on the wide area disturbance event analysis of 10 out of 64 significant events in the past 5 years which is considered appropriate to identify the priorities of PMU applications and a revision of the events is recommended to be done every year. The table below shows the comparison of the analysis from the different wide area disturbance events and the mapping with the corresponding synchrophasor application as part of the proposed method for PMU applications prioritization.

Table 3-3: Mapping of PMU applications and Wide area disturbance analysis recommendations

Wide area disturbance analysis	Corresponding PMU application
Out of step	Advanced applications
Improvement in interconnection	Advanced applications
Monitoring to study system dynamics. SCADA reporting rate is not adequate.	Oscillation monitoring
Determine safe generation limits for stressed system conditions.	Base lining power system, Model validation and calibration
Power system modeling and fine tuning	Model validation and calibration
Verification of generators frequency contributions	Model validation and calibration

This kind of mapping was used for all the events considered and the applications that were most present were given more priority.

Application readiness for deployment

The factor for PMU application readiness for deployment relates to the industry maturity of the application. The scores used for this factor are:

- Score 1: Concept and R&D. It refers to applications that are still as a plan, or an idea, are envisioned as necessary and useful for the operators, but have not yet been implemented and need more R&D.
- Score 2: In product development. It refers to applications that are not fully developed or are still in the test phase.
- Score 3: It is a developed application, where a product to implement the applications is available. These are mature applications ready for deployment and with full vendor support.

The literature review presented in section 2 helps support the scores given for the readiness level of the applications.

Table 3-4: Scoring for Application readiness for deployment

Application	Readiness for Deployment Score	Comment
Real-time applications		
Advanced applications for system level phenomenon (Includes SIPS and out of step protection)	1	SPS and RAS are being developed, but an application that includes PMU based/assisted SIPS is at a concept level at this time.
Advanced Situational Awareness (ASA) (includes EMS and phasor management system)	1	For PMU based visualization: some places like WECC, PJM, CAISO, BPA, MISO, ERCOT, and FPL have implemented it or are planning to do so. However, combined EMS and phasor based visualization is still at a concept level.
Collaborative protection	1	It is a new idea, and it is in a concept stage.
Complex Event processing	1	It includes all the elementary alarms to derive information about events that caused the elementary alarms to be generated. Alarming is available (for oscillation detection mainly ISO-NE, WECC, BPA) but not a way this application requires it. It is in development, long-term.
State Estimation	2	PJM, WECC, BPA, ISO-NE, Dominion, Duke Carolinas, and NYSIO use or soon will be using synchrophasor data into state estimator
Frequency monitoring and control	3	It has started to be used (WECC, CAISO, BPA, ATC) but needs some tuning.
Oscillation monitoring	3	Duke energy, ISO-NE, BPA, NYPA have this application.
Power flow monitoring	3	ATC is implementing this application for the operators and engineers to have detailed information about grid conditions and power flows. PJM has done studies on this.
Real Time Data Validation	2	ISO-NE has developed a unique in-house Data Quality Monitoring System (DQMS) for its SIDU project not seen in other SGIG projects.
Voltage stability monitoring	2	There is voltage stability based on measurements, based on models, and hybrid. FPL had a project where some of the advantages of having this application are presented. ISO-NE, WECC, CAISO, MISO, NYISO, OG&E, among others; use or soon will be using synchrophasor data for voltage stability monitoring

Table 3-4: Scoring for Application readiness for deployment (Continued)

Application	Readiness for Deployment Score	Comment
Off-line applications		
Base-Lining	1	These studies are part of research programs.
Model Calibration and Validation	2	WECC, CAISO, BPA, use model validation studies of disturbance events. BPA: 10+Yrs using PMUs for generator model validation. However, it has still has a lot of challenges to be implemented in a whole system.
Operator Training Simulator	1	It is part of lessons learned, and challenges, but it is not ready commercially.
Post-mortem Event Analysis	3	One of the first applications for PMUs.
Synchrophasor system simulator	2	R&D has been done, but it is not a mature application.
System separation/Islanding	1	There is a definition for it, and an idea, but it is still at a concept stage. Virginia Tech and Dominion have done some studies in islanding.

Additional Effort to Implement

This factor refers to the required additional effort needed in order to implement and gain effective use of an application.

