Title

Real Time System Operations 2006-2007

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FINAL PROJECT REPORT

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A CIEE Report

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Preface

The Public Interest Energy Research (PIER) Program 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.
The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit C alifornia.
The PIER Program strives to conduct the most promising public interest energy research by partn ering with RD&D entities, including individuals, businesses, utilities, and public or private resear ch institutions.
PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Real Time System Operations (RTSO) 2006 - 2007 is the final report for the Real Time System Operations project (contract number 500-03-024 MR041 conducted by the Consortium for Electric Reliability Technology Solutions (CERTS). The information from this project contributes to PIER's Transmission Research Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier or contact the Energy Commission at 916□654□5164.

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Report Organization

The Real Time System Operations 2006 – 2007 project consisted of two parallel technical tasks:

- Task 2.0 Real-Time Applications of Phasors for Monitoring, Alarming and Control
- Task 3.0 Real-Time Voltage Security Assessment Prototype Tool

The tasks that are funded under this work authorization represent the third phase of a multi-project ongoing RD&D activity that is coordinated by the Consortium for Electric Reliability Technology Solutions (CERTS) for the Energy Commission's Public Interest Energy Research (PIER) Transmission Research Program (TRP). Earlier phases of this research were conducted through an RD&D contract directly with Lawrence Berkeley National Laboratory (LBNL), Contract # 150-99-003, and through several task orders from the California Institute for Energy and Environment (BOA#20, Task Order 21, Task Order 24, and Work Authorization # MR-036, PIER Contract #500-02-004). Additional research on Task 2.0, through a separate subsequent contract, has been proposed which will build upon the work that was initiated in this work authorization.

An overview of Real Time System Operations 2006 – 2007 is provided in the Project Introduction. Additional reporting is organized separately for each technical task.

Project Introduction

The increased need to manage the U.S. electricity grid more actively in real time is in large part a result of the ongoing transition from a system operated by vertically-integrated utilities to one that's operation is coordinated through the actions of a competitive energy market. Markets have replaced utilities in performing the match between generation and demand, adding to the operator's burden of controlling the grid with revised operational responsibilities and more unpredictable system behavior. This transition has confronted system operators with dramatic changes from past practice, including unregulated generation owners and market participants engaging in increased volumes of energy trades over large distances. To meet these new needs operators have had, until now, only the previous generation of grid management tools, which were designed for a centrally planned and controlled system whose relatively predictable conditions did not require the kind of minute-by-minute decision making demanded by today's electricity markets. In fact, the traditional approach was to analyze, months in advance, a few contingencies for a handful of selected peak load conditions, ignore other periods and contingencies, and then set conservative operating limits for the system. The increasing incidence of not only managed and unmanaged power outages but also transmission congestion, energy price spikes, frequency abnormalities, and voltage degradation on today's grid makes it clear that the traditional management tools and approaches must now be enhanced.

The best strategy for new analytical tools development is to equip system operators with better real-time information about actual safe operating margins so that they can better manage the system within its true limits. Such tools need to analyze geographically dispersed events in real-time. This requires using time-stamped data to combine information collected over wide areas for dynamic system analysis to inform dynamic response through automatic system controls and operator alarms. Analytical tool development is challenged by the system complexity caused by the thousands of components, and the multitude of operating conditions created by minute-to-minute changes in demand, generation, planned and unplanned equipment outages, and market participant actions.

The strategic direction the Energy Commission has sponsored for this research includes: (1) enhancement of tools that obtain and translate real-time data for analysis and operator actions; (2) better system dynamic models; and (3) improved understanding of system parameters (e.g. loads and generators) during system emergencies. The new tools collect and analyze a myriad of data from multiple sources, rapidly calculate the risk of system failure, and translate the information into multi-view graphic displays that allow operators to quickly grasp grid conditions and take action to address emerging problems. These tools and technologies will set the stage for a future smart, switchable electricity grid that will be able to automatically sense and respond to system emergencies.

The objectives of this project were to research, develop, test and evaluate prototypes for new, first-of-a-kind real-time software tools that support reliability management by California Independent System Operator (California ISO).

The overall goals of this project were to:

Improve the reliability and quality and cost/value of California's electricity through the use of new and better real-time operational tools.

Improve the energy cost/value of California's electricity.

- Research, develop, test and evaluate the operational performance of two new prototype real-time operational tools to meet California ISO specifications.
- Initiate the transfer of these prototypes to a vendor selected (and paid for) by California ISO for implementation as production-grade operating tools
- Communicate research results to California utilities, Bonneville Power Administration and other entities involved in the Transmission Research Program (TRP).

The tasks that were funded under this work authorization represent one phase of a multi-project ongoing RD&D activity that is being coordinated by the Consortium for Electric Reliability Technology Solutions (CERTS) for the Energy Commission's TRP. Earlier phases of the PIER sponsored research were through an RD&D contract directly with Lawrence Berkeley National Laboratory (LBNL) under PIER Contract # 150-99-003, and through several task orders from the California Institute for Energy and Environment (BOA#20, Task Order 21, Task Order 24, and Work Authorization # MR-036, PIER Contract #500-02-004). Additional research through a separate subsequent contract has been proposed to build upon the work initiated on Task 2.0 in this work authorization.

Tasks and deliverables described below refer solely to accomplishments that have been completed under the funding for this work authorization.

Abstract

The Real Time System Operations (RTSO) 2006-2007 project focused on two parallel technical tasks: (1) Real-Time Applications of Phasors for Monitoring, Alarming and Control; and (2) Real-Time Voltage Security Assessment (RTVSA) Prototype Tool. The overall goal of the phasor applications project was to accelerate adoption and foster greater use of new, more accurate, time-synchronized phasor measurements by conducting research and prototyping applications on California ISO's phasor platform - Real-Time Dynamics Monitoring System (RTDMS) – that provide previously unavailable information on the dynamic stability of the grid. Feasibility assessment studies were conducted on potential application of this technology for small-signal stability monitoring, validating/improving existing stability nomograms, conducting frequency response analysis, and obtaining real-time sensitivity information on key metrics to assess grid stress. Based on study findings, prototype applications for real-time visualization and alarming, small-signal stability monitoring, measurement based sensitivity analysis and frequency response assessment were developed, factory- and field-tested at the California ISO and at BPA. The goal of the RTVSA project was to provide California ISO with a prototype voltage security assessment tool that runs in real time within California ISO's new reliability and congestion management system. CERTS conducted a technical assessment of appropriate algorithms, developed a prototype incorporating state-of-art algorithms (such as the continuation power flow, direct method, boundary orbiting method, and hyperplanes) into a framework most suitable for an operations environment. Based on study findings, a functional specification was prepared, which the California ISO has since used to procure a production-quality tool that is now a part of a suite of advanced computational tools that is used by California ISO for reliability and congestion management.

Key Words: Electricity grid, reliability, real-time operator tools, time synchronized phasor measurements, voltage security.

1.0 Task 2.0: Real-Time Applications of Phasors for Monitoring, Alarming and Control

1.1. Executive Summary

Introduction

Electric industry restructuring in California has led to the formation of larger control areas with correspondingly larger areas of reliability oversight, as well as increased energy transactions over long, region-wide transmission paths. These developments have introduced greater uncertainty into real-time grid operations, which, in turn, have led to the need for better real-time information on actual conditions that can supplement traditional operating guidelines based on off-line studies. Currently, control areas depend on static nomograms produced from off-line simulations conducted several months before the operating season to manage power flows on critical transmission paths. Because actual operating conditions may differ significantly from those assumed in preparing the off-line simulations, the California Independent System Operator (California ISO) system is operated without complete information on adequate reliability margins. To help the California ISO make more accurate and timely assessments of grid instabilities, the Consortium for Electric Reliability Technology Solutions (CERTS) project team enhanced a monitoring, alarming, and control tool—the Real-Time Dynamics Monitoring System (RTDMS)—with phasor technology, creating the first prototype tool to provide the California ISO with real-time information about the dynamic stability of the grid.

Purpose

This is the third phase of a multi-year research activity through which CERTS developed real-time phasor technology–based tools that will provide operating staff with previously unavailable information on the dynamic stability of the grid. The goal is to foster and expedite the adoption of new, more accurate time-synchronized phasor measurements by California ISO and Bonneville Power Administration (BPA) reliability coordinators and control area operators, as well as by California and Western Electricity Coordinating Council (WECC) utility transmission dispatchers. The project significantly leverages companion efforts, also managed by CERTS for the DOE, to promote the use of phasor measurements nationally. For this project, prototype versions 4, 5, and 5.5 of the CERTS Real-Time Dynamics Monitoring System (RTDMS) were developed and delivered for testing and feedback from the California ISO and Bonneville Power Administration (BPA).

Project Objectives

The main objective of Task 2.0 was to research, develop, and factory- and field-test prototypes for several California ISO phasor applications, with project oversight provided by the California ISO. Additional objectives included performing RD&D for an enhanced real-time monitoring tool (i.e., an expansion of a current phasor monitoring application); conducting a feasibility assessment studies, obtaining results from testing new algorithms driven by phasor measurements, developing new prototype applications implementing these algorithms and preparing a project research report on these results; and providing PIER and California utilities with technical research and development support, including technical and system integration support for utility projects, research roadmaps, Western Electric Coordinating Council (WECC) coordination, and North American Synchrophasor Initiative (NASPI) liaison.

Project Outcomes

To complete Task 2.0 objectives to research, develop, and factory- and field-test prototypes for several California ISO phasor applications, the CERTS team conducted feasibility assessment studies on utilizing phasor measurements to validate and improve existing stability nomograms, evaluated small-signal stability monitoring algorithms, conducted frequency-response analyses, and obtained real-time sensitivity information on grid-stress directly from phasor measurements.

These rigorous RD&D studies enabled the CERTS project team to successfully develop prototype applications offering a rich set of features for wide-area monitoring and analytics, which were factory- and field-tested at the California ISO and at BPA. For example, significant improvements were made to the RTDMS Visualization, version 4, including the incorporation of innovative visualization techniques to deal with screen clutter and information overload, and a dashboard display that uses easy-to-grasp signals akin to traffic-lights (i.e., green, yellow, and red), to provide information on the status of the overall system. For the RTDMS Visualization, version 5, visualization and navigational features were improved through data from algorithm research and end-user feedback. For offline analysis of frequency response, the Event Analyzer prototype was developed. In addition, the CERTS team also developed two new dedicated displays for measurement-based angle sensitivity and voltage sensitivity (incorporated into RTDMS version 5.5) as key indicators of grid-stress and proximity to instability. These advanced real-time applications, while they still remain research prototypes, have been migrated onto the California ISO's production-grade hardware and into its control room, are now an integral and growing part of the California ISO's real-time operations and decision-making processes.

Conclusions

The CERTS project team's efforts to develop phasor applications for real-time monitoring, alarming, and control and test prototype applications on the RTDMS platform has led to the California ISO's adoption of time-synchronized phasor measurements for real-time applications in the Western Interconnection. Not only has the California ISO adopted CERTS' prototype real-time phasor applications, it has now made significant investments in the underlying hardware and supporting maintenance practices to host the prototypes and enable needed future research to develop functional specifications to enable acquisition of commercially-supported, production-quality tools.. The infrastructure that now supports the RTDMS prototype applications now meets California ISO production-quality standards and resides on the California ISO's secure network, where it operates very reliably, with over 90 percent of the devices reporting 99 percent data availability, and no system downtime.

The CERTS project team designed RTDMS to meet the California ISO's need for real-time monitoring, alarming, and control, through features such as wide-area monitoring and analytics. Wide-area monitoring will allow operators to evaluate stability margins across critical transmission paths, detect potential grid instabilities in real time, and mitigate these problems through the system's manual or automatic controls. The system may also be used to improve state estimations and to determine the optimal location for additional phasor measurements. The first of its kind, the system will facilitate technical exchange, collaboration, and resource leveraging with companion phasor measurement–based activities supported by the operating entities and DOE throughout North America, and may lead to further developments in advanced real-time control applications.

Recommendations

The CERTS project team recommends continuing RD&D for prototype applications towards development of functional specifications that California ISO can use to acquire production-quality tools from commercial vendors. The CERTS project team also recommends continuing efforts through the WECC to expand and link phasor measurement units across the entire Western Interconnection.

Benefits to California

The enhanced reliability of the California ISO and the Western Interconnection benefits California by providing reliability coordinators and control area operators with the latest advances in phasor measurement applications. Specifically, these applications will both improve transmission loadability from the point of view of transient stability and also help operate the system within safe regions.

1.2. Introduction

Task 2.0 had three overall goals: 1) accelerating adoption and fostering greater use of new, more accurate, time-synchronized phasor measurements by California ISO reliability coordinators and control area operators, as well as by California and BPA utility transmission dispatchers, 2) providing these real-time operators, starting with California ISO, with previously unavailable information on the dynamic stability of the grid, which in the long run may also provide the basis for the introduction of a new generation of automatic grid controls, and 3) providing technical support and assistance in coordinating phasor applications being researched and developed by California investor-owned utilities.

1.2.1. Background and Overview

California ISO's traditional security-assessment approach, which is based on Supervisory Control and Data Acquisition (SCADA) data and off-line model-based studies conducted long in advance of real time operations, is becoming increasingly unrealistic for real-time operations because it cannot fully anticipate all the conditions that operators may encounter. New technologies, which rely on accurate, high-resolution, real-time monitoring of actual (not modeled) system conditions, are needed to support the California ISO's real-time operations. These new tools and systems will enhance the California ISO's ability to monitor, assess, enable, and, ultimately, automatically take necessary control actions to prevent or mitigate problems in real time.

