Consortium for
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Solutions

Phasor
Applications

CA ISO Phasor Applications
Summary Report

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1. INTRODUCTION AND BACKGROUND INFORMATION

A PIER TRP funded multi-year project is currently being conducted by CERTS in cooperation with CA ISO aimed at research and demonstration activities of Real-Time Applications of Phasors for Monitoring, Alarming, and Control. The proposed applications of phasor measurements will provide the real-time operating staff with the previously unavailable, yet greatly needed, tools to avoid voltage and dynamic instability, and monitor generator response to abnormal significant system frequency excursions. Perhaps of equal or greater importance, in the near term, the measurement infrastructure will provide CA ISO with an alternate, independent real-time monitoring system that could act as an end-of-line backup for failures affecting CA ISO's current SCADA/EMS; in the long term, it would become a key element of CA ISO's next generation monitoring system necessary for advanced real time control. Some of the proposed applications include the use of phasor measurements for wide-area visibility, real-time monitoring and alarming, small-signal stability assessment, frequency data collection, nomogram validation and improvements, improved state estimation, and real-time control.

Phasor measurement technologies are a leading example of a new generation of advanced grid monitoring technologies that rely on high speed, time-synchronized, digital measurements. These characteristics are essential for monitoring real-time grid performance, validating (or replacing) off-line nomogram studies, providing advance warning of potential grid instabilities, and, ultimately, enabling the development and introduction of advanced automatic grid control approaches (such as adaptive islanding).

1.1. Description of Problem

CA ISO's traditional security assessment approach - based on SCADA data and off-line studies conducted long in advance of real time operations - are becoming increasingly unreliable for real time operations because they cannot fully anticipate all the conditions currently faced by operators. New technologies, which rely on accurate, high-resolution, real-time monitoring of actual (not hypothesized) system conditions, are needed to support the CA ISO's real-time operations. The purpose of these tools and systems is to monitor, assess, enable, and, ultimately, automatically take the necessary control action to prevent or mitigate problems in real time.

On August 10, 1996, a major disturbance separated the WECC system into four electrical islands (Northern Island, Southern Island, Northern California Island, and Alberta Island), interrupting service to 7.5 million customers for periods ranging from several minutes to about nine hours. This disturbance effectively began with the loss of the Keeler-Allston 500-kV line in the Portland area, due to inadequate right-of way maintenance, which overloaded parallel lines and depressed transmission voltages. These conditions led to subsequent tripping of additional lines and McNary generating units, triggering oscillations that increased in magnitude for approximately 70 seconds, until the protective devices tripped the three 500-kV California-Oregon Intertie (COI) lines due to low voltage (less than 315 kV on the Malin 500 kV bus) and subsequent islanding of the WECC system [1]. The growing oscillations can be attributed to an increased electrical angle between northwest generation and COI.

On October 18, 1996, the WECC investigation team analyzing August 10, 1996, blackout strongly recommended that "the WSCC CWG shall investigate the cause of the undamped oscillations…" and that "all WSCC owners of generators, in conjunction with the WSCC TSS and CWG shall assess whether installed excitation systems and PSS on units with capacity of 10 MW or greater, are properly tested, tuned, and correctly modeled in transient stability studies." [1].

Summarizing the outcome of the previous blackout investigations, the U.S.-Canada Power System Outage Task Force that conducted the analysis of the August 14, 2003 which impacted 50 million people in the Eastern Interconnection, indicated several causes or contributory factors in common with the earlier outages including [2]"

- Inadequate situational awareness and regional-scale visibility over the bulk power system

- Inability of system operators or coordinators to visualize events on the entire system
- Failure to ensure operation within secure limits
- Failure to identify emergency conditions and communicate that status to neighboring systems
- Inadequate training of operating personnel

The bi-national investigation team recommended the need for "wide-area visibility and situational awareness to address problems before they propagate..., use of time-synchronized data recorders…, improved system modeling, data quality and data exchange practices…, and better real-time tools for operators and reliability coordinators" [2].

Phasor technology is one of the key promising technologies on the horizon that offers new possibilities in providing the industry with new tools and applications to address these blackout recommendations and to tackle reliability management and operational challenges faced by CA ISO operators and WECC reliability coordinators. Such data that recorded during the 1996 blackout was invaluable in investigating the causes of the major 1996 blackout. It also complements existing SCADA systems by providing the high sub-second resolution and global visibility to address the new emerging need for wide area grid monitoring; real-time dynamics and stability monitoring; dynamic system ratings to operate system closer to the margin to reduce congestion costs and increased asset utilization; and improvements in state estimation, protection and control.

1.2. Overview of WECC-CA ISO Phasor Network

Under PIER support, CERTS and CA ISO have made significant progress towards accomplishing the CA ISO's goal of using phasor technology for wide-area real-time monitoring and control. On September 4, 2002, a Phasor Data Concentrator (PDC) was installed at CA ISO in Folsom, CA. At the start of the project almost 4 years ago, the initial phasor network consisted of only 14 Phasor Measurement Units (PMUs) gathering data at 30 samples/second and sending it in real-time to the PDC at Bonneville Power Administration (BPA). This setup included 12 PMU devices located at various substations within and around BPA's jurisdictional area that were sending data directly to the BPA PDC for time synchronization, and communication links between BPA and Southern California Edison (SCE) comprising of an analog microwave circuit between BPA in Vancouver (WA) and LADWP in Los Angeles (CA) and a digital link from there to SCE in Rosemead (CA) for real-time data exchange of selective signals (2 phasors and 1 frequency) from 2 of their respective PMUs between the two utilities. This collective set of time-synchronized phasor data from the BPA PDC was then forwarded to the CA ISO PDC in real-time using the existing WECC/CA ISO Wide Area Network (WAN) used to exchange control center data between utilities.

Subsequent expansion work on the network has resulted in greater wide-area visibility across the WECC. Presently, the CA ISO PDC receives data from 42 PMUs from geographically distributed locations via the WECC WAN which connects the BPA, SCE and PG&E PDCs with the PDC at CA ISO. PMUs belonging to BPA feed directly to the BPA PDC while WAPA PMU data is fed from the WAPA PDC to the BPA PDC over the WECC/CA ISO WAN. The SCE and PG&E PMUs feed into their corresponding PDCs, and this data is further transmitted in real-time to the CA ISO PDC. Figure 1 below shows the current Western Electricity Coordinating Council (WECC)-CA ISO synchronized data communication network and the proposed expansions.

