Energy Research and Development Division
FINAL PROJECT REPORT

DEMONSTRATION OF ADVANCED SYNCHROPHASOR TECHNOLOGY FOR THE INTEGRATION OF RENEWABLES ON THE CALIFORNIA GRID

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Prepared by: Electric Power Group, LLC

Electric Power Group

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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- Renewable Energy Technologies
- Transportation

Demonstration of Advanced Synchrophasor Technology for the Integration of Renewables on the California Grid is the final for the California ISO Synchrophasor project (contract number 500-08-048) conducted by Electric Power Group, LLC. The information from this project contributes to Energy Research and Development Energy Systems Integration Program.

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ABSTRACT

Synchrophasor technology can improve reliability, increase transmission asset utilization, reduce costs and facilitate integration of intermittent resources and distributed smart grid technologies through:

- Time-synchronized high-resolution data at 30 samples per second compared to one sample every two to four seconds with current supervisory control and data acquisition technology.
- Wide-area real-time situational awareness and observation of the entire interconnection, rather than by utility or Independent System Operator footprint.
- The ability to measure grid dynamics through metrics that indicate grid health such as phase angles, oscillations and damping, frequency coherency and voltage and angle sensitivities that enable operators to utilize measured values in real-time operations, rather than values based on engineering studies or estimated values from models.

The California Independent System Operator has been at the forefront of utilizing synchrophasor technology, having implemented the first generation Real Time Dynamics Monitoring System. The purpose of this research was to improve the first generation synchrophasor technology applications and develop new tools that rely on phasor-measurements. The research focused on operator visualization and decision support tools that would enable operators and engineers to integrate synchrophasor technology in their daily operations to harness the potential benefits. Researchers successfully met all the project objectives, working with California Independent System Operator staff, utility technical leaders and Independent System Operators in the Western Electricity Coordinating Council. This research has enabled the California Independent System Operator to maintain its technology leadership in using synchrophasor technology in real-time operations and engineering analysis. They now have interconnection wide-area real-time visibility and situational awareness of the grid. In addition, they are equipped with state-of-the-art applications operating on the Real Time Dynamics Monitoring System platform for voltage stability, oscillation detection, oscillation monitoring, phasor-based nomogram, phase angle monitoring, voltage and angle sensitivities, and a multiyear roadmap for synchrophasor technology.

Keywords: Phasor data concentrator, phasor measurement unit, renewable portfolio standard, voltage stability, small signal stability, nomograms, phasors, oscillation detection, phase angles, damping

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Introduction

Major blackouts such as those that occurred in August 1996 in the western United States and August 2003 in the Northeastern United States and Canada imposed billions of dollars of damage to the economy and disrupted the lives of people and businesses. Investigations of these and other major blackouts around the world have found some common contributing factors:

- Lack of real-time wide-area visibility and situational awareness.
- Lack of time-synchronized data over a wide area.
- Lack of high-resolution data resulting in an inability to monitor dynamics of the grid in real time.
- Reliance on models and engineering studies that are often not reflective of the current system state.
- Lack of state-of-the-art-tools and technologies that provide actual measurements of metrics such as phase angles, damping, oscillations and frequency coherency, which are indicators of the health of the grid. Deterioration of these metrics is often a precursor to major blackouts.

Project Purpose

The California Independent System Operator (California ISO) has been at the forefront of utilizing synchrophasor technology, having implemented the first generation Real Time Dynamic Monitoring System (RTDMS) developed by Electric Power Group in 2003. The purpose of this research was to improve the first generation synchrophasor technology applications and develop new tools that rely on phasor-measurements. The research focused on operator visualization (look and feel) and decision support tools that will enable operators and engineers to integrate synchrophasor technology in their daily operations to harness the potential benefits. The key research areas included:

- Voltage stability.
- Enhanced visualization displays that make it easier for operators to monitor, diagnose and act based on observed system dynamics, voltage stability, oscillations, phase angles and other metrics such as stability monitoring for oscillation detection and monitoring.
- Real-time stability nomograms to enable increased transmission utilization. Nomograms consist of two dimensional graphs that define the operational limits (represented as power flows) as a result of the interactions between two or more interrelated electric grid parameters.
- Analysis for operational integration of renewables.
- Improvements in data exchange, network and infrastructure to make the system robust and reliable for operators.

- Development of a long-term research roadmap.
- Technology dissemination through interactions with Southern California Edison (SCE), Bonneville Power Administration (BPA), Pacific Gas and Electric (PG&E), the Western Electricity Coordinating Council (WECC) and the North American Synchrophasor Initiative, as well as preparation of technical papers and briefings.

The objective of this project was tconducting research addressing the shortcomings of existing technologies and delivering tools and technologies to the California ISO for the benefit of California consumers.

Project Results

Electric Power Group developed a Real Time Dynamics Monitoring System that delivered state-of-the art wide-area visualization and real-time grid monitoring utilizing synchrophasor technology. The system was built upon the GRID-3P platform (U.S. Patent 7,233,843, and U.S. Patent 8,060259).

Researchers adapted the RTDMS for use by California ISO and supplemented its capability through research tailored to meet California ISO needs for wide-area situational awareness with state-of-the-art high-resolution visualization using sub-second phasor data. RTDMS offered dynamic visibility of the wide-area power grid that enabled operators to identify:

1. Grid stress indicated by higher phase angles of separation between predefined phasor measurement units.
2. Grid robustness indicated by damping status and trends.
3. Oscillations with high energy and low damping.
4. Frequency instability indicated by large variations or incoherency in frequency at different measurement points across interconnections.
5. Voltage instability indicated by any sudden drop in voltage magnitude from normal operating conditions.
6. Reliability margin, which is based on the calculation of power voltage (P-V) and power angle (P-δ) sensitivities that can provide operators with an indication of reliability margins.

Operators rely on engineering studies and model results to help them manage voltage stability. Models are often not reflective of actual system conditions and model inaccuracies have been contributors to some major blackouts including the 1996 blackout in the western United States. The project team researched algorithms that do not rely on models but utilize real-time phasor measurements to provide a real-time dynamic assessment of voltage stability and margins. Researchers used an algorithm based on the Double Voltage Source (DVS) method and demonstrated this approach for Southern California Edison's Rector Substation, part of the Big Creek 230 kilovolt (kV) transmission system. Researchers developed and tested a prototype that demonstrated phasor data can be used to produce P-V curves to determine the reactive margin at a particular substation. This model-less method was most effective at calculating P-V curves for radial systems such as the Big Creek system. Further research was required to apply this model to networks and to transfer paths. Integrating voltage stability monitoring with Supervisory Control and Data Acquisition (SCADA) or State Estimator data would enhance the operator's ability to perform "what if" analyses and manage reliability more effectively while at the same time increasing transmission utilization.

Oscillation detection was integrated into the RTDMS platform and enhanced algorithms were integrated into the Small Signal Stability Monitoring module. The oscillation detection module runs continuously to monitor and detect transient event. Once an event is detected, the module collects a preconfigured amount of data from selected signals, process the data through several different algorithms and cross-check results from the different algorithms and consecutive time windows to conclude that an oscillation has been reliably detected. If an event is determined to be reliably detected then an alarm message is generated.

Operating nomograms have been used to manage the real-time operation of the western electric grid for over twenty years. Researchers investigated the feasibility of utilizing synchrophasors to develop dynamic nomograms instead of current methods based on models and studies. The research focused on the Pacific AC Intertie (the California Oregon interconnection) since it is heavily loaded during the summer and is frequently limited by the nomogram conditions. The research was based on the hypothesis that utilizing combinations of synchrophasors that accurately measure absolute voltage angles would allow angular differences (grid stress indicators) between two or more substations in the Western grid to be determined in real time. This would result in a simpler operational nomogram across an otherwise complex transmission interface such as the California Oregon interconnection.

The research to develop angle difference-based nomogram was based on five principles. The angle pair(s) selected should meet the following criteria: 1) span the portion of the grid where the limitations are experienced; 2) have some relationship to the power flows that give rise to transmission limits, 3) provide the ability to check stability limits over paths affected by the loss of two Palo Verde units and for the loss of the Pacific Direct Current Intertie; 4) provide the ability to check power flow activity within an internal loop across the Alternating Current intertie in the northwest, northern California and southern California; and 5) ideally, the angle differences across the selected angle pair(s) should not change much across the various power flow combinations that describe the nomogram limits.

Currently the California ISO develops nomograms consisting of diagonals, which establish the relationship between megawatt (MW) flow on the California Oregon Intertie and the percentage of hydroelectric generation in northern California. These nomograms are developed using power flow and stability models. To effectively monitor the safe operating limit using the traditional nomogram requires monitoring the power input to the grid at six locations. The proposed nomogram established the maximum angle difference that should be expected for a critical path (in this case the Malin-Tesla 500 kV path) under normal and outage conditions. The benefits of the angle pair difference nomogram were:

- The use of a dynamic nomogram can be utilized to validate safe operation under a static nomogram while gaining experience with the dynamic nomogram.

- Angle pair difference based nomograms are simple to use because only one input must be monitored.
- Phasor data is available for real-time monitoring.
- Transmission capacity can be better utilized.
- Deployment of additional phasor measurement units will allow the further development of dynamic nomograms on other key transmission paths.

Researchers performed a feasibility assessment study for using phasor measurements to monitor the impact of wind integration on grid reliability. Grid reliability concerns could include such issues as adequate reactive support, voltage ride-through, harmonics, dynamic and small signal stability concerns, post-transient behavior, and frequency response characteristics. These issues are critical for enabling efficient and reliable integration of intermittent resources to meet California Renewables Portfolio Standard goal of 33 percent (an addition of 20,000 MW of new renewables capacity). Three sources were found for wind-related phasor data that could be used for the analysis: Oklahoma Gas & Electric, Electric Reliability Council of Texas, and the University of Texas, Austin.

Analysis of the available data led to the following conclusions:

1. Phasor data enabled accurate monitoring and plotting of frequency, voltage, and power. These accurate plots not only helped determine the impact of wind generation during contingencies but also helped validate models used by planners and operators in their simulation studies to predict the behavior of the grid.
2. Voltage behavior depended on local conditions of reactive support. Phasor information plus granular information about local wind production was useful for assessing the impact of wind generation on voltages at critical buses and wind's ability to ride-through a fault (remain connected to the grid and providing power and voltage support).
3. Phasor measurements were particularly useful for detecting oscillations in the grid. This was important since oscillations can seriously affect grid reliability. Proper and timely detection coupled with successful analysis and mitigation could prevent grid instability and improve reliability.
4. Phasor measurement units could enable the accurate measurement capability needed to quantify any changes in frequency and voltage response due to the addition of wind generation.

Analysis could not be performed using California data as it was not available during the course of the project. This analysis should be part of future research to characterize wind impacts on the California grid to enable operators to effectively integrate large amounts of renewables while maintaining reliability and improving transmission utilization.

The California ISO's synchrophasor system has been operating on a single, non-redundant RTDMS server. The research objective was to investigate platform, network infrastructure and applications architecture for reliable data exchange and full system coverage. This was an essential step to continue to position California ISO as an industry leader and to enable integration and connectivity to WECC's Western Interconnection Synchrophasor Project (WISP). Researchers provided California ISO with recommendations on platform, infrastructure and applications to enable transition to a production-grade reliable system for use in real-time operations.

The research team relied on its extensive synchrophasor technology experience, knowledge of industry trends and understanding of California ISO's priorities (including review of California ISO's "Five Year Synchrophasor Plan" dated July 2011) to develop a multi-year roadmap action plan that advanced the technology and met the California ISO's needs. Topics addressed in the multi-year roadmap action plan included:

1. Integration with the WECC WISP project.
2. Management and analysis of phasor measurement unit data, including validation, quality, baselining and on-line scanning.
3. Dynamic (generation and load) model validation.
4. Event analysis and operator training including developing a library of significant events.
5. Voltage sensitivity analysis.
6. Phase angle difference dynamic limits.
7. Dynamic nomogram validation.
8. Small signal analysis.
9. Grid restoration tool.
10. Generation resource performance, including renewable and conventional generation performance during events.

Industry coordination and technology dissemination were carried out through interaction with SCE, BPA, PG&E, WECC and the North American Synchrophasor Initiative and by developing technical papers and briefings.

Project Benefits

The research performed in this project positioned the California ISO to harness the benefits of synchrophasor technology in both operations and planning and deliver benefits to California citizens that included improving reliability, increasing transmission asset utilization, reducing costs, and facilitating integration of intermittent resources and distributed smart grid technologies.

The California Energy Commission has made a significant investment in phasor technology research to maintain and enhance California's technology leadership. The California ISO now has the ability to provide their system operators with accurate wide-area situational awareness of the grid via the RTDMS platform.

CHAPTER 1:
Voltage Stability with Phasors

1.1 The Goal

The goal of this task was to conduct research and expand the current capabilities of the phasor platform to include real-time computation of voltage sensitivities, real and reactive margins, and other voltage stability indices with respect to voltage collapse position that are solely based on phasor measurement data and do not require modeling information.