Applications of phasor measurements will provide the real-time operating staff with 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, the measurement infrastructure will provide the California ISO, in the near term, with an alternate, independent real-time monitoring system that could act as an end-of-line backup for failures affecting California ISO's current SCADA/Energy Management System (EMS); in the long term, it will also become a key element for enabling advanced real-time control with the California ISO's next-generation monitoring system.

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. (Adaptive islanding is the automated reconfiguration and separation of the power system into self-contained electrical "islands" as a preventative measure to avoid cascading outages and major blackouts.)

The first research-grade demonstration of phasor technologies was undertaken by the Department of Energy (DOE), the Electric Power Research Institute (EPRI), BPA, and the Western Area Power Administration (WAPA) in the early 1990s (J. F. Hauer, etal. 1999). The investment was paid in full when data recorded by the system was effectively used to investigate causes of the major 1996 West Coast blackouts. DOE has continued to support outreach for these technologies, and has provided technical support to the Western Electricity Coordinating Council (WECC) committees that rely on these data for off-line and model validation reliability studies. PIER has supported installation of an initial data connection and workstation to support off-line analysis by California ISO staff in 2002. In 2003 and 2004, PIER supported the deployment of a real-time application using phasor technology—a phasor-data link to BPA and WAPA for real-time data—to monitor actual grid conditions (J. Eto, et. al. 2007).

In July 2004, the CERTS Program Review Committee recommended that the Energy Commission and the California ISO continue research, development, and application of this technology. Research focused on determining (1) the appropriate phase angles, rates of phase angle changes, associated ranges around these quantities, including appropriate boundaries or thresholds, and recognizing inescapable uncertainties for various locations in the system; (2) the actions that operators or automatic control equipment should take if there are major deviations; and (3) the desired location for additional phasor monitoring equipment around the WECC. This approach, developed in conjunction with California ISO staff, introduced phasor information to operators, and allowed the CERTS project team to work closely with them to modify and enhance the applications (including training) to increase their confidence in the new real-time application to support their day-to-day activities (CERTS 2007).

During 2004 and 2005, the phasor visualization prototype Real-Time Dynamics Monitoring System (RTDMS), which was initially developed as a stand-alone application, was transformed into a phasor technology research and development platform. The prototype's underlying functionalities complied with the long-term goal to use phasor technology for wide-area monitoring, alarming, and control (CERTS 2007).

Additionally, in July 2005, CERTS worked with the California ISO to formalize and relate prior and planned phases of the research into a single RD&D roadmap (Figure 1). The roadmap identified three research tracks: (1) input data requirements, (2) applications research and development, and (3) system integration and support. Each track has been implemented in three phases, which are described below:

The first phase established the initial starter phasor network, and built the prototype visualization and monitoring capabilities providing real-time, wide-area visibility to the California ISO operators and Reliability Coordinators. This application included long-term archiving of frequency data collected from the phasor network at high-, sub-second resolution to meet the North American Electric Reliability Corporation / Western Electricity Coordinating Council (NERC/WECC) disturbance monitoring requirements. Support was provided to each of the three California utilities on an as-needed basis. Each utility identified a pilot project to demonstrate phasor technology to address their utility-specific problems. During this phase, Southern California Edison (SCE) expressed its interest in local remedial action controls with phasors; San Diego Gas & Electric (SDG&E), its desire to use phasor measurement unit (PMU) measurements to improve the state estimation results; and PG&E, its interest in monitoring critical paths via PMUs.

The second phase expanded the phasor network coverage by incorporating PG&E's PMU measurements into the network as well as new PMU installations with the BPA and SCE footprints; improved the visualization and monitoring capabilities on the RTDMS platform (e.g., real-time alarming, event detection and capture); evaluated possible advanced applications that could be developed on the platform for wide-area security assessment (WASA); and continued supporting the California utilities' on their pilot projects. In 2005, the CERTS project team formulated a survey to gather industry experts' comments, suggestions, and recommendations for the WASA, and found that the majority of respondents agreed that the use of phasor measurements for modal estimations to assess small-signal stability was an ideal first step towards achieving the WASA project objectives.

During the third phase, which is the subject of this report, research was conducted to assess the feasibility of using phasor measurements for a variety of advanced applications including small-signal stability monitoring, frequency-response assessment, new measurement-based sensitivity metrics, stability nomograms using phasors, and event identification and classification. Many of the applications have also been prototyped on the RTDMS platform (e.g., small-signal stability monitoring, voltage sensitivity monitoring) and factory-tested by the RD&D team, and have undergone field trials at the California ISO and BPA.

During the next phase of this task, currently under discussion with the Energy Commission, research is expected to lead to development of functional specifications that will describe the design, functional, and visualization requirements for commercial-grade tools.

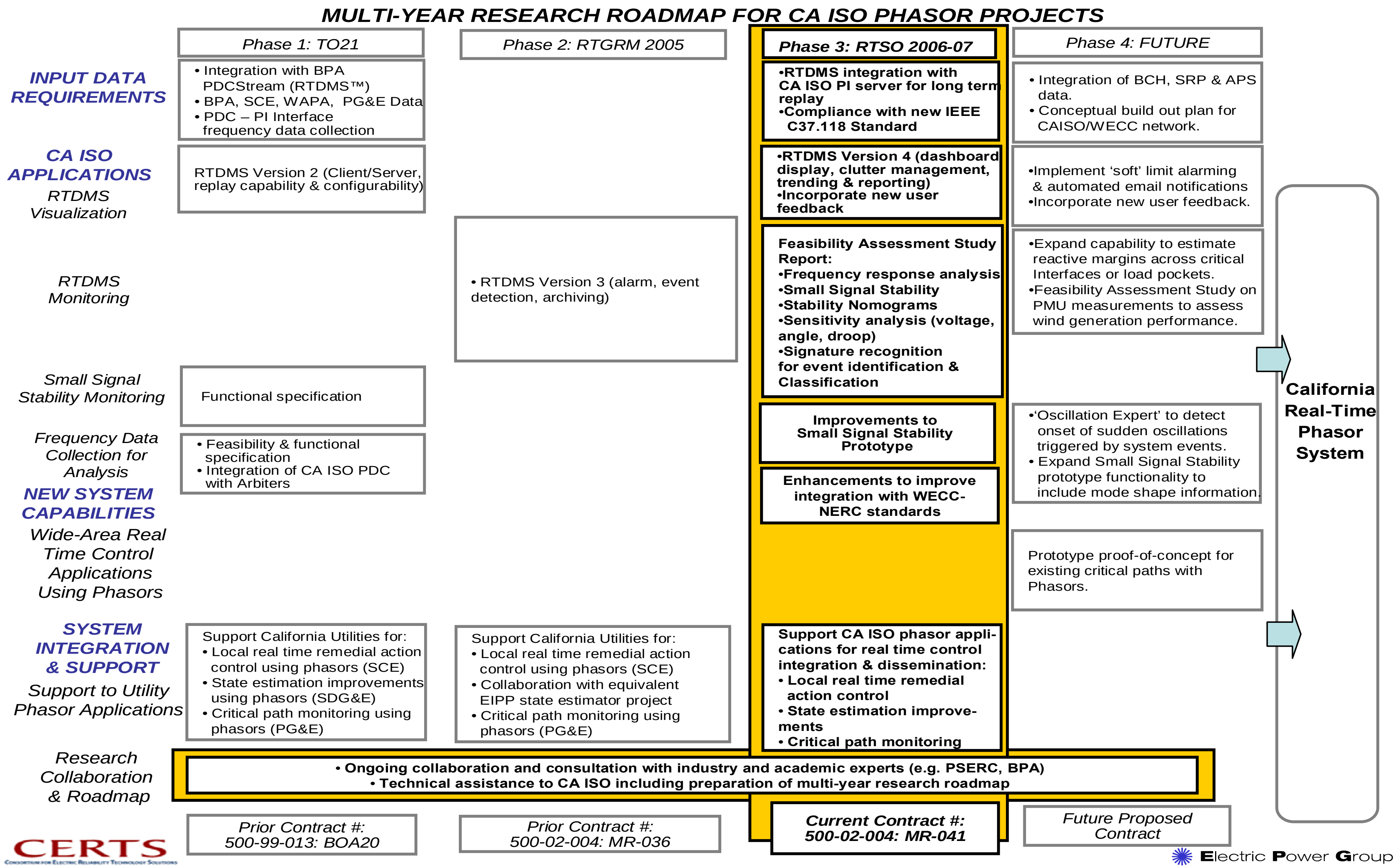

Figure 1. Task 2.0 Multi-Year Research Roadmap for California ISO Phasor Project

1.3. Task Objectives

The objective of this task was to research, develop, factory- and field-test prototypes for several California ISO phasor applications in close coordination with, and with oversight provided by California ISO.

The original Task 2.0 objectives, taken from the contract, were to:

- Perform RD&D for an enhanced real time monitoring tool (the functional expansion of current phasor monitoring application) to include:
    1. Real Time Dynamics Monitoring System (RTDMS) Visualization version 4 with dashboard display, clutter management, trending and reporting;
    2. RTDMS Small Signal Stability Monitoring application prototype development, factory-, and field-testing, and production quality commercial functional specification;
    3. RTDMS Wide-Area Real Time Control applications prototype development, factory-, and field-testing and production quality commercial functional specification;
    4. RTDMS Frequency Data Collection and Analysis System prototype development, factory-, and field-testing, and technical support for integration with California ISO system; and
    5. RTDMS Frequency Response and Sensitivity Analysis application, prototype development, factory, and field-testing.
- Prepare a Feasibility Assessment Studies Report to include, but not be limited to, a feasibility assessment and initial scoping for development of a prototype tool for pattern/signature recognition.
- Prepare an Algorithm Results Report for the applications of items 1, 2, 3, & 4 above
- Prepare Production-Quality Functional Specifications for the applications of items 2 & 3 above
- Provide technical research and development support to PIER and California utilities for phasor applications including technical and system integration support for utility projects, research roadmaps, WECC coordination, and EIPP Liaison.
- Prepare the Phasor Applications Project Research Report. This report shall be a summary that includes, but is not limited to, research performed on real-time applications of phasors, research support and coordination.

Principal evidence that objectives of this project have been met:

The CERTS team performed the following RD&D to enhance the real time monitoring tool:

- RTDMS Visualization version 4 incorporated innovative visualization techniques to deal with screen clutter and information overload. A dashboard display was developed that uses easy-to-grasp visuals based on traffic lights (i.e., green, yellow, red) to provide information on the status of the overall system.

- RTDMS Visualization version 5 incorporated visualization and navigational improvements based on algorithm research and end-user feedback.
- PDC to PI interface for Phasor and Frequency Data Collection and Analysis within California ISO's pre-existing, commercial-grade PI Historian tool, which is linked to the California ISO's EMS
- In RTDMS version 5.5, the CERTS team developed two new dedicated displays for measurement based angle sensitivity and voltage sensitivity (i.e. measurement-based Sensitivity Analysis). An RTDMS Event Analyzer prototype tool was also developed to assist with post-disturbance assessment functions such as frequency Response Analysis.

RTDMS Visualization (versions 4, 5, and 5.5), *RTDMS Small-Signal Stability Monitoring*, and *RTDMS Event Analyzer (*Frequency Response) prototype applications for an enhanced real-time monitoring tool have been installed and tested at the California ISO. These real-time applications have been migrated by California ISO onto production-grade hardware, and, while they remain research prototypes, they are now being used in the California ISO control room where they are rapidly becoming an integral part of real-time operations, and the decision-making processes.

The Phasor Feasibility Assessment and Research Results Report, which is attached as Appendix A to this report, includes the Feasibility Assessment Studies Report, the Algorithm Results Report, and the Phasor Application Project Research Report.

The CERTS project team held discussions with Southern California Edison (SCE), San Diego Gas & Electric (SDG&E), Pacific Gas & Electric (PG&E), and the California ISO to determine how best to support their research and development needs. CERTS then provided assistance and support to California utilities in their efforts to (1) use phasor measurements to control local remedial actions, (2) improve state estimation, and 3) monitor critical paths. CERTS also provided technical assistance to the California ISO in preparing their multi-year research roadmap, which included the North American Synchrophasor Initiative (NASPI) collaboration and knowledge exchange, the formation of the WECC Wide Area Measurement Task Force (WAMTF), and increased collaboration with industry and academic experts.

1.4. Task Approach/Methods

The task approach involved research on the third phase of each of the three project tracks identified in Figure 1: (a) input data requirements, (b) applications research and development, and (c) system integration and support. Key highlights of the phasor applications project research report entitled Feasibility Assessment and Research Results Report (see Appendix A, Phasor Feasibility Assessment and Research Results Report) are summarized below.

Real-Time Dynamics Monitoring System (RTDMS) Visualization version 4 with dashboard display, clutter management, trending and reporting

The CERTS project team met with California ISO staff to identify requirements for RTDMS version 4. The CERTS team then developed a prototype that featured dashboard displays, clutter management, trending and reporting functions, and factory-tested the application before installation at California ISO for field-testing and feedback. During the feedback phase, additional functionalities were discussed with the California ISO.