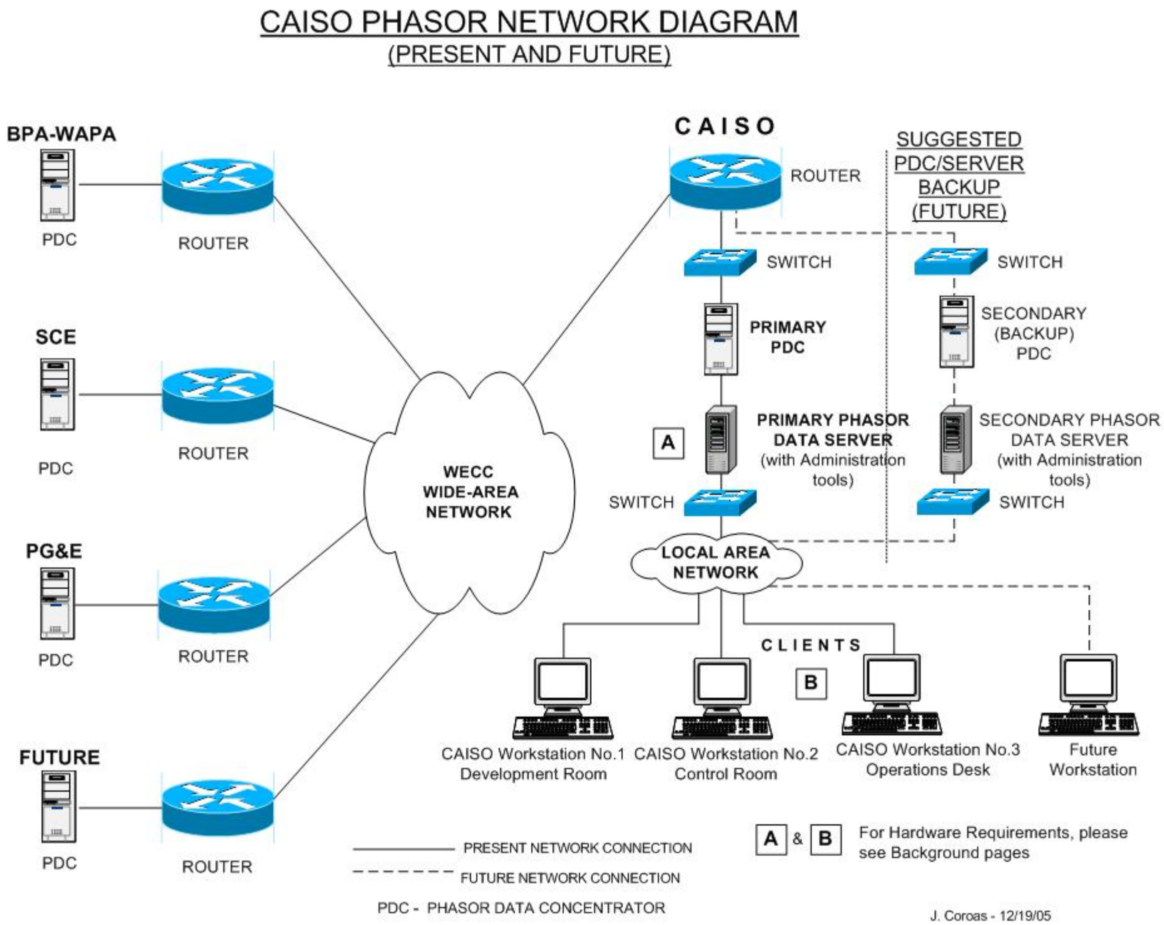


Figure 1: Current and Future WECC-CA ISO Phasor Data Communication Network

The current Real-Time Dynamics Monitoring System™ (RTDMS) application at CA ISO reads the collective set of phasor data output from the CA ISO PDC and displays it in real-time. This complete set of time-synchronized high-resolution data provides the desired wide-area visibility across the western interconnection required for security monitoring by dispatchers including dynamic performance assessment and post disturbance analysis.

Future plans for the network include exploring the integration of phasor data from Arizona and British Columbia into the WECC phasor network which would close any observable gaps that currently exist in the network. Furthermore, it would also benefit the CA ISO to extend the phasor data stream all the way to CA ISO's Alhambra facility and create a secondary backup system there for redundancy.

The RTDMS phasor system display station which was initially installed at the CA ISO control room has recently been relocated to the WECC Reliability Coordinator's desk It will not be long before the long-awaited phasor data could be presented to all the WECC reliability coordinators in real-time and within standardized displays. With this phasor network in place, reliability coordinators as well as system operators will be able to monitor over 250 voltage and current phasors at key 500 kV, 345 kV and 230 kV substations throughout the WECC.

2. PROJECT OVERVIEW

The current WECC and CA ISO phasor infrastructure has matured to the point that this infrastructure can be used as a new data source to support real-time system operations applications. The emphasis of this project over the next few years therefore is to focus on applications that are uniquely suited for phasors and will provide the real-time operating staff with the previously unavailable, yet greatly needed, tools to monitor grid reliability and avoid voltage and dynamic instability, as well as key metrics for tracking grid performance, such as generator response to abnormal significant system frequency excursions. It will also enable CA ISO, California and WECC utilities to explore closely related issues, such as use of phasor data to improve system planning models, to improve state estimation, to determine the optimal location of additional phasor measurements, and ultimately to gain the experience with the technology needed to begin developing real-time control applications.

In July of 2004, the CERTS Program Review Committee recommended that the Energy Commission and CA ISO continue the research, development and application of this technology including research to determine what phase angles and rates of change of phase angles (and associated ranges around these quantities, including appropriate boundaries or thresholds, recognizing inescapable uncertainties) are appropriate for various locations in system, what actions should be taken by operators or automatic control equipment, if there are major deviations, and the desired location for additional phasor monitoring equipment around the WECC. The proposed approach, developed in conjunction with CA ISO staff, represents a phased approach toward addressing these issues, centered around introducing phasor information to operators and working closely with them to modify and enhance the applications (including training) to increase their confidence in relying on this information to support their day-to-day activities.

2.1. Project Overall Goals

This overall objective of this project is to accelerate the adoption and foster greater use of new, more accurate, time-synchronized phasor measurements by CA ISO reliability coordinators and control area operators as well as by California and WECC utility transmission dispatchers towards achieving the long-term goal of using phasor technology for wide-area monitoring, alarming and control. The specific research objectives of this task are:

- To provide real-time operators with new tools which provide previously unavailable wide-area visibility and information on the dynamic stability of the grid.
- Design the conceptual look of operator displays for phasor applications.
- Define functional specifications such that, upon completion, the tools can be transferred to a vendor (selected by CA ISO) for implementation as a production-grade operating tools
- Provide technical support to and assist in coordinating phasor applications being researched and developed by CA utilities.
- In the long run, provide the basis for the introduction of a new generation of automatic grid controls.

At the conclusion of this project, prototypes for several CA ISO phasor applications will have been researched, developed, factory- and field-tested, all in close coordination with and oversight provided by CA ISO, such that the findings from these activities will be summarized in the functional specifications for commercial-grade, production-quality tools that can be acquired by CA ISO [3].

2.2. Research Roadmap

In July of 2005, CERTS worked with CA ISO in developing an R&D Roadmap to guide the Phasor Applications technology research and development effort. This multi-year roadmap shown in Figure 1 layouts out the research and development plans by the various task activities that need attention as well as through the various phases of the development cycle including research, development, demonstration, and technology transfer, and the intermediate milestones and deliverables [3]. The end product of many of the activities listed in the tasks is to develop functional specifications for production quality applications that could be passed on to commercial vendors of CA ISO's choosing for implementation. The various tasks identified within the roadmap are summarized below:

Input Data Requirement: The present WECC-CA ISO Phasor Network uses the BPA developed proprietary PDCStream format for real-time data transfer between BPA, WAPA, SCE, PG&E and CA ISO. The new industry phasor format standard for real-time data transfer, IEEE C37.118, has recently been approved. As the phasor devices migrate to the new standard, the various phasor prototype applications developed will have to comply with this new standard. Furthermore, as additional devices, such as relays or disturbance fault recorders, that have phasor measurement and GPS time synchronization capabilities (such as DFRs, relays) comply to the new standard, they could also be integrated into the phasor system to close any observability gaps that present exist.

CA ISO Applications: Various applications which are well suited for phasor measurements and that meet the CA ISO needs have been identified, all of which are planned for development on the existing RTDMS platform. These applications include identifying and addressing wide-area visualization needs on this phasor data within standardized displays and summary screens with special attention towards avoiding screen clutter, and real-time monitoring, alarming and reporting capabilities based on advanced monitoring metrics and indicators on this high resolution phasor data. Other applications include a Small-Signal Stability monitoring application to detect the low frequency electromechanical oscillations when observable in the power system and to closely monitor and track their oscillatory frequency and associated damping to provide early warning on poorly or lightly damped situations where there is a danger of the oscillations growing unstable. There is also a Frequency Data Collection project to collect and archive sub-second frequency data from PMUs to meet new NERC-WECC Western Interconnection frequency data collection requirements.

New System Capabilities: This task addresses a wide-area research need that extends beyond the CA ISO, which is the use of phasor measurements for real-time wide-area control. As a first step towards achieving this goal, the objective is to research and develop methods for utilizing phasor measurement to validate and possibly improve stability nomograms.

System Integration and Support: Each of the CA utilities has identified pilot projects to demonstrate the application of phasor technology to problems that are of interest to these utilities. In particular, SCE is interested in local remedial action controls with phasors, SDG&E would like to demonstrate improvements in the state estimation results using PMU measurements, and PG&E's interest lines in monitoring critical paths via PMUs. To the extent possible, CERTS will be providing assistance and support to each utility's undertaken projects. Additionally, CERTS will be coordinating collaboration activities with academic and industry experts as needs arise.