The following sections provide a summary description of the research, findings and conclusions

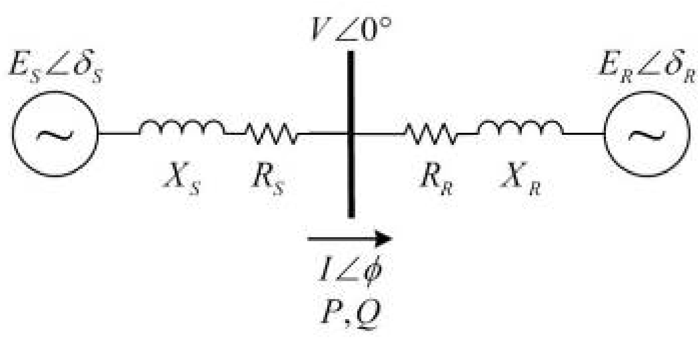
1.2 Method and Algorithm Selected For Voltage Stability

Electric Power Group, LLC (EPG) performed a literature review to identify phasor-based voltage stability algorithms. Based on the results of the literature review, EPG, in conjunction with the California ISO staff, used the algorithm based on Double Voltage Source (DVS) method developed by Dr. Joe Chow, Rensselaer Polytechnic Institute. This was selected for the following reasons:

- Topology independent.
- Exclusive use of phasor data – no need to use model information.
- Ability for real-time updates with fast response.

Dr. Chow's algorithm posits that any point in the system can be represented by an equivalent "sending" and "receiving" bus. Figure 1 below is a generalized example of a "send" side and "receive" side of a given bus or flow path.

Figure 1: Double Voltage Source Model (Chow et al 2006)



From Figure 1 above, the following equations are derived:

$$E_s\angle\delta_s - (R_s + jX_s)I\angle\phi = V$$

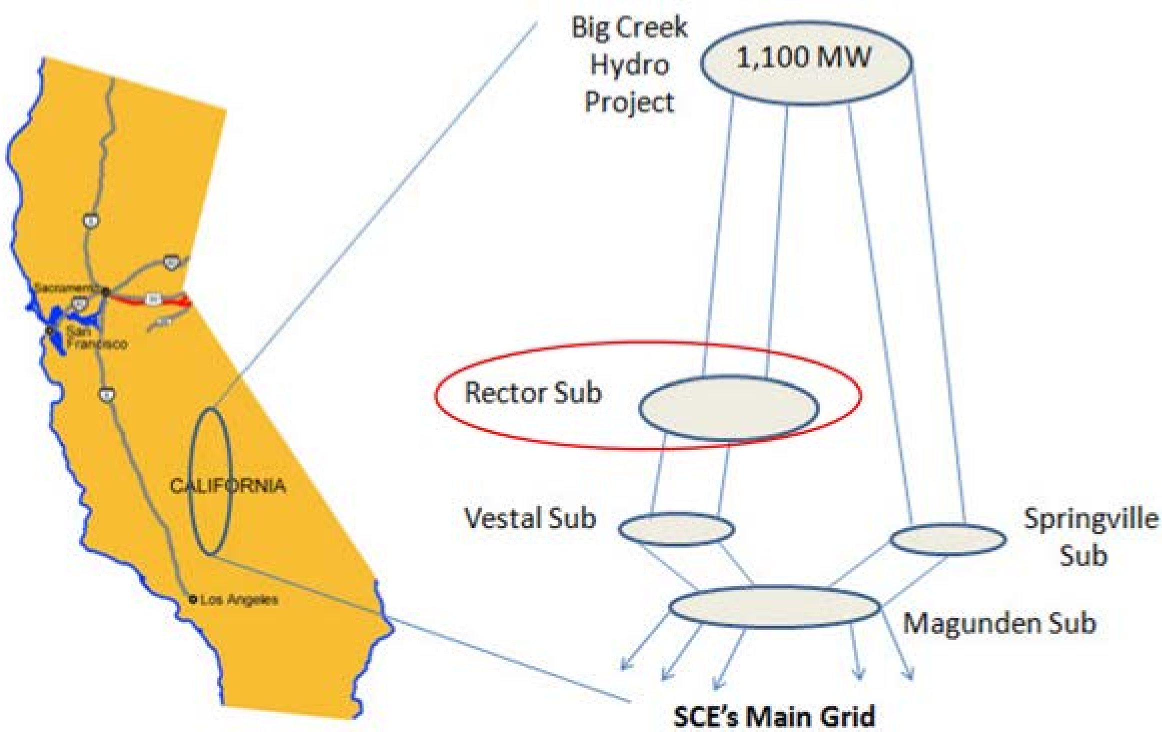
$$E_r\angle\delta_r - (R_r + jX_r)I\angle\phi = V$$

1.3 Prototype – Algorithm Implementation

EPG implemented the DVS algorithm in a prototype application to test and validate the methodology using real phasor measurement unit (PMU) measurements. In consultation with California ISO and Southern California Edison (SCE), EPG selected the Rector Substation in SCE's Big Creek System (Figure 2) based on the following:

- Known voltage stability problems.
- Availability of phasor data.
- Radial system – suitable for testing and validation.
- Rector has both load and throughput (typically south to the Vestal substation), key characteristics of the system layout described by Chow *et al.*

Figure 2: Big Creek Transmission System



Attributes of prototype developed based on Dr. Chow's algorithm:

- Topology independent.
- Utilizes only Phasor Measurement Unit data.

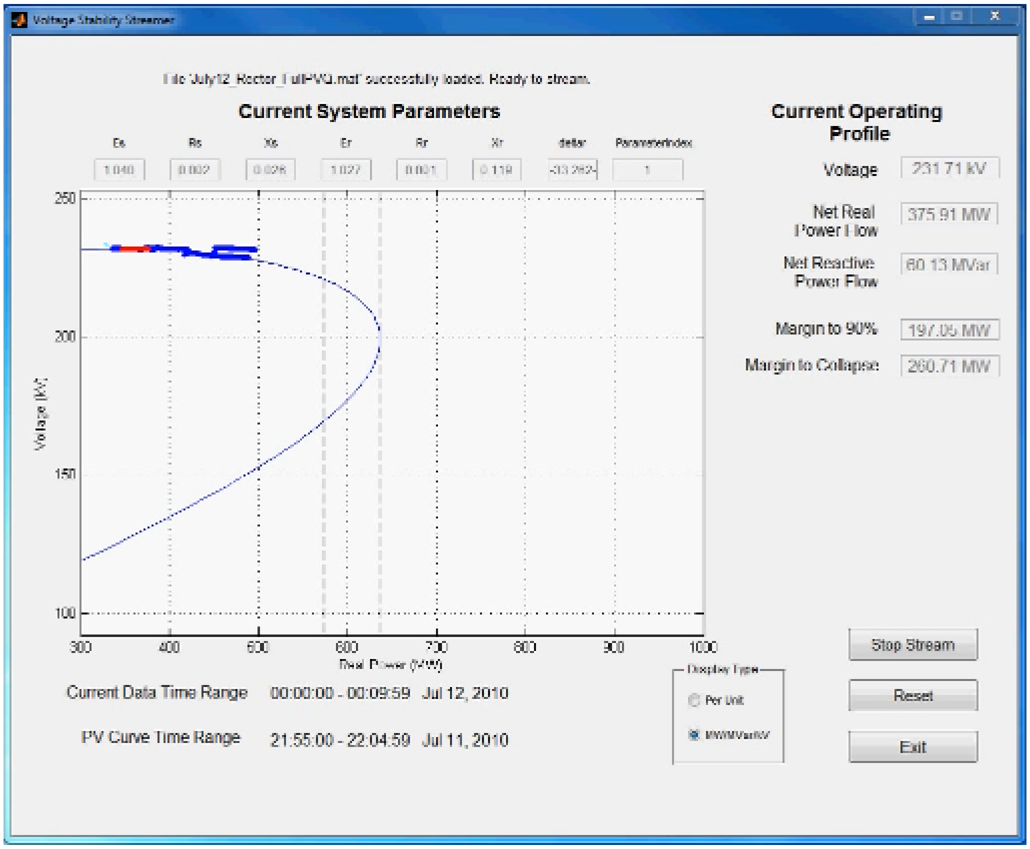
- Estimates Power-Voltage relationships from measured data.
- Method uses system equivalency and is suited for radial systems (or equivalent) and local areas.

The prototype application was developed using MATLAB to create a basic user interface and display calculation output.

1.3.1 Prototype Output

Figure 3 below shows a typical P-V curve obtained with the prototype using phasor data available for the Rector substation. Note, that the P-V curve display also includes the megawatt (MW) margin.

Figure 3: Sample P-V Curve



Demonstration of the voltage stability monitoring prototype can be seen by clicking on the icon in Figure 4 below.

Figure 4: Icon Link to Demo of the Voltage Stability Monitoring Prototype

1.4 Research Findings

1. Development and testing of this prototype has demonstrated that phasor data can be used to produce P-V curves based on real time measurements without use of models to determine the reactive margin at a particular substation in a radial system.
2. The prototype recognizes changes in voltage support at a particular substation and adjust the P-V curve to reflect the change in reactive margin.
3. Reactive margins will be best identified when the P-V curve is obtained with phasor data that includes significant changes (that is, 30 MW) in power flow and voltage. System changes or transients are needed to "tune" the algorithm using measured values of the real time system.
4. The prototype cannot yet anticipate reactive margins as a result of contingencies, but can provide the reactive margin corresponding to a post contingency condition.

1.5 Research Conclusions

1. The prototype is able to produce P-V curves for voltage stability monitoring using only phasor measurements; it will reflect changes in system reactive support.
2. This prototype is most accurate under conditions when there are significant variations in voltage and power; namely, system contingencies. A trigger mechanism embedded in the model will allow the application to automatically run to obtain a P-V curve.
3. This prototype is most effective in calculating P-V curves for radial systems such as the Big Creek system in the SCE system. Further research work is required to apply this model to networks and to transfer paths.
4. Integrating the voltage stability monitor with some Supervisory Control and Data Acquisition (SCADA) or State Estimator data would enhance the operator's ability to perform "what if" analysis.

CHAPTER 2: Oscillation Detection (Small Signal Stability) with Phasors

2.1 Goals

The goals for the research were to investigate use of algorithms and develop prototype system for:

1. Oscillation Detection algorithms.
2. Small Signal Stability Assessment algorithms.
3. Corrective actions to mitigate poor damping.

2.2 Background

EPG has implemented the oscillation detection algorithms from Dr. Mani Venkatasubramanian, Washington State University, and Small Signal Stability and Mode Meter Monitoring algorithms developed by Dr. Dan Trudnowski, Montana Tech. These have been integrated with the Real Time Dynamics Monitoring System (RTDMS®) platform and demonstrated to California ISO. During the research, the algorithms were tested and calibrated to understand the parameters and conditions under which the algorithms work most effectively.

2.3 Oscillation Detection

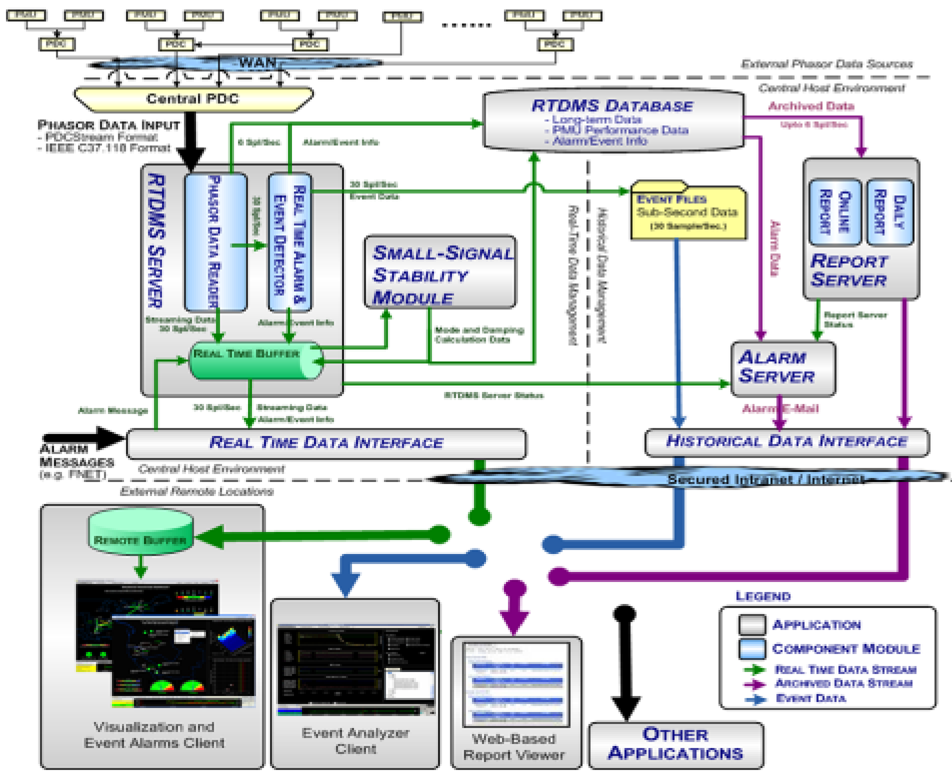
The oscillation detection module that was developed for RTDMS system has the following functions:

1. Runs continuously along-side of the RTDMS Server for the purpose of monitoring and detection of transient event by the Server.
2. If a transient event is detected, the module collects a preconfigured amount of data from selected signals (usually set to 3-5 data windows of 10 sec duration with 2 sec steps).
3. Process the data through several different algorithms for identification of local and inter-area oscillation modes (modal frequency, energy and damping levels).
4. Cross check results from the different algorithms and consecutive time windows to conclude if an oscillation has been reliably detected.
5. Generate an alarming message if the detected oscillation has exceeded user-defined damping tolerances and modal frequency tolerance limits.
6. Provide the alarm message in real-time to be displayed in the RTDMS client.