RTDMS Small Signal Stability Monitoring application prototype development, factory-, and field-testing, and production quality commercial functional specification

The CERTS project team met and collaborated with BPA and California ISO to discuss algorithms and framework for the small-signal stability monitoring application. The project team then worked on the algorithms and developed the application based on these algorithms. The application was then factory-tested before it was installed at both the California ISO and BPA for field-testing and feedback. During the feedback phase, additional functionalities were discussed and incorporated into the application.

RTDMS Wide-Area Real-Time Control applications prototype development, factory-, and field-testing, and production quality commercial functional specification

Based on the feasibility assessment study completed in an earlier contract, 500-02-004, the CERTS project team met with the California ISO to develop the use of phasor technology to enhance stability nomograms. The project team then investigated methodologies for improving and enhancing the existing operation nomograms with phasor measurements. During follow-up meetings with Dave Hawkins and Nan Liu from the California ISO, the project team was directed to focus its efforts on the small-signal stability monitoring application. Resources were therefore redirected to conducting research and developing this higher-priority application.

RTDMS Frequency Data Collection and Analysis System prototype development, factory-, and field-testing, and technical support for integration with California ISO system

The CERTS project team met with California ISO to discuss the architecture and definitions of the RTDMS Frequency Data Collection and Analysis System application. The project team then developed, factory-, and field-tested the application to allow users to save frequency data in the California ISO's PI Historian, a commercial- grade production database that resides on the California ISO EMS.

RTDMS Frequency Response and Sensitivity Analysis application prototype factory and field testing

The CERTS project team met with the California ISO to discuss requirements for the RTDMS Frequency Response and Sensitivity Analysis application. The project team then developed, factory-, and fielded tested the new RTDMS Event Analysis application incorporating frequency response analysis capabilities, and additional sensitivity analysis displays within RTDMS version 5.5.

Prepare a Feasibility Assessment Studies Report

The CERTS project team conducted research and evaluated the feasibility of using phasors by performing an extensive on-line literature review of all known existing publications on phasor technologies and applications. In addition, the project team consulted with university professors at Washington State University, the University of Wisconsin, Rensselaer Polytechnic

Institute, and Montana Tech, and with staff at the California ISO. The feasibility assessment studies report was written and incorporated into the Phasor Applications Project Research Report.

Prepare an Algorithm Results Report

Based on the findings from the feasibility assessment studies it had conducted earlier, the project team evaluated possible solutions to address the feasibility of using phasors to (1) improve stability nomograms; (2) monitor small-signal stability; (3) measure key sensitivities related to voltage stability or dynamic stability; (4) assess interconnection frequency response; and (5) apply graph theory concepts for pattern recognition. The project team wrote algorithms conduct tests of these solutions using data provided by the California ISO. The algorithm results were incorporated into the Phasor Applications Project Research Report.

Prepare the Phasor Applications Project Research Report

The CERTS team summarized Task 2.0 research in the Phasor Applications Project Research Report. See Appendix A, Phasor Feasibility Assessment and Research Results Report, which includes the feasibility assessment study and algorithms results.

Prepare Production-Quality Functional Specifications for the Small Signal Stability Monitoring and RTDMS Wide-Area Real-Time Control applications

If the California ISO agreed that the research had advanced sufficiently, the CERTS project team was to next develop the functional specification for a production-quality small-signal stability tool. In March 2007, the California ISO directed CERTS to perform additional research on this application, and not to prepare the production-quality functional specifications at this stage of development.

Provide technical research and development support to PIER and California utilities for phasor applications including technical and system integration support for utility projects, research roadmaps, WECC coordination, and EIPP Liaison

CERTS provided assistance and support to (1) SCE in its use of phasor measurements for local remedial action control, (2) SDG&E in its use of phasor measurements to improve its state estimator, and (3) PG&E's in its use of phasor measurements to assist in monitoring critical paths. CERTS also provided technical assistance to the California ISO in preparing a multi-year research roadmap, which included NASPI collaboration and knowledge exchange, the formation of the WECC-WAMTF, and increased collaboration with industry and academic experts.

1.5. Task Outcomes

The project team completed research on the third phase of each of the three project tracks identified in Figure 1: (a) input data requirements; (b) applications research and development; and (c) system integration and support. This summary reviews key finding and highlights derived from a separate appendix that provides greater technical detail on each of these accomplishments. (See Appendix A, Phasor Feasibility Assessment and Research Results Report).

With respect to input data requirements, CERTS utilized and expanded the current WECC and California ISO phasor infrastructure as the input data source for the real-time applications. Then, when C37.118 became the approved Institute of Electrical and Electronics Engineers (IEEE) standard for real time streaming phasor data, the RTDMS platform was adapted to support this new format. Finally, as discussed below, RTDMS version 5 included development of an interface to the California ISO's PI Historian, which provides a bridge for phasor data to migrate into other applications that reside on California ISO's EMS

With respect to applications research and development, the key accomplishment of the project was development, factory-testing, installing, and field-testing of RTDMS versions 4, 5, and 5.5 at the California ISO. Prior to each development cycle for an enhanced version of RTDMS, a prototype functional specification document was provided to the California ISO for its review and feedback. Comments from the California ISO were then incorporated into each version.

The CERTS project team worked closely with the California ISO operations staff to solicit their input on enhancements to expand the visualization, monitoring, and alarming capabilities of the RTDMS platform. The RTDMS Visualization version 4 included dashboard display, tiered visualization architecture to manage display clutter, and long-term trending capacities (Figure 2). RTDMS Visualization version 5 included visualization and navigation improvements based on operator feedback, PDC-PI interface for archiving data into California ISO's PI historian and reporting services. RTDMS Visualization version 5.5 included measurement based sensitivity displays.

In addition, the first ever small-signal stability monitoring prototype application was developed. This application assesses the stability of low frequency inter-area oscillations in real-time, and from data captured under ambient system conditions. This tool has the ability to display dynamic activity using spectral waterfall plots, and to trace mode estimates, both their characteristic frequency and damping properties, using visuals geared towards a real-time operations environment.

Preliminary work was completed on the RTDMS Wide-Area Real-Time Control, but at the California ISO's request, resources were redirected to developing other higher-priority applications.

The successful completion of these tasks was made possible by off-line analyses and research conducted by the CERTS project team in consultation with California ISO staff, feedback from operators on the usability and usefulness of the information provided by the network, and the means developed to present the information. These interactive processes continued in direct parallel with the delivery of specific functionalities and prototype displays.

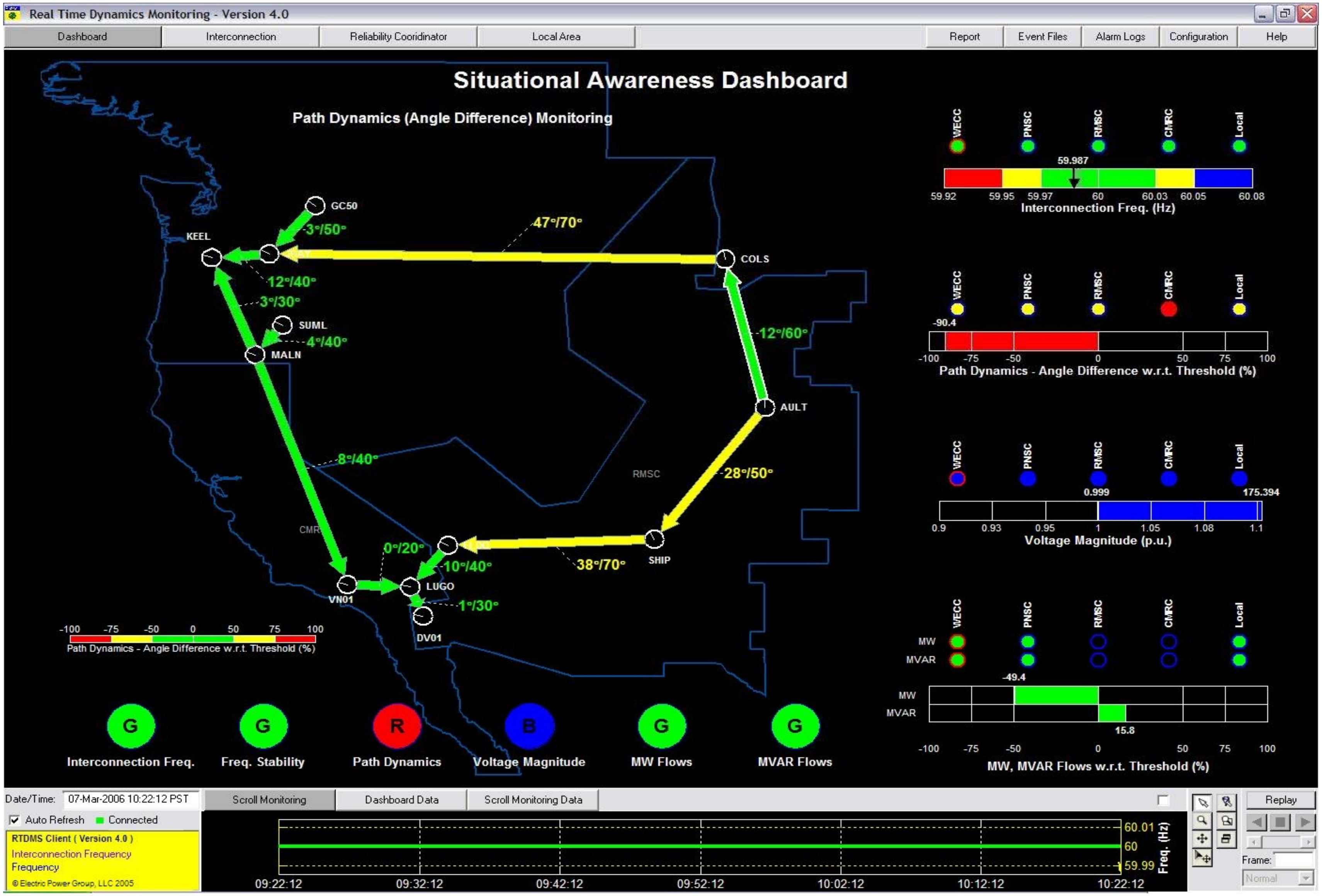

Figure 2. RTDMS Situational Awareness Dashboard

With respect to systems integration and support, the CERTS project team supported the California ISO in its migration of the RTDMS platform and phasor applications from the RD&D test bed to the California ISO's production-quality hardware, which resides in the California ISO operations environment. This major accomplishment significantly advances the development of this promising technology into an actual commercial application (Figure 3).

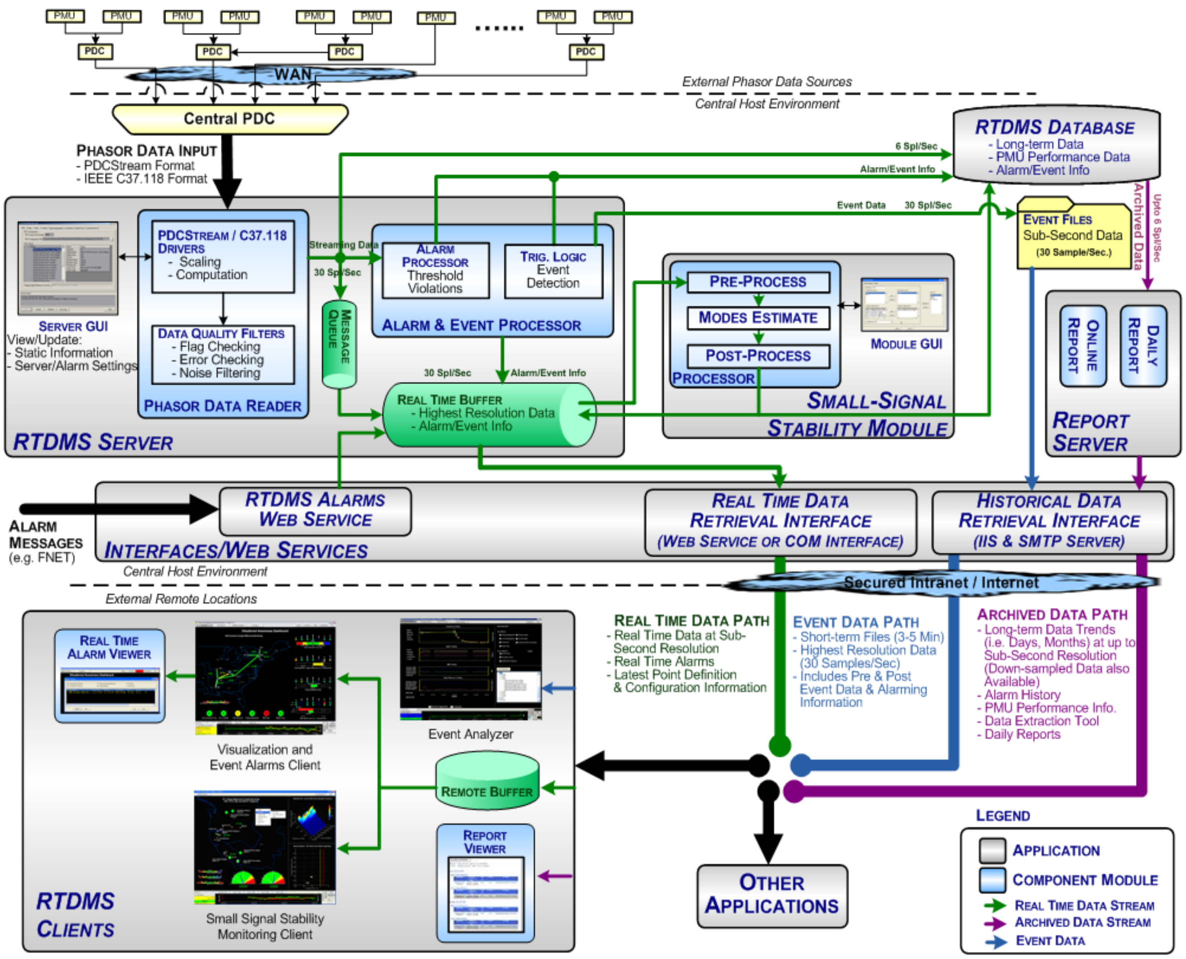

Figure 3. RTDMS Platform System Architecture

The specific project objectives have been taken directly from the contract. The outcomes of each research task are as follows:

Real-Time Dynamics Monitoring System (RTDMS) Visualization version 4 with dashboard display, clutter management, trending and reporting

The RTDMS Visualization version 4 incorporated innovative visualization techniques to deal with screen clutter and information overload. With the rapidly growing number of PMUs within the WECC phasor network, a key focus was on improved visualization to integrate information within standardized displays. Careful attention was placed on avoiding clutter. The solution included tiered visualization architecture with drill-down capabilities from centrally configured and standardized "global" displays for wide-area viewing at the Interconnection and Reliability Coordinator levels. This tiered visualization facilitates communication across utilities for consistency, but also provides a means for development of "local" end-user customized displays at the utility level that complement the wide-area displays. The highest tier consists of a "dashboard" summary display that uses easy-to-grasp traffic-light visuals (Figure 2) and gauges to provide information on a set of predefined metrics that characterize the overall system status. Green signifies that the metric is well within its threshold limit and that things are normal; yellow indicates that the metric is approaching its threshold limit and further investigation is needed; and red or blue means that the metric is low or high, respectively, and that immediate action is required. Other enhancements included reporting capabilities on PMU performance, alarm history, and long-term trends and statistics on various metrics to assist with the system baselining functions.

