Public Interest Energy Research (PIER) Program

FINAL PROJECT REPORT

SYNCHROPHASORS FOR THE INTEGRATION OF RENEWABLES

Prepared for: California Energy Commission

Prepared by: Lawrence Berkeley National Laboratory

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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, conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research 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 Technology Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Synchrophasors for Integration of Renewables is the final report for the Synchrophasors for Integration of Renewables project (Contract Number 500-08-054) conducted by CERTS. The information from this project contributes to the PIER Program's Energy Technology Systems Integration 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 916-327-1551.

ABSTRACT

This report describes research undertaken into the development of new grid operating tools that rely on an emerging new class of monitoring data called time-synchronized phasor-measurements. These tools will ultimately enable grid operators—for the first time ever—to directly observe and, therefore, enable real-time responses to the problems that led to the 1996 and 2003 blackouts. The focus of this research effort is on operator visualization and decision-support tools based on using phasor measurements in real-time. There are no current precedents for such real-time applications of phasor measurements. Ultimately, the research performed will support applications that could be developed, prototyped, demonstrated, and relied upon by grid operating staff to develop and support the implementation of new operating guidelines and controls. These guidelines and controls would respond to problems—such as those that occurred during the 1996 and 2003 blackouts—either manually or automatically.

The key activities were to:

- Conduct research on automated alarming/email notifications for operators when system conditions are deemed abnormal based on analysis of the real-time phasor data
- Conduct research on advanced applications to identify real-time key monitoring points/interfaces with significant participation in a particular mode (i.e., mode shape information)
- Conduct research to develop algorithms to calculate damping levels when sudden events in the system trigger sizeable oscillations deemed unsafe, and suggest corrective actions
- Conduct research to assess of the impact of wind generation on grid reliability
- Support the update of a detailed California and WECC-specific roadmap for advanced phasor applications

This project was performed in close coordination with a project conducted by Electric Power Group (EPG), under Energy Commission contract Number 500-08-048, which, among other things, integrated the research into prototypes and led the development of the updated roadmap.

Keywords: grid operating tools, real-time applications, phasor measurements

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REPORT ORGANIZATION

The Syncrhophasors for Integration of Renewables for Integration project consists of two technical tasks, the first of which was divided into four subtasks:

- Task 1 Phasor Application Research
  - Sub-task 1.1. Research on automated alarming/email notifications for operators when system conditions are deemed abnormal based on analysis of the real-time phasor data
  - Sub-task 1.2. Research to develop algorithms to calculate damping levels when sudden events in the system trigger sizeable oscillations deemed unsafe, and suggest corrective actions
  - Sub-task 1.3. Research on advanced applications to identify real-time key monitoring points/interfaces with significant participation in a particular mode (i.e. mode shape information)
  - Sub-task 1.4. Research on the impact of wind generation on grid reliability.
- Task 2 Research Roadmap, Industry Coordination and Research

  Support the update of a detailed California and WECC specific roadmap for advanced phasor applications.

EXECUTIVE SUMMARY

Introduction

This report describes research undertaken into the development of new grid operating tools that rely on an emerging new class of monitoring data called time-synchronized phasor-measurements. These tools will ultimately enable grid operators—for the first time ever—to directly observe and, therefore, enable real-time responses to the problems that led to the 1996 and 2003 blackouts. The focus of this research effort is on operator visualization and decision-support tools based on using phasor measurements in real-time. There are no current precedents for such real-time applications of phasor measurements. Ultimately, the research performed will support applications that could be developed, prototyped, demonstrated, and relied upon by grid operating staff to develop and support the implementation of new operating guidelines and controls. These guidelines and controls would respond to problems—such as those that occurred during the 1996 and 2003 blackouts—either manually or automatically.

Purpose

The purpose of this project is to research and develop new software-based smart grid applications that provide the California grid operators real-time monitoring of the health and stability of the power system, and suggest necessary corrective actions when the grid is stressed, vulnerable to cascading blackouts, or is operating in an unsafe zone.