2.4 System Architecture

Oscillation detection module runs as a windows service and will interface with the RTDMS Server through the real time data buffer. The integration of the module with the RTDMS system architecture is shown below (Figure 5):

Figure 5: RTDMS Architecture with Oscillation Detection Integrated



As seen in the architecture, the oscillation detection module "listens" to the real time data buffer and waits for occurrence of transient event. When a transient event is detected, the module looks for oscillations in the post-event data and performs mode and damping calculation. This processed information is then sent back to the real time buffer to be broadcast as an alarm message in the RTDMS client application. The RTDMS client application, which is connected to the RTDMS server through secure internet or local area network (LAN), receives oscillation detection information and displays it on the alarming window for the user who may need to take some necessary action.

2.5 Small Signal Stability

In 2009, small signal analysis capability was added in the California ISO's RTDMS application. This capability is often referred to as "Mode Meter". In 2010, as part of this research project, Dr. Trudnowski provided the project with an enhanced mode meter algorithm that was tested and integrated into RTDMS. This module estimates the frequency of oscillations, their damping and energy levels.

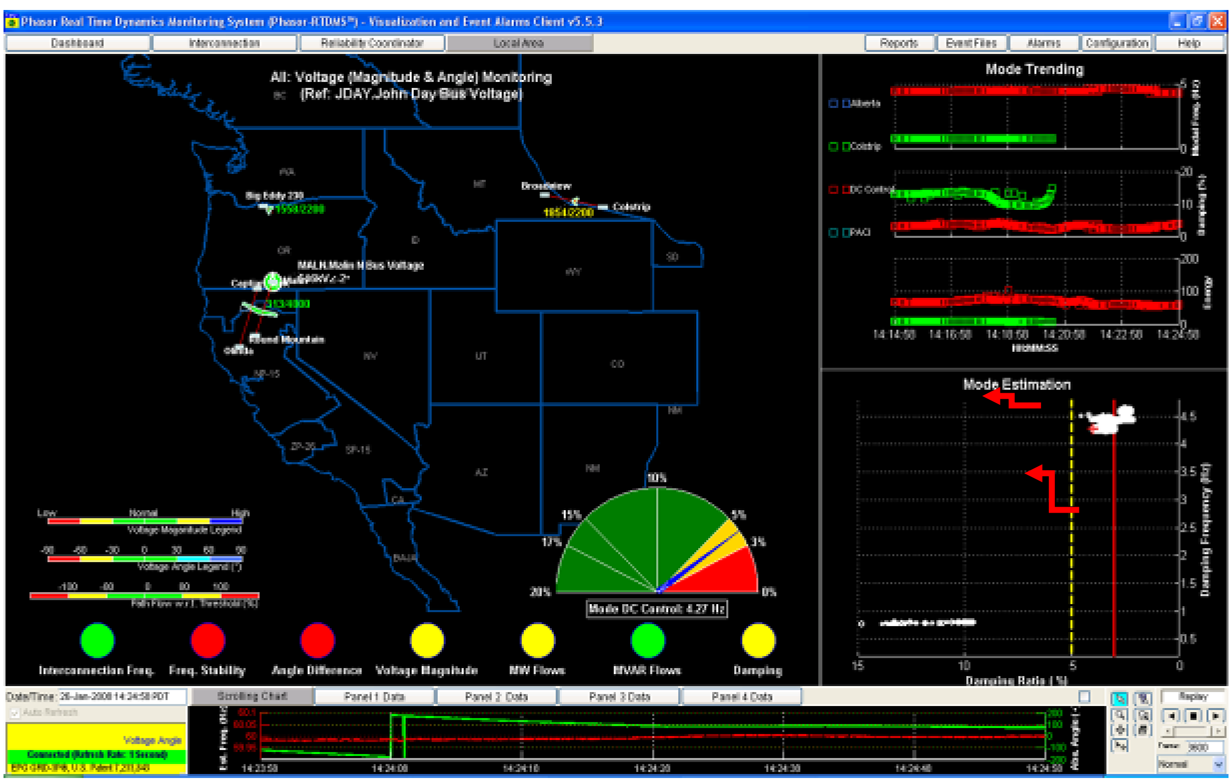
The algorithm was implemented and tested using artificially generated data and several real phasor files. Several operating parameters were varied to find an ideal combination for real time monitoring. The results of the tests indicate that the mode meter algorithms cited above, known as the Yule-Walker and Yule-Walker Spectral algorithms, were very effective at identifying modal frequencies in a sample set. In some cases time windows on the order of one or two minutes were sufficient to identify underlying modal frequencies.

The accuracy of damping calculations however, was generally sporadic and highly sensitive to different time window lengths and sampling rates. Ambient noise also had a pronounced effect the accuracy of damping calculation. Using simulated signals (for example, signals with known modal frequencies and damping coefficients) with a low to moderate level of noise, no set of parameters was identified that could reliably calculate damping to within 10 percent accuracy.

Despite this volatility, the damping calculations appear to have a suitable amount of precision for establishing real-time alarm ranges. This study recommends establishing several damping levels from which to judge the severity of oscillations, ranging from levels of "least" to "most" concern.

Figure 6 below is a sample of the Mode Meter visualization displays that are available for real-time monitoring.

Figure 6: Illustration of RTDMS Oscillations and Damping Monitoring and Alarms Screen



2.6 Findings and Conclusions

Based on testing and consultation with leading industry experts, EPG reports the following:

- Low damped oscillations do occur in the system. Their quick identification is important.
- The mode meter algorithms developed and implemented in cooperation with Dr. Trudnowski are effective at identifying power system oscillations.
- The computational performance of the mode meter algorithm is better than the performance of the Prony-based oscillation detection system
    - The oscillation detection system is therefore valuable for use in post-event analysis
    - The mode meter algorithms are better-suited for real-time analysis, but are less sensitive and less accurate when applied to sudden system changes (for example, frequency disturbances)
- Calculating damping with precision remains challenging due to a variety of interference and noise issues.
    - As such, the recommended course of action is to set damping ranges, paying particular attention to damping in the range of 0-5 percent (very low) and 5-10 percent (moderately low).
    - These damping ranges are currently implemented and used in RTDMS.
    - When an event is identified and low damping observed in the mode meter algorithm, this can be further confirmed and analyzed by taking a small portion of data and analyzing it using the oscillation detection system code.

CHAPTER 3: Phasor Visualization and Alarming

3.1 Introduction

The goal of this task is to conduct research necessary for enhancing the alarming and visualization (look and feel) capabilities of the Real Time Dynamics Monitoring System (RTDMS®) prototype platform at California ISO tailored to use RTDMS for root-cause analysis for all end-users, for example, transmission grid operations and operating engineers. First generation phasor visualization displays require constant monitoring. Enhancements are designed to free operators from the task of constant visual monitoring to take note only when there is an alarm condition, and appropriately diagnose and take corrective action. The alarms will notify operators when system conditions are deemed abnormal based on analysis of the real-time phasor data, including:

- Sudden transients observed within the grid due to discrete events such as line trips, generator outages, or load drops.
- Gradual excursions beyond safe operating limits – wide angle-of-separation, frequency excursions, and low/high voltages for extended periods.
- Recognize when most of the current system state as characterized by key monitored metrics deviate from observed trends over the past 24 hours (for example, soft limits).

3.2 Alarming Methodology in RTDMS

SynchroPhasor Technology provides high resolution time-synchronized data that enables wide area visibility over multiple control areas and regions, presents the users with real-time measurements of key system performance metrics, such as angle differences. While visualization of key system performance metrics provides useful information on the current state and historical trend of a metric, a user is not expected to constantly monitor the visualization application. Hence, it is important to draw user's attention by providing visual or audible alarms upon which the user can diagnose the problem and make informed decisions. Similarly, it is equally important to generate alarms based on realistic thresholds that indicate truly abnormal system conditions. In order to define what the alarming thresholds are, it is first required to identify what normal system operating conditions are. Significant effort has been devoted to baseline system performance metrics that allow identification of abnormal system conditions, which in turn helps in determining meaningful alarming limits.

The Real Time Dynamics Monitoring System (RTDMS) currently features visual alarms that enable quick identification of abnormal system conditions. These alarms include:

1. Threshold Alarms - gradual excursion of a metric beyond safe operating limits.
2. Transient Alarms - sudden change in a metric due to system disturbances.

® Electric Power Group. Built upon GRID-3P platform, U.S. Patent 7,233,843. All rights reserved.

3.3 Threshold Alarms

Threshold alarms are generated when a metric gradually exceeds a user specified safe operating limit. For example, gradual increase in angle difference for an angle pair beyond its specified limit of 10° - also illustrated in Figure 1 below. These threshold alarms are available in RTDMS for the following metrics:

a. High and Low Frequency.
b. High and Low Voltage Magnitude.
c. High Angle Difference.
d. High MW flows.
e. High Mega Volt Ampere Reactive (MVAR) flows.
f. Low Damping of oscillatory modes.
g. High Voltage Sensitivity.
h. High Angle Sensitivity.

Threshold alarms are good indicators of adverse system conditions. These alarms may be a result of after-effects of system disturbances, such as low voltage conditions following a transmission line trip. Moreover, these alarms are useful event pre-cursors such as high angle differences that were observed prior to the 2003 blackout in the Eastern Interconnection.

In RTDMS, threshold alarms are indicated by color-coded traffic lights where the following color scheme has been utilized:

- Green – indicates normal operating conditions - metrics well within the limits.
- Yellow – indicates close proximity of the metric to its limit, between 80 percent and 100 percent of the specified threshold.
- Red – indicates metric operating above the specified threshold and also for low voltage magnitudes.
- Blue – indicates high voltage magnitude conditions only.