In January 2006, under the prior contract, the CERTS team provided training at the California ISO on an earlier version of the RTDMS, version 3, platform. During these training sessions, California ISO reliability coordinators Dave Hawkins, Nan Liu, Greg Tilitson, and Paul Bluess were consulted on their requirements for RTDMS, version 4. During the next development stage, the project team incorporated the California ISO's requirements for dashboard displays, clutter management, and trends and reporting functions. Training commenced on the application that was installed in May 2006 on two machines in the testing room, and one machine installed on the Reliability Coordinators desk on the dispatch floor (Control Room) at the California ISO.

In addition, the real-time phasor monitoring applications on the RTDMS platform underwent a series of functional enhancements incorporating new capabilities that were extensively field-tested at the California ISO and at BPA; RTDMS Visualization version 5, which included visualization and navigation improvements based on operator feedback, and a PDC-PI interface for archiving data in the California ISO's PI historian and reporting services, was released. RTDMS Visualization, version 5.5, included measurement-based sensitivity displays. Prior to each development cycle, a prototype functional specification document was provided to the California ISO for their review and feedback. Comments from the California ISO were then incorporated into each version. The RTDMS platform currently supports 12 clients at the California ISO's main Folsom Facility and two at the Alhambra backup center.

RTDMS Small Signal Stability Monitoring application prototype development, factory-, and field-testing, and production quality commercial functional specification

The first ever small-signal stability monitoring prototype application was developed and delivered to the California ISO. This application assesses the stability of low-frequency inter-area oscillations in real-time using data captured under ambient system conditions. The key capacities of this tool are its ability to display dynamic activity using spectral waterfall plots, and to trace mode estimates, both their characteristic frequency and damping properties, using visuals geared towards a real-time operations environment.

In February 2006, the CERTS project team met with Bill Middelstadt, Carson Taylor, Ken Martin, Dmitry Kosterev, and Jim Gronquist from BPA, which has been a technical leader among utilities in the industry on the topic of small-signal stability. The discussion focused on algorithms and framework for the small-signal stability monitoring application. During the next several months the project team worked on the algorithms and developed the application based on the algorithms.

During 2006, a *Small-Signal Stability Monitoring* application was developed to utilize these algorithms to monitor and track the low-frequency inter-area modes prevalent within the power system in real time and under ambient system conditions. The application underwent field trials at both the California ISO and BPA prior to being placed in control rooms. In October 2006, the project team reviewed the application with California ISO staff Dave Hawkins, Nan Liu, Greg Tillitson, Paul Bluess, Jim Herbert, and Alan Amark. The application was further refined in response to their feedback, and later installed in the California ISO testing room and on the engineers' desks. In December 2006, after factory-testing the application, it was installed in the testing room at the California ISO.

In February 2007, Jim Detmers and Jim McIntosh from the California ISO organized a Grid Oscillation Workshop, which gathered industry experts including the CERTS project team, General Electric, Virginia Tech and Montana Tech researchers, and others to discuss the next steps required to eliminate grid oscillations. For the short term, the workshop participants recommended the development of an oscillation-detector alarm system, and for the long-term, a robust control strategy based on real-time observations.

In March 2007, the California ISO requested that the CERTS project team to focus additional efforts on the small-signal stability monitor application to RD&D instead of developing a functional specification for a production-quality tool. However, in preparation for the eventual preparation and acquisition of such a tool, in June 2007, the prototype application was migrated to the California ISO's new production-quality hardware for further research and development.

The CERTS project team participated in a follow-up grid oscillations meeting held at BPA in June 2007. The overall strategic vision for a collaborative grid oscillation, diagnosis, and control effort was discussed.

In late 2007/early 2008, the Small-Signal Stability tool's algorithms, visuals (Figure 4), and features were further enhanced through additional research and end-user feedback. Some of the key enhancements included improved mode estimation algorithms and graphics to quantify the uncertainty associated with the mode estimates. Specifically, a newly developed "bootstrapping" method was embedded into the tool to compute the uncertainty region or error bounds (i.e., confidence intervals) associated with each estimate. At the California ISO's request, other improvements included the capability to load single or multiple phasor disturbance files and perform small-signal stability forensics (i.e., the Event Analyzer tool) to assess the stability of the power system prior to and after the event through various analysis techniques.

While this new application sparked greater interest in phasor technology and its capabilities, the California ISO considers it pre-mature to pursue a commercial-grade small-signal stability tool, and has requested that the CERTS team conduct additional RD&D in this area. A second version of this tool incorporating more advanced algorithms and improved visuals, and extending its analysis capability to off-line disturbance files, was therefore developed in lieu of the functional specification for the commercial-grade tool. The updated tool was delivered to the California ISO in March 2008 and is currently undergoing field testing at the California ISO and the BPA.

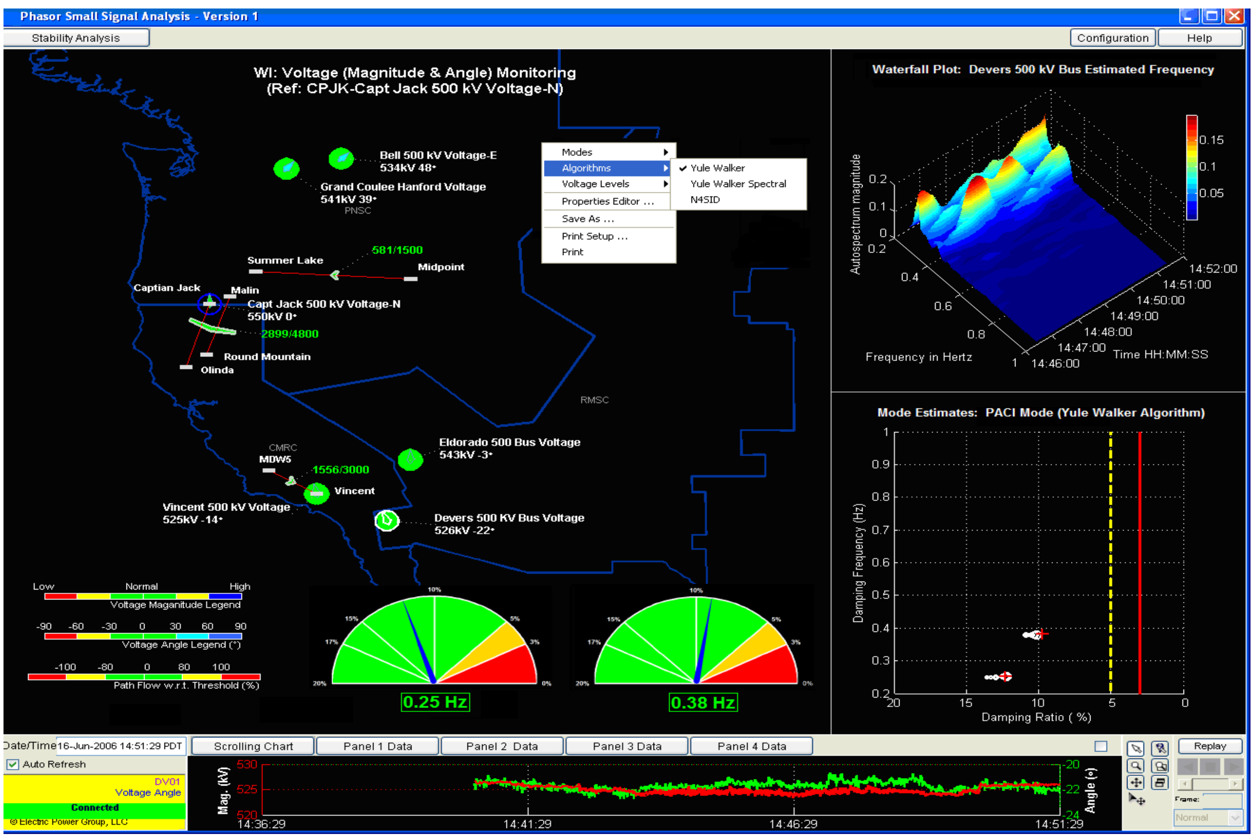

Figure 4. Small-Signal Stability Monitoring Display

RTDMS Wide-Area Real-Time Control applications prototype development, factory-, and field-testing and production quality commercial functional specification

A feasibility assessment study exploring various methodologies for using phasor measurements to improve or augment existing operational nomograms was conducted. The California ISO and the CERTS project team agreed that this was a good first step towards using phasor measurements for wide-area real-time control, as nomograms are an integral part of the real-time dispatch process. The California ISO supported the proposed concept of developing a completely new type of wide-area nomograms for monitoring, which consists of inequalities being applied to the voltage angle differences measured at different locations within the Interconnection, and are unlike traditional power flows (e.g., interface flows, total generation, total load, etc). (See Appendix A, Phasor Feasibility Assessment and Research Results Report.)

The traditional operating nomogram, which defines secure operating conditions, are constructed using off-line power flow, voltage, transient, and post-transient stability simulations for a worst- case scenario. They, therefore, have an inherent conservatism embedded in them. The use of real-time measurements provided by phasor measurement units (PMUs), and the results of real-time stability assessment applications, can complement these nomograms by providing a direct measure of system stress and actual (rather than predicted) operating margins. Using phasor measurements in this manner would enable safe, yet less conservative operation.. Phasor measurements can also provide data that could replace select critical nomogram parameters for visualization based on real-time information and determine new areas and situations where additional nomograms may be required.

The use of PMUs to monitor existing nomograms would help to provide a tighter real-time monitoring of the operational limits. The sub second information from the problem area would increase the situational awareness of the real-time dispatch personnel and allow for more time for timely manual and automatic remedial actions in the future (Figure 5).

Some of the proposed concepts included (1) the use of PMUs for estimating reduced dynamic equivalents and its most current parameters in real time to augment existing nomograms, and (2) a completely new type of wide-area nomograms for monitoring, which consists of inequalities being applied to the voltage angle differences measured at different locations within the Interconnection. Voltage angle differences are a more direct measure of transient stability than the traditional power flows (e.g., interface flows, total generation, total load, etc.), and are therefore better for coordinating the system for observing transient stability. Any topology changes, such as line outages, are directly observable in the angle measurement, which may otherwise be absent in the MW flows. A prototype tool that utilizes the above-mentioned concept is being discussed with the Energy Commission.

After meeting with the California ISO, significant research was conducted to carry out the RTDMS Wide-Area Real-Time Control applications prototype and associated efforts described above, and in greater detail in Appendix A, Phasor Feasibility Assessment and Research Results Report. During reviews and discussions with Dave Hawkins and Nan Liu at the California ISO, this activity emerged as a lower priority for California ISO compared to other research included in this contract. California ISO therefore requested the CERTS project team to direct its focus toward developing the aforementioned small-signal stability monitoring application.