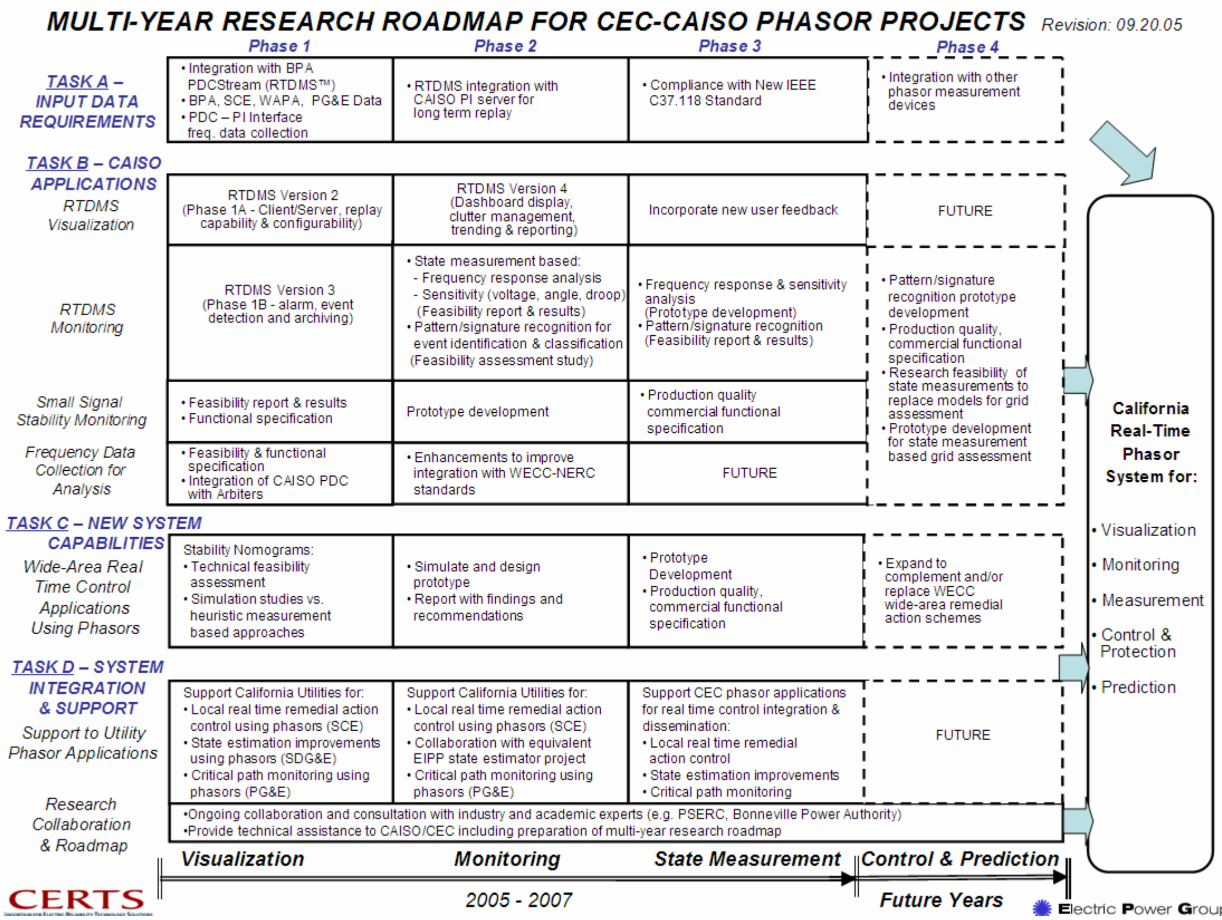


Figure 2: Multi-Year Research and Development Roadmap for the Phasor Applications

2.3. Proposed Approach

To successfully accomplish the tasks outlined within the roadmap, we propose a phased out approach for each of the various applications which would include the following stages:

- Conduct the initial research and feasibility assessment on the defined problem
- Perform an extensive review of existing methods and algorithms, and select the most appropriate algorithm(s) to be used in the prototype application
- Work closely with CA ISO staff to develop a functional specification for the prototype tool
- Implement and test the prototype in the field
- From the understanding gained with the prototype tool, develop a functional specification for the production quality application to be implemented by commercial vendors.

The level of research and development associated with the various applications would be a major contributing factor in defining the amount of effort spent with each of these different stages of the proposed approach.

A Technical Advisory Committee (TAC) consisting of representatives from the CA ISO, California utility, BPA, DOE and other organizations provides strategic guidance for this Real-Time Operations R&D program and foster rapid adoption of R&D results by these organizations.

3. PHASE 1 TASK DESCRIPTIONS

The various activities within the research roadmap that were performed during Phase 1 of the project are described in greater detail within this section. Depending on where these activities stand within the proposed approach, the effort during this phase can be categorized as Development Activities (RTDMS Versions 2 and 3, Frequency Data Collection), Research Activities (Small-Signal Stability Monitoring), and Support Activities (Support to Utilities).

3.1. Development Activities

Real-Time Dynamics Monitoring System (RTDMS - Version 2 and Version 3): The Real-Time Dynamics Monitoring System (RTDMS – Version 1) was initially developed as a stand-alone visualization application. During Phase 1 of the project, this application was transformed into a phasor technology research and development platform, supporting a central server / multi-client architecture as well as additional underlying functionalities required to support the development of additional phasor applications as outlined within the roadmap. Some of the key functional enhancements include:

RTDMS Version 2 (Phase 1A) – Delivered to CA ISO in January 2005
- Implement multi-user capability
- Expand system wide-area visibility to include SCE phasor data
- Research and improve wide-area visuals through configurability
- Research and improve display for frequency response monitoring
- Research and implement replay capability

RTDMS Version 3 (Phase 1B) – Delivered to CA ISO in August 2005
- Research and incorporate transient detector
- Research and enhance alarming capability
- Research and add event archiving capability for transient events
- Expand system wide-area visibility to include PG&E phasor data
- Research and improve wide-area visuals to reduce cluttering

A conceptual overview of the system hardware and software architecture is shown in Figure 3 [13]. The RTDMS platform now supports a server-client architecture with the central RTDMS Server responsible for data management functions such as data acquisition, filtering, data processing and caching, and a thin client layer where multiple RTDMS Client applications installed on different machines can simultaneously access data from the central server. By centralizing the data management process, this architecture minimizes the necessary performance requirements for all Client machines and this translates to a reduction in hardware cost. Additionally, any new Client applications that would be developed under this project could connect to the common RTDMS Server for data access and retrieval.

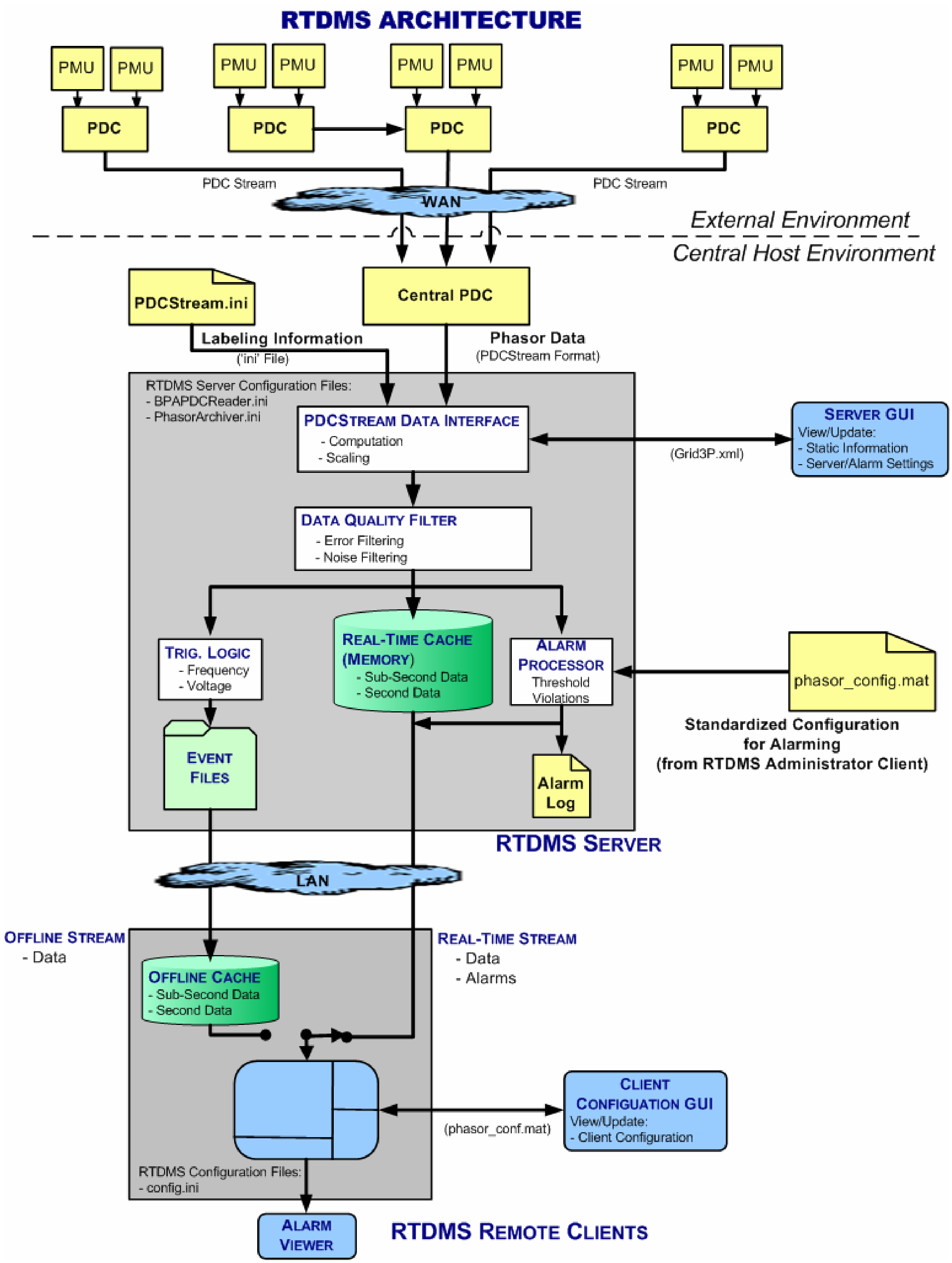


Figure 3: RTDMS Version 3 System Architecture

Some of the additional enhancements include the configurability capabilities that allow the end user to grow and customize the overall RTDMS system and the visualization displays to reflect changes within the phasor network as new PMUs are added into the WECC phasor network and additional data from these new units is made available (see Figure 4).