- Score 1: Additional infrastructure deployment / expansion to support is required
- Score 2: A procurement and commission process is required
- Score 3: Development of supporting operation processes/procedures and user training is required.

The scores for all previously discussed factors are captured and computed in the evaluation matrix. The score in the "Total Rank" column is the arithmetic sum of these three factors:

a. Application readiness for deployment,
b. Power system need,
c. Additional effort required to implement the application.

More weight was given to the "power system need" factor, since this factor considers how much each application is necessary to increase power system observability and mitigate the effects of wide area phenomena based on the analysis presented in this thesis. This factor is system specific and critical for the PMU application prioritization being proposed in this thesis.

3.5 PMU applications prioritization results

Some of the requirements for the deployment of synchrophasor are financial support as well as planning. Planning should include a clear roadmap development and deployment as well as a comprehensive training for all operators. For the deployment of synchrophasor technology not only budget is needed, but also planning including roadmap development and training is essential for a more optimal deployment and implementation. The work in this thesis suggests that PMU application prioritization should be one of the first steps to take for synchrophasor technology applications deployment. When funds and budget is limited, it is advised to start with the applications with high impact and continue then with those of somehow lower importance and/or contribution to the overall goal of the company. However, this approach is still “ideal” since it is not always feasible to implement the synchrophasor applications that the power system needs the most from the beginning, some applications might require more R&D, communications upgrades, etc. The advantage of the method proposed by this thesis is that all these factors are taken in to account for an optimal and more realistic synchrophasor technology deployment and PMU applications development.

By prioritizing PMU applications, a utility, RTO, etc. will have a better idea of what to focus on for the roadmap development and what additional technology and software is needed. The following table presents the PMU prioritization results obtained from the wide area measurement done on a specific power system.

Table 3-5: PMU Applications Prioritization Results

Application	Application Readiness for Deployment	System Need	Additional Effort to Implement	Total Rank
Real-time Applications				
Frequency monitoring and control	3	6	3	12
Oscillation monitoring	3	6	3	12
Voltage stability	2	6	2	10

monitoring				
Advanced applications	2	6	1	9
State Estimation	2	6	1	9
Real Time Data Validation	2	6	1	9
Advanced Situational Awareness (ASA) (includes EMS and phasor management system)	1	6	1	8
Power flow monitoring	3	2	3	8
Off-Line Applications				
Post-mortem Analysis	3	6	3	12
Model Calibration and Validation	2	6	2	10
Base-Lining	1	6	1	8
Synchrophasor system simulator	2	4	2	8
Operator Training Simulator	1	4	1	6
System separation/Islanding	1	2	1	4

Based on the results obtained from the PMU prioritization table shown above, the applications were divided into categories according to the ranking obtained.

The first category is comprised of the applications that the roadmap should focus on for the first years. The applications in this category are presented next:

a. Frequency monitoring and control
b. Oscillation monitoring
c. Voltage stability monitoring
d. Post-mortem analysis
e. Model Calibration and Validation

The second category is comprised of the application that should be developed next, or that will help the system to improve its reliability and fault restoration. These applications are presented below:

a. Advanced applications

b. State Estimation
c. Real time data validation
d. Advanced situational awareness (ASA)
e. Power flow monitoring
f. Base-lining
g. Synchrophasor system simulator

The PMU applications that obtained lower rankings are considered not a priority for the system. These are applications that are good to have, but are not necessarily going to make a big impact in the prevention and mitigation of the faults that the system presents the most. These applications are:

a. Operator Training Simulator
b. System Separation/Islanding

4 Discussion

Based on the evaluation of the methodology proposed, it was found that the system analyzed should place emphasis of their efforts of the advantages of synchrophasor technology specially:

a. Frequency monitoring and control,
b. Oscillation monitoring,
c. Voltage stability monitoring,
d. Post-mortem analysis,
e. Model Calibration and Validation

The PMU-based applications identified, have the goal of help mitigate and increase the situational awareness of possible future wide area disturbance events in the system, and are applications possible to be deployed for their budget and technology development.

These five applications were the result of the analysis of the status of research and development needed or that has been done for each application. Another factor taken into account was the resources that the company currently has in their control center as well as in the substations, including communications infrastructure, software, PMU deployment, human resources; for some applications not there was not considerable need for extra resources which made these applications more feasible, for example oscillation monitoring. Lastly, the analyses of the different events lead to identify what type of contingencies have cause the system to collapse or to fail and the possible causes, for example the event that was cause due to the lack of safe generation limits cause the system to reach a stressed condition that could have been prevented with previous model validation and calibration.

