MODERNIZING THE TRANSMISSION GRID:

Research to Improve Infrastructure, Operations, and Planning

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Date: February, 2012

A CIEE Report

ACKNOWLEDGMENTS

The CIEE Electric Grid Research team - Merwin Brown, Lloyd Cibulka, Jim Cole, Gilda Garcia, Lorraine Hwang, Larry Miller, and Sascha von Meir - is grateful to the other researchers and their institutions – MCEER, Pacific Earthquake Engineering Research Center, Pacific Northwest National Laboratory, and Virginia Tech – for their expertise and dedication in conducting the research and development accomplished in this effort. The team also wants to thank the many advisors, especially Policy Advisory Committee (PAC) and the Technical Advisory Committees (TAC) which support it. Committee membership was composed primarily of personnel from the 3 major investor owned utilities (IOU) in California – Pacific Gas and Electric (PG&E), San Diego Gas and Electric (SDG&E), and Southern California Edison (SCE)–and the California ISO (CAISO,) and chaired by an Energy Commission commissioner. Additional participants were often included to share knowledge on the meeting's focus including the Assistant Secretary of the Office of Electricity for the U.S. Department of Energy, a representative of the Bonneville Power Association, and the Utility Variable-Generation Integration Group.

This work was funded by the California Energy Commission PIER program under Contract 500-07-037. CIEE is especially grateful for this financial support which has made a significant contribution to advancing the technology needed for the modernization of California's electric grid for meeting California's energy policy goals. Electric Grid Research at CIEE is creating technologies for new tools to modernize the grid and maximize its ability to meet customer needs and California's aggressive energy-policy goals. The vision is a smarter, more responsive, more robust grid — the heart of California's quest to reduce greenhouse gases, improve energy efficiency, and deploy more renewable energy, all while satisfying the new and growing ways customers use electricity. With funding and direction from the California Energy Commission's Public Interest Energy Research (PIER) program, CIEE has worked, and is prepare to continue working, to make these new technologies reality through research. This report was prepared by the CIEE. CIEE makes no warranties as to the suitability of this product for any particular purpose.

PREFACE

The California Energy Commission 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 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 Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Transmission Grid Research is the final report for the Transmission Grid Research project, contract number 500 - 07 - 037, conducted by the California Institute for Energy and Environment. The information from this project contributes to PIER's Energy Systems Integration Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

ABSTRACT

This report presents results of eleven public interest research projects which advance science and technologies related to the electric power transmission grid. These projects fall within three focus areas: infrastructure, real time operations, and planning and environmental. Three projects summarized current status, research gaps, and recommended research for each focus area. In the infrastructure area, two projects evaluated the seismic issues associated with transformer bushings and substation insulators and made recommendations for adoption by IEEE Standard 693, which specifies testing of these components. Three projects were in the area of real time operations. The Wide Area Energy Management Storage Systems project analyzed the combination of both fast and slow storage over two balancing areas. A project on Oscillation Detection developed new algorithms for measuring oscillations in real time. Modal Analysis for Grid Operation (MANGO) on the Western Interconnection developed a decision support tool to suggest mitigation steps for poorly damped wide area oscillations. In the planning and environmental areas, two projects were completed. Adaptive Relay Technology Development and Measurements studied four different applications of the use of synchrophasor data to improve protective systems. Online Tools for Wind and Solar developed tools for use by the California Independent System Operator to forecast system demands for ramping and regulation and possible congestion over the following 24-hour period. Finally, the Technology Transfer Research focused on disseminating research results and encouraging further commercialization of the research.

Keywords: electric transmission, renewables, renewable energy integration, greenhouse gases (GHG), emissions, reliability, renewable penetration, energy efficiency, electric power system, Smart Grid, infrastructure, renewable portfolio standard (RPS), transmission and distribution (T&D), transmission planning, transmission operations, transmission infrastructure, once though cooling, technology transfer

Please use the following citation for this report:

Brown, Merwin; Miller, Larry; Cibulka, Lloyd; Von Meier, Alexandra; Hwang, Lorraine; California Institute for Energy and Environment, 2012. ***Transmission Grid Researc***h, California Energy Commission. Publication number: CEC-XXX-2010-XXX.