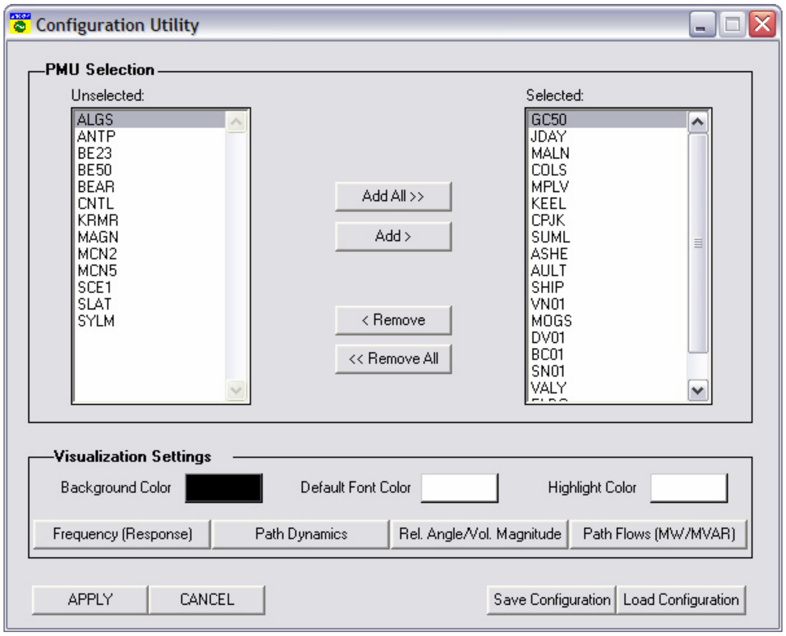


Figure 4: Sample Configuration Graphic User Interface

Alarming logic has also been built into the Server to analyze the streaming real-time data to detect and alarm on either threshold violations or significant rate-of-change (i.e. change within a second interval exceeding a specified threshold) on identified signals and metrics. Some of the alarming conditions presently set within the RTDMS Server include:

- System frequency exceeding specified threshold limits
- Sudden changes in system and local frequencies
- Voltage magnitudes exceed minimum or maximum thresholds (i.e. low or high voltages)
- Sudden changes in voltage magnitudes
- Angle difference across specified paths exceed defined threshold limits
- MW/MVAR flows across specified paths exceed defined threshold limits

Not only are the generated alarms permanently logged at the Server, these alarms are immediately made visible on all RTDMS Clients that are connected to the Server. All relevant information pertaining to these alarms (such as the metric associated with the violation, the start time of violation, the end time of violation, the violation value and corresponding threshold, the violation type, etc) are continuously shown in the alarming window (see Figure 5). The end user must acknowledge the alarm to make it disappear.

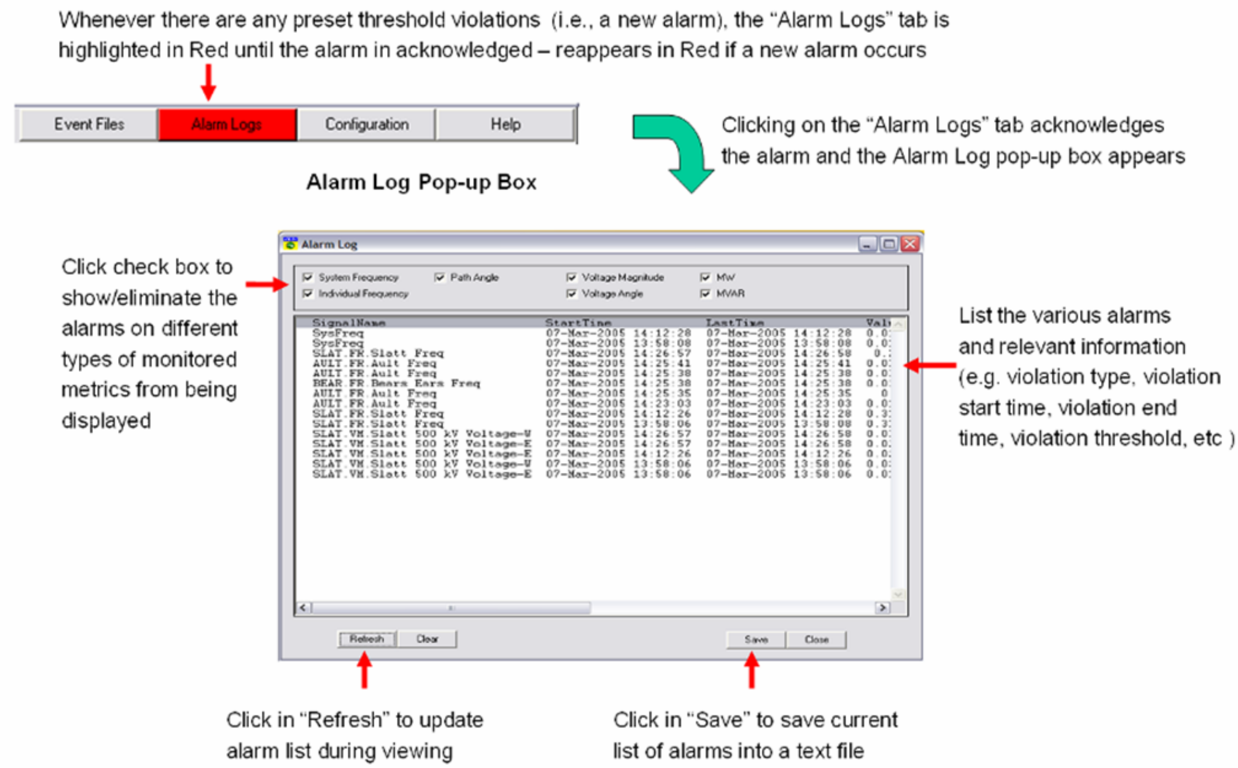


Figure 5: Real-Time Alarming on Monitored Metrics

Additionally, abrupt changes sensed in the voltage or frequency measurements may suggest that the system is undergoing a transient event such as a fault in the system or the loss of generation and/or load. Whenever a transient is detected, the application automatically saves, both, pre- and post-disturbance data and an alarm summary log into an event file that is labeled by the date and time of the event. This archived data can be loaded into RTDMS Clients in an Offline study mode and this set of data is adequate to recreate and payback all its visuals (see Figure 6).

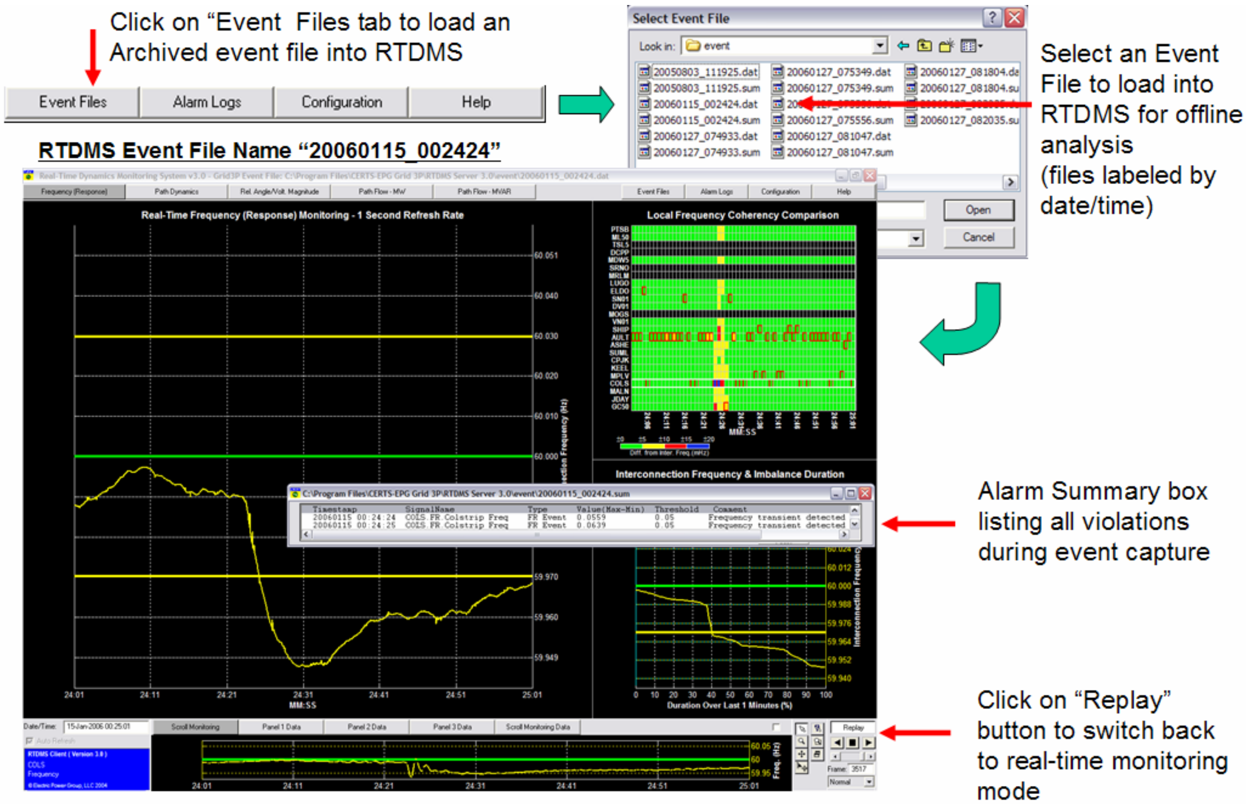


Figure 6: Event Archiving and Playback

During real-time operation, the Replay functionality (Figure 7) permits the user to switch from the Real-Time monitoring mode to the Replay mode to view cached data for historical tracking and analyses. Once in the Replay mode, the auto-rewind/auto-forward buttons or the slider can be used to move back/ahead in time for closer inspection of the data and metrics.