In order to be able to reach the goal of successfully implementing the applications listed above in the Colombian system, time, budget, planning, training, R&D, among others are needed. The importance of PMU applications prioritization is not only to know what use to give to the synchrophasor technology, but also to know "where to go", spend funds efficiently, have realistic goals and dates set, and to know what other resources are necessary.

This can be achieved by developing a roadmap with yearly milestones with the specifications of what needs to be developed or acquired. The roadmap is also a basis for the budget allocation, by using each milestone as a reference, the necessary equipment and its cost can be determined, based on the time determined in the roadmap for research and development for the specific milestone, the amount of hours to spend and the number of specialized staff required can be estimated.

5 Conclusions and next steps

For the deployment of a technology and its applications, certain budget, installations, training, and possibly other technologies are needed. This thesis work came from the need identified in some systems which are in the initial stage of adoption of synchrophasor technology and need guidelines and a source, or a method to determine which applications to start implementing in their system according to the technology available, the training needed, and the financial constrains in order to have a better idea of the limits of their system, mitigate disturbances or cascading events, and time of unserved energy.

In the case of this thesis, the Colombian system was used. This system has 16 PMUs currently installed and they plan to have about 30 PMUs by 2016 according to information provided by XM. However, the potential of this technology is not being used yet due to a lack of guidance and execution plan. The main function of the PMUs at the moment is to collect data, but this data is not being explored completely; therefore, the idea of this work has been to propose an itemized procedure for how to properly invest the sources a company has for the development of PMU-based applications suitable for the specific system to mitigate and identify possible events and failures in the power system.

Throughout this work, it has been shown that wide area measurement events can be used as a basis for PMU applications prioritization. There are other factors that must be considered for this method, but wide area measurements events are essential, they are specific of each system and can give enough information to target the areas where the system needs more monitoring and support.

The analysis performed for the Colombian system was based on the system needs of monitoring and control from the wide area event analysis, the state of the art readiness level of each application, and the additional effort needed by the company to implement each application. The following PMU-based applications were identified as priorities for the system, and are the ones that should get most of the company's investments regarding PMU-applications, communications upgrades, modifications, among other factors.

a. Frequency monitoring and control,

b. Oscillation monitoring,
c. Voltage stability monitoring,
d. Post-mortem analysis,
e. Model Calibration and Validation

For projects where large amounts of investments are needed, require the progress to be shown at certain stages of the development, in order to prove that the funding is being used correctly and that the milestones are being accomplished. In the case studied in this thesis, when the first applications are deployed, and a reliable monitoring of the system is achieved, and when events mitigation and detection can be performed, it can be shown that the investments for PMU technology were the right activities for the funding. This would be a next step, after the PMU applications prioritization has been analyzed and determined and with the help of the roadmap.

The main added value of this work is to present a practical method to prioritize PMU-based applications, depending on the resources, technology, and wide area events present in the system. With this data, a ranking criterion can be developed to rank the different PMU applications and determine which ones are more important for the specific system needs.

Synchrophasor technology has promoted research and development not only of PMUs, but also of communications, data storage, data processing, training tools, and visualization, among others. Some of these developments are done by suppliers, universities, or in in-house laboratories by the company interested in deploying this technology. One of the main aspects of this prioritization methodology is that it takes into account non-quantifiable criteria like training required for the personnel to operate and use the applications, additional materials and modifications needed for the implementation of an application. The ranking methodology proposed, gives more or less weight to certain solutions according to the criteria and the weight given to each one in order to come up with a prioritization.

After the systems needs have been determined based on previous wider area measurement events, another future implementation of wide area measurements is PMU placement. Virginia Tech has developed algorithms for PMU placement to ensure monitoring of critical buses based on the important buses of the network and the transient stability studies[17], as well as gradual optimal PMU placement approach that guarantees minimum regional observability at the initial stage and full observability for the complete implementation of the Central American Power

System (CAPS) [18], and University of Texas at Austin in 2009 performed PMU placement algorithm to identify buses that are the best candidates for PMU placement based on certain requirements[19]. With the approach of this research, non-quantifiable criteria can also be used to determine optimal PMU placement, considering the substation's communications infrastructure and capabilities, the readiness level of the company to install the PMUs and the additional work and modifications that come with it, hence taking the most advantage of the investments and conditions that the company already has.