Project Objectives

The key activities were:

- Task 1
  - Sub-task 1.1. Conduct research on automated alarming/email notifications for operators when system conditions are deemed abnormal based on analysis of the real-time phasor data
  - Sub-task 1.2. Conduct research to develop algorithms to calculate damping levels when sudden events in the system trigger sizeable oscillations deemed unsafe, and suggest corrective actions
  - Sub-task 1.3. Conduct research on advanced applications to identify real-time key monitoring points/interfaces with significant participation in a particular mode (i.e., mode shape information)
  - Sub-task 1.4. Conduct research to assess the impact of wind generation on grid reliability
- Task 2. Support the update of a detailed California and WECC-specific roadmap for advanced phasor applications

This project was performed in close coordination with a project conducted by Electric Power Group (EPG), under California Energy Commission (Energy Commission) contract Number 500-08-048, which, among other things, integrated the research into prototypes and led the development of the updated roadmap. (Electric Power Group 2012)

Project Outcome or Results

Sub-task 1.1. Research on automated alarming/email notifications for operators when system conditions are deemed abnormal based on analysis of the real-time phasor data

The project team produced a method to apply phasor computations to an area that can increase the practicality of algorithms that use both the phasor measurements and a system model. The project has also suggested new quantities that could easily be computed from phasor measurements that could be used to measure the stress across an area of the power system. These algorithms would ultimately help in providing operator advice to run the power grid of California in a more economic and reliable way.

Sub-task 1.2. Research to develop algorithms to calculate damping levels when sudden events in the system trigger sizeable oscillations deemed unsafe, and suggest corrective actions

The project team developed oscillation-monitoring algorithms that have been integrated into an EPG Real-Time Dynamics Monitoring System (RTDMS), which has been implemented at the California Independent System Operator (California ISO) to prevent future oscillation problems from affecting California power grid customers.

The project team also developed algorithms for corrective redispatch of generation to restore sufficient oscillation damping. Confidence in being able to mitigate poor damping could suppress harmful oscillations and allow larger power transfers that reduce the cost of electricity and limit damage to the environment.

Sub-task 1.3. Research on advanced applications to identify real-time key monitoring points/interfaces with significant participation in a particular mode (i.e., mode shape information)

The project team's research provided valuable insight into how problematic oscillations on western power system can be mitigated by real-time operator actions. When the observations are validated and implemented, the recommendations can serve to improve the operational reliability of the western electric power system by preventing crippling blackouts from affecting California residents.

Sub-task 1.4. Research to assess the impact of wind generation on grid reliability

The project team conducted performance evaluations based on actual phasor measurements from the field taken close to wind farms and from monitored wind farm feeder lines. The research has contributed to a better baseline understanding of how actual wind generation within California's electric grid is affecting the frequency performance of the power system.

Conclusions, Recommendations, Benefits to California

The project teams completed research on a variety of advanced algorithms and concepts aimed at applying data produced by synchrophasor monitoring technologies to improve the economic and reliable operation of the California (and Western) high-voltage transmission system. Some of the research has already been incorporated into advanced software tools that are being used by the California ISO. Others will require additional research, prototyping, and demonstration before they can be used.

This research was used to support the development of a research and technology development roadmap for the California ISO, which was prepared under a separate contract (Task 2). Adoption and implementation of this roadmap is recommended.

California will benefit from implementation of the roadmap by having a more reliable electricity system and one that will cost consumers less to operate.

CHAPTER 1: Task 1. Phasor Applications Research

1.1 Introduction

This report describes research undertaken into the development of new grid operating tools that rely on an emerging new class of monitoring data called time-synchronized phasor-measurements. These tools will ultimately enable grid operators—for the first time ever—to directly observe and, therefore, enable real-time responses to the problems that led to the 1996 and 2003 blackouts. The focus of this research effort is on operator visualization and decision-support tools based on using phasor measurements in real-time. There are no current precedents for such real-time applications of phasor measurements. Ultimately, the research performed will support applications that could be developed, prototyped, demonstrated, and relied upon by grid operating staff to develop and support the implementation of new operating guidelines and controls. These guidelines and controls would respond to problems—such as those that occurred during the 1996 and 2003 blackouts—either manually or automatically.