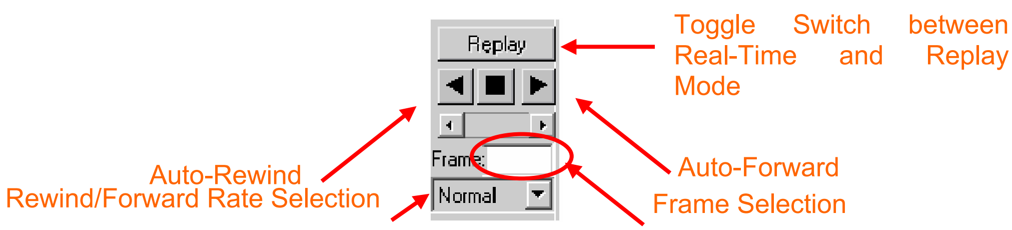


Figure 7: Replay Capability

The use of the replay capability as described above can also be used to interrogate event files when they are loaded into the RTDMS Client. Other enhancements included expanded wide-area visibility to include SCE and PG&E phasor data.

The RTDMS phasor system with above mentioned features was delivered to CA ISO in 2Q 2005, and has been installed at the Reliability Coordinators desk.

Frequency Data Collection: In response to the USA-Canadian August 14th, 2003 Blackout Investigation Task Force blackout recommendations which emphasized the need for the collection and archiving of synchronized wide-area data, NERC-WECC and some of its subcommittees have been working during the last two years in defining functional requirements for the collection and archiving process. The CA

ISO Frequency Data Collection project was defined to meet these new guidelines by acquiring sub-second frequency data from two main sources: the CA ISO Arbiter Frequency Monitors at Folsom and Alhambra, and the PMUs presently operational at BPA, SCE, WAPA, and PG&E. Joint meetings were held between CA ISO and CERTS/EPG in January and February, 2005, to discuss and review proposed system architectures and cost estimates.

CA ISO management decided that for this project, the primary data source for CA ISO frequency data would be the two CA ISO Arbiter systems, and the secondary data source will be the from at least 6 geographically and electrically separated PMU devices within the Western Interconnection. CERTS/EPG would be responsible for integrating the secondary data source; i.e. the Phasor Data Services software running as a Windows NT service to collect GPS time-stamped frequency data from the CA ISO PDC with a rate greater than 10 samples/second and accuracy of 0.001Hz, data filtering to eliminate noise or data dropouts, and storing the collected data into the Folsom and alternate PI Historians [21]. The PI database deployment, integration and redundancy would be CA ISO's responsibility (see Figure 8).

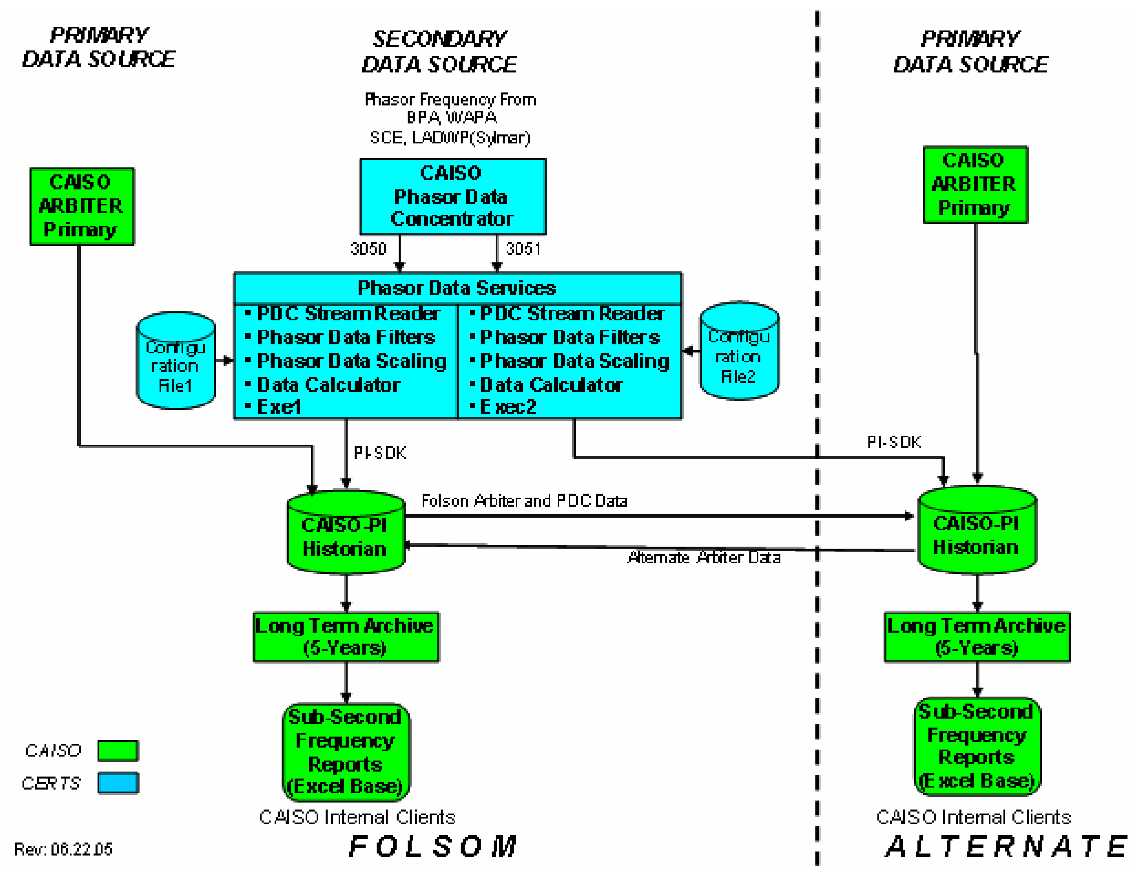


Figure 8: CA ISO Frequency Data Collection Redundant System

The project and system architecture was approved by CA ISO IT and management in April, and the functional specification was delivered to CA ISO in June. The development began shortly thereafter and the factory test was complete in July.

The field test and delivery to CA ISO on integrating the secondary data source was place on hold due to CA ISO restructuring. The primary system is presently operational at CA ISO and fulfills the immediate project needs of archiving sub-second frequency data. CA ISO management at this time has elected not to archive the PMU frequency data into their historian but are interested in archiving the PMU phasor data instead. The CERTS/EPG development on this project could easily be adapted to fulfill this objective.

3.2. Research Activities

In late 2004, CA ISO shared their interest in pursuing a Wide-Area Security Assessment (WASA) project to monitor security margins (i.e., “distance to instability”) across the entire interconnection in real-time based on geographically dispersed PMUs, and voltage magnitudes and static angle measurements in particular. A key limitation here is lack of full observability by the PMU devices. In early 2005, CERTS/EPG formulated a survey to reach out to experts in the field for their comments, suggestions, and recommendations on the 2 projects: Voltage Security Assessment (VSA) and Wide-Area Security Assessment (WASA). The survey was sent to 51 academic and power industry experts worldwide with sixteen responses received; eight of the respondents were from the power industry and eight from academia. A common consensus was that the use of phasor measurements for modal estimation to assess small-signal stability was am ideal first step towards achieving the WASA project objectives. Mathematically, small-signal stability is a *Hopf bifurcation* where a stable equilibrium becomes oscillatory unstable and the consequence is either steady state oscillation or a growing oscillatory transient process. Hopf bifurcations are associated with a pair of complex conjugate eigenvalues whose real parts are changing their sign from negative to positive [20].

Small-Signal Stability Monitoring: Low-frequency poorly damped electromechanical oscillations that are observed in the power system are of interest as they characterize the stability of the power system and often limit power flows across the grid. While there is a danger that such modes can lead to instability following a sizable disturbance, there is also the risk of these modes becoming unstable (i.e., negatively damped) due to gradual changes in the system conditions. The ability to continuously track these modes in real-time would therefore be a valuable tool for dispatchers and power system operations engineers.