Once PMU applications prioritization has taken place, a next step to be considered is a roadmap development for the applications identified as more important for the system. The roadmap should have milestones for certain period of time; the roadmap should have short-term and long-term goals with specific activities to help reach those goals. With the roadmap, the resources needed including: tools, training, materials, personnel, budget, etc. that is needed in order to meet the milestones can be easily determined. In addition, a more structured plan for the development of the synchrophasor technology for that specific system can be reached, and the progress of the PMU applications can be forecasted.

Bibliography

1. Giri, Jay. "Distribution System Synchrophasor-based Control Systems." IEEE Smart Grid Newsletter (Jan. 2014): n. pag. IEEE Smart Grid. IEEE, Jan. 2014. Web. 28 June 2014. <http://smartgrid.ieee.org/january-2014/1026-distribution-system-synchrophasor-based-control-systems>.
2. Novosel, D., "Wide area disturbances: overall issues and solution and impact of protection systems," Power Systems Conference and Exposition, 2004. IEEE PES , vol., no., pp.1784,1785 vol.3, 10-13 Oct. 2004
3. Zhang, Qiang. “Synchrophasor Data Validation & Applications Test at ISO-NE”. WSU PMU Test Workshop, March 16, 2012. *PDF file.*
4. Qiang Zhang; Xiaochuan Luo; Bertagnolli, D.; Maslennikov, S.; Nubile, B., "PMU data validation at ISO New England," Power and Energy Society General Meeting (PES), 2013 IEEE , vol., no., pp.1,5, 21-25 July 2013.
5. J. Zhu, A. Abur, M. J. Rice, G. T. Heydt, and S. Meliopoulos, “Enhanced State Estimators”, Final Project Report, PSERC, Nov. 2006
6. A. Abur and A. G. Exposito, *Power System State Estimation*, New York: Mercel Dekker, 2004.
7. S. Chakrabarti, E; Kyriakides, G. Ledwich, and A. Ghosh, “A Comparative Study of the Methods of Inclusion of PU Current Phasor Measurements in a Hybrid State Estimator”, IEEE PES Meeting, 2010.
8. Planning Implementation Task Team (PITT) and Operational Implementation Task Team (OITT) of North-American Synchro-Phasor Initiative (NASPI) identified base-lining of phase-angles as their highest priority.
9. Pourbeik, P. “Approaches to Validation of Power System Models for System Planning”, White Paper prepared by EPRI with funding from FirstEnergy, April 23, 2008.
10. This report can be found at: http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/BlackoutFinal-Web.pdf
11. Portal XM. Web. 19 Sept. 2014. <http://www.xm.com.co/english/ourcompany/Pages/AboutUs.aspx>.

12. Gomez, J. E; Gomez C. Leon, R.A., “La Medición Fasorial del Sistema Interconectado Colombiano, un Proyecto Piloto de la Compañía de Expertos en Mercados XM,” Jornadas Tecnicas ISA 2010.

13. Camargo Suan, L. A. Synchrophasors in the Colombian Power System [PowerPoint slides]. Retrieved from http://www.xm.com.co/BoletinXM/Documents/PresentacionNASPIFeb13-2013.pdf.

14. Leon, R.A; Gomez, J. E., "Colombian National Defense System against Large Scale Events," Power and Energy Society General Meeting, 2011 IEEE , vol., no., pp.1,6, 24-29 July 2011.

15. Leon, R.A; Gomez, J. E., “Sistema de Respaldo Nacional ante Eventos de Gran Magnitud SIRENA, Una aplicación de Redes Inteligentes en el Sistema de Transmisión Nacional de Energía,” http://www.xm.com.co/BoletinXM/PublishingImages/Boletin256/PresentacionXMSIRENA_PremioAsocodisCNO.pdf

16. "Energy Overview of Colombia." Fossil Energy International. 6 Feb. 2003. Web. 20 Sept. 2014. <http://www.geni.org/globalenergy/library/national_energy_grid/colombia/EnergyOverviewofColombia.shtml>.

17. Pal, A.; Sanchez-Ayala, G.A.; Centeno, V.A.; Thorp, J.S., "A PMU Placement Scheme Ensuring Real-Time Monitoring of Critical Buses of the Network," Power Delivery, IEEE Transactions on , vol.29, no.2, pp.510,517, April 2014.