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Introduction

California has adopted energy policies that require substantial increases in the generation of electricity from renewable resources. Extensive improvements are needed to California's electric transmission infrastructure to get the electricity generated by new renewable power facilities to consumers.

California must take immediate action to develop and maintain a cost effective, reliable transmission system capable of responding to important policy challenges, including global climate change. While the achievement of state greenhouse gas policy objectives by the electricity sector will depend to a large degree on the interconnection and operational integration of renewable resource generation with the transmission grid, resolving these important issues will ease California's transition to a more carbon constrained generation base. California utilities must also ensure that projects meeting traditional reliability and congestion management objectives are developed in a timely manner. Actions already underway at the state and federal levels to address planning, permitting, financing, and integration barriers to renewable generation interconnection need to be assessed to ensure that state policy objectives are met. California must continue to address important transmission project and transmission corridor planning and permitting barriers to help achieve the state's renewable generation and environmental policy goals.

The California Energy Commission (Energy Commission) formed the Public Interest Energy Research (PIER) Transmission Research Program (TRP) in 2003 in response to SB 1038, legislation that revised PIER's mandate to include projects that have the potential to enhance transmission and distribution capabilities. More recently, SB 1250 (2005-2006, Reg. Sess.), with an emphasis on renewable energy delivery, greenhouse gas (GHG) reductions, and energy efficiency, provides additional research direction.

The goal of this research was to conduct public interest RD&D to advance science and technologies that:

- Enhance transmission integration of renewables;
- Make the transmission system operate with a higher efficiency and reduce the GHG emissions from the transmission system;
- Accelerate new transmission through new planning tools & technologies;
- Expand the capacity of transmission corridors; and
- Enhance the ability to operate the transmission systems under uncertain and complex conditions.

Specific objectives of this research were to advance transmission science and technology by:

- Facilitating new transmission investment;
- Increasing power flows in a given corridor;
- Managing increased power flows and associated reliability risks;
- Reducing response times for wide-area network protection to less than minutes for operators and less than seconds for automation;
- Enhancing the integration of renewable power with the grid; and

- Reducing greenhouse gas impacts and increasing energy efficiency of the electric grid in California.

Report Organization

This project was organized around three primary transmission focus areas, Infrastructure, Real Time Operations, and Planning & Environmental. In each focus area, multiple tasks or subprojects were conducted with selections determined, in part, by synergy, i.e., how well they worked in concert to a common goal. A total of eleven tasks were performed under the technical guidance and administrative management of the California Institute for Energy and Environment (CIEE), UC–Berkeley, Electric Grid Research (EGR) group, formerly called the CIEE Transmission Research Program (TRP). On many of these tasks,). CIEE assisted in the definition of the scopes of work for the research tasks, coordinated the input and participation of stakeholders and advisors, selected research organizations and Principal Investigators to support its research, awarded the work, and oversaw the progress of the work and the development of task deliverables.

Three tasks were performed under the Infrastructure category:

1. Transmission Infrastructure Research
2. Improved Seismic Performance of Transformer Bushings
3. Seismic Post Insulator Analysis

Task 1 was an overview of needed research for Infrastructure, while Tasks 2 and 3 addressed similar problems of seismic reliability of components.

There were four tasks in the Real Time Operations area:

4. Transmission Real Time Operations Research
5. Wide Area Energy Storage Management Systems
6. Oscillation Detection
7. Modal Analysis for Grid Operations

Task 4 provided the overview of needed research. Task 5 addressed a novel approach to the use of storage to mitigate renewable integration issues, while Tasks 6 and 7 were complementary approaches to dealing with wide area low frequency oscillations. Task 7 utilized the oscillation detection approach developed by Task 6.

For the Planning & Environmental focus area, three tasks were performed. Task 8 again provided an analysis of research needed in this area, while Task 9 examined 4 different protection applications of synchrophasors and Task 10 developed forecasting tools for intermittent resources.

8. Transmission Planning and Environmental Research
9. Adaptive Relaying
10. Online Tools for Wind and Solar

Finally, a separate Task 11 provided technology transfer activities for the previous ten tasks.

Future Transmission Infrastructure Research

The goal of this project was to identify new or expanded transmission infrastructure research activities that could:

- Increase the transmission of electricity from renewable resources,

- Increase the efficiency of the transmission system, and
- Reduce the emissions of greenhouse gases (GHG) that are associated with the transmission system.