The focus of this project is to develop a prototype application that analyzes phasor data in real-time to identify dominant low-frequency electromechanical modes in the system and detect lightly damped oscillations under ambient conditions (i.e. mode frequencies, shapes, and damping). The idea is to alert operators when the system is experiencing poor damping.

Recently there have been multiple efforts to identify the dominating modes from phasor measurements. The underlying idea is that small fluctuations such as random load switching act as a constant low-level excitation to the electromechanical dynamics in the power system and are observed in the power-flows through, for example, voltage angle variations across transmission corridors [8,9,10,16,17,18,19]. Assuming that the random variations are white noise and stationary over the frequency range of interest (typically of 0.1+ Hz), then the spectral content of phasor measurement signals ,which is colored by power-system dynamics, can be used to estimate the inter-area modal frequencies and damping.

Bonneville Power Administration (BPA) also shares a common interest in the area of small-signal stability. BPA has been a pioneer in the phasor technology area and presently has over 15 of their own PMUs installed and connected to the WECC phasor network. They are very interested in extracting data both for real-time processing to provide alarms for system operators for impending trouble as well as observing the state of the system during staged system tests. Both CERTS/EPG and BPA have decided to collaborate on this small-signal stability prototype application research and development effort, thereby leveraging off each others expertise and eliminating unnecessary duplication. A Statement of Collaboration is presently in place between the two entities with the following key tasks identified (see Figure 9):

- Identify platform for algorithms evaluation and implementation plan
- Algorithm development and refinement including reviewing existing work to date, evaluating methodology alternatives on actual and model test data
- Prototype implementation and testing
- Online operation and evaluation of prototype

- Application studies to determine relationships between observed modal behavior and power system stress conditions.

Prof. Dan Trudnowski, who is a leading expert in estimating mode properties from system measurements and has published several papers in this area, is also a key advisor on the project. Some of the proposed algorithms that shall be reviewed include but are not limited to:

- Yule Walker methods
- Autocorrelation with Prony Analysis
- Sub-space identification methods
- Least-squares ARMA methods

Monte Carlo simulations shall be used to evaluate the performance of each algorithm under consideration before incorporating them into the prototype application.

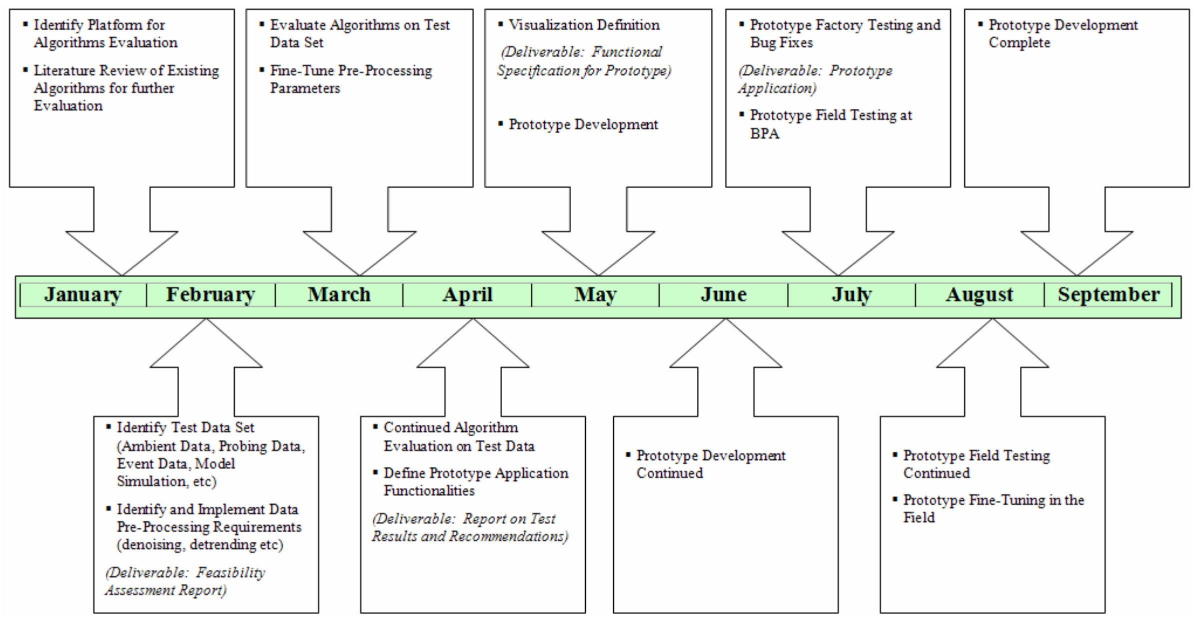


Figure 9: Small-Signal Stability Monitoring Prototype Implementation Plan

Stability Nomogram Validation: The objective during the current phase of the project was to conduct a feasibility assessment study to propose several approaches of using these time synchronized, high resolution PMU measurements, and possibly other EMS/SCADA data, for better assessment of the system operating conditions with respect to their stability limits, and consequently improve or validate existing nomograms.

The need for a more dynamically adjustable nomogram is well understood at the California ISO, and several ideas have been generated around the potential use of manually or automatically adjusted nomograms. In general terms, the proposed concept deals with the tradeoff between the pre-calculated fixed operating limits that are based on extensive computations (which tend to be more conservative due to the uncertainty about the applications) and the limits calculated in real time and adjusted to the current system conditions (which are computationally less expensive, but based on better knowledge of current conditions). Additionally, the real-time operating conditions can deviate from the simulated conditions that have been used to build the pre-calculated existing nomograms. The existing nomograms have been developed using a very limited number of critical parameters that can hardly reflect the changes of the remaining system parameters that are not included in the nomograms. Hence, these conservative limits adversely effect the definition of congestion costs on the one hand, and do not completely exclude system problems on the other hand.

By shifting the focus from some of the pre-calculated operating constraints to real-time calculations, it is possible to build more flexible nomograms. Specifically, the use of real-time measurements provided by PMUs and the results of real-time stability assessment applications can complement the existing nomograms by making the pre-calculated nomograms less conservative. These measurements can also provide data to select critical nomogram parameters for visualization based on real-time information and determine new areas and situations where additional nomograms may be required. Some of the ways in which phasor measurements can be used to validate or improve nomograms are [12]:

- Detection of potential "holes" in the existing nomograms (Figure 10a)
- Detection of excessive "conservatism" in the existing nomograms (Figure 10b)
- Use of reduced dynamic equivalents whose parameters are estimated by phasor measurements in both transient stability and small-signal oscillatory studies.

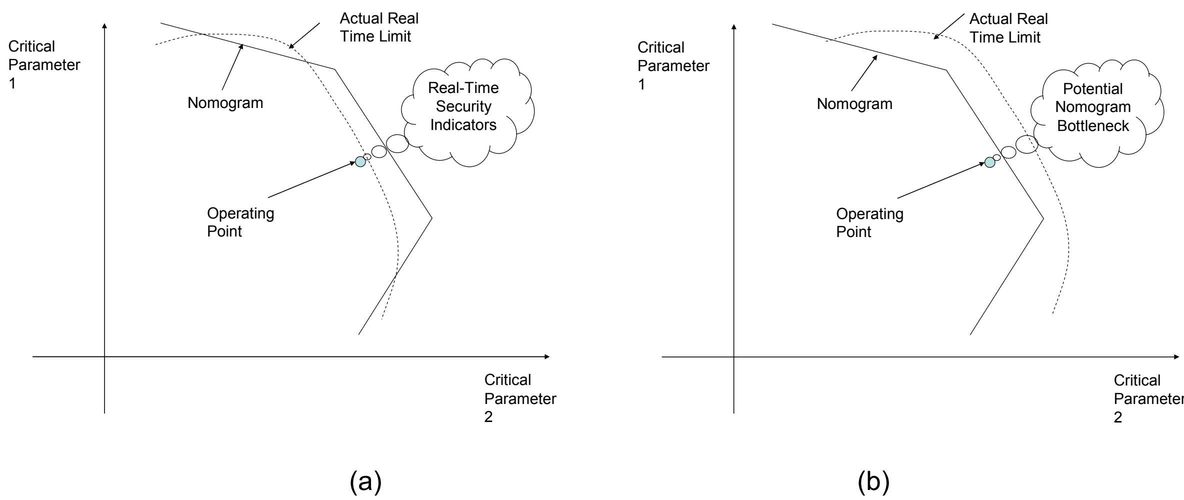


Figure 10: Using Phasor Measurements to Detect (a) Potential "Holes" and (b) Excessive "Conservatism"