18. Sanchez, G.A.; Pal, A.; Centeno, V.A.; Flores, W.C., "PMU placement for the central american power network and its possible impacts," Innovative Smart Grid Technologies (ISGT Latin America), 2011 IEEE PES Conference on , vol., no., pp.1,7, 19-21 Oct. 2011.

19. Kulkarni, S.; Allen, A.; Santoso, S.; Grady, W.M., "Phasor measurement unit placement Algorithm," Power & Energy Society General Meeting, 2009. PES '09. IEEE , vol., no., pp.1,6, 26-30 July 2009.

20. “Real-Time Application of synchrophasors for improving reliability”. NERC report. Retrieved from: http://www.nerc.com/docs/oc/rapirtf/RAPIR%20final%20101710.pdf

21. Silverstein, Alison. “NASPI and Synchrophasor technology progress”. NERC OC-PC Meetings, December, 2013. PDF file.
22. Synchrophasor Roadmap. SOS Meeting, 01 March, 2012.
23. “Project Specific Deployment.” SmartGrid. U.S Department of Energy. Web. 25 Feb, 2014.<www.smartgrid.gov/recovery_act/deployment_status/project_specific_deployment >.
24. “Deployment Status.” SmartGrid. U.S Department of Energy. Web. 25 Feb, 2014.<<www.smartgrid.gov/recovery_act/deployment_status>.
25. Jansen, Kim. "ISO New England Completes Synchrophasor Deployment." Metering.com. Spin Telligent (Pty) Ltd, 08 Oct. 2013. Web. 03 Feb, 2014
26. "Innovation Leader: MISO Uses Real-Time Synchrophasor Technologies to Enhance Reliability." PRNewswire. Midcontinent Independent System Operator, Inc., 24 July 2013. Web. 03 Feb. 2014.
27. Bhargava, Bharat. “Eastern Interconnection Phase Angle Base Lining Study”. DOE/OE Transmission Reliability Program, June 27-28, 2013. PDF file.
28. Damir Novosel. (2013). Real-Time Voltage Stability Monitoring. JSIS Meeting, Tempe, AZ, USA, January 15-17.
29. “New technology can improve electric power system efficiency and reliability”. Today in Energy. U.S Energy Information Administration, 30 March 2012. Web. 05 Feb 2014.
30. Patel, Mahendra. “PJM Synchrophasor Technology Deployment Data Network & Applications”. Applied Solutions, PJM. PDF file.
31. Dagle, Jeff. “North American SynchroPhasor Initiative (NASPI) Overview”. Data exchange panel iPCGRID 2013, March 28, 2013. PDF file.
32. “Grid Operations – Program 39”. EPRI. Research Portfolio, 2013. *PDF file*.
33. “NASPI Report of Task Force on Testing and Certification”. NASPI TF, Report on PMU testing and certification, Oct 17, 2013. PDF file.
34. Niglye, N.; Peritore, F.S.; Soper, R.D.; Anderson, C.; Moxley, R.; Guzman, A., "Considerations for the Application of Synchrophasors to Predict Voltage Instability," Power Systems Conference: Advanced Metering, Protection, Control, Communication, and Distributed Resources, 2006. PS '06 , vol., no., pp.169,172, 14-17 March 2006

35. Schaefer, Joseph H. "Florida Power & Light Smart Grid Investment Grant Synchrophasor Update". NASPI Work Group Meeting, Oct 12-13, 2011. Microsoft PowerPoint.
36. Dagle, Jeff. "North American SynchroPhasor Initiative (NASPI) Overview". Data exchange panel iPCGRID 2013, March 28, 2013. PDF file.
37. Paul T. Myrda, Kris Koellner. "NASPInet - The Internet for Synchrophasors" System Sciences, 2010. Proceedings of 43rd Hawaii International Conference on System Sciences.
38. "Data Bus Technical Specifications for North American Synchro-Phasor Initiative Network (NASPInet)," Yi Hu Project Manager, May 29, 2009
39. Zhang, Junshan.; Vittal, Vijay.; Sauer, Peter W. " Networked Information Gathering and Fusion of PMU Measurements". PSERC Future Grid Initiative Webinar Series. Apr, 2012.