The project addressed a description of what future transmission infrastructure research activities could be conducted in the context of the following:

- Equipment and devices to provide direct improvements to the transmission infrastructure for the integration of renewable energy resources.
- Smart Grid technologies for their application to improve the transmission infrastructure to increase the transmission of electricity from renewable resources.
- Equipment and devices that increase the efficiency of the transmission infrastructure and reduce emission of GHG that are directly associated with the transmission infrastructure.

Improved Seismic Performance of Transformer Bushings

The goal of this research was to investigate the seismic response of the combined transformer/bushing interaction to enable future analysis and physical seismic qualification of transformer bushings. This information is being used to recommend changes in the industry standards (IEEE 693) that specify the performance requirements of these important transmission system components.

The project consisted of:

- Conducting a workshop of manufacturers, utilities and other researchers to identify outstanding technical issues that remain to be addressed by future research on transformer bushings.
- Developing test protocols, conducting seismic tests and developing advanced mathematical and analytical modes of bushings and transformers,
- Recommending changes to IEEE Standard 693 for the seismic qualification of transformer bushings based on test results.

Improved Seismic Performance of Substation Insulators

The goals of this research were to develop an experimental framework for the seismic testing of post insulators, perform finite element (FE) simulations of insulators, and provide recommendations to the IEEE 693 Working Group for changes to the seismic qualification procedures of different types of high voltage electrical substation disconnect switches. This information will then be used by the Working Group to develop revisions to IEEE 693 that better specify the seismic performance requirements of these important transmission system components.

The project consisted of:

• Identifying candidate manufacturer participants for the study, and arrange for manufacturers to loan or donate specimens.

• Identifying important standards and characteristics affecting insulator strength, e.g., size, material composition, manufacturing process, type of joint, and type of grout. Collect data on breaking strengths, including characteristics identified previously.

• Performing statistical analysis of the data collected, and establish measures of variability.

• Developing acceptance criteria for the case when composite insulators are used in a seismic qualification test, including practical means for measuring the required quantities (e.g., strain, deflection) that establish acceptability.

• Developing appropriate factors of safety for different mechanical loading conditions.

• Developing expressions of strength prediction, and variability.

• Coordinating outcome with manufacturer participants.

• Recommending language for inclusion in future revisions of IEEE Standard 693, and working with the IEEE Standards Committee on inclusion of this language in the Standard.

Future Transmission Real Time Operations Research

The goal of this task was to identify new or expanded transmission operational research activities that improve transmission operations to:

- Increase the transmission of electricity from renewable resources.
- Increase the efficiency of the transmission system.
- Reduce the emissions of GHG that are associated with the transmission system.

The project addressed a description of what future transmission real time operations research activities could be conducted in the context of the following:

- Technologies to provide improvements to the operation of the transmission system to increase the integration of renewables.
- Smart Grid technologies for their integration into operations to increase the transmission of electricity from renewable resources
- Grid operation for possible improvements in the efficiency of the operation of transmission system and reductions in the emission of GHG that are associated with transmission operations.

Wide Area Energy Storage Management System

The goal of this task was to determine the extent that energy storage technologies, shared among multiple balancing areas, can mitigate the impact of the intermittent and fast ramp nature of renewable generation upon the transmission system managed by CAISO.

The project examined scenarios where a slow acting, but large and inexpensive resource (hydropower) could be combined with a fast, but more expensive resource (flywheels) over a wide area to more cost effectively provide regulation. In cooperation with both the California Independent System Operator and the Bonneville Power Administration, simulated control signals were generated and performance characteristics for each regulation resource were calculated for both the existing wind generation penetration levels and projected higher penetration levels of wind energy in these systems. An additional task was to evaluate operational, market, and regulatory opportunities and limitations concerning the use of PG&E Battery Storage Facility. Project results indicated that the combination of multiple technologies and multiple balancing areas provided a significant economic improvement.

Oscillation Detection

The goal of this task was to create a method to mitigate the impact of electric transmission system oscillations that occur at the Western Interconnect, using phasor measurement units (PMUs) to monitor and measure the phenomenon as it occurs in the field.