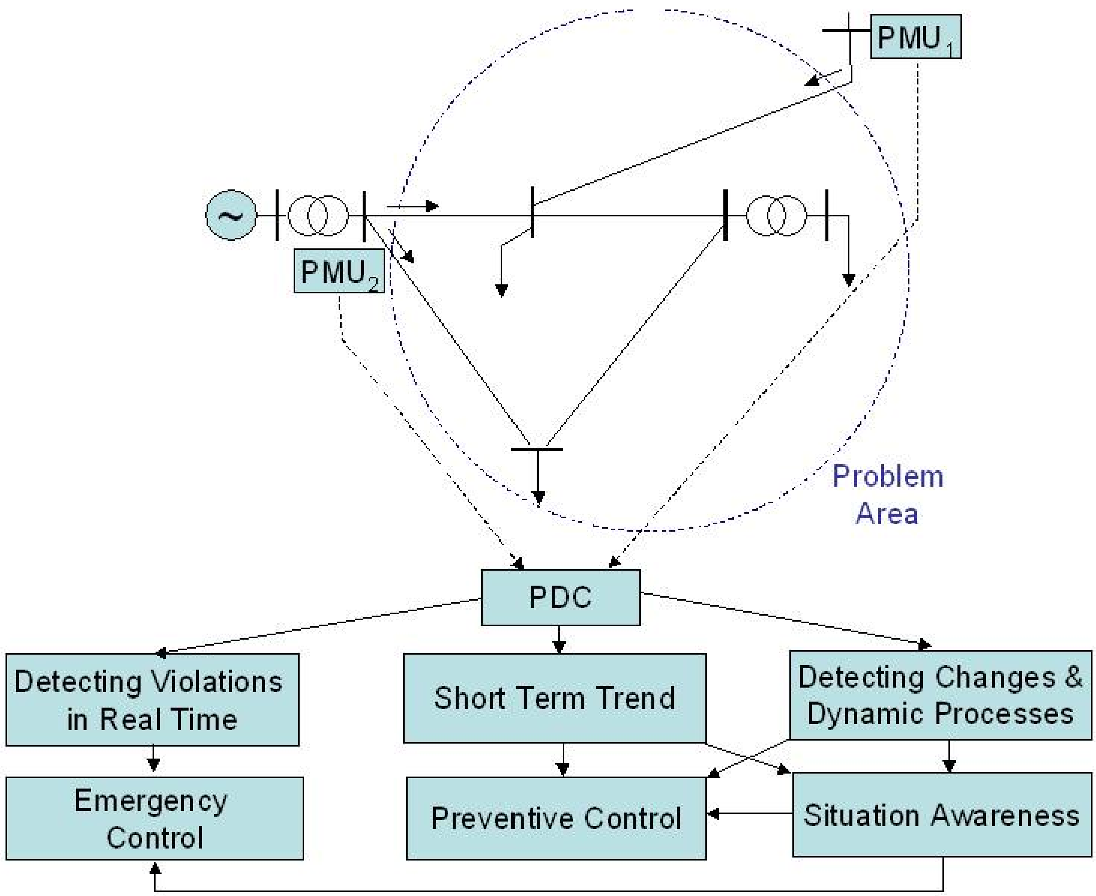

Figure 5. Use of Additional PMUs to Monitor Existing Nomograms in Real-Time

RTDMS Frequency Data Collection and Analysis System prototype development, factory-, and field-testing, and technical support for integration with California ISO system

A PDC-PI interface that continually parses real-time streaming data and populates the PI Historian was developed, factory-tested, and installed on the production quality system at the California ISO in July 2007. It is currently in use to save frequency data from PMUs and Arbiter Frequency Meters into the PI Historian. This interface is also equipped to perform data quality checks prior to storing the data in PI Historian to ensure good data quality within their production system.

The CERTS project team met with the California ISO to discuss the architecture and definitions of the RTDMS Frequency Data Collection and Analysis System application. CERTS began development of the application to allow frequency data to be saved in the California ISO's PI Historian (a commercial-grade production database) that resides on the California ISO's energy management system). The project team designed the prototype, which is the first application designed to transfer phasor data to the PI Historian. CERTS reviewed the prototype with California ISO staff, and then built the interface between phasor data and the PI Historian.

The California ISO concluded that the analysis capabilities within their PI Historian were adequate to meet their needs for a production-quality commercial-grade system for long-term data collection and analysis.

RTDMS Frequency Response and Sensitivity Analysis application, prototype development, factory, and field-testing

The feasibility of using phasor measurements to assess the Interconnection's frequency responses during significant events and to compute key grid sensitivities directly from phasor measurements, was evaluated. It is well understood that additional loading on the power system is associated with voltage degradation across the system. This relationship is typically represented by P-V or Q-V curves, which illustrate real and reactive power and voltage relationships. The gradient at any point along such a curve provides the voltage sensitivity with respect to the loading conditions at that bus. The traditional method for obtaining this information is dependent on the system model, especially the load model, which is built by historical data. It was determined that phasor measurements offer the ability to obtain the same information directly from the real-time measurement without requiring any modeling information. There is enough loading variation within the system to estimate the local gradient of curves that map changes in one variable (MW or MVARs) to changes in the other (voltages), i.e., the current voltage sensitivities at that location/interface.

The CERTS project team met with the California ISO during the summer of 2007 to discuss the approach and to develop new applications. As a result of the meeting, two separate applications were researched and developed: (1) sensitivity analysis displays, and (2) frequency response. The frequency-response application became the off-line *RTDMS Event Analyzer*, and was demonstrated at California ISO in December 2007. The CERTS team also developed two new dedicated displays for measurement-based angle sensitivity and voltage sensitivity, respectively. The sensitivity analysis displays were incorporated into RTDMS, version 5.5, which was installed at the California ISO in March 2008. This has facilitated better understanding of voltage-real/reactive power and phase angle–real power relationships for key corridors, and at critical generation and load buses where PMUs have been installed. The next steps for these applications are currently being evaluated by the California ISO. They will be included in a proposal for additional RD&D on these applications.

Prepare a Feasibility Assessment Studies Report

The CERTS project team researched and evaluated the feasibility of using phasors to (1) improve stability nomograms, (2) monitor small-signal stability, (3) measure key sensitivities related to voltage stability or dynamic stability (Figure 6), (4) assess interconnection frequency response, and (5) apply graph theory concepts for pattern recognition. The project team performed an extensive on-line literature review of all known existing publications on phasor technologies and applications, and consulted with university experts at Washington State University, the University of Wisconsin, University of Wyoming, and Montana Tech. Based on this research, the CERTS project team proposed new technologies to the California ISO. The results of the feasibility assessment studies were incorporated into the Phasor Applications Project Research Report (see Appendix A, Phasor Feasibility Assessment Research Results Report).

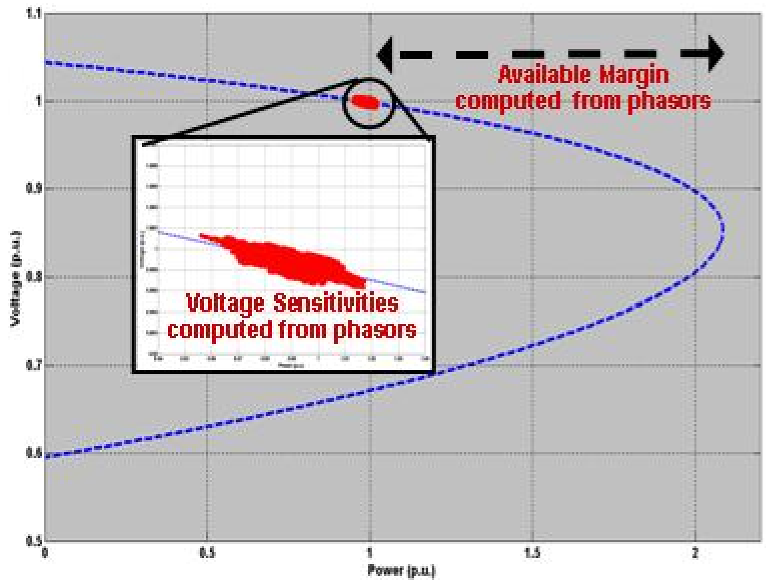

Figure 6. Predicting P-V Curves and Voltage Stability Using Phasors

Prepare an Algorithm Results Report

Based on the findings from the feasibility assessment studies, the CERTS project team developed alternative solutions to address the feasibility of using phasors to (1) improve stability nomograms, (2) monitor small-signal stability, (3) measure key sensitivities related to voltage stability or dynamic stability, (4) assess interconnection frequency response, and (5) apply graph theory concepts for pattern recognition. The project team wrote algorithms and tested data provided by the California ISO, and algorithms results were incorporated into RTDMS. Algorithm results were also incorporated into the Phasor Applications Project Research Report.

Prepare the Phasor Applications Project Research Report

The Phasor Applications Project Research Report is provided in Appendix A, Phasor Feasibility Assessment and Research Results Report. The Phasor Applications Project Research Report also summarizes research for the Feasibility Assessment Studies Report and the Algorithm Results Report.

Prepare Production-Quality Functional Specifications

Preliminary efforts were undertaken to develop the production-quality functional specifications for the RTDMS Small Signal Stability Monitoring and RTDMS Wide-Area Real-Time Control applications. Based on California ISO's request for additional research on higher priorities, resources were redirected and preparation of functional specifications for production quality applications based on research conducted to date was not undertaken.

Provide technical research and development support to PIER and California utilities for phasor applications including technical and system integration support for utility projects, research roadmaps, WECC coordination, and NASPI Liaison

CERTS provided assistance and support to (1) SCE's use of phasor measurements for local remedial action control, (2) SDG&E's state estimation improvements, and (3) PG&E's critical path monitoring. CERTS also provided technical assistance to California ISO in preparing their multi-year research roadmap, which included NASPI collaboration and knowledge exchange, the formation of the WECC WAMTF, and increased collaboration with industry and academic experts.

The CERTS team provided assistance to California utilities on demonstration projects that had been previously identified by each utility. In particular, the RTDMS platform was provided to PG&E for critical path monitoring. Additionally, in late 2006, CERTS/EPG met SDG&E staff to layout a project plan for installing PMUs and integrating them with SDG&E's state estimator. An outcome of this effort was that SDG&E formally requested CERTS/EPG to provide consultation services on their state estimation project, and a separate contract was formed between CIEE and EPG (Subcontract No: MTX-06-02B) to this effect. During 2006-2008, the EPG staff has supported SDG&E in successfully integrating the phasor data with their state estimator and evaluating the performance improvements in the state estimator results.

CERTS also provided technical assistance to California ISO in preparing their multi-year research roadmap, which included NASPI collaboration and knowledge exchange, the formation of the WECC WAMTF, and increased collaboration with industry and academic experts.

In 2005, under a prior contract, CERTS worked with the California ISO to develop an RD&D roadmap for the phasor applications technology RD&D effort. In 2007, this roadmap was updated to include tasks, roles, and responsibilities at both the California ISO and WECC levels to grow the phasor infrastructure for greater coverage, and to move the phasor applications from research into an operational environment as identified in discussions with California ISO staff. The updated roadmap was presented to the California ISO in early 2007 and at the WECC-WAMTF meeting in April 2007. In early 2008, the roadmap was further refined to incorporate future CERTS research priorities planned for 2008–2010. As a result of these efforts, the phasor network now integrates over 50 PMUs streaming real-time data into the California ISO from various locations across WECC. In addition, at the California ISO, and the RTDMS platform and phasor applications have now been migrated from the R&D test bed onto production-grade hardware and into the California ISO operations environment.

1.6. Conclusions and Recommendations

1.6.1. Conclusions

The development and testing of a prototype RTDMS with California ISO system operators has accelerated the adoption and use of time-synchronized phasor measurements for real-time applications in the Western Interconnection. As the network has grown and matured and RTDMS applications have expanded, California ISO has invested in upgrading the hardware infrastructure to support the system. The phasor real-time applications, which initially ran on PC/Workstation machines in an isolated research environment, have now migrated to a production grade hardware platform on the California ISO secure corporate network, which is supported 24/7 by California ISO Information Technology staff. The system is also operating reliably, with over 90% of the devices reporting 99% data availability, and no system downtime. An indication of the improved reliability is that RTDMS is now at the Reliability Coordinator (RC) Desk in the Folsom Control Room and is an integral part of the real-time operations decision-making process.

The system now offers a rich set of features for wide-area monitoring as well as analytics. This wide-area, common view will allow operators to evaluate stability margins across critical transmission paths, detect potential system instability in real time, and, in the future, take manual or initiate automatic actions to mitigate or dampen these potential problems. It will also enable California ISO, California, and WECC utilities to explore closely related issues, such as the use of phasor data to improve state estimations, to determine the optimal location of additional phasor measurements, and to gain experience with the technology required to develop these advanced real-time control applications. Finally, it will facilitate technical exchange, collaboration, and resource leveraging with companion phasor measurement-based activities supported by the operating entities and DOE throughout North America.

1.6.2. Recommendations

The CERTS project team recommends continuing research and development of prototype applications toward ultimately providing the California ISO with functional specifications for acquisition of production-quality commercial phasor-based tools. CERTS also recommends continuing efforts through WECC to expand and link PMUs across the entire Western Interconnection.

Aspects of additional RD&D required have been proposed and are being considered by the Energy Commission for a follow-on contract.

1.6.3. Benefits to California

The benefit to California is the enhanced reliability of the California ISO and the Western Interconnection by providing reliability coordinators and control area operators at the California ISO, and California's major utilities with the latest advances in phasor measurement applications. Ultimately, system operators will be able to evaluate stability margins across critical transmission paths, detect potential system instability (pattern recognition) in real time, and then provide control signal(s) to devices or controls that will mitigate or dampen the instability. The wide-area, common view will also allow operators to detect unanticipated system limitations in real time, even when the grid is operating within perceived safe portions of the existing operating nomograms. Thus, the system will serve a dual purpose to both improve transmission loadability from the point of view of transient stability and help operate the system within safe regions.