The purpose of this project is to research and develop new software-based smart grid applications that provide the California grid operators real-time monitoring of the health and stability of the power system, and suggest necessary corrective actions when the grid is stressed, vulnerable to cascading blackouts, or is operating in an unsafe zone.

In earlier research Lawrence Berkeley National Laboratory (LBNL), in close coordination with Electric Power Group (EPG), validated the research concepts and worked with California Independent System Operator (California ISO) personnel to demonstrate the viability and value of synchrophasor software application prototypes when adapted and integrated with California ISO operations and reliability monitoring functions. This proposed project will build on earlier research to develop next-generation synchrophasor applications for California ISO to arm operators and reliability coordinators with decision-support tools that can visualize the entire Western grid and provide real-time system status to the California ISO and California utilities; monitor the dynamics and delivery of intermittent wind generation resources; dynamically optimize the use of available transmission in light of fluctuating output of renewable generators and increase transmission capacity utilization; assess the grid's vulnerability to instability; and enable operators to take corrective actions to prevent system collapse.

This project employed and integrated technology developed and demonstrated in five prior Energy Commission projects: 150-99-003; 500-99-013, BOA 20-21 and BOA 20-24; and 500-02-004 MRA 036 and MRA-041. Under these five prior contracts, research on synchrophasor technology was used to:

- Establish the initial California ISO phasor acquisition network to collect synchrophasor data in real time, including connectivity to other organizations such as Bonneville Power Administration (BPA), Pacific Gas & Electric (PG&E), Southern California Edison (SCE), San Diego Gas & Electricity (SDG&E), and Western Area Power Administration (WAPA) for data exchange.

- Adapt an EPG-developed Real Time Dynamics Monitoring System (RTDMS) platform and make it suitable for use by California ISO. EPG's RTDMS is currently the only real time synchrophasor application platform that is available for use by operators.
- Test the first generation RTDMS prototype synchrophasor platform by California ISO researchers in 2003.
- Demonstrate viability of phasor software during a multiple contingency event at California ISO in 2003 and, more recently, the use of phasor RTDMS visualization displays to identify operating anomalies and take corrective action in real time with respect to operation of the DC Intertie and pumped storage.
- Leverage resource and equipment investments made by California ISO during 2006 to install research prototype versions of RTDMS on production-grade hardware, including 14 RTDMS client consoles for test use by system operators at the primary and backup control centers, operating engineers, reliability coordinators, and researchers at California ISO.
- Develop an industry-leading, multi-year research roadmap by California ISO, CERTS, and the California Energy Commission to continue research on applications, development of algorithms, development and testing of prototypes, and other research activities to harness the benefits of this next-generation technology for California consumers.

1.2 Task Objectives

The key activities and task objectives under Task 1, Phasor Applications Research, are:

Sub-task 1.1. Conduct research into automated alarming/email notifications for operators when system conditions are deemed abnormal based on analysis of the real-time phasor data

This research was led by Ian Dobson, then at the University of Wisconsin. The objective of Dr. Dobson's research is to find better ways to process and interpret phasor measurements from many locations. In particular, the task objectives are to process phasor measurements so that they can be used to detect line outages in an area without a model of the entire interconnection and to demonstrate examples of angle stress measurements across an entire area.