This project utilized historical data to simulate the small signal dynamics of the Western Interconnection. An algorithm was developed based on "ringdown," the transient response of the grid to minor disturbances. This resulted in high quality real time estimations of the current state of damping of oscillations as measurements could be made in a few seconds with this algorithm rather than the several minutes that were required for the previous method. The project then developed a graphical user interface to interpret and display results. This algorithm was subsequently employed in the Modal Analysis for Grid Operations (MANGO) project.

Modal Analysis for Grid Operations (MANGO)

The goal of this project was to develop a real-time modal analysis application of phasor measurements for enhancing modal control of the Western Interconnection through operator controllable variables (e.g., transformer taps, dispatch-able loads and generations). The developed procedure (known as MANGO) enables greater operational stability and reliability in power grid operations.

The project consisted of identifying a list of potential controllable variables and their properties in the Western Interconnection and performing a sensitivity analysis to evaluate the influences of the controllable variables on the inter-area modes. A MANGO model for the Western Interconnection was integrated with techniques for measuring the real time characteristics of inter-area modes and utilizing the known sensitivities of controllable parameters in order to recommend actionable steps that an operator could take to mitigate poor damping conditions.

Future Transmission Planning and Environmental Research

The goal of this task was to identify new or expanded transmission planning and environmental research activities that improve transmission operations to:

- Increase the transmission of electricity from renewable resources.
- Increase the efficiency of the transmission system.
- Reduce the emissions of GHG that are associated with the transmission system.

The project addressed a description of what future transmission planning and environmental research activities could be conducted in the context of the following:

- Technologies to provide improvements to the upgrading, siting, construction, and installation of transmission equipment to increase the integration of renewables.
- Methodologies and analytical techniques to provide improvements to the upgrading, siting, construction, and installation of transmission equipment to increase the integration of renewables.
- Smart Grid technologies for the inclusion into the planning process for transmission to increase the transmission of electricity from renewable resources.
- Variations of transmission planning methods to improve efficiency and reduce GHG.

Adaptive Relaying Technology Development

The goal of this task was to develop and demonstrate the role of automation in the protection of the electric transmission grids, necessary for implementation of energy from renewable resources, which are anticipated to be widely distributed geographically and highly variable in their energy production characteristics. This task specifically focused upon using PMUs implemented as a wide area network to collect and analyze operating data, and then implement certain management strategies that enhance transmission system stability. These operating strategies included adaptive supervision of redundant sources of supply, intelligent load shedding and damping control of low frequency oscillations.

The research resulted in techniques to automatically adjust the settings of remote protective relays based on real time system measurements, to reduce the likelihood of inappropriate triggering which might increase the effects of a disturbance. It developed and demonstrated techniques, based upon real-time data collected from phasor measurement units, to automate the intelligent implementation of load shedding, which currently is implemented manually when the grid is under severe stress, to prevent a decline in frequency. It also developed strategies that utilize phasor measurement units to prevent electric generator protection systems from premature tripping, which has been responsible for large-scale cascading failures in the recent past. Finally, the research examined the application of phasor measurements for damping of low frequency oscillations in the absence of precise knowledge of the oscillations.

Tools for Online Analysis and Visualization of Operational Impacts of Wind and Solar Generation

The goal of this task was to increase the contribution of electricity generated from renewable resources in California by mitigating the impact that intermittent, "must-take" energy resources have upon the electric transmission system's operational performance (such as voltage and transient stability), other electric generators, and energy production costs.

Three online analysis and visualization tools were developed. The first, a Ramping Tool, makes power system operators aware of current ramping requirements (including load and intermittent generation ramps), compares these against available ramping capability of the online units, projects the situation into the future, and suggests measures to address possible related problems. An alpha version of this tool was demonstrated at CAISO and subsequently improved. A beta version was ultimately delivered to CAISO and is currently in routine use.

A second tool, a Transmission Tool, was developed to the prototype stage. It predicts, for the next several hours, unexpected impacts of intermittent generation on congested paths, voltage levels, and reactive power margins.

A third tool, the Day Ahead Regulation Tool, was developed and demonstrated. This tool calculates the regulating capacity, ramping and ramp duration requirements for each operating hour of a day, separately for the generation used for upward and downward regulation.