Figure 7: Enhanced Dashboard

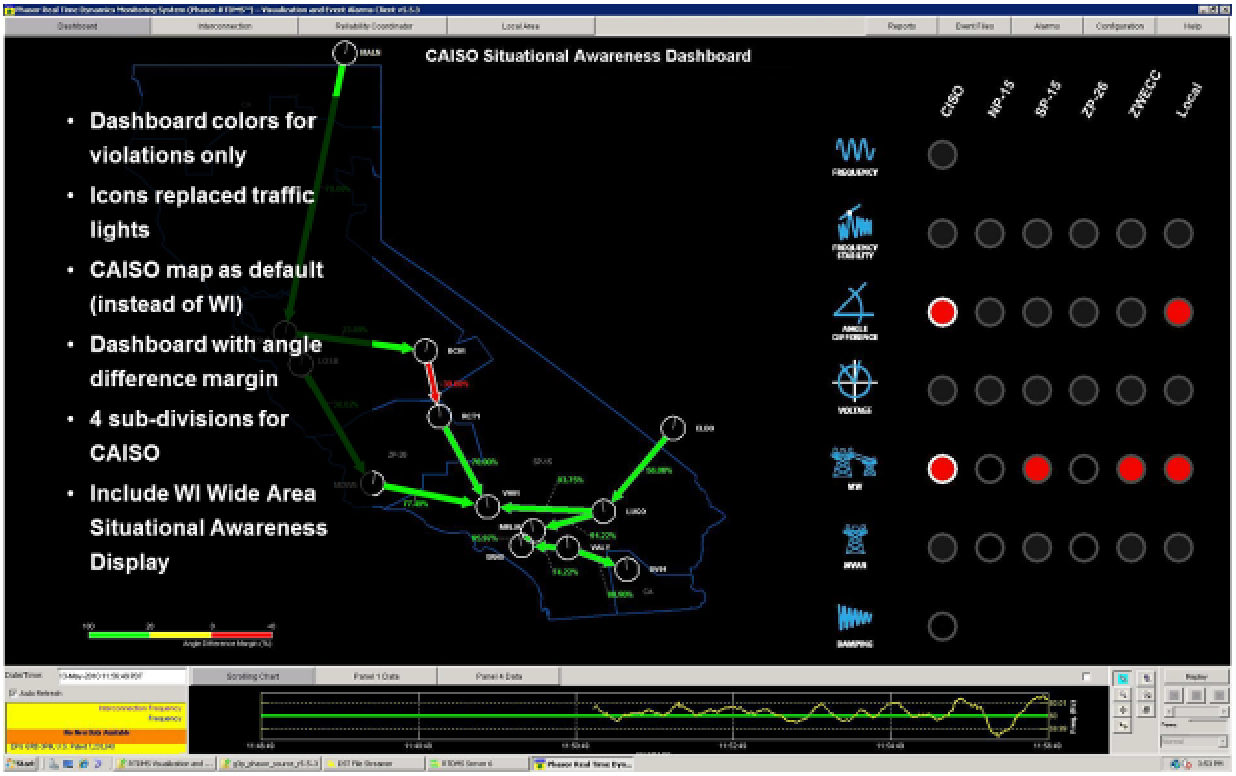


Figure 8: Enhanced Performance Reports

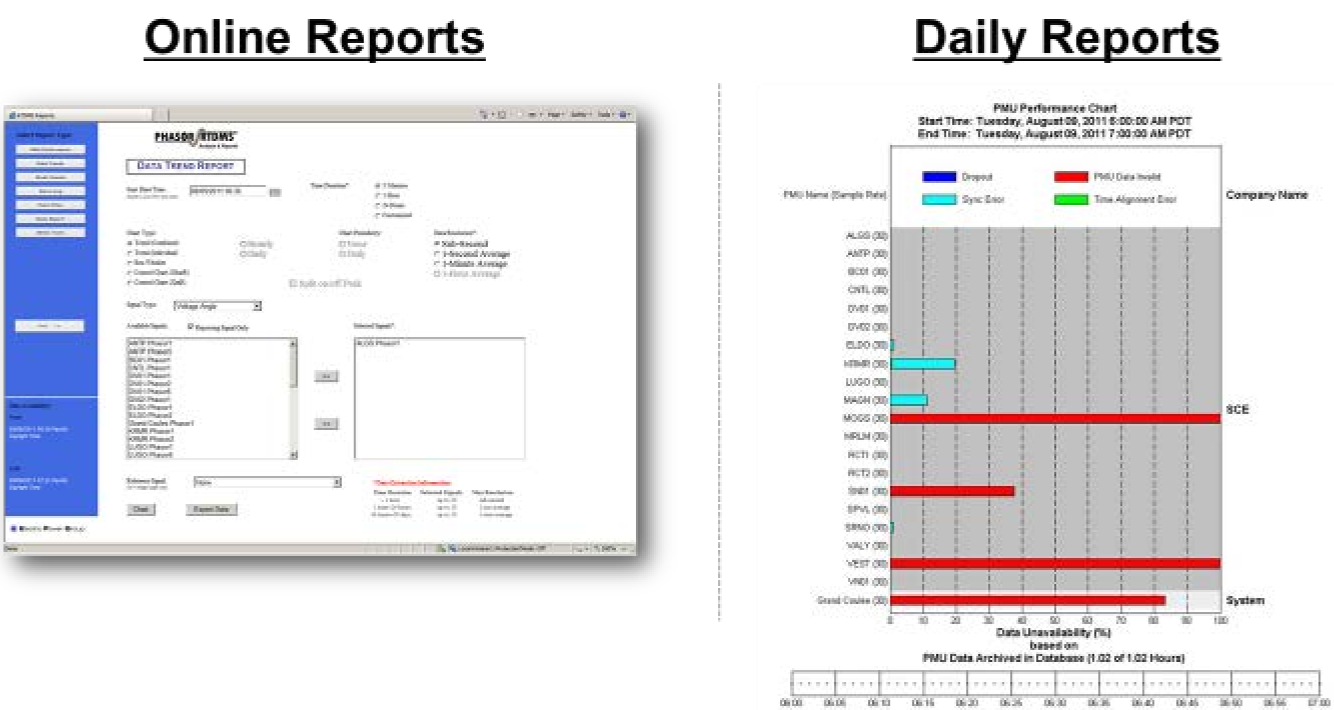


Figure 9: Enhancements to Alarm Management

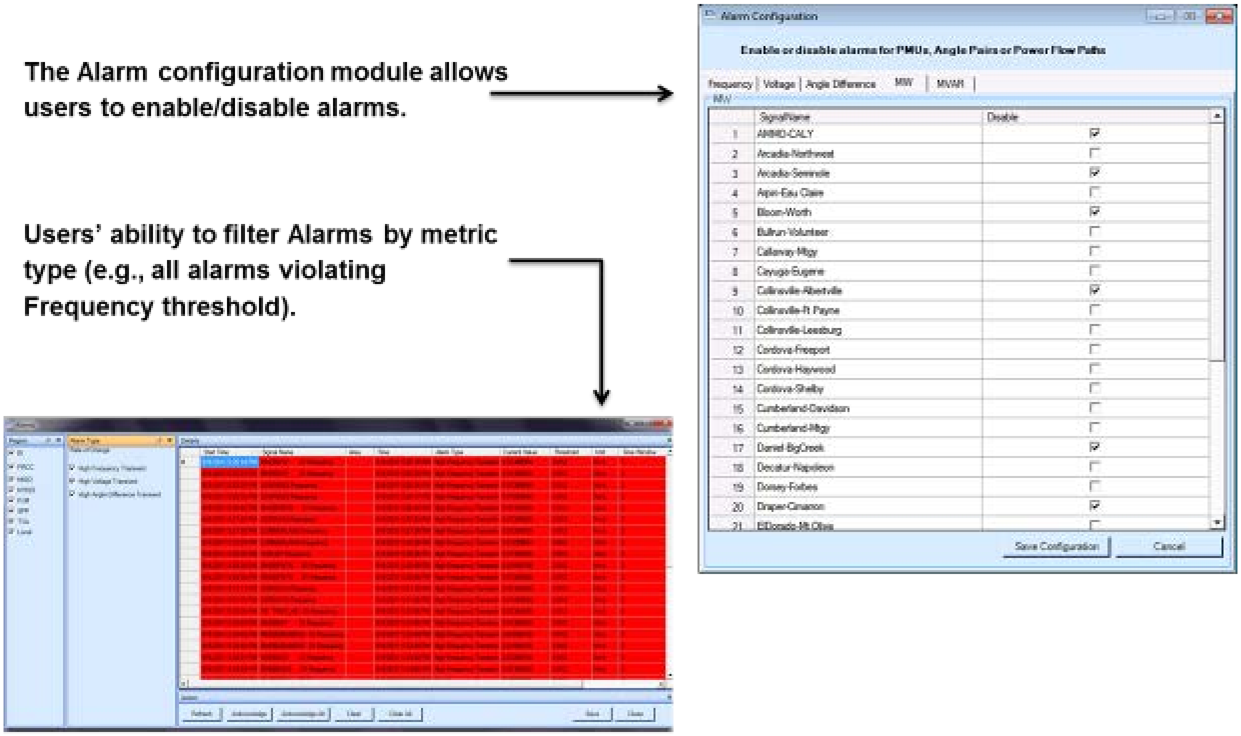


Figure 10: Enhancements to Historical Data Access

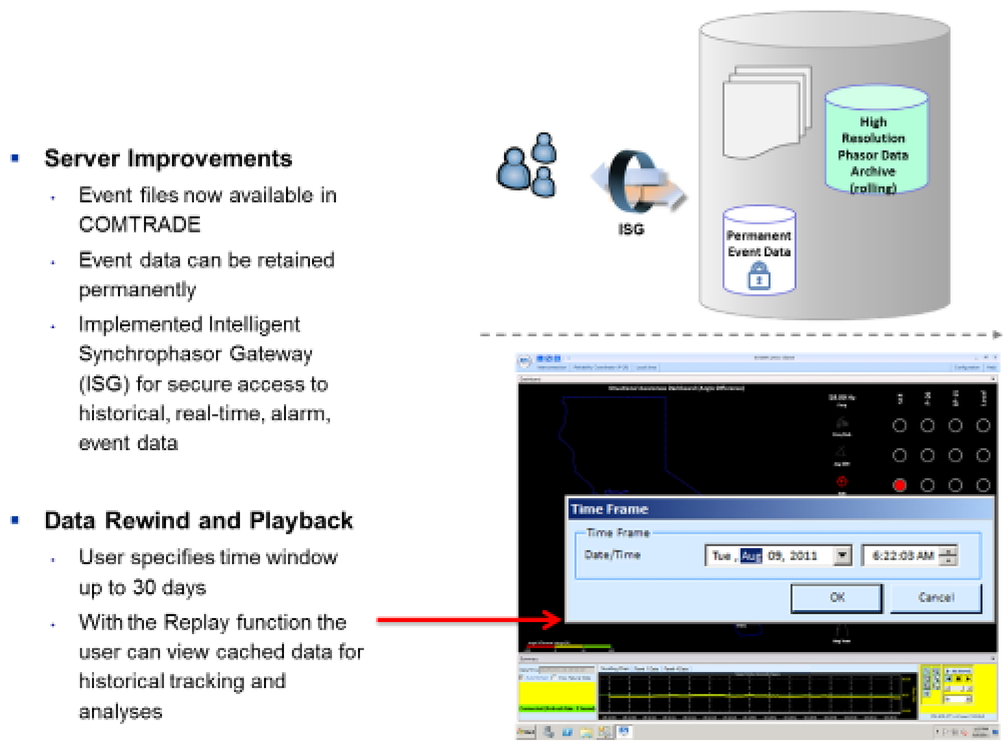
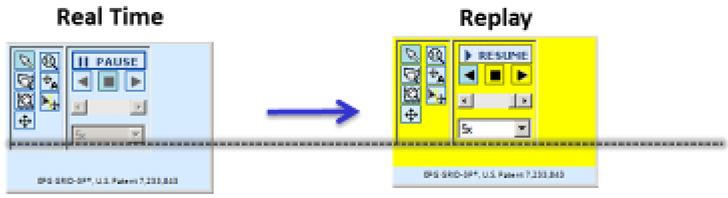
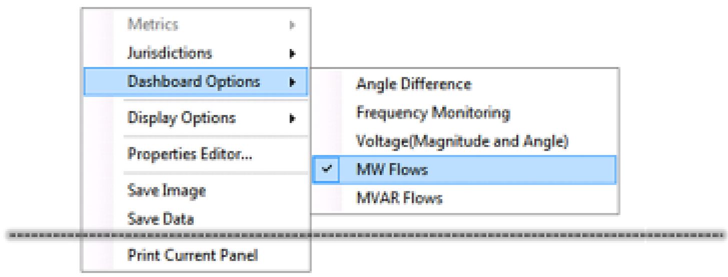


Figure 11: Enhanced Client Navigation

✓ **Flag Replay Function**



✓ **User Selected Metrics for Dashboard Display**



✓ **Alarm Lights with On-Demand Annotation**

CHAPTER 4:
Stability Nomograms with Phasors

4.1 Background

Operating nomograms have been used to manage the real-time operation of the western electric grid for over twenty years. Nomograms consist of two dimensional graphs that define the operational limits (represented as power flows) as a result of the interactions between two or more inter-related electric grid parameters. For instance, the Southern California Interconnected Transmission (SCIT) nomogram describes the safe operating region by relating the sum of the power flows into southern California from the east and north to the sum of the rotating inertia of all the on-line generators in southern California.

4.2 Project Objective

The objective of this research task was to investigate the feasibility of utilizing synchrophasors to describe operational nomograms instead of combinations of measured power flows. Historically, nomograms were developed to describe the safe operating regions based on the power flows measured in two or more transmission paths. Some nomograms were based on thermal loading limits, while others were based on transient stability limits. The expectation was that by utilizing combinations of synchrophasors, which could describe the angular difference between two or more substations in the Western grid, a simpler nomogram could be developed. Moreover, because loading limits are typically determined with loading conditions near maximum levels, a nomogram based on synchrophasors could, theoretically, more accurately portray the overall stress on the grid under both maximum and normal loading levels. Thus, it was expected that a nomogram based on synchrophasors may reveal additional capability on a transmission path during less than maximum system loading conditions.

4.3 Transmission Path Selection – California-Oregon Intertie (COI)

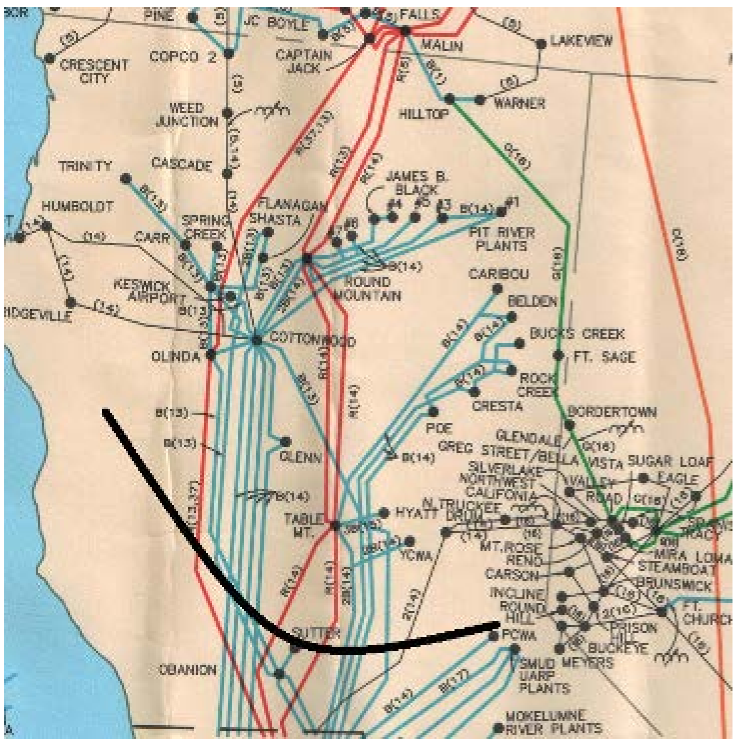
After meeting with the California ISO staff to identify nomograms with adequate PMU coverage for this research project, it was determined that the project should focus on the COI, since is heavily loaded during the summer and is frequently limited by the nomogram conditions. When selection of the COI nomogram was initially made in 2010, this nomogram was based on transient stability limitations. However, for the summer 2011 nomogram, even though the limits were based on thermal overloads in northern California, it was determined to complete the research project using phasors to describe the thermal based nomogram. This report presents the results of that research and it is expected that the results of this research can also be extended to stability based nomograms.