Sub-task 1.2. Conduct research to develop algorithms to calculate damping levels when sudden events in the system trigger sizeable oscillations deemed unsafe, and suggest corrective actions

This research was led by Mani Venkatasubramanian at Washington State University and by Ian Dobson at Iowa State University. The objective of Dr. Venkatasubramanian's research is to develop and implement algorithms for oscillation monitoring of disturbances in the western electric power system. The objective of Dr. Dobson's research is to specify generator redispatch that is guaranteed to damp inter-area electromechanical oscillations, based on phasor measurement unit (PMU) measurements, in a way that is grounded in analysis. This analytic approach is complementary to simulation-based or heuristic approaches.

Sub-task 1.3. Conduct research on advanced applications to identify real-time key monitoring points/interfaces with significant participation in a particular mode (i.e., mode shape information)

This research was led by Mani Venkatasubramanian at Washington State University. The objective of Dr. Venkatasubramanian's research is to associate oscillatory modal properties such as mode shape information with power-flows on key transmission paths and corridors.

Sub-task 1.4. Conduct research to assess the impact of wind generation on grid reliability

This research was led by Yuri Makarov at Pacific Northwest National Laboratory. The objective of Dr. Makarov's research is to develop methods for monitoring the level of system inertia and frequency response based on WECC system data for different levels of wind generation and then, to determine if and how the inertia and response are influenced by the level of renewable energy generation.

This project was performed in close coordination with a project conducted by Electric Power Group (EPG), under California Energy Commission (Energy Commission) contract Number 500-08-048, which, among other things, integrated the research into prototypes and led the development of the updated roadmap. (Electric Power Group 2012)

1.3 Project Approach

Sub-task 1.1. Research on automated alarming/email notifications for operators when system conditions are deemed abnormal based on analysis of the real-time phasor data (Dobson)

The project team developed several examples of area angles for areas of the WECC, and illustrated the area stress changing as lines outaged (Sehwail and Dobson 2012b). In one of the examples, the team tracked the large changes in stress across the area of the Southwestern blackout as some of the main blackout outages occurred.

Sub-task 1.2. Research to develop algorithms to calculate damping levels when sudden events in the system trigger sizeable oscillations deemed unsafe, and suggest corrective actions (Venkatasubramanian)

The project team developed Matlab codes along with recommended parameters for implementing three algorithms: Prony algorithm; Matrix Pencil algorithm; and Hankel Total Least Square (HTLS) algorithm for ring-down analysis of disturbance responses from wide-area synchrophasor measurements in a real power system (Powertech DSA Tools 2012).

Sub-task 1.2. Research to develop algorithms to calculate damping levels when sudden events in the system trigger sizeable oscillations deemed unsafe, and suggest corrective actions (Dobson)

The project team derived analytic formula for the eigenvalue sensitivity to the possible generator redispatches that involves only measurable quantities (a formula depending on unobservable quantities such as left eigenvectors or eigenvector derivatives has long been known, but is intractable), verified it numerically in some small examples, and finally verified a more streamlined form of the derivation.

Sub-task 1.3. Research on advanced applications to identify real-time key monitoring points/interfaces with significant participation in a particular mode (i.e., mode shape information)

The project team used power-flow and stability models of the western power system for 2009 heavy summer condition to study the modal properties of the 0.22 Hz California-Oregon Intertie (COI) mode and the 0.33 Hz Alberta mode. Small-signal stability analysis (SSAT) and transient stability analysis program (TSAT) developed by Powertech Labs (Powertech DSA Tools 2012) were also used for the analysis. The relationships between mode damping ratios and power-flows on key transmission paths were studied using SSAT and TSAT.

Sub-task 1.4. Research to assess the impact of wind generation on grid reliability

The project team used synchrophasor measurements, generation disturbance and system status data collected in the Western Interconnection to evaluate the observed impacts of renewables on the frequency response and inertia. The approach involved the following steps:

- Identify generation trip events in WECC system, including their time and MW output of the lost generator at the moment of disturbance
- Find total WECC generation at the moment of disturbance
- Find information on the levels of wind and solar generation when the events occur (for all WECC system)
- Find the corresponding frequency variation curves using PMU data
- Evaluate the system inertia and frequency response
- Conduct a statistical p-value analysis to determine the likelihood of influence of online renewable generation on frequency response and inertia characteristics in the WECC system

1.4 Project Outcomes

Sub-task 1.1. Research on automated alarming/email notifications for operators when system conditions are deemed abnormal based on analysis of the real-time phasor data

The project team improved methods of processing, interpreting and applying phasor measurements by showing how to apply phasor measurements to one area of a power system, improving line outage detection methods, and illustrating the area angle concept that combines together phasor measurements around the border of a power system in a meaningful way.