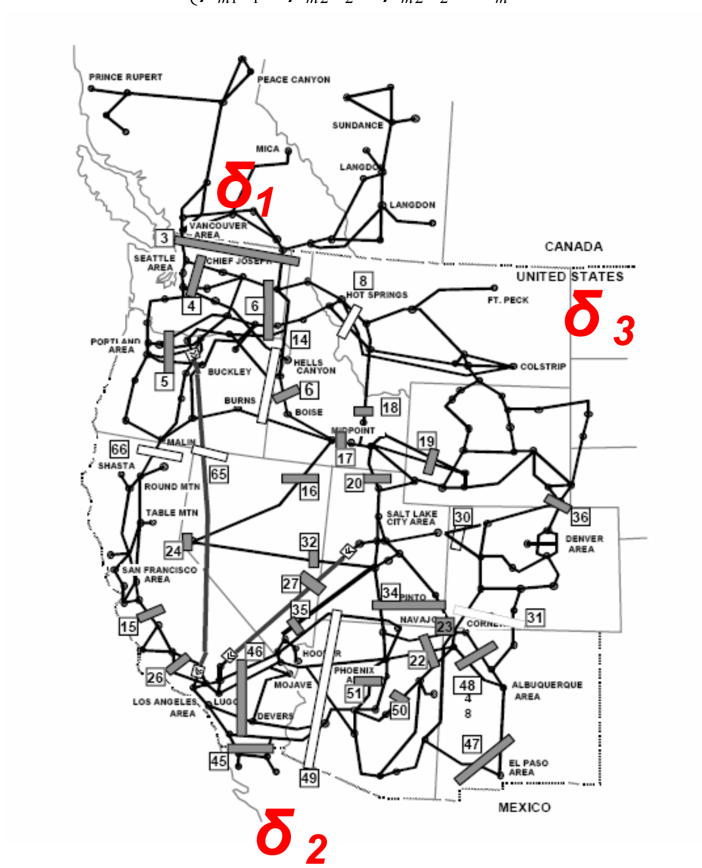
At the same time, there are several limiting factors that need to be considered while addressing these tasks:

- The nomograms reflect various contingency and system conditions. The real-time measurements reflect just the current system state/contingency, and therefore are not indicative of potential stability problems that might happen for the same load and generation pattern under different contingency conditions or under heavier loading conditions.
- Although PMUs can track the dynamics of certain grid variables in real time, there are only a limited in number of PMUs distributed over a wide area. Since PMUs do not provide full observability of the system state – additional data from the state estimation and SCADA may be required.
- The number and location of the existing PMUs may not be adequate to the task of monitoring of local stability limits such as those induced by voltage stability problems.

Nevertheless, phasor measurements do provide wide area observability of system swing or oscillatory dynamics where the state estimator performance is too slow, and certain approaches that exploit these attributes can be suggested for nomogram validation purposes.

Although the existing set of PMU measurements do not provide complete system observability, they could nevertheless provide wide-area visibility and one could conceptualize a completely new type of Wide-Area Nomograms for monitoring where nodal voltages (magnitude and/or angle) may provide a more convenient coordinate system for measuring certain stability margins when compared with nodal power injections that are traditionally used for this purpose. For example, angle differences may indicate more stress posed on the system, and that there are certain limits of this stress that make the system unstable or push it beyond the admissible operating limits such as thermal or voltage magnitude limits. At the same time, conditions applied to the angle differences are quite primitive and do not provide an acceptable accuracy of approximation of the power flow stability boundary, especially due to the nonlinear shape of this boundary. A hypothetical wide area nomogram for three angles (shown in Figure 11) could be described by the following set of inequalities [7]:

$$\begin{cases} \rho_{11}\delta_1 + \rho_{12}\delta_2 + \rho_{12}\delta_2 \le \delta_1^{\max} \\ \rho_{21}\delta_1 + \rho_{22}\delta_2 + \rho_{22}\delta_2 \le \delta_2^{\max} \\ \ldots \\ \rho_{m1}\delta_1 + \rho_{m2}\delta_2 + \rho_{m2}\delta_2 \le \delta_m^{\max} \end{cases}$$



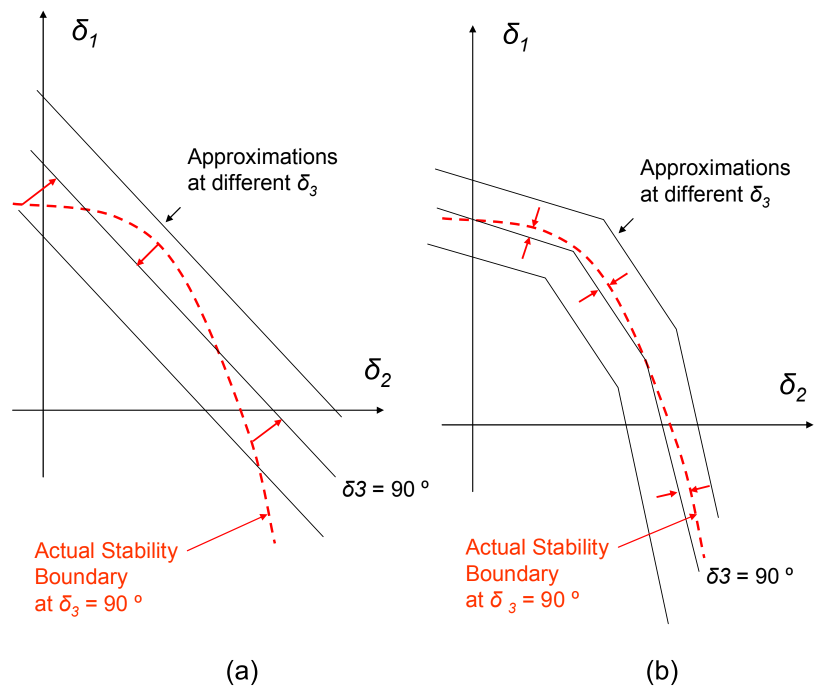


Figure 11: Conceptual View of Simple Angle Difference and Advanced Angle Nomograms

Additionally, a CA PIER funded parallel effort by CERTS is currently underway in developing a Voltage Security Application (VSA) that runs in real time and provides real time dispatchers with real time reliability metrics related to voltage stability limits. This VSA platform can easily be expanded to study wide-area voltage stability problems by selecting global stressing directions and developing the corresponding security regions. The algorithms being developed in the VSA application provide voltage magnitude and angle information as well as their corresponding sensitivities and participation factors in voltage collapse. Hence, while the proposed VSA framework uses data from the CA ISO state estimator and assumes full observability, this same VSA framework could also be used to develop wide-area nomograms whose coordinates would be nodal voltage magnitudes and angles, and the PMU measurements could directly be used to monitoring the system conditions with respect to these new nomograms for a wide-area security assessment.

A Feasibility Assessment Study describing the above mentioned approaches has been delivered to CA ISO. The next steps on this project are:

- Review this report with the CA ISO Planning and Operating Eng. staff
- Solicit their comments and feedback
- Determine if they support the continuation of research in this area
- Identify a specific transmission path and associated nomogram that would be well suited for this type of research.
- Review the above CA ISO feedback with CIEE/ Energy Commission for their approval.

3.3. Support Activities

At the Technical Advisory Committee (TAC) meetings, the California utilities shared their plans on various applications of phasor measurements such as local remedial control interests by SCE, state estimation improvements by SDG&E, and critical path monitoring by PG&E.

Local Remedial Control (SCE): As a pilot project, Southern California Edison has suggested implementing a phasor based control scheme internal to the CA ISO grid, which would not require WECC review or approval and would also avoid impacts on other utilities.

The first suggestion is to utilize phasors data to enhance or replace a Remedial Action Scheme (RAS) for an outage of the two 115 kV transmission lines (Control-Haiwee-Inyokern # 1 and 2) south of Control Substation, located in Bishop, CA. SCE has generating resources (hydro and geothermal) in and north of the Bishop area that also serve the load in the Mammoth ski resort area (winter peaking). At times, the generation is greater than the load and the excess flows south on SCE's 115 kV lines and to LADWP's system, via the Control-Inyo 115 kV lines. For an outage of the two Control-Haiwee-Inyokern 115 kV lines, SCE has a RAS to trip generation and avoid a total collapse of the remaining system north of Bishop and to avoid an out-of-step condition with LADWP. Currently, the arming of this RAS is a manual process by the operator located at Control Substation.

With PMUs located at Bishop and Kramer, the objective of the project is to perform studies of the south of Control system, and to use phasor (and possibly SCADA) data to clearly define the limits and thresholds for action including:

- suggesting arming and disarming points to the operator
- suggesting or selecting RAS tripping requirements

Eventually the phasor and SCADA data can automatically select tripping requirements and arm/disarm the RAS.

A second suggestion is to utilize the phasor data to automate the N-1 and N-2 RAS between SCE's Big Creek area and Magunden Substation in a phased approach similar to the suggestion above.

CERTS/EPG met with SCE engineers on December 16th, 2005 to discuss the status of this project. SCE informed that due to other priorities and limited resources, there hasn't been much progress on this activity. CERTS/EPG has offered to provide assistance in moving this project forward and will be meeting again with SCE's operations staff during 1Q 2006 to better understand the existing RAS at Bishop. SCE also informed that they will be look further into the possibility of sharing the SCE phasor data with other WECC members and the required Non-Disclosure Agreements (NDAs).