In 2011, the California ISO replaced the 2010 stability limited summer nomogram with a COI-Northern California Hydro (NCH), thermally limited, 2011 summer nomogram based on improved power factor of load in the Pacific Gas and Electric (PG&E) area. Reactive support in this area has been increased by about 775 MVARs. This new nomogram was limited by overload on the Table Mt-Rio Oso 230 kV line for a double line outage of the two lines south of Table Mountain.

The cut plane for the COI Nomogram is shown in Figure 12 below and consists of:

- Pacific AC Interconnection (Malin-Round Mt. 1 & 2 500 kV lines).
- California Oregon Transmission Project (Captain Jack-Olinda 500 kV line).
- Northern California Hydro.
- Hatchet Ridge and Colusa Generation.

Figure 12: COI Nomogram Cut Plane



Source: WECC Map of Principal Transmission Lines, January 2010

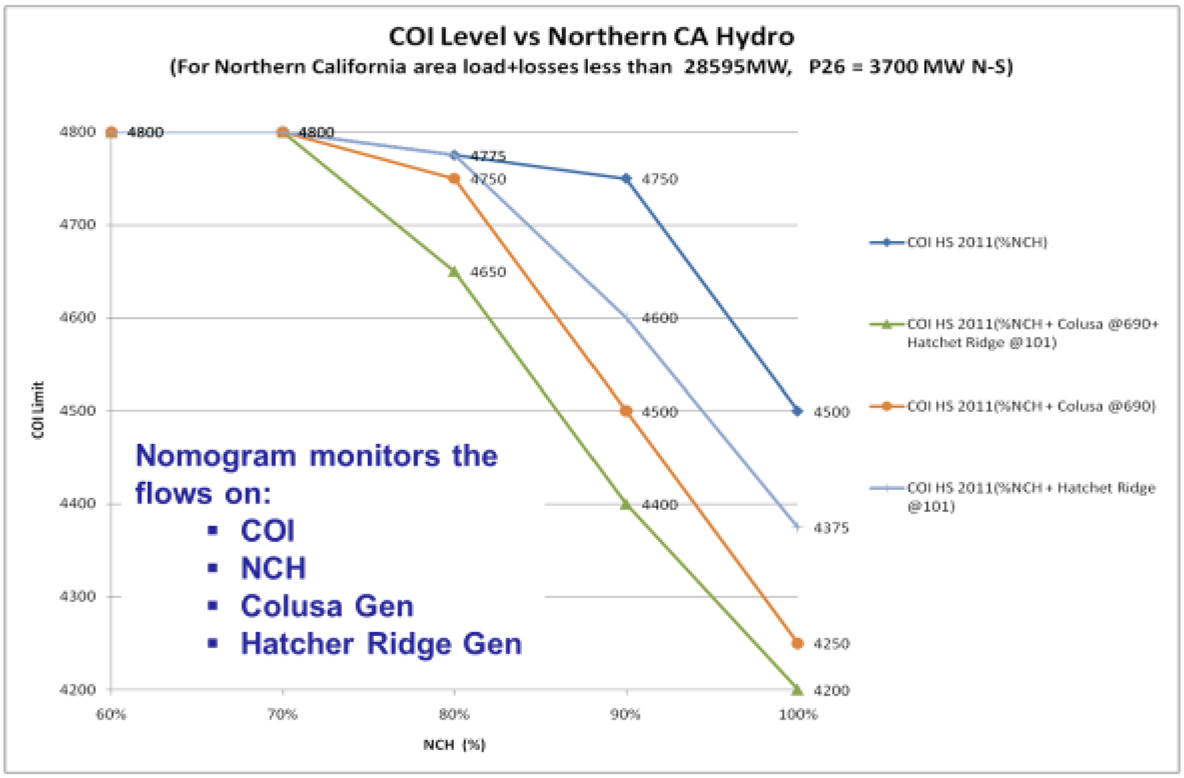
The COI nomogram describes the safe operating region by relating the total power flow on the three 500 kV lines between Oregon and California to the total of Northern California Hydro generation plus the Hatchet Ridge and Colusa generators. The boundaries, which are a product of extensive off-line simulation studies, are set with respect to limits representing various reliability standards.

Since the development of the 2011 summer nomograms, the Table Mt-Rio Oso 230 kV line has been upgraded and some other facility is likely to become the limiting factor for the 2012 summer nomograms. The results of this research can still be applied to the new nomogram with some adjustments that would depend on the nature of the new limitation.

4.4 California ISO 2011 Summer Nomogram

The nomogram used during the 2011 summer to operate the COI transmission system was thermally limited. California ISO provided the power flow studies that were used to define the limiting corner points of the summer 2011 nomogram. In addition to identifying the nomogram limiting corner point line loading limits, the California ISO's power flow cases also provided detailed information about the voltage phase angles across the grid. The objective of this research project was to use voltage phase angles to develop a simpler, more robust summer nomogram. The 2011 Summer Nomogram is described by the family of curves shown below in Figure 13. The safe operating region is below and to the left of the appropriate NCH/generation based loading limit.

Figure 13: COI Vs. Percent N. CA Hydro Nomogram



Source: 2011 Summer California-Oregon Intertie, Pacific DC Intertie, Path 26 and SCIT Paths. System Operating Limit Study Report. April 7, 2011

4.5 Developing a Phasor-Based Nomogram

Stress across a single transmission line, or across a network of transmission lines can be described by either monitoring the power flows on each of the lines, or by monitoring the voltage angles between substations at opposite ends of the network. Higher power flows across the network translate directly to higher differences in voltage angles across the network. This research project was based on the hypothesis that by utilizing combinations of synchrophasors, which are capable of accurately measuring absolute voltage angles, and from which the angular difference between two or more substations in the Western grid could be determined in real-time, a simpler operational nomogram could be developed to describe the limits across an otherwise complex transmission interface, such as the COI. Moreover, because loading limits are typically determined with loading conditions near maximum levels, a nomogram based on synchrophasors could, theoretically, more accurately portray the overall stress on the grid under both maximum and normal loading levels. Thus, it was expected that a nomogram based on synchrophasors may reveal additional transmission capability during less than maximum loading conditions.

The development of an angle difference based nomogram to describe the COI summer limits was based on the following principles:

1. The angle pair(s) must span the portion of the grid where the limitations are experienced.
2. The angle pair(s) selected should have some relationship to the various power flows that give rise to the transmission limits.
3. The angle pairs should provide the ability to check stability limits over paths affected by loss of two Palo Verde units and for loss of the PDCI.
4. The angle pairs should provide the ability to check power flow activity within internal loop across the AC intertie in the Northwest, Northern California and Southern California.
5. Ideally, the angle differences across the selected angle pair(s) should not change much across the various power flow combinations that describe the nomogram limits.

The following presentation slides will summarize the research findings and conclusions:

Figure 14: Selecting Angle Pairs for Monitoring COI

- Angle differences for numerous source-sink (angle pair) locations along the Pacific AC Intertie were analyzed
- Seven stressed cases from CAISO 2011 summer nomogram study were used; these cases have different levels of COI and NCH
- Angle differences for stressed conditions were extracted from the study cases provided by the CAISO
- The angle difference between Malin and Tesla best correlates with COI power flow.
- PMUs are installed at Malin and at Tesla; however there are data quality issues at Tesla

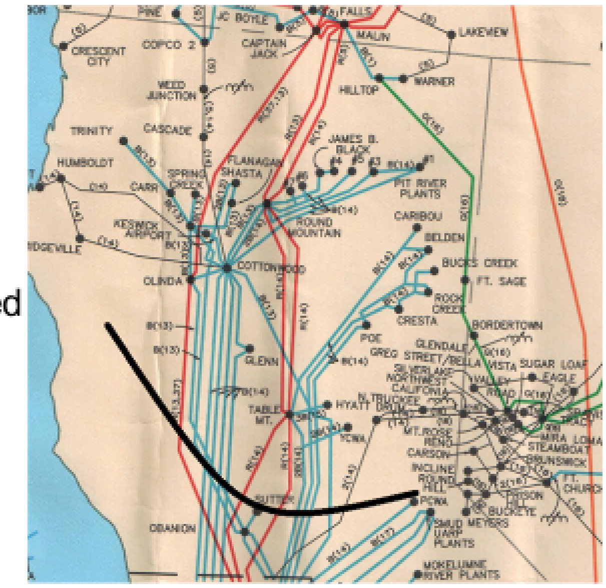


Figure 15: Angle Differences Between Malin and Tesla

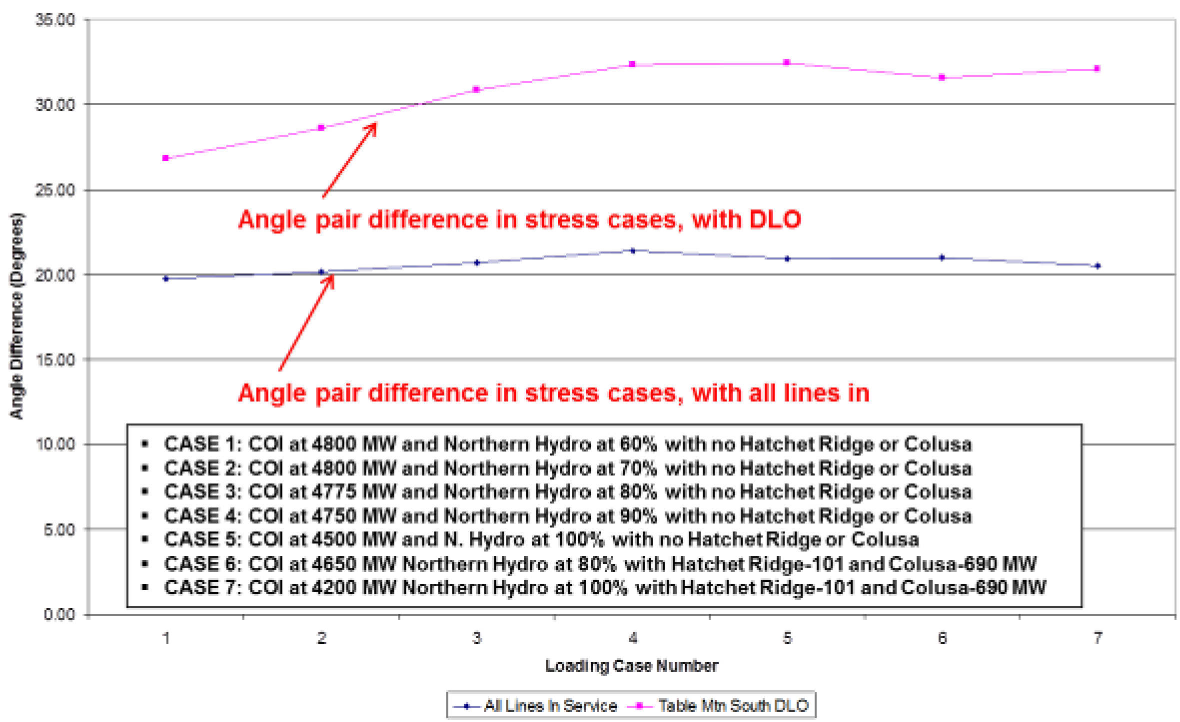
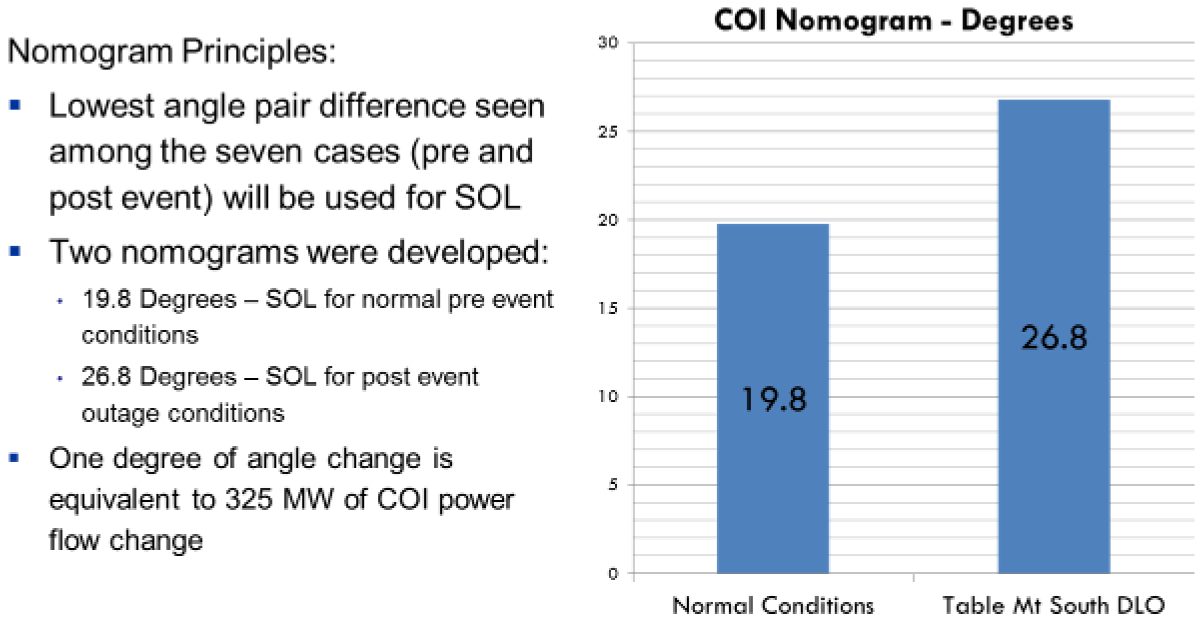


Figure 16: COI Nomogram – Malin Tesla Angle Pair Differences



4.6 Benefits

- Simple to use.
- Phasor data is available for real-time monitoring.
- Has the potential to allow better utilization of transmission capacity.