There are good opportunities for calculations that combine phasor measurements with system models. However, in large interconnections, it is often convenient or practical for utilities to maintain network models only for their own area. The project team found a way to perform the calculations using phasor measurements at the border of an area and superposition. Phasor measurements at all the border buses of an area of a power system can be used to effectively decouple the area from the rest of the power system (Sehwail and Dobson 2013). Calculations combining models and phasor measurements can then be applied using only models of the area and area measurements. The processed measurements only respond to changes inside the area, and do not change when changes occur outside the area.

The project team illustrated the decoupling for a line outage detection algorithm that uses both measurements and a DC load flow grid model (Sehwail and Dobson 2013). The project team used the line outage algorithm of Tate and Overbye that applies to an entire interconnection, and showed how to adapt the algorithm and use the decoupling to do line outage detection in an area of the power system (Sehwail and Dobson 2012). The line outage detection algorithm was also improved by extending it to line outages that island the area.

The project team previously developed a new concept of area angles (Dobson 2012). These angles indicate the stress across an area in a particular direction and are computed by combining together phasor measurements with particular weights that make the area angle satisfy standard circuit laws. The computation of the area angles from the phasor measurements is a simple linear formula with coefficients that can be obtained from a DC load flow. The phasor measurements must be made at all the border buses around the border of the area that that have tie lines to the rest of the power system.

Sub-task 1.2. Research to develop algorithms to calculate damping levels when sudden events in the system trigger sizeable oscillations deemed unsafe, and suggest corrective actions (Dobson)

The project team discovered that there was a simple analytic formula and principle governing the change in oscillation damping when generation is redispatched.

The analytics of oscillation damping are difficult, and this objective had been pursued multiple times for over a decade. In 2012, the project team finally discovered a way to solve it. A dynamic model of generator swing equations and frequency-dependent loads is assumed. (While this combines together and equivalences other dynamics, this standard model probably captures the relevant electromechanical oscillation physics. Since the implementation will rely on measurements, the project team does not have to know the parameters of the lumped swing equation dynamics in order to apply the results of the analysis.)

The key is an analytic formula for the eigenvalue sensitivity to the possible generator redispatches that involves only measurable quantities (a formula depending on unobservable quantities such as left eigenvectors or eigenvector derivatives has long been known, but is intractable). The new formula shows that the eigenvalue sensitivity to redispatch depends proportionally in a simple way on the pattern of oscillation (the right eigenvector that is measured in task 2.1.2) and the power flow. The formula is elegant and judged to be of both practical value and theoretical interest.

The project team discovered how generator redispatch damps interarea elecromechanical oscillations based on analysis. Engineering experience suggests that operator actions based on insight, analysis, and physical principles are likely to be more effective and robust. In particular, when it works and how it works when it does work should emerge from the analysis. The analytic approach is complementary to simulation based or heuristic approaches, and can be expected to strengthen, optimize, justify, and give the bounds of applicability of these other approaches. Understanding how generator redispatch works to damp oscillations is expected to underpin algorithms that extract additional value from the nation’s investment in PMUs.

Sub-task 1.2. Research to develop algorithms to calculate damping levels when sudden events in the system trigger sizeable oscillations deemed unsafe, and suggest corrective actions (Venkatasubramanian)

The three algorithms (Prony, Matrix Pencil, and HTLS) are excellent tools for analyzing oscillatory properties of the power system following disturbances. The algorithms provide a snapshot of dominant modes, as well as mode-damping ratios needed for initiating suitable operator actions to mitigate the oscillations, when the oscillations become problematic.