Technology Transfer Activities

The goal of this task was to make the knowledge gained, experimental results and lessons learned available to key decision-makers. The project consisted of:

- Preparing a Technology Transfer Plan. The plan explained how the knowledge gained in this project was made available to the public and stakeholders.
- Conducting technology transfer activities such as making presentations, encouraging the publication of results by investigators, and making draft information available on the CIEE website.
- Developing Fact Sheets, presentations, briefings, papers and other products for the CEC and other stakeholders, in support of various information dissemination activities.

CHAPTER 1: Introduction

1.1 Background

California has adopted energy policies that require substantial increases in the generation of electricity from renewable resources. Extensive improvements are needed to California's electric transmission infrastructure to get the electricity generated by new renewable power facilities to consumers.

California must take immediate action to develop and maintain a cost effective, reliable transmission system capable of responding to important policy challenges, including global climate change. While the achievement of state greenhouse gas policy objectives by the electricity sector will depend to a large degree on the interconnection and operational integration of renewable resource generation with the transmission grid, resolving these important issues will ease California's transition to a more carbon constrained generation base. California utilities must also ensure that projects meeting traditional reliability and congestion management objectives are developed in a timely manner. Actions already underway at the state and federal levels to address planning, permitting, financing, and integration barriers to renewable generation interconnection need to be assessed to ensure that state policy objectives are met. California must continue to address important transmission project and transmission corridor planning and permitting barriers to help achieve the state's renewable generation and environmental policy goals. The California Energy Commission (Energy Commission) formed the Public Interest Energy Research (PIER) Transmission Research Program (TRP) in 2003 in response to SB 1038, legislation that revised PIER's mandate to include projects that have the potential to enhance transmission and distribution capabilities. More recently, SB 1250 (2005-2006, Reg. Sess.), with an emphasis on renewable energy delivery, greenhouse gas (GHG) reductions, and energy efficiency, provides additional research direction.

1.2 Goals

The goal of this project is to conduct public interest RD&D to advance science and technologies that:

- Enhance transmission integration of renewables.
- Make the transmission system operate with a higher efficiency and reduce the GHG emissions from the transmission system.
- Accelerate new transmission through new planning tools & technologies.
- Expand the capacity of transmission corridors.
- Enhance ability to operate transmission under uncertain & complex conditions.

1.3 Objectives

The objectives of this research are to advance transmission science and technology to:

- Facilitate new transmission investment.
- Increase power flows in a given corridor.
- Manage increased power flows & associated reliability risks.

- Reduce response times for wide-area network protection to less than minutes for operators and less than seconds for automation.
- Enhance the integration of renewable power with the grid.

1.4 Report Organization

This project was organized around three primary transmission focus areas, Infrastructure, Real Time Operations, and Planning & Environmental. In each focus area, multiple tasks or subprojects were conducted with selections determined, in part, by synergy, i.e. how well they worked in concert to a common goal. A total of eleven tasks were performed under the technical guidance and administrative management of the California Institute for Energy and Environment (CIEE), UC–Berkeley, Electric Grid Research (EGR) group, formerly called the CIEE Transmission Research Program (TRP).). CIEE assisted in the definition of the scopes of work for the research tasks, coordinated the input and participation of stakeholders and advisors, selected research organizations and Principal Investigators to support its research, awarded the work, and oversaw the progress of the work and the development of task deliverables.

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For the Planning & Environmental focus area, three tasks were performed. Task 8 again provided an analysis of research needed in this area, Task 9 examined four different protection applications of synchrophasors, and Task 10 developed forecasting tools for intermittent resources.

8. Transmission Planning and Environmental Research
9. Adaptive Relaying
10. Online Tools for Wind and Solar

Finally, a separate Task 11 provided technology transfer activities for the previous ten tasks.

For ease of understanding, this report is organized as a sequence of reports, one for each task.

CHAPTER 2: Future Transmission Grid Infrastructure Research

This project was performed by the California Institute for Energy and Environment (CIEE) Electric Grid Research (EGR) group (formerly called the Transmission Research Program (TRP) Group), University of California – Berkeley. The Principal Investigator was Merwin Brown.

2.1 Purpose

This project defined the approach, framework and initial plan for Task 2.0, "Future Transmission Grid Infrastructure Research Plan," of the California Energy Commission Contract 500-07-037, which is to identify new or expanded transmission infrastructure research activities that:

1. Increase the transmission of electricity from renewable resources,
2. Increase the efficiency of the transmission system, and
3. Reduce the emissions of greenhouse gases (GHG) that are associated with the transmission system.