4.7 Conclusions

- Seasonal offline studies will be used to establish SOL using angle pair differences.
- A phasor-based nomogram can be utilized to validate safe operation under a static (power-flow based) nomogram, while gaining experience with the phasor-based nomogram.
- Angle pair difference-based nomograms are simple to use
- Deployment of additional PMUs will allow further development of phasor-based nomograms on other key transmission paths

CHAPTER 5:
Operational Integration of Renewables

5.1 Project Goal

The goal of this Task is to assess the use of phasor measurements in monitoring impact of wind integration on grid reliability and evaluate/validate related concerns such as adequate reactive support and voltage regulation issues, harmonics, prevailing dynamic and small signal stability concerns, post-transient behavior, and frequency response characteristics, and so forth. The principle benefit will be a better baseline understanding of the actual wind generation performance within California's electric grid in terms of the issues identified above. In this research, the goal is to conduct performance evaluation based on actual phasor measurements from the field taken close to wind farms and from monitored wind farm feeder lines.

This report represents EPG's findings from its Feasibility Assessment Study of the feasibility of using PMU measurements to assess wind generation impact on the grid.

5.2 Background

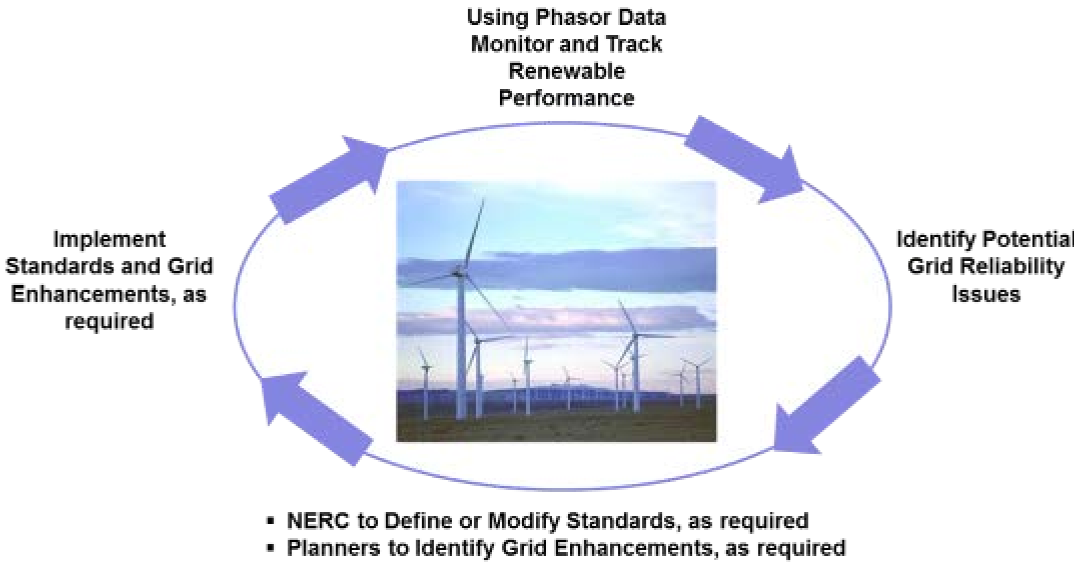
In 2002, the California Legislature established the RPS to diversify the state's generation portfolio and reduce growing dependence on fossil fuels. At that time, the target was to increase the amount of renewable energy in the state's power mix to 20 percent by 2017; the state's RPS has subsequently been revised to 33 percent by December 31, 2020. To achieve the goal of 33 percent calls for adding 20,000 MW of new renewable capacity, most of which is expected from wind projects (approximately 8,000 MW) by 2020, (source - per the Energy Commission 2011 Integrated Energy Policy Report).

In addition to California, every state and province in the WECC has established RPS goals for 2020, and the dominant renewable resource will be wind.

The WECC's 10-Year Transmission Plan, dated September, 2011, (Page 20, Table 1: Generation - Existing, Additions and Retirements) forecasts that by 2020 there will be approximately 15,000 MW of conventional generation retired, and that 56 percent or 33,000 MW of the new generation additions will be made up of renewable resources. By 2020, approximately 17 percent of WECC's energy requirements will be supplied by renewable resources, with wind representing nearly half the total energy production.

As the California and WECC generation infrastructure undergoes major changes (new resources providing limited attributes [that is, inertia, frequency response]) over the next decade, so will the grid infrastructure. These changes will have implications for power system reliability and overall grid performance. Given the pace of these changes, California ISO, utilities, and the WECC need to develop a strategy to effectively monitor grid performance, identify grid reliability issues, development of mitigation solutions and/or reliability standards, and implement solutions/standards (see Figure 17).

Figure 17: Wind Integration Strategy



5.3 Phasor Data from Wind Farms in California

Currently, there are approximately 3,900 MWs of wind generation connected to the California grid at eight different locations (see **Error! Reference source not found.** below). More than 13,000 of California's wind turbines, or 95 percent of all of California's wind generating capacity and output, are located in three primary regions: Altamont Pass (east of San Francisco), Tehachapi (south east of Bakersfield), and San Gorgonio (near Palm Springs).

In 2009, as this research project was getting under way, the plan for getting phasor data related to wind projects was twofold. First, was to request currently available phasor data that is in the proximity of wind projects; and, second was to request data as new PMUs are being deployed as part of the U.S. Department of Energy's (DOE) Smart Grid Investment Grant Program (SGIG).

Even with access to the historical phasor data, our research found that in northern California there was no phasor data available from any substation in the proximity of an existing wind project. In the southern California region, EPG found there was some phasor data from SCE’s Antelope Substation and Devers Substation. As EPG analyzed the phasor data from the 66 kV busses at Antelope Substation, the data was found to be unusable in the research, because of load between wind projects and Antelope. EPG then moved on to analyze the phasor data from the 115 kV busses at Devers Substation, which is about 15 miles east of San Gorgonio, and once again we found the data to be lacking in coverage and unusable.

In discussions with the California ISO and California TOs with regard to the deployment of new PMUs, as part of the WISP/SGIG, they provided the following:

- A list of the existing substations with PMUs installed.
- A list of the proposed PMUs to be deployed as part of the WISP/SGIG project.

- There will be a significant improvement in the overall PMU coverage of the grid, with a corresponding significant improvement in wind project monitoring (highlighted in Table 2).
- Unfortunately, the deployment of the critical wind related PMU will not be completed until the end of 2012. This late deployment of the critical wind related PMU meant that the necessary wind phasor data would not be available in time to incorporate into the research and analysis.

With no usable wind related phasor data in California, our alternative was to reach out to TOs outside of California, who have historical wind-related phasor data and who were willing to share it with our research team. In the team's search for wind-related phasor data three sources were found: Oklahoma Gas & Electric, Electric Reliability Council of Texas (ERCOT), and the University of Texas, Austin. The balance of this report will reflect the findings using the data these organizations made available.

CHAPTER 6: Platform/Infrastructure Enhancements

6.1 Research Goal

The goal was to conduct research related to synchrophasor platform, network infrastructure and applications for reliable data exchange and full system coverage. These are cross-cutting research activities that are needed to support the evolution of the local and regional data infrastructure that is necessary to support the ultimate deployment of the tools that are being developed under this contract.

The process used for this research was to conduct a series of meetings with California ISO starting in late 2009 to identify applications platform, data exchange, and system coverage gaps and issues, and to describe plans to resolve the identified issues AResearch findings were documented and included in a report on recommendations of architectural design on phasor network architecture, identification of existing observe-ability gaps, and steps for improved data quality, network reliability, and full observability and system coverage of California utilities and WECC.

6.2 Background

The California ISO synchrophasor system is currently operating on a single, non-redundant Real Time Dynamics Monitoring System[1] server. Data is being archived from the RTDMS server into a California ISO Structured Query Language (SQL) database. Over the course of several months (September 2009 through March 2010), several meetings have identified emerging issues, and resolution action items have been identified. These issues and action items are described below.

Issues and Action Items from Meetings:

1. California ISO to review their data retention policy and storage capability, and start retaining all available data. To facilitate this, EPG supplied the California ISO with two external hard drives, and California ISO began dumping each month's worth of data to the external hard drives.
    a. California ISO to keep 90 days of Historical StreamReader files on-line, and beyond 90 days will be kept off line.
    b. All StreamReader and RTDMS (disturbance files) server data for one year.
    c. California ISO began retaining StreamReader data on the external hard drives in October, 2009.

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[1] ®Electric Power Group. Built upon GRID-3P platform, U.S. Patent 7,233,843. All rights reserved.

2. California ISO asked for a summary of the factors that increase central processing unit (CPU) utilization, and a forecast of CPU usage for the RTDMS application server and the *enhanced* Phasor Data Concentrator (*e*PDC). Currently both the RTDMS application server and the ePDC use very little CPU.
    a. EPG provided a summary of factors that affect CPU utilization, and a forecast of CPU usage. Appendix A, page 1, details the factors that affect RTDMS CPU utilization. Appendix A, page 2, presents the ePDC CPU load testing results for various PMU load levels.
3. California ISO identified that there was high loading on the (SQL) data base server about every ten minutes, corresponding to data storage activities within the RTDMS application server.
    a. EPG has modified the data base schema and code to provide a unified data base for *enhanced* Phasor Data Concentrator (*e*PDC) and RTDMS that will significantly reduce the loading on the data base server. New code was delivered to the California ISO in December 2009. Installation of the new data base server is awaiting upgrades of the server hardware to the production grade equipment.
4. California ISO is planning to upgrade their data base server to SQL 2008, which should also reduce some of the data base query loading; upgrade is expected in April 2010.
5. Figure 1 reflects the current architecture of the California ISO's phasor network. EPG recommended to the California ISO that plans should be developed for the implementation of a production-grade phasor system architecture, as shown in Figure 2. The California ISO approved EPG's recommendation and will make the necessary internal plans for implementation. EPG, on behalf of the California ISO, has requested additional funding from the California Energy Commission (Energy Commission) for expansion of the California ISO synchrophasor system into this redundant production grade phasor system and integration with the WECC developing phasor network.
6. California ISO has asked for RTDMS data to be ported into their PI data base system. EPG is working with California ISO staff to identify the most appropriate PI interface module to use for this data porting effort.