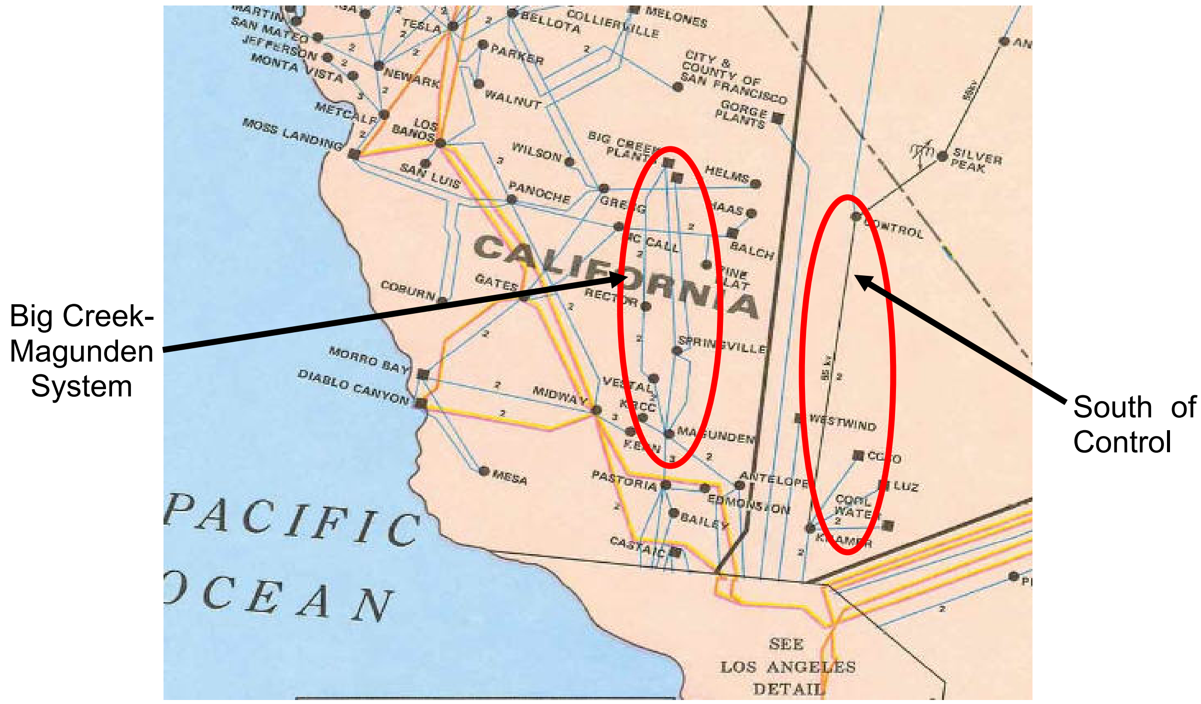


Figure 12: Local Remedial Control by SCE

State Estimation with Phasors (SDG&E): San Diego Gas & Electric (SDG&E) has proposed a two year Research Development and Demonstration (RD&D) project to integrate time-synchronized phasor measurement data into the WLS State Estimator on the EMS at SDG&E. The successful completion of the project will be measured by demonstration of improved state calculations and enhanced congestion management as a result of the phasor measurement integration. Direct benefits to SDG&E will include improved power system security assessment and congestion cost savings for ratepayers. Direct benefits to the CA ISO will include additional phasor visibility for use in its own suite of operator tools and software applications.

SDG&E proposes to install approximately 4-6 PMU's at key locations, particularly SDG&E's 500kV interconnection with Arizona. The South West Power Link (SWPL) is one of the two major interstate tie lines connecting Arizona and California. A PDC and associated software will be installed to aggregate this phasor data which shall be shared with CA ISO and other utilities to enhance the Wide Area Measurement System (WAMS) and Wide area Control system (WACS) initiatives in WECC.

SDG&E also plan on evaluating the following three possible methods for incorporating phasor measurements from the PMUs into present state estimation calculations and a selection will be made [22]:

1. Using weighted least squares with significant weight on the PMU measurements
2. Eliminating the equations associated with the voltage phase angle measurements made by the PMU
3. Employing a hybrid estimation model that uses the measurements of PMU to modify the WLS estimates with the PMU

A technical report on the evaluation and selection will be part of this task.
Some of other objectives of the project include the use of phasor data and the improved estimates to optimize congestion management on SWPL and particularly at Miguel (western terminus of SWPL), demonstrate to what extent the improved estimates lead to better congestion management, financial benefits and improved reliability and to investigate related benefits such as improvement to the calculation of ATC.

To assist SDG&E with the project, CERTS/EPG has prepared and delivered a *PMU Measurement Unit Installation and Cost Estimates* document to SDG&E [11], and is available to provide assistance as required.

Path Monitoring (PG&E): PG&E would like to use phasor measurements to monitor two of their critical paths: Path 15 and Path 26. Path 15 is composed of six transmission lines located near Fresno, California. There are two 500 kV lines and four 230 kV lines (Figure 13). The flow on Path 15 is normally South-to-North, except for heavy exports from Northern California to Southern California, which may create North-to-South flow on Path 15 during normal system conditions. The maximum South-to-North Operating Transfer Capacity (OTC) of this path is 3950 MW, and the maximum North-to-South OTC is 1275 MW with normal system conditions. Path 26 is composed of three 500 kV transmission lines between Northern and Southern California (Figure 13). The flow on Path 26 in normally North-to-South, except during high South-to-North flows on Path 15. With high South-to-North flows on Path 15, Path 26 is normally lightly loaded during normal system. Path 15 and Path 26 are electrically in series – one path may restrict the flows on the other due to a constraint.

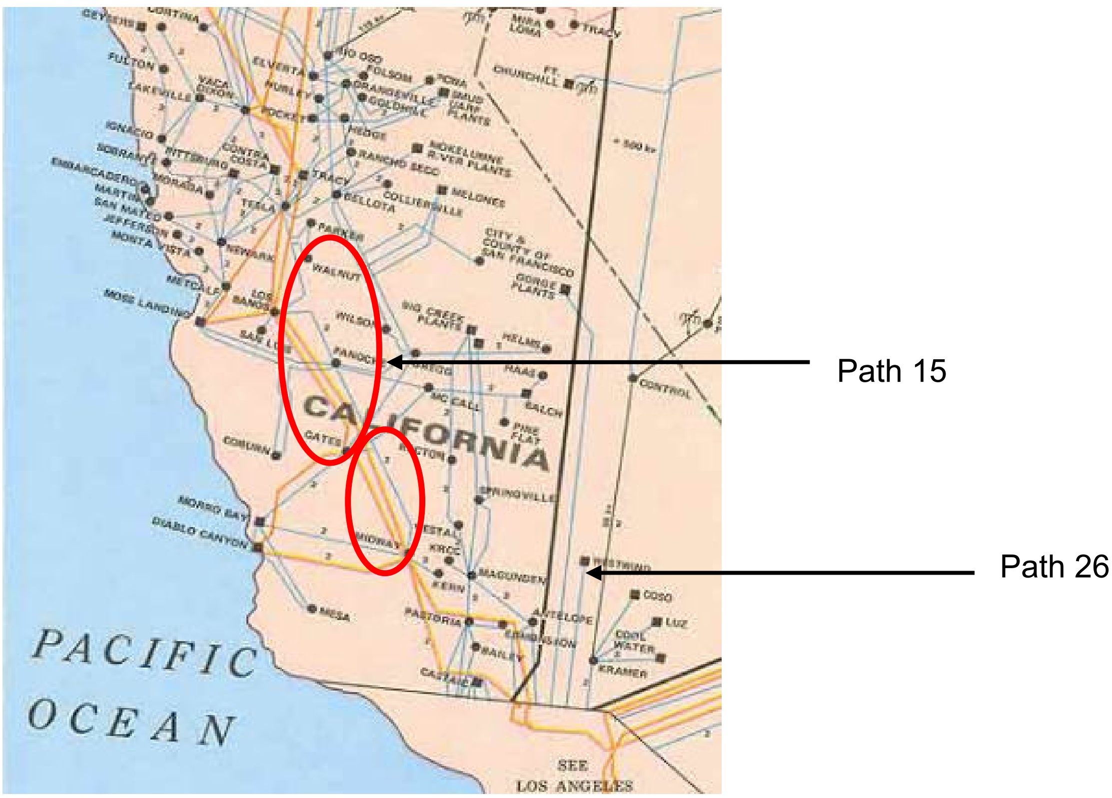


Figure 13: Critical Path Monitoring by PG&E

PG&E has PMUs installed at Midway, Moss Landing, Pittsburgh, Diablo Canyon, and Tesla, and intend to instal PMUs at Gates and Los Banos during 1Q 2006. CERTS met with PG&E staff on December 8, 2005 to share the CA ISO research roadmap, and demonstrate the RTDMS application. They are presently working towards real-time sharing of phasor data with BPA, and the RTDMS system will be installed at PG&E as soon as this data exchange is established.

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