As a result, this research ultimately will have the following benefits for the California ISO and California utilities:

1. California ISO will immediately benefit from increased reliability.
2. The successful implementation of advance phasor applications by California ISO and BPA will accelerate market acceptance of phasor measurements and applications throughout the WECC, leading to a promulgation of these reliability benefits.
3. Ultimately, incorporation of phasor measurements into California ISO's suite of advanced computational tools for reliability and congestion management should also improve the accuracy of locational marginal pricing (LMP) calculations, which would follow the initial roll-out of California ISO's Market Redesign Technology Update. This update seeks to correct problems in California's electricity markets that contributed to the market disruptions experienced in 2000 and 2001. This objective is accomplished, in part, through better congestion management, potentially at lower cost, for the California ISO system;[1]

[1] The Market Redesign and Technology Update includes three foundational designs – a full network model of the electricity grid, an integrated day ahead forward market and LMP. The LMP is the result of the integrated forward market which provides nodal prices so that all market participants know the cost of generating power, serving load and resolving congestion at each location on the system. LMPs reflect physical constraints under all load and system conditions and offer better economic measures and signals with which to manage the system. These pricing patterns also indicate where additional generation and transmission upgrades are needed in the future.

2.0 Task 3.0 Real-Time Voltage Security Assessment (RTVSA) Prototype Tool

2.1. Executive Summary

Introduction

California ISO system operators need to know how to more effectively manage the grid and its reactive resources, as well as coordinate with other organizations (interconnected system operators, load-serving entities, and generators) within today's changed operational environment, especially during periods of system stress. Real-time assessment of voltage security is an important means for achieving this end. However, the California ISO does not have a tool that can perform these assessments within short time windows required for real-time operations.

In this, the third and final, phase of research to enable the California ISO to acquire such a tool, CERTS developed and successfully demonstrated a prototype real-time voltage security assessment (RTVSA) tool that met all of California ISO's performance requirements. Based on this research, the project team developed a complete functional specification and then supported the California ISO in acquiring a production-quality tool from a commercial vendor

The RTVSA project consisted of three research tracks: (1) data requirements, (2) algorithms, and (3) prototype development and testing. Each research track was implemented in three phases: (1) conceptualization of the overall framework, and creation of a simulation platform with which to conduct the research; (2) development of algorithms and proof-of-concept simulations; and (3) implementation and validation of even more advanced algorithms, including demonstrations using data from sub-regions within the California ISO and development of the final functional-specification document.

This report summarizes results from the third and final phase of the project. Earlier phases of the project were supported under two prior PIER contracts.

Purpose

The goal of the RTVSA project was to develop and successfully demonstrate a prototype voltage security assessment tool that could run in real time within California ISO's new reliability and congestion management system. The specific requirements of the RTVSA tool included: (1) a wide-area, situational-awareness, geographical displays to manage the voltage and volt-ampere-reactive (VAR) resources for California's transmission system; (2) calculation of available voltage security margins, as well as contingency ranking according to a severity index for voltage stability–related system problems; (3) detection of the most dangerous stresses in the system, which could lead to voltage collapse, the regions most affected by potential voltage problems, and abnormal voltage reductions in the grid; (4) identification of controls or actions to increase the available stability margin and avoid instability; and (5) dispatch information about voltage problems for look-ahead operating conditions and worst-case contingencies.

Project Objectives

The overall objective of the RTVSA project was to support the California ISO in acquiring a production quality RTVSA tool. Additional objectives included working closely with California utilities and California ISO operators to develop a prototype that met their specifications, demonstrating the prototype RTVSA tool by using it to examine selected areas under the control of the California ISO, developing a set of production-quality RTVSA functional specifications, and then providing technical support for the California ISO's efforts to work with a commercial vendor to integrate a production-quality RTVSA tool into the California ISO's new reliability and congestion management system.

Project Outcomes

The project team completed a number of important technical milestones in its effort to meet the ultimate objectives of the real-time VSA project. These milestones included validation of the continuation power flow algorithm, the direct method, a boundary-orbiting technique, and the hyperplane approach; the creation of an initial prototype real-time VSA tool by using these validated mathematical techniques; the successful testing of these aspects of the prototype tool on the Humboldt and San Diego areas; the subsequent incorporation of these results into the development of a complete prototype, which can monitor voltage stability margin in real time, and help operators manage this margin in real time by controlling resources on the transmission system; and, finally, the preparation of a functional-specification document that describes functional, design, and visualization requirements for a production-quality VSA tool that could be acquired from a commercial vendor.

In summer 2007, the California ISO used the functional-specification document prepared by the CERTS project team to select a commercial software vendor to develop a production quality real-time VSA tool and integrate it into the California ISO's Energy Management System (EMS). The tool is scheduled to go online the third quarter of 2008.

Conclusions

The research conducted by the team led to development of a robust design for a RTVSA tool based on the parameter continuation technique, and improvements in accuracy and performance from the direct method and boundary-orbiting technique. The resulting functional specifications directly supported California ISO's acquisition and installation of a production-quality tool incorporating these research findings.

Recommendations

The project team recommended and California ISO has since used the team's functional-specification document to engage a commercial vendor to deliver a production quality real-time VSA tool. The project team also recommends use the underlying concepts researched for this project in future research to explore the entire voltage security region in the parameter or power injection space, including application to a simple one-dimensional approach or to a more complex multidimensional stressing.

Benefits to California

The RTVSA Tool offers significant benefits to California, including the increased reliability of the California ISO, the Western Interconnection, and California's major utilities. Improved voltage monitoring should also improve the accuracy of the California ISO's locational marginal pricing calculations, and thereby lead to better management of congestion on the California ISO system, potentially at lower total cost.

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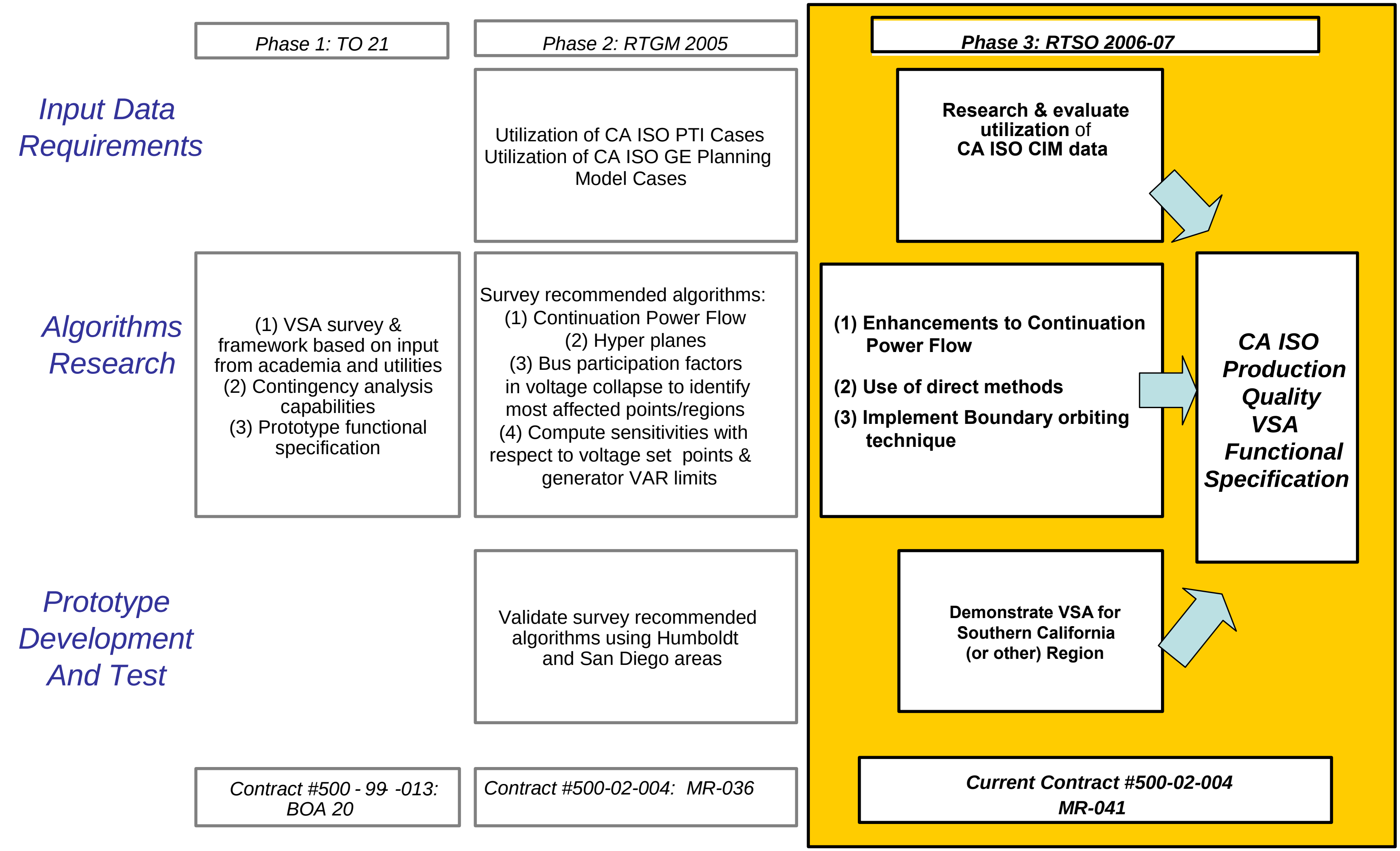
This report summarizes results from the third phase of the project. Earlier phases of this project were supported under earlier contracts as shown in the overall research roadmap for the project. See Figure 7. These earlier phases were completed under Contract No. 500−99−013, BOA-20, and Contract No. 500−02−004, MRA−036, Real-Time Grid Reliability Management 2005.



CERTS

Electric Power Group

Figure 7. Task 3.0 Multi-Year Research Roadmap for Real-Time Voltage Security Assessment (VSA)

2.2.1. Background and Overview

Over the past 40 years, more than 30 major blackouts worldwide have been caused by voltage instability and collapse. Among them, at least 13 voltage-related blackouts have taken place in the United States, including two major blackouts in the Western Interconnection in 1996, and a wide-scale blackout in the Eastern Interconnection in 2003. In examining the causes of these blackouts, investigation teams have, on several occasions, concluded that online power flow and stability tools, and indicators for system-wide voltage performance in the real-time operating environment are needed to prevent future blackouts.

Research for the VSA Project was motivated by California ISO operators' desire to acquire a real-time dispatcher's VSA tool and corresponding wide-area visuals to manage the voltage and Volt-Ampere Reactive (VAR) resources for the transmission system. The California ISO sought a tool that could calculate the following:

- Available voltage security margin.
- The most dangerous stresses in the system leading to voltage collapse.
- Worst-case contingencies leading to voltage collapse, and/or contingencies with an insufficient voltage stability margin.
- Abnormal reductions of nodal voltages.
- Contingency ranks according to a severity index for voltage stability–related system problems.
- Weakest elements within the grid, and the regions most affected by potential voltage problems.
- Controls to increase the available stability margin, and to avoid instability.
- Information about voltage problems for look-ahead operating conditions and worst-case contingencies (i.e., contingencies with large severity ranks) that may appear in the future.
- A real-time dispatcher's situational-awareness, wide-area graphic, and geographic displays.

CERTS developed an initial VAR-Voltage Management prototype tool funded by DOE's Transmission Reliability Program in 1999 and 2000. This prototype tool was a direct response to the California ISO's desire to improve procedures for implementing WECC's revised voltage-VAR requirements (Martinez, et.al. 2003). Prototype tailoring and enhancements for demonstration at the California ISO began under PIER support in 2001, and led to the following key project milestones: (1) in 2001–2002, the installation of the initial prototype with snapshot displays of the San Diego system only; (2) in 2003, the development of a full California ISO system model, including the incorporation of California ISO user feedback, but still based on snapshots; (3) in summer 2004, the California ISO developed specifications for the prototype of a new RTVSA tool that incorporates and extends the functionality of the original CERTS VAR-Voltage Management prototype for voltage security assessment purposes (CERTS 2005). The prototype was enhanced to run contingency simulations and perform contingency rankings, which were required for the VSA prototype phase of the project; these new features were tested on the California ISO system.

In July of 2004, the PIER TRP Review Committee recommended that RD&D continue in developing a RTVSA tool prototype. In forming its recommendations, the TRP identified current VAR margins, what VAR margins would be needed around the system, and options to address shortfalls as they arose. The TRP also recommended research to identify the information needed by operators to make better operating decisions, as well as factors that would improve their comfort with, and confidence in, new real-time operating tools.

In 2005 and early 2006, under PIER Contract No. 500–99–013, BOA-20 and Contract No. 500-02-004, MR-036, the project team conducted an extensive review of existing VSA approaches, and identified and selected a state-of-the-art combination of approaches and computational engines for implementation in this project. Key elements of the final approach selected include the use of (1) parameter continuation, (2) direct methods, (3) the boundary-orbiting method, and (4) hyperplane approximation of the voltage stability boundary. The real-time VSA project development team also successfully implemented the parameter continuation (also known as the predictor-corrector) method. This method is quite robust and useful, since it overcomes several mathematical obstacles; it is able to find a continuum of power flow solution starting at some base load, and leads to the steady state voltage stability limit (critical point) of the system.

Under this contract, research work included enhancements to the Power Systems Engineering Research Center's (PSERC's) parameter continuation program,, the implementation of direct methods to quickly and accurately determine the exact Point of Collapse (PoC), the implementation of boundary-orbiting techniques to trace the security boundary, the investigation of descriptive variables, the implementation of hyperplanes to approximate the voltage stability boundaries as well as identify the controllable elements in the space of power injection, and the validation of techniques for analyzing margin sensitivities.