Figure 18: Current Architecture of the California ISO Phasor Network

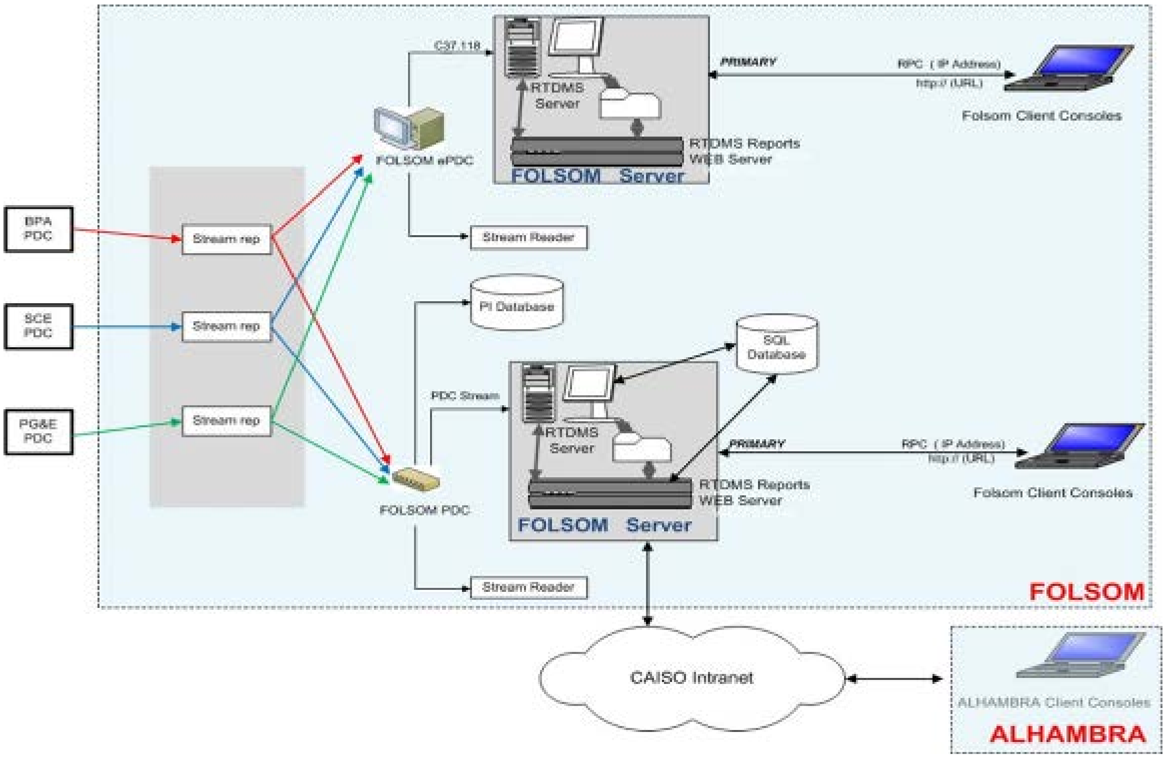
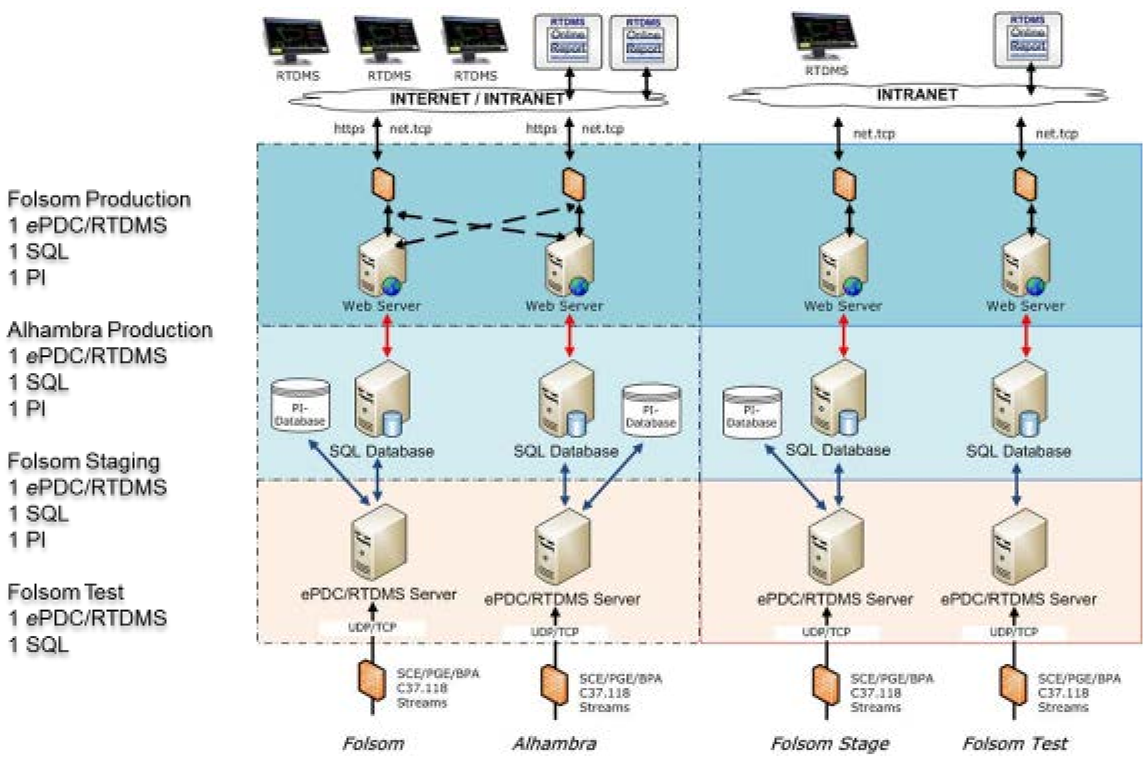


Figure 19: Recommended Architecture for the California ISO Phasor Network



6.3 Architecture Overview

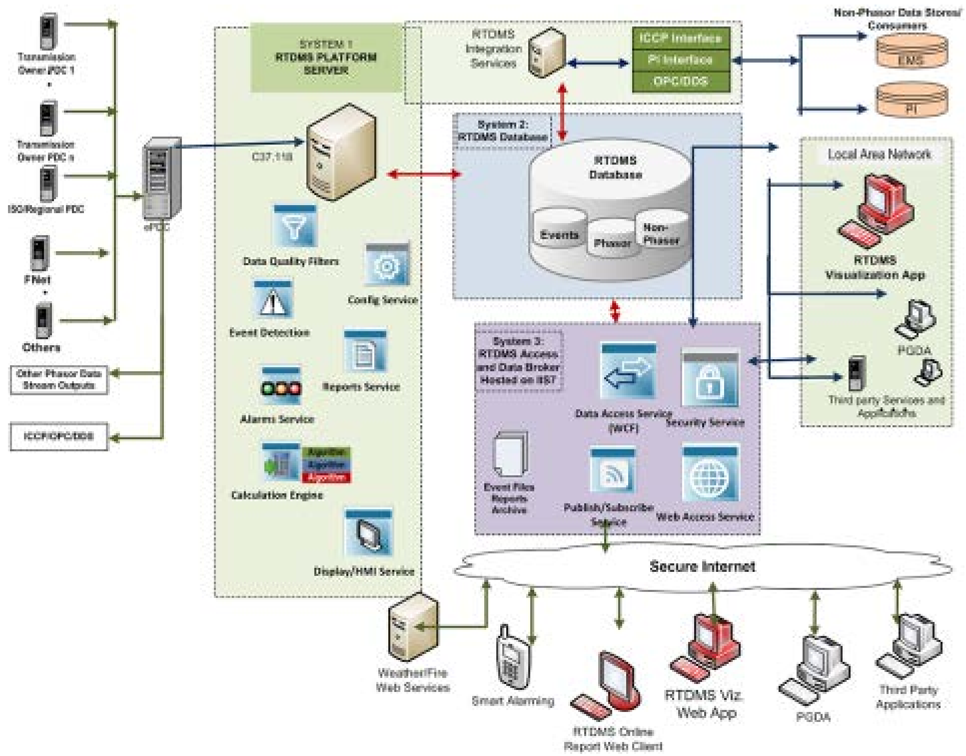
The RTDMS platform is a comprehensive portfolio of software applications for providing real time, wide area situational awareness and real time dynamics monitoring of the power grid for use by Operators, Reliability Coordinators, Planners and Operating Engineers, as well as the capability to analyze system performance and events. RTDMS has been deployed and in use at California ISO. The RTDMS platform and infrastructure has been enhanced for reliable data exchange and full system coverage in support of California ISO's five year synchrophasor technology roadmap. In addition, this enhanced architecture will enable California ISO to interface with WECC's WISP. The RTDMS enhanced platform is referred to as RTDMS 2012.

This enhanced RTDMS multi-tiered platform includes:

- RTDMS Server (see System 1 in Figure 20 below) program designed to accept phasor data input from a phasor data concentrator (PDC) using either C37.118 or PDCStream stream data format. From here, a series of calculations are executed and the results are stored in the RTDMS database. System 1 also includes a Reports Service that sends out daily reports.
- RTDMS database stores the raw phasor data with full resolution (see System 2 in Figure 20) as well as calculated values. This is a relational database designed to work with SQL Server, MySQL and Oracle.
- RTDMS Data Access Broker or Intelligent Synchrophasor Gateway (ISG) provides an interface between clients and the data base (middleware) which allows for the exchange of data between the RTDMS Database and the various client applications (System 3 in Figure 20). This will also facilitate data exchange with utilities and WECC.
- RTDMS Online Reports website that enables users to download event files, PMU performance metrics, download raw phasor data, download daily report and generate customized reports. This is also part of System 3.

Direct access to the RTDMS Server is available programmatically via RTDMS Data Access Interface SDK-API. Access to the archived data in the RTDMS database is available via an RTDMS data access broker or Intelligent Synchrophasor Gateway (ISG), an open interface for programmers utilizing Microsoft Windows Communication Foundation (WCF). The ISG has been designed to operate in an efficient publish and subscribe model.

Figure 20: RTDMS Platform System Architecture



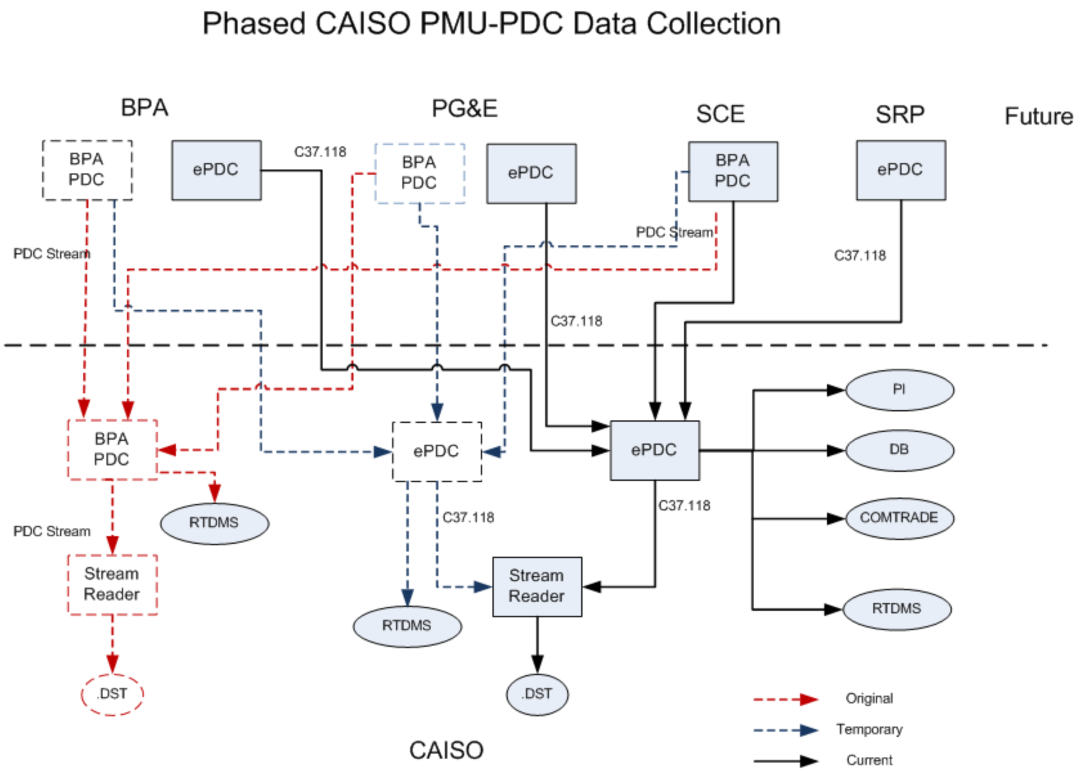
6.4 Functional Specifications

California ISO has been using the RTDMS from EPG to provide the wide area monitoring through phasor functions for Energy Commission PIR-10-068 project. To meet the requirements of the "Transition RTDMS to Production Quality Grade" task of the contract, EPG submitted the design and functional specification of RTDMS 2012 to California ISO.

6.5 California ISO Phasor Network Architecture

California ISO's PMU-PDC Data Collection architecture has been upgraded from a BPA PDC to an EPG *e*PDC, and from BPA standard PDCStream format to international standard Institute of Electric and Electronic Engineers (IEEE) 37.118. In the current system, BPA, PG&E, and Salt River Project (SRP) are sending data to California ISO in IEEE format. SCE is still sending data in PDCStream format. When the SCE Phasor Project is completed, SCE will migrate to IEEE 37.118 format also, as shown in Figure 21 below. The migration has increased the reliability, high availability, and attainability. The adoption of open IEEE 37.118 standard makes it easy to integrate phasor data from WECC utilities, such as BC Hydro, Alberta, BPA, SRP, Arizona Public Service, in addition to California ISO utilities (PG&E, SCE, and San Diego Gas & Electric). Figure 21 shows the California ISO's PMU-PDC data collection network migration from the older (original) phasor technology equipment and data format to the more advanced (current) equipment and data format.

Figure 21: Phased California ISO PMU-PDC Data Collection



CHAPTER 7: Roadmap/Coordination

7.1 Research Goal

The research goal was for EPG to develop a multi-year synchrophasor technology research roadmap (included in Appendix B) for the California ISO and carry out technical coordination with utilities and ISOs in WECC and rest of North America.

Electric Power Group relied on its extensive synchrophasor technology experience, knowledge of industry trends, understanding California ISO's priorities (including review of California ISO's "Five Year Synchrophasor Plan, dated July 2011) to develop a multi-year roadmap action plan that both advances the technology and meets the California ISO's needs. Topics addressed in the multi-year roadmap action plan include:

1. Integration with WECC WISP.
2. Management and analysis of PMU data.
    - validation, quality, base lining, on-line scanning
3. Dynamic (generation and load) model validation.
4. Event Analysis and Operator Training.
    - library of significant events
5. Voltage Sensitivity Analysis (VSA).
6. Phase Angle Difference Dynamic Limits (PADDL).
7. Dynamic Nomogram Validation.
8. Small Signal Analysis (SSA).
9. Grid Restoration Tool.
10. Generation Resource Performance.
    - renewable and conventional generation performance during events

Industry coordination and technology dissemination was carried out through interaction with Southern California Edison, Bonneville Power Administration, Pacific Gas & Electric, WECC, NASPI and preparation of technical papers and briefings.