The project team's three algorithms have all been implemented by EPG into RTDMS (EPG RTDMS 2012). RTDMS has been implemented at several California utilities, including California ISO.

Sub-task 1.3. Research on advanced applications to identify real-time key monitoring points/interfaces with significant participation in a particular mode (i.e., mode shape information)

The project team made several key findings:

- Mode shapes for 0.22 Hz COI Mode and the 0.33 Hz Alberta Mode for SSAT suggest that the most effective ways to improve damping of these modes is by changing transfers on the respective COI and Alberta–BC paths.
- Damping of the COI Mode can be improved by decreasing the COI tie-line flow. Variation of COI flow appears to have much lesser effect on damping of the Alberta Mode.
- Decreasing generation in BC and Alberta is more effective than decreasing generation in NW to improve damping of the COI Mode.
- Redispatch of generation in Northern or Southern California to vary COI flow have similar effectiveness for changing damping of the 0.25 Hz mode.
- Inserting the Fort Rock series capacitors help improving the damping of the COI Mode. The effectiveness of this increased with increasing COI loading.
- The Double Palo Verde contingency significantly reduces damping of both the COI Mode and the Alberta Mode.
- Variation of COI flow appears to have little effect on Alberta Mode damping.
- Damping of the Alberta Mode can be most effectively changed by varying Alberta–BC flow. Generally the damping gets better when the Alberta–BC tie-line flow is moved towards zero irrespective of the flow direction. The nonlinear results found are similar to the results for 2005 data and the damping of the Alberta Mode needs further investigation.
- Shifting generation from BC to the NW appears to have little effect on either the COI Mode or the Alberta Mode.
- Varying the NW–Idaho tie-line flow has little effect on damping of the Alberta Mode.
- Damping of the COI Mode can be adjusted by varying the NW–Idaho tie-line flow.
- SSAT damping estimation of the 0.25 Hz mode tends to be more conservative (less damped) than TSAT based Prony damping estimates. For this study SSAT and TSAT

results agree with each other very well at low COI flow, but diverge somewhat at high COI flow in both damping and frequency.

- The Alberta Mode has a nonlinear relationship against path loading with both SSAT and TSAT.
- SSAT mode shapes provide clear insight into the nature of the 0.25 Hz and 0.4 Hz modes.
- The apparent 0.85 Hz Colstrip mode is not easily observable in SSAT or TSAT for the 2009 data.
- TSAT should be used to verify SSAT results.

Sub-task 1.4. Research to assess the impact of wind generation on grid reliability

The project team developed a practical statistics-based methodology to help evaluate the current and future effect of renewable resources on power system inertia and frequency response characteristic based on field data. The idea behind these analyses is that the renewables are displacing a certain fraction of conventional generators that are primarily responsible for these important characteristics contributing to overall system reliability and control performance.

The statistical methodology performed adequately in capturing the actual impacts of system parameters on inertia and frequency response. Using actual WECC system data, it was shown that system load and online conventional generation have the expected decisive effect on these characteristics. This fact was properly depicted, even based on a limited fraction of the WECC system field data made available for the research team (the project team used only California ISO and BPA generation and load data).

Some initial indications were obtained that the WECC system inertia may have been already affected in some extent by renewable generation output fed into the system. At the same time, this evidence cannot be recognized as statistically significant, because its p-value is only 31%, which means only a 69% probability that the described dependence really exists. (In order to be statistically significant, the p-value should have stayed within the several percent range.)

No dependence was found between the system frequency response and inertia characteristics and renewable generation output. The p-value for this dependence is 99%, which means only 1% probability of this dependence.

The experimental results were heavily scattered, so that although the trend line could be identified and sometimes verified statistically, it cannot be easily traced visually without some reasonable doubts. The observed dispersion of results is explained by the use of California and BPA load and generation data, instead of the required use of all WECC system data, so that hidden effects of generation and load outside of these two systems created the scatter. For a more accurate analysis, WECC wide data should be used.