The project addressed, but was not limited to, a description of what future transmission infrastructure research activities could be conducted in the context of the following:

- Research into equipment and devices to provide direct improvements to the transmission infrastructure for the integration of renewable energy resources.
- Research Smart Grid technologies for their application to improve the transmission infrastructure to increase the transmission of electricity from renewable resources.
- Research equipment and devices that increase the efficiency of the transmission infrastructure and reduce emission of GHG that are directly associated with the transmission infrastructure.

The report for this project incorporates research activities identified as of the report date for this research area. The complete final report is provided in Appendix A.

2.2 Introduction

California has adopted aggressive energy policy goals to significantly reduce greenhouse gases, improve energy efficiencies and increase penetration of renewable energy generation. The electric transmission and distribution (T&D) system in California is a factor in being able to meet each of these goals. Although fractionally small, there are substantial energy losses in transporting electricity, which could be reduced with efficiency improvements. While T&D per se directly contributes relatively little to increasing GHG on a sustained basis, there are opportunities to reduce GHG emissions in design, construction, operations and maintenance. Perhaps most significantly, however, T&D is absolutely essential to meet the state's renewable portfolio standard (RPS) goals. Substantial increases in the generation of electricity from renewable resources in remote locations will be necessary to achieve the RPS goals, and must rely on adequate, economical and reliable T&D for delivering renewable electricity to consumers. The current T&D system will be challenged in performing its roles in meeting these goals.

Meeting these challenges will require new or expanded capabilities for the grid. New transmission technologies offer the prospect of providing a substantial portion of the new or expanded capabilities to supplement traditional solutions. These technologies can be classified among three broad categories: a) infrastructure, b) real time systems operation, and c) transmission planning, uncertainty analysis and environmental research. This project addresses the first of these.

Many of these new technologies will require additional development before they can be commercially or routinely deployed. The process for identifying the research activities of most value starts with identifying the most critical issues facing the electric industry community, and matching new technologies to address those issues. However there are often gaps between the current and desired status of each technology. These gaps have been identified along with the research, development and demonstration to work toward closing the gaps. The degree of success of this process depends largely on obtaining the best and latest policy, industry and technology knowledge by engaging public and private stakeholders and technology developers.

2.3 Stakeholder Engagement

A significant amount of situational analysis, technology identification, and evaluation of research and development needs, have been, and will be, accomplished by means of meetings that include representatives of key public and private stakeholders, and research and technology developer organizations. CIEE has found that the most effective means to obtain comprehensive and meaningful information about promising new research avenues is to meet at stakeholder and researcher sites so as to be accessible to a wide array of scientific, engineering, and business personnel to solicit their viewpoints and ideas. Where feasible, this is the preferred approach. It can be augmented by telephone conversations and interviews; participation in industry conferences, symposia and workshops; and other means as appropriate and feasible.

In addition, CIEE also holds Technical Advisory Committee meetings, typically "brainstorming" types of meetings to discuss stakeholder and CIEE perspectives on new technology, planning, operations and environmental needs. Follow-up meetings are sometimes held to discuss draft versions of the major findings.

The following are organizations which hold meetings that could contribute to the development of the technical information described in this report. This is not an exclusive list; indeed, many additional, unanticipated meeting and conference opportunities are expected to arise, some on relatively short notice.

- IEEE Power Engineering Society (PES) General Meeting

The IEEE/PES General Meeting is the premier annual conference for the electric power industry; CIEE may be invited to participate as a presenter, panelist or session chair. It is a valuable opportunity to gather intelligence on electric power technologies developments and to network with other utilities, researchers, manufacturers, consultants and engineers.

- IEEE/CIGRE Joint International Symposium on Integration of Renewables

CIGRE is the European research organization that is concerned with power system technology issues. In 2009 IEEE and CIGRE held a Joint Symposium on the topic of "Integration of Wide-Scale Renewable Resources into the Power Delivery System." Participation in CIGRE activities such as this one would provide significant additional information on international technology developments in power systems.

- Electric Power Research Institute (EPRI) Workshops

EPRI has a number of research program areas that directly relate to the infrastructure research activities of PIER TRP. The CIEE EGR has participated in EPRI Working Groups, Task Forces, and Project Advisory Groups, and will continue to do so, as it is advantageous to leverage EPRI's activities with PIER TRP's.