GLOSSARY

Acronym	Original Term
AC	**Alternating Current**
BPA	**Bonneville Power Administration**
COI	**California Oregon Intertie**
CPU	**Central Processing Unit**
DC	**Direct Current**
DVS	**Double Voltage Source**
***e*pdc**	***enhanced* Phasor Data Concentrator**
ERCOT	**Electric Reliability Council of Texas**
IEEE	**Institute of Electric and Electronics Engineer**
ISG	**Intelligent Synchrophasor Gateway**
ISO	**Independent System Operator**
kV	**Kilovolt**
LAN	**Local Area Network**
MVAR	**Mega Volt Ampere Reactive**
MW	**Megawatt**
NCH	**Northern California Hydro**
PADDL	**Phase Angle Difference Dynamic Limits**
PDC	**Phasor Data Concentrator**
PDCI	**Pacific Direct Current Intertie**
PG&E	**Pacific Gas & Electric Company**
PI	**a mathematical constant equal to a circle's circumference divided by its diameter**
PIER	**Public Interest Energy Research**
PMU	**Phasor Measurement Unit**
P-δ	**Power Angle**

P-V	**Power Voltage**
RPS	**Renewable Portfolio Standard**
RTDMS	**Real Time Dynamics Monitoring System**
SCADA	**Supervisory Control and Data Acquisition**
SCE	**Southern California Edison Company**
SCIT	**Southern California Interconnected Transmission**
SDG&E	**San Diego Gas & Electric Company**
SDK-API	
SGIG	**Smart Grid Investment Grant**
SSA	**Small Signal Analysis**
SQL	**Structured Query Language**
TO	**Transmission Owner**
U.S. DOE	**United States Department of Energy**
WCF	**Windows Communication Foundation**
WECC	**Western Electricity Coordinating Council**
WISP	**Western Interconnection Synchrophasor Program**

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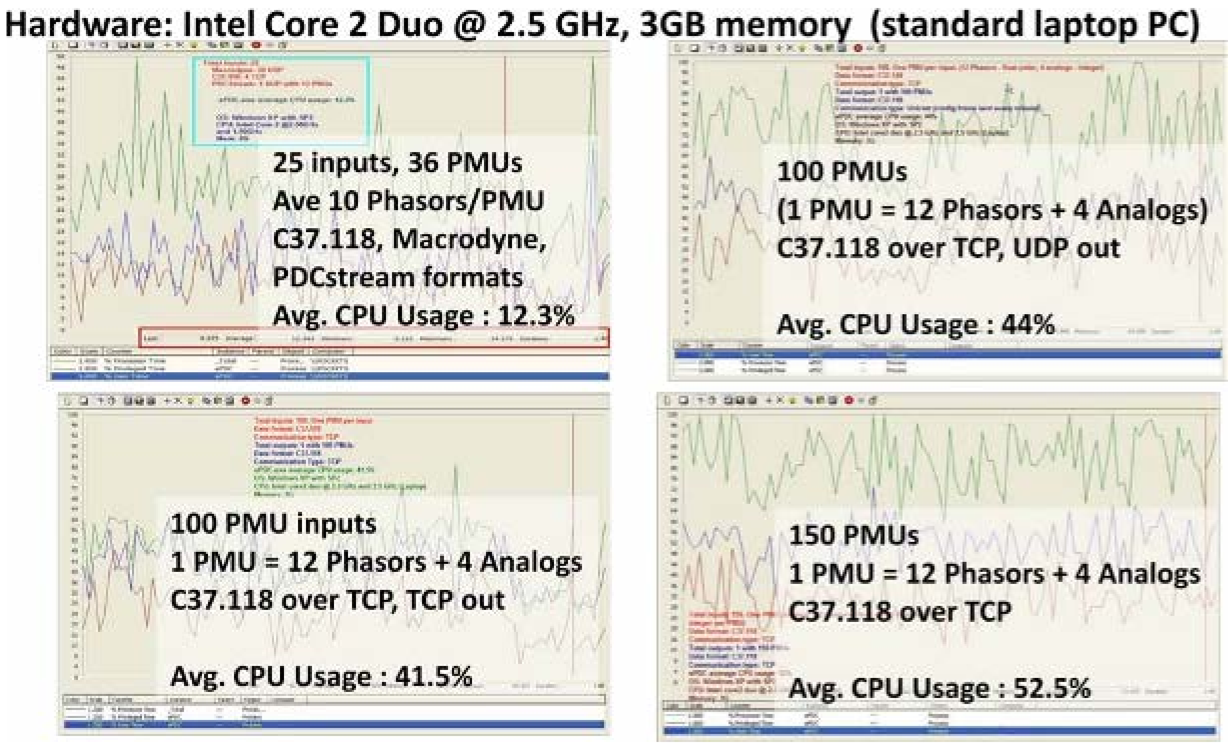
APPENDIX A:
Factors That Affect CPU Utilization And A Forecast Of CPU Usage

Summary of Factors Affecting RTDMS Server CPU Loading

	CPU USAGE
Functionality: Parse streaming data, alarming logic & event capture (*RTDMS Server*) **Periodicity:** ongoing	0% - 1% 3% During Event Capture (Note: ~20% spike at the onset of Event Capture)
Functionality: Small Signal Stability Module (*Mode Meter*) **Periodicity**: every 4 sec	70% spikes every 4 seconds
Functionality: Handle RTDMS Client Requests (*Phasor Archiver*) **Periodicity**: Refresh Rate (ever 4-5 sec)	3% - 6% (Note: Negligible increase in CPU usage with the number of RTDMS Clients connected)
Functionality: Archive data into database (*PhasorBPC & BPC*) **Periodicity**: Refresh Rate (every 1 min)	~10% spikes every 1 minute
Observations • Primary functionality associated with the most CPU usage is the Small Signal Stability module which is ~ 70% (currently configured to monitor 3 modes) • CPU usage associated with data archival is ~10% every 1 minute • CPU usage associated with event capture is ~3% • Number of RTDMS Clients online has minimal impact on RTDMS Server performance	

Summary of ePDC CPU Loading Testing

CPU testing results for *e*PDC (for 100 & 150 PMUs, each PMU is one input)



APPENDIX B: Future Synchrophasor Technology Research Roadmap and Action Plan for the California ISO

May 16, 2012

Prepared by

John Ballance, Jim Dyer, Bharat Bhargava, Romulo Barreno

Electric Power Group

Demonstration of Advanced Synchrophasor Technology for the Integration of Renewables on the California Grid, Agreement Number 500-08-048-01, Task 8

Table of Contents

Introduction

As part of the California Energy Commission PIER funded research project, "Demonstration of Advanced Synchrophasor Technology for the Integration of Renewables on the California Grid, Agreement Number 500-08-048-01," Task 8, Electric Power Group (EPG) is responsible for outlining future synchrophasor technology research needs.

As a starting point, EPG reviewed the CAISO's "Five Year Synchrophasor Plan, dated July 2011." The document describes a high-level synchrophasor technology plan for using and advancing visualization tools and applications over the next five years. The CAISO's near-term focus is on achieving wide-area situational awareness that is trusted by the operators and coordinated with neighboring control areas.

After understanding the direction the CAISO wants to go with this technology, EPG was able to leverage its achievements and experience in this technology, and develop a sound multi-year research roadmap and action plan that both advances the technology and meets the CAISO's needs.

This document presents the roadmap and action plan, including recommendations for future research areas to meet CAISO and California objectives.

Infrastructure

Procurement of Production Grade Hardware for the CAISO - *In Progress – CAISO needs to complete commissioning of Production Grade Hardware and train operators and engineers in use of the software.*

Data Quality and Management

3.1 Management and analysis of data

Operators' use of synchrophasor technology in real time depends on data quality. CAISO to have an efficient process and procedure for:

Establishment of an on-going data validation and monitoring of data quality performance as well as periodic data quality audits.

Coordination and communication with other parties to achieve resolution of data quality issues.

Automated scanning of phasor data for event signatures and ongoing baselining.

Action plan:

Review process for automated data quality reporting and identify issues/problems preventing accurate transfer of data.

Implement a daily data exchange status report and distribute to both PMU owners and users.

Develop modifications of the process as required to ensure PMU owners and users quickly resolve data transfer issues.

Draft functional specifications for automated scanning of phasor data for event signatures and ongoing baselining.

Implement an automated system to scan phasor data for event signatures and ongoing baselining.

Develop an on-going process for data quality validation and audits.

Develop algorithms and processes for archived data scanning to identify events and prepare grid performance summaries (e.g. annual reliability performance reports)

Model Validation

4.1 Dynamic model validation

Validate generation and load models using phasor data to improve the models and provide better operating guidance for use in real-time operations by comparing model results with actual recorded system performance during events.

Action plan:

Coordinate with CAISO staff and generator owners, if necessary, to develop a plan and process for validating generation and load models.

Determine if any portion of the model validation process can be automated.

Draft functional specifications for automation of process.

If feasible, implement a suitable model validation process that can be automated.

Implement the generation and load model validation processes that are not being automated.

Draft a report of findings, with recommended model enhancements.

Review findings with CAISO staff and other interested parties (e.g., California utilities, generator owners, and other WECC members).

Event Analysis and Training Cases for Operators

5.1 Develop a library of significant events

Analyze significant events and use the results for operator training.

Action plan:

Identify significant events from archived data or operational logs

Analyze events and summarize findings, root causes, and lessons learnt

Use events for operator training

Tool Development/Enhancements

6.1 Voltage Sensitivity Analysis (VSA)

Identify critical substations on the 500 kV and 230 kV transmission grid that would be sensitive to reactive availability, and perform VSA for those critical 500 and 230 kV buses.

Action plan:

Integration of Real Time Dynamics Monitoring System[2] (RTDMS®) 2012 with CAISO's EMS/SE and PI.

Identify locations where an on-line VSA tool will be useful.

Draft functional specifications for a VSA application to provide voltage sensitivity evaluation for both current operating conditions and for what-if scenarios.

Develop and test a VSA application to provide voltage sensitivity for both current operating conditions and for what-if scenarios.

Test new prototype of VSA application using actual and mutually agreed critical buses.

6.2 Phase Angle Difference Dynamic Limits (PADDL)

Develop and incorporate dynamic limits for phase angle differences in RTDMS.

Action plan:

Perform research to identify method(s) to effectively incorporate accurate dynamic limits for angle differences into RTDMS, for safe and efficient operation of the grid.

Draft functional specifications for implementing dynamic limits, using data or information from CAISO's State Estimator (SE), EMS or PI system.

Develop a prototype and evaluate the implementation of dynamic limits, with a report of findings.

6.3 Phasor Based Nomogram and Validation

[2] ®Electric Power Group. Built upon GRID-3P platform, U.S. Patent 7,233,843, and U.S. Patent 8,060259. All rights reserved.

Update California Oregon Interconnection (COI) nomogram work that was part of CEC contract 500-08-048-01 and develop a phasor-based nomogram to establish limits for safe operation on other key transmission paths in the CAISO's footprint.

Action plan:

Update COI nomogram work completed under CEC 500-08-048-01 contract, Task 5, by defining safe angle pair limits for the current COI-NCH thermal limitation(s).

Establish and plot phasor-based operating nomogram and compare with static nomogram.

Identify and retain the operating margin (- or +) each time the application runs and incorporate alarm function for violations.

Develop and provide training for use of new phasor-based nomograms.

Perform research for the development of phasor-based dynamic nomograms on other transmission paths in the CAISO's footprint.

Identify potential paths for consideration.

CAISO to select a path for research.

Identify phasor data requirements and substations where installation of new PMUs is necessary.

Draft project SOW.

Perform research and develop a prototype.

Draft a report of research findings.

6.4 Small Signal Analysis (SSA)

Enhance RTDMS oscillation detection application to accurately identify specific resources and/or regions of the WECC that are contributing to a undesirable oscillatory mode

Action plan:

Perform research to determine a reliable and consistent method for accurately identifying specific resources and/or regions of the WECC that are contributing to an undesirable oscillatory mode.

Perform research to determine safe and reliable corrective action(s) that can be suggested to real-time operations, and that can be incorporated into RTDMS oscillation detection app, when undesirable oscillations are detected.

Develop a prototype for application that identifies resources/regions that are contributing to small signal oscillations, and suggested corrective action(s).

6.5 Enhanced Event Playback - *to be incorporated in RTDMS 2012*

6.6 Implementation of Automatic Event Analyzer - *to be incorporated in RTDMS 2012*

6.7 Integration with State Estimator - *to be incorporated in RTDMS 2012*

RTDMS Look & Feel

7.1 Production Grade Visualization - *to be incorporated in RTDMS 2012*

Generation Resource Performance

8.1 Performance of Renewable Resources and Conventional Generation Resources During Events

The ability to accurately predict how generating resources will perform during system events is critical to grid reliability.

Action plan:

Determine what data is currently being received from generation resources within the CAISO's footprint.

Determine which performance standards should be evaluated.

Identify the appropriate metrics to be monitored and tracked.

Draft functional specifications for a resource performance evaluation application.

Develop a prototype Resource Performance Analysis application to evaluate how both renewable and conventional generating resources perform (in key metrics, e.g. frequency, voltage, etc.) during system events.