1.5 Conclusions and Recommendations

Sub-task 1.1. Research on automated alarming/email notifications for operators when system conditions are deemed abnormal based on analysis of the real-time phasor data

Some new ideas for processing and combining phasor measurements based on circuit theory appear promising in providing some practical advantages. The most significant direction for future research is to find ways to determine limits on area angles that correspond best to the limits of the power system, demonstrate the robustness of these choices, and find out more about how monitoring area angles compares to the current practice of monitoring path power flows.

Sub-task 1.2. Research to develop algorithms to calculate damping levels when sudden events in the system trigger sizeable oscillations deemed unsafe, and suggest corrective actions (Venkatasubramanian)

The three algorithms (Prony, Matrix Pencil, and HTLS) are excellent tools for analyzing oscillatory properties of the power system following disturbances. The algorithms provide a snapshot of dominant modes, as well as mode damping ratios needed for initiating suitable operator actions to mitigate the oscillations, when the oscillations become problematic. It is important to continue research on other efficient algorithms for oscillation analysis. It is also important to develop a good understanding of recommended operator actions to improve the damping properties of problematic oscillatory modes when such problems are detected by algorithms implemented in this task.

Sub-task 1.2. Research to develop algorithms to calculate damping levels when sudden events in the system trigger sizeable oscillations deemed unsafe, and suggest corrective actions (Dobson)

The application of the discovered principle and formula to damp oscillations using generator redispatch should be further worked out and tested in dynamic power system models. The ways in which the analytic work can strengthen and inform the range of applicability of other heuristic and simulation-based approaches should also be considered.

Sub-task 1.3. Research on advanced applications to identify real-time key monitoring points/interfaces with significant participation in a particular mode (i.e., mode shape information)

Project findings provide valuable insight into the modal properties of key oscillatory modes in the western electric grid. Reduction of MW flows on key transmission paths as indicated above can play a significant role in improving the damping of problematic oscillatory modes. Further investigation of the modal relationships summarized above is recommended for recent models of the western power system.

Sub-task 1.4. Research to assess the impact of wind generation on grid reliability

The project team believes that the limited success of its effort to see statistically significant impacts of renewables on system inertia may be explained by the limited nature of these impacts at the current levels of renewable energy penetration. In preparation for expected future increases in renewable energy penetration, the project team recommends the following activities for future research:

- Expand the study into the second phase by including all needed WECC-wide data, as well as by involving more generation trip events into the analysis. This will help us to additionally verify the dependencies, minimize the scattering effect observed in this analysis, and enhance the methodology.
- Develop a WECC-wide frequency response and inertia real-time monitoring system based on state estimation results, disturbance information, and synchrophasor measurements.
- Develop a similar local system for California.
- Conduct research and analyses to more scientifically quantify the minimum frequency response obligation (FRO) for California and other systems.
- Develop methodologies expanding the p-value analysis into a statistics-based sensitivity method to determine the most influencing factors influencing frequency response and inertia characteristics.
- Develop proactive system planning, control and market approaches to provide the required level of frequency response and inertia in the most efficient and reliable way.

1.6 Benefits to California

The project teams completed research on a variety of advanced algorithms and concepts aimed at applying data produced by synchrophasor monitoring technologies to improve the economic and reliable operation of the California (and Western) high-voltage transmission system. Some of the research has already been incorporated into advanced software tools that are being used by the California ISO. Others will require additional research, prototyping, and demonstration before they can be used.

This research was used to support the development of a research and technology development roadmap for the California ISO, which was prepared under a separate contract. Adoption and implementation of this roadmap is recommended.

California will benefit from implementation of the roadmap by having a more reliable electricity system and one that will cost consumers less to operate.