These techniques were tested using a ~6000 bus state estimator model covering the entire Western Interconnection for Southern California problem areas suggested by the California ISO, and the results were reported in Appendix B, Real-Time Voltage Security Assessment Report on Algorithms and Framework.

At the completion of this project, a functional specification document was developed to describe the design, functional, and visualization requirements for a Real-Time Voltage Security Assessment (RTVSA) tool, as well as the California ISO's preferences for certain implementation and visualization techniques.

2.3. Task Objectives

The overall objective of Task 3.0 was to support the California ISO in acquiring a production quality VSA tool that runs in real time. A secondary objective was to conduct the research in consultation with California (CA) utilities, such that the results of the work could be evaluated by the CA utilities for their own possible future adaptation and application.

The specific research objective was to work closely with California ISO operators to assess the feasibility of algorithms that could be incorporated into and enhance a prototype tool to meet their specifications. Once the prototype was completed and successfully demonstrated, it was to be transferred via a functional specification to a commercial vendor (selected by California ISO) for implementation as a production-grade operating tool. As part of this phase of the research, the VSA tool was to be demonstrated in Humboldt or Southern California.

The specific objectives of Task 3.0 included the following:

- Perform RD&D of suitability of algorithms for continuation power flow and hyper plane construction.
- Prepare a Real-Time VSA Report to include, but not be limited to, the analysis of continuation power flow algorithms and analysis of hyper plane construction for defining safe operating regions.
- Demonstrate these algorithms in the Humboldt and San Diego areas, and report on the demonstration results.
- Research and develop a prototype VSA platform to include preparing a RTVSA Research Report on the expanded capability of the prototype VSA platform.
- Demonstrate the prototype VSA for Southern California region (or another region under the control of California ISO) and report on the demonstration results.
- Prepare an Enhanced RTVSA Research Report to include, but not be limited to, integration with California ISO Common Information Model (CIM) data and topology translator, remedial and corrective action, and expanded test areas to include the entire California ISO system.
- Develop a set of Production-Quality VSA Functional Specifications.
- Prepare a Real-Time Wide-Area VSA Project Report. This report shall include, but not be limited to, a summary of work done.
- Provide technical support for California ISO efforts to work with a vendor to integrate and deliver a production-quality VSA tool.

The primary technical objective of Task 3.0 has been accomplished, as demonstrated by the California ISO's acceptance of the final functional specifications used to procure a production-quality RTVSA software tool. The functional specification document lays out, in great detail, the design, functional, and visualization requirements for a real-time VSA tool that incorporated California ISO’s preferences for specific implementation and visualization techniques.

2.4. Task Approach/Methods

The task approach involved research on each of the final phases of the three project tracks identified in Figure 7: (1) implementation of suitable algorithms; (2) integration with California ISO's EMS; and (3) validation of the implemented algorithms on California ISO test cases. The following summarizes key aspects of the approach/methods, which are documented fully in appendices to the report.

The project team conducted an extensive review of existing VSA approaches, and identified and selected a state-of-the-art combination of approaches and computational engines for implementation in this project. Key elements of the final approach selected include the use of (1) parameter continuation, (2) direct methods, (3) the boundary-orbiting method, and (4) hyperplane approximation of the voltage stability boundary.

These elements were first approved by a panel of leading experts during the course of a survey conducted at the onset of the project. The elements were also verified in the course of face-to-face personal meetings with well-known university professors, industry experts, and software developers, and included email discussions, telephone exchanges, and feedback from industrial advisors and brainstorm meetings with the projects' consultants.

CERTS industrial advisors reviewed these developments during Technical Advisory Committee (TAC) meetings conducted in 2006. The TAC consisted of representatives from the California ISO, California utilities, Bonneville Power Authority (BPA), DOE, and other organizations.

The project team prototyped the proposed algorithms on a platform, also developed by the project team, to validate the tool, and tested it with a California ISO-provided test case. The project team used the PSERC parameter continuation program and MATLAB programming language as a basis for building the VSA prototype.

The project team validated the VSA algorithm results through numerous meetings and correspondence with California ISO staff who helped identify test cases and appropriate stressing conditions. In particular, the California ISO provided information on (1) the local voltage problem areas, stress direction, or procedure (which specifies how the system parameters change from their base case values as a function of increased amounts of stress), (2) the descriptor variables (which reflect the most influential or understandable combinations of parameters, or derivative parameters that influence the voltage stability margin), as well as (3) a list of critical contingencies associated with these stressing conditions. These data were used to:

- Compute the Point of Collapse (PoC) and reactive margins under the particular stressing condition using the parameter continuation technique in conjunction with the direct method.
- Calculate hyperplanes to approximate the voltage stability boundary.
- Compile a list of abnormal reductions in nodal voltages that highlighted the elements and regions most affected by potential voltage problems.
- Apply the boundary orbiting technique to trace the boundary under changed stressing situations.

The results of the research were presented and discussed with the California ISO staff, who were consulted extensively throughout the project and the functional specification development process. In addition, as a final input to development of the functional specification, a second survey was conducted of vendors and utilities to evaluate existing power system voltage security tools and to identify industry best practices in using them.

2.5. Task Outcomes

The project team completed research on the third and final phase of each of the three research tracks identified in Figure 7: (1) implementation of suitable algorithms; (2) integration with California ISO energy management system (EMS); and (3) validation of the implemented algorithms on the California ISO test cases.

With respect to the project objectives, the project team:

- Conducted a technical assessment of the continuation power flow algorithm, direct method, boundary-orbiting technique, and the hyperplane approaches.
- Enhanced the VSA prototype software tool by incorporating the above mentioned features.
- Utilized a ~6,000 bus (1,188 generators) state estimator model covering the entire Western Interconnection for the algorithm validation as suggested by the California ISO. This detailed model includes all buses/lines at or above the 115 kV level and some of the lower voltage levels within the California ISO region.
- Tested the prototype software tool on areas in Southern California.
- Provided a functional specification to the California ISO that included functional, design, and visualization requirements for a production-quality VSA tool that can be produced by a commercial vendor.

The following summarizes key aspects of these task outcomes, which are documented fully in appendices to the report. (See Appendix B, Real-Time Voltage Security Assessment Report on Algorithms and Framework, Appendix C, Real-Time Voltage Security Assessment Algorithm's Simulation and Validation Results; Appendix D, Real-Time Voltage Security Assessment Summary Report; and Appendix E, Real-Time Voltage Security Assessment Functional Specifications for Commercial Grade Application.)

The project team's research suggested that while the continuation method worked well in reaching the proximity of the collapse point in a particular stressing direction, several iterations of the algorithm and associated step-halving within the vicinity of the point-of-collapse were required to obtain the functions needed to extract accurate information about hyperplane boundaries, weak elements, and control elements.

The advantage to applying the direct method at this point is that it is a one-step approach to finding the collapse point within a predefined tolerance, and therefore overcomes accuracy limitations in the continuation method. Having accurately reached a point on the stability boundary, it is also theoretically feasible to apply the underlying continuation method framework to the direct method equations (as opposed to the powerflow equations as in the traditional continuation powerflow) and systematically trace the voltage stability boundary (i.e., boundary-orbiting method). This adaptation further reduced the computational time, because there is no longer a need to return to the operating point and move in a different stress direction to find a second point on the stability boundary.

Additionally, the efficacy of using hyperplanes to approximate the voltage stability boundaries as well as identifying the controllable elements in the space of power injections was corroborated. A hyperplane is a linear geometry in multi-dimensional space. In one-, two-, and three-dimensional space, this happens to be a point, a line, and a plane, respectively. In power systems, a two-dimensional security region constructed by hyperplane approximation describes a region of safe operation (also referred to as operating nomograms). This is the most promising method for determining the available voltage stability margin in real time using such piece-wise linear approximations of the voltage collapse boundary in coordinates of independent power system parameters.

The project team demonstrated that the attributes of hyperplanes (i.e. coefficients of the hyperplane) can be interpreted as the parametric sensitivities of the margin to power injections and therefore are particularly useful in ranking the most appropriate corrective actions to steer away from the stability boundary. Similarly, the participation factors at the various buses in the voltage collapse also fall out of the proposed methodology and aid in identifying weak areas with the worst voltage degradation during a voltage collapse.

In summary, the validation process confirmed that (1) hyperplanes, or piecewise linear approximations, can be extracted from the solution at the point of collapse in a particular stressing direction; (2) piecewise linear approximations are appropriate for the stability boundary; (3) the properties of these boundaries (e.g., the orientation of the hyperplanes) offered valuable information on ”control” elements indicating dangerous conditions that need corrective action, or weak elements where the impact of the voltage collapse phenomenon is the most severe; (4) a hybrid approach wherein the continuum power flow algorithm augmented with the direct method and the boundary-orbiting method can meet these performance requirements.

The final RTVSA algorithm consists of the following steps (which are illustrated in the flowchart in Figure 8):

1. Initial system stressing procedure for a given stress direction to reach a vicinity of the PoC in this direction.
2. The direct method is used then to refine the PoC location along the initial stress direction (the continuation method would require multiple iterations to find the PoC with the required accuracy).
3. The inverse iteration method or Arnoldi algorithm is applied to find the left eigenvector, which is used to build the set of approximating hyperplanes.

4. The boundary-orbiting procedure is then applied to trace the voltage stability boundary along a selected slice. This procedure is a combination of a predictor-corrector method and the transposed direct method.
5. In case of divergence, the algorithm is repeated starting from Step 1 for a new stress direction predicted at the last iteration of the orbiting procedure. Divergence may be caused, for example, by singularities of the stability boundary shape along the slice.
6. For a given voltage stability problem area and the corresponding descriptor parameters, the voltage stability boundary is built using the set of approximating hyperplanes.

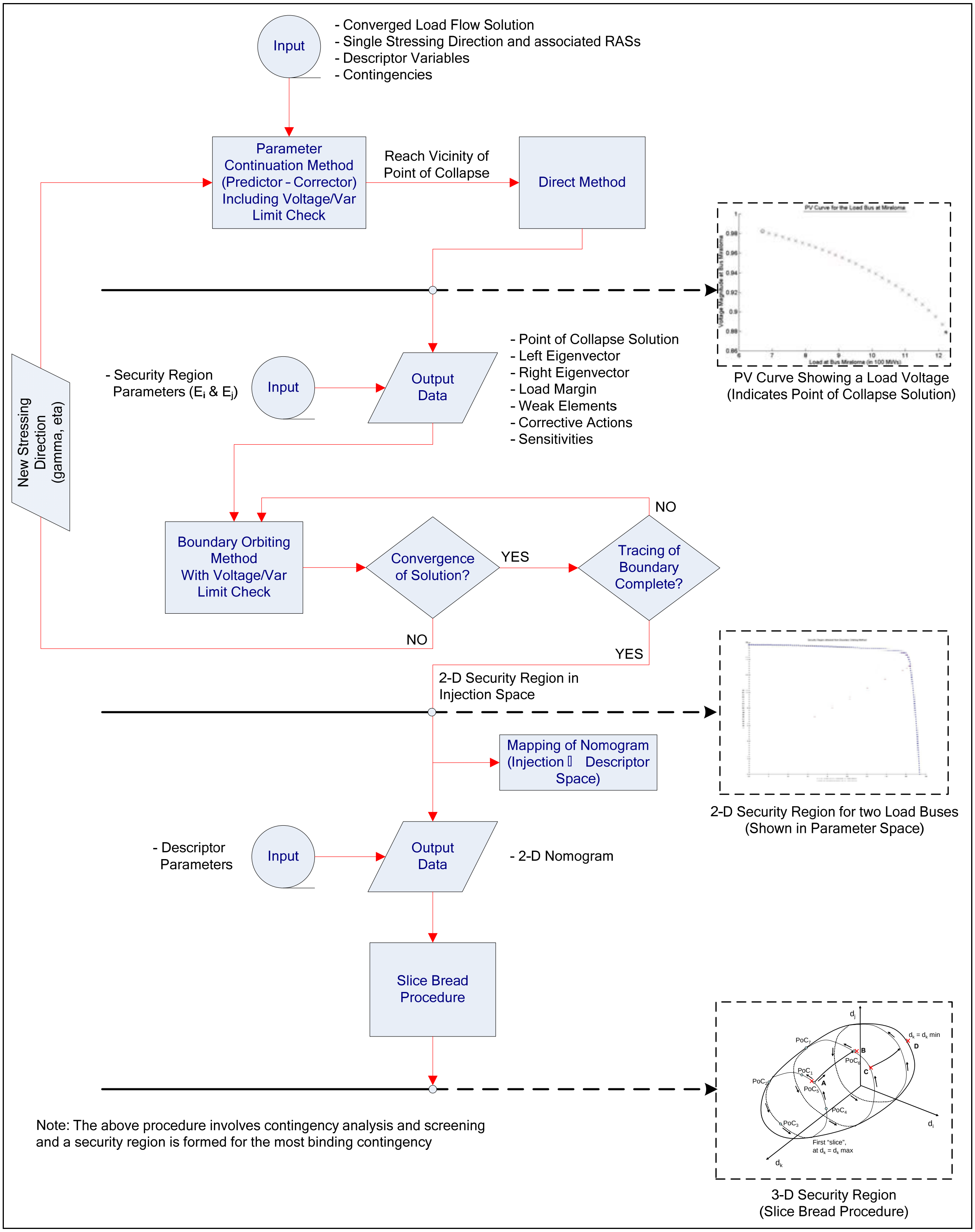


Figure 8. RTVSA Algorithms Flowchart

The proposed algorithm was successfully implemented on the RTVSA platform and tested on areas in Southern California (see Appendix C, Real-Time Voltage Security Assessment Algorithm's Simulation and Validation Results). The efficacy of using hyperplanes to approximate the voltage stability boundaries as well as to identify the associated weak elements and the "controllable" elements for these boundaries were corroborated.

The approximated voltage stability boundary was compared to results obtained from the GE Positive Sequence Load Flow Software (GE PSLF) program, which is commonly used in the Western Interconnection; the results of this comparison were within a few percentages of each other. The main contributing factor to these discrepancies was the California ISO state estimator model, which had deficiencies that required manual modifications to get it to solve. The GE PSLF handles such scenarios differently, and these differences show up in the stability boundary calculations.

As a final input to development of the functional specification, a second survey was conducted of vendors and utilities to evaluate existing power system voltage security tools and to identify industry best practices in using them. The survey collected information on the following topics:

- Interfaces and protocols that are currently used to import/export/exchange data, such as OPC or CIM/XML, in a power system simulation software, and thus, choose the one most appropriate for RTVSA tool.
- Available visualization capabilities within existing applications (to identify the best available solutions and gaps between what is available and RTVSA vision).
- Processing capabilities of available applications, in order to recommend improvements for the RTVSA tool.

Several vendors and utilities responded to the survey request, providing valuable information about their tool's interoperability, processing and visualization capabilities. The detailed findings from the survey are reported in Appendix D, Real-Time Voltage Security Assessment Summary Report.

Following presentation and discussion of these research results with California ISO staff, the CERTS project team developed a functional-specification document for the production-quality RTVSA tool.

The overall functionality of the RTVSA application was subdivided into three interdependent modules addressing (1) the input subsystem (including the various interfaces, protocols, and formats that the tool must support to integrate with the California ISO EMS; (2) the central server (addressing the various centralized functions such as topology processor, simulation engine, flat file storage, etc.), and (3) the user interface (operator display consoles and stand-alone consoles) requirements. The system architecture illustrates the affiliations among the various modules, as well as the constitutive functionalities of each of the consoles (Figure 9).

The functional specifications fully describe a production quality RTVSA tool that can monitor voltage stability margin in real time, and help operators manage this margin in real time by enabling them to more confidently control reactive resources, generation dispatch, and other resources on the transmission system. The monitoring function is accomplished by integration of the tool within the California ISO's real-time network analysis sequence, which will run the tool automatically, at five-minute intervals or on demand, after each successful state-estimation process. The operator support function includes automatic identification of:

1. Available voltage security margins.
2. The most dangerous stresses in the system leading to voltage collapse.
3. Worst-case contingencies resulting in voltage collapse and/or contingencies with insufficient voltage stability margins.
4. Contingency ranking according to a severity index for voltage stability–related system problems.
5. Weakest elements within the grid, and the regions most affected by potential voltage problems.
6. Controls to increase the available stability margin, and to avoid instability.
7. Information about voltage problems for look-ahead operating conditions and worst-case contingencies (i.e., contingencies with large severity ranks) that may appear in the future.

The RTVSA tool also features situational-awareness, wide-area graphic and geographic displays for two modes of operation: (1) real-time and (2) look-ahead. The functionalities offered by these two modes of operation are summarized in **Error! Reference source not found.** below.

	RTVSA Modes		*Study Modes*
	Real-Time	*Look-Ahead*	
Unidirectional Stressing			
Contingency screening & ranking	×	×	×
Real-time alarming	×		
Voltage profiles	×	×	×
MW/MVAR reserves	×	×	×
Single-line diagrams	×	×	×
Loading margins	×	×	×
Margin sensitivities to reactive support	×	×	×
Ranking of corrective controls	×	×	×
Identification of weak elements	×	×	×
Multidirectional Stressing			
2-D, 3-D or N-D Security Regions (Nomograms) developed offline			×
Real-time assessment of operating points including contingency ranking, margins	×	×	×
Real-time ranking of controls to steer away from the boundary	×	×	×

Table 1. Summary of RTVSA capabilities

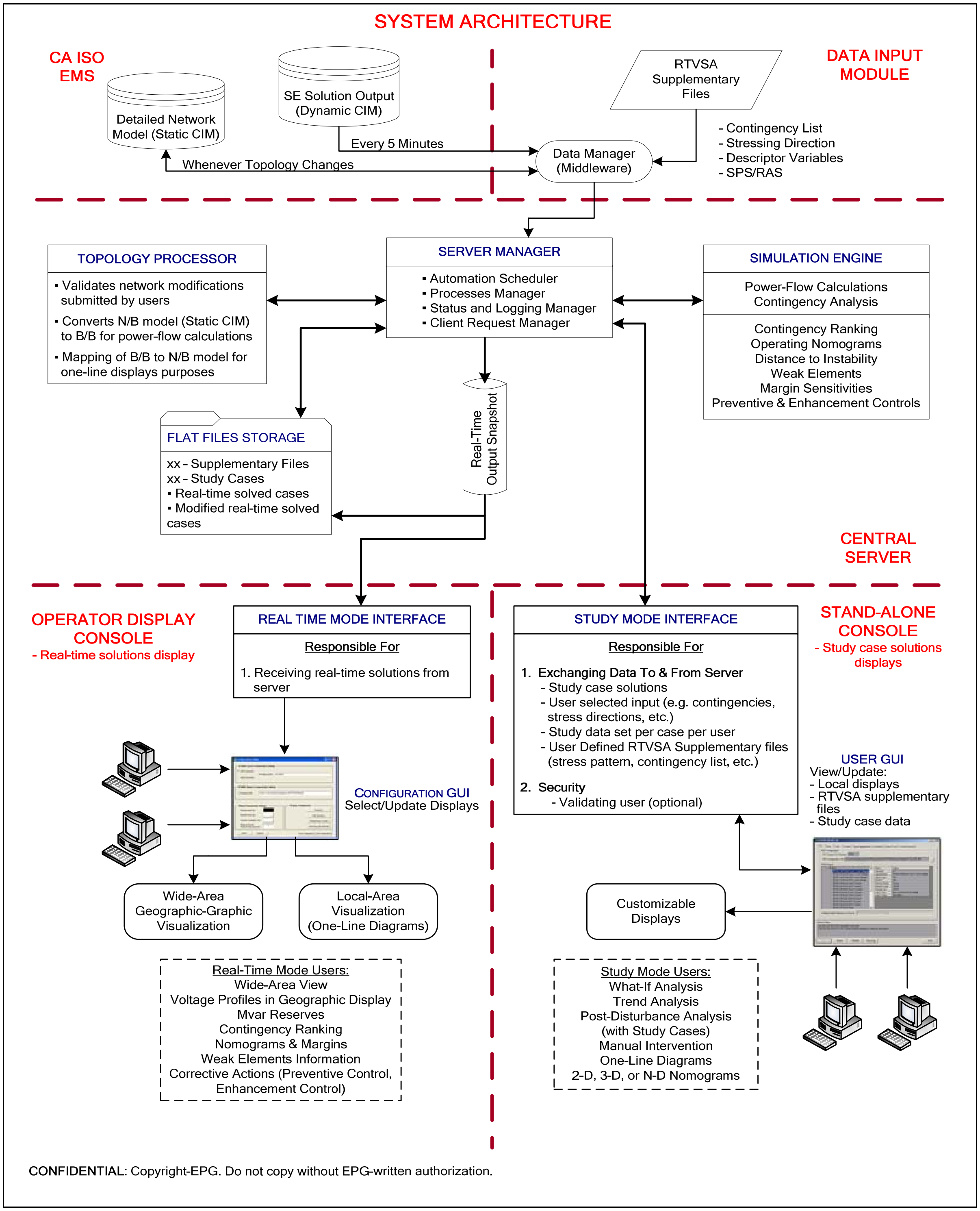


Figure 9. RTVSA System Architecture

The final functional specification for the production-grade VSA system was delivered to the California ISO in March, 2007 (see Appendix E, Real-Time Voltage Security Assessment

Functional Specifications for Commercial Grade Application). In summer 2007, the California ISO used the functional-specification document prepared by the CERTS project team to select a commercial software vendor to develop a production quality real-time VSA tool and integrate it into the California ISO's Energy Management System (EMS). The tool is scheduled to go online the third quarter of 2008.

2.6. Conclusions and Recommendations

2.6.1. Conclusions

The prototype RTVSA tool developed under this project was based on an extensive analysis of existing VSA approaches, surveys responses of the leading power-system experts from around the world, and interviewing vendors on their existing commercial offerings and utilities on current implementation practices within the industry. The research conducted by the team led to development of a robust design for a RTVSA tool based on the parameter continuation technique, and improvements in accuracy and performance from the direct method and boundary-orbiting technique.

The resulting functional specification has directly supported California ISO's acquisition and installation of a production-quality tool incorporating these research findings. The production quality RTVSA tool will form an integral element of the advanced suite of computational tools for congestion management that California ISO will utilize for reliability and congestion management.

2.6.2. Recommendations

The project team recommended and California ISO has since used the team's functional-specification document to engage a commercial vendor to deliver a production quality RTVSA tool. The project team also recommends use the underlying concepts researched for this project in future research to explore the entire voltage security region in the parameter or power injection space, including application to a simple one-dimensional approach or to a more complex multidimensional stressing.

2.6.3. Benefits to California

The RTVSA tool will provide significant benefits to California. Most of the VSA tools that are currently available commercially are well-suited for the planning environment, where they are used in an offline mode to conduct studies and define safe operating regions and margins (or nomograms). However, these nomograms, which are utilized to operate the grid in real time, tend to be conservative when dealing with uncertainties, worst-case conditions, and any discrepancies between real-time operating conditions and those used in the offline planning studies. Therefore, the ability to dynamically adjust voltage security regions to changing system conditions, and to compute margins in real time that accurately reflect true system conditions, which are embodied in the RTVSA tool, offer the following benefits to the California ISO and California utilities:

1. California ISO will immediately benefit from increased reliability.
2. Improved voltage monitoring should also improve the accuracy of locational marginal pricing (LMP) calculations. which will accompany the roll-out of California ISO's

Market Redesign Technology Update. This update seeks to correct problems in California's electricity markets that contributed to the market disruptions experienced in 2000 and 2001. This objective is accomplished, in part, through better congestion management, potentially at lower cost, for the California ISO system;[2] and

3. The successful implementation of the RTVSA tool by California ISO will likely accelerate market acceptance of this and similar operating tools, leading to a promulgation of the first two benefits above to other regions of the country.

[2] The Market Redesign and Technology Update includes three foundational designs – a full network model of the electricity grid, an integrated day ahead forward market and LMP. The LMP is the result of the integrated forward market which provides nodal prices so that all market participants know the cost of generating power, serving load and resolving congestion at each location on the system. LMPs reflect physical constraints under all load and system conditions and offer better economic measures and signals with which to manage the system. These pricing patterns also indicate where additional generation and transmission upgrades are needed in the future.

3.0 References

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4.0 Glossary

Acronym	*Definition*
BPA	Bonneville Power Administration
California ISO	California Independent System Operator
CIEE	California Institute for Energy and Environment
CIM	Common Information Model
CERTS	Consortium for Electric Reliability Technology Solutions
CPR	Critical Project Review
DOE	Department of Energy
EIPP	Eastern Interconnection Phasor Project
EMS	Energy Management System
EPRI	Electric Power Research Institute
GE PSLF	General Electric Positive Sequence Load Flow (GE PSLF is the load-flow component of the GE power systems analysis package)
IEEE	Institute of Electrical and Electronic Engineers
LBNL	Lawrence Berkeley National Laboratory
MATLAB	MATrix LABoratory (programming language for technical computing from The MathWorks, Natick, MA
MW	Megawatt
MRTU	Market Redesign and Technology Update
MVARs	Mega Voltage-Ampere Reactive
NERC-WECC	North American Electric Reliability Corporation – Western Electricity Coordinating Council
PG&E	Pacific Gas and Electric
PI	Principal Investigator
PIER	Public Interest Energy Research
PMUs	Phasor Measurement Units
PoC	Point of Collapse
PSERC	Power Systems Engineering Research Center
RD&D	Research Development & Demonstration
RTDMS	Real Time Dynamics Monitoring System

RTSO	Real Time System Operations
RTVSA	Real Time Voltage Security Assessment
SCADA/EMS	Supervisory Control and Data Acquisition/Energy Management System
SCE	Southern California Edison
SDG&E	San Diego Gas & Electric
TRP	PIER Transmission Research Program
VAR	Volt-Ampere Reactive
VSA	Voltage Security Assessment
WAPA	Western Area Power Administration
WASA	Wide-area Security Assessment
WECC	Western Electricity Coordinating Council

Appendices

Appendices are available as separate documents.

Appendix A, Phasor Feasibility Assessment and Research Results Report

Appendix B, Real-Time Voltage Security Assessment Report on Algorithms and Framework.

Appendix C, Real-Time Voltage Security Assessment Algorithm's Simulation and Validation Results

Appendix D, Real-Time Voltage Security Assessment Summary Report

Appendix E, Real-Time Voltage Security Assessment Functional Specifications for Commercial Grade Application