1.7 Task References

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CHAPTER 2: Task 2. Research Roadmap, Industry Coordination, and Research Dissemination

2.1 Introduction

2.1.1 Background and Overview

Under Task 1, the project teams completed research on a variety of advanced algorithms and concepts aimed at applying data produced by synchrophasor monitoring technologies to improve the economic and reliable operation of the California (and Western) high-voltage transmission system. Some of the research has already been incorporated into advanced software tools that are being used by the California ISO. Others will require additional research, prototyping, and demonstration before they can be used.

In this task, the project team's research was used to support the development of a research and technology development roadmap for the California ISO, which was prepared under a separate contract that was led by EPG (Energy Commission contract Number 500-08-048). Under that contract, EPG, among other things, integrated the research into prototypes and led in the development of the roadmap.

2.1.2 Task Objectives

The objective of this task is to support EPG's efforts to update the research roadmaps based on research results and user needs.

2.2 Project Approach

The project team supported EPG's efforts to involve the California ISO staff when decisions were required and to update a detailed California and WECC specific roadmap for advanced phasor applications, indicating linkages with on-going and planned research activities by other entities including BPA, and the United States Department of Energy (DOE), to serve as one vehicle for furthering formal research collaboration with these entities.

2.3 Project Outcomes

EPG developed a multiyear roadmap action plan and delivered it to the Energy Commission and the California ISO (Electric Power Group 2012b). The seven recommendations from the multiyear roadmap action plan included the following:

- Infrastructure: Procurement of Production Grade Hardware for the California ISO
- Data Quality and Management: Management and analysis of data
- Model Validation: Dynamic model validation
- Event Analysis and Training Cases for Operators: Develop a library of significant events
- Tool Development/Enhancements including:

  - Voltage Sensitivity Analysis (VSA)
  - Phase Angle Difference Dynamic Limits (PADDL)
  - Phasor Based Nomogram and Validation
  - Small Signal Analysis (SSA)
  - Enhanced Event Playback
  - Implementation of Automatic Event Analyzer
  - Integration with State Estimator
- RTDMS Look & Feel: Production Grade Visualization—to be incorporated in RTDMS
- Generation Resource Performance: Performance of Renewable Resources and Conventional Generation Resources During Events

2.4 Conclusions and Recommendations

The California ISO is now in a better position to take advantage of the growing deployment of phasor technology and can perform wide-area monitoring and situational awareness of the grid.

The project team recommends adoption and implementation of the updated roadmap

2.5 Benefits to California

California will benefit from implementation of the roadmap by having a more reliable electricity system and one that will cost consumers less to operate.

2.6 Task References

(Electric Power Group 2012b) J. Ballance, J. Dyer, B. Bhargava, and R. Barreno. *Future Synchrophasor Technology Research Roadmap and Action Plan for the California ISO*. May 16, 2012.

Glossary

Acronym	Definition
BPA	Bonneville Power Administration
California ISO	California Independent System Operator
CERTS	Consortium for Electric Reliability Solutions
COI	California-Oregon Intertie
CPUC	California Public Utilities Commission
Energy Commission	California Energy Commission
EPG	Electric Power Group
ERCOT	Electric Reliability Council of Texas
FRO	Frequency response obligation
HTLS	Hankel Total Least Square algorithm
Hz	Hertz
IEEE	Institute of Electric and Electronics Engineers
JSIS	Joint Synchronized Information Subcommittee
LBNL	Lawrence Berkeley National Laboratory
MW	Megawatt
NERC	North America Electric Reliability Corporation
PJM	PJM Interconnection
p-value	The p-value determines the statistical significance of the slope of trend lines
PADDL	Phase Angle Difference Dynamic Limits
RPS	Renewables portfolio standard
RTDMS	Real-Time Dynamics Monitoring System
SSA	Small Signal Analysis
SSAT	Small-Signal Stability Analysis Tool
TSAT	Transient Stability Analysis Tool
WAPA	Western Area Power Administration
WECC	Western Electricity Coordinating Council