- HVDC Technologies Workshop

HVDC Technologies have been identified as a key technology that can potentially provide near-term benefits to the California transmission system, particularly in terms of renewable integration. CIEE TRP is in the planning stages of hosting a Workshop to assist in developing recommended new avenues of research.

- Underground Transmission Technologies Workshop

Underground Transmission Technologies have been identified as another key technology and are particularly relevant to efforts to facilitate the siting and approval of new transmission lines. CIEE TRP is in the planning stages of hosting a Workshop to assist in developing recommended new avenues of research.

- Energy Storage Technologies Workshops and Conferences

The storage of electric energy has been identified as a key enabling technology. Electric storage is a wide and diverse field of technology development, and there will be numerous conferences, workshops, meetings and tutorials that will be held, so CIEE TRP will look for opportunities to participate in high-value events.

- Meetings with IOUs and the CAISO

In general, CIEE TRP will schedule meetings with these entities on an ad-hoc basis, as needed to meet with key engineers and researchers at stakeholder sites, to develop the information necessary for defining the needed research in transmission infrastructure technologies.

CHAPTER 3: Seismic Bushing Analysis

This project was performed by the Research Foundation and Multidisciplinary Center for Earthquake Engineering Research at State University of New York, Buffalo. The Principal Investigator was Andrei Reinhorn.

3.1 Overview

Earthquakes are a significant threat to the integrity of the California electric transmission system. Prolonged, widespread electric outages can cause significant hardships and economic losses to many Californians, and degrade public safety. Much of the California electric system, including most of the large urban areas, is in highly active seismic regions. Previous research studies have resulted in significant knowledge of electric system seismic behavior, have led to substantial improvements in key areas, and have identified remaining vulnerabilities in the electric system. These studies have also identified several areas of high-value seismic research that can lead to a more reliable, robust and resilient electric system.

One of these high-value research areas is also one of the least understood: the dynamic interactions between the high voltage transformer housings and other components in large substation transformers due to seismic motions. Components of transformers, such as the bushings and surge arresters, are vulnerable to excessive vibrations caused by earthquakes. When such components fail in earthquakes, or their oil contents catch fire in the aftermath of an earthquake, there is a danger that the entire grid might be affected leading to power interruptions and losses to the economy.

The consensus of the electric power community, based on experience from laboratory tests and analysis of damage from actual earthquakes, indicates that the currently-accepted standards and qualification procedures for certifying the seismic performance of transformer bushings are not entirely valid. The seismic qualification procedures, as provided in the current industry standards and used by the electric equipment industry to certify their products, do not properly account for the dynamics of the as-installed bushing/transformer combination in actual practice. This situation has led to unexpected performance, including catastrophic failure, of bushing/transformer systems from seismic events which the equipment was expected to survive.

3.2 Purpose

Current evaluations and qualification procedures, based on IEEE Standard 693-2005 protocols, consider both the bushing and the transformer in isolation from the other, but fail to explicitly recognize the influence of bushing installation on, and interaction with, the transformer in actual in-service conditions. Such interactions include the flexibility of the transformer tank walls and roof, the effect of use of a turret at the interface of the tank roof and the bushing flange, and the effect of bus connections at the top of the bushings. The purpose of this project is to determine the seismic response of the combined transformer-bushing interaction and to enable more accurate analysis and physical seismic qualification of bushing-transformer systems.

3.3 Objectives

The objectives of this project are to develop experimental techniques to determine the true strength capacity of bushings, and, by using advanced mathematical and analytical modeling of bushings and transformers, to derive mechanical models that enable better evaluation of seismic demands and adequacy. Moreover, since the issues address usage practices, the project aimed to develop and explore the ability of simplified qualification procedures to consider the significant interactions among the assemblies and the structure of the entire transformer. A key goal was to provide improved scientific data to support recommended revisions to the IEEE 693 Standard.

3.4 Accomplishments and Recommendations

The research was based on: (i) evaluating the current state of the art on vulnerability and qualification testing of bushings; (ii) analytical modeling and evaluation of motions affecting the bushings mounted on transformers; (iii) testing, using a large seismic simulator (shake table), of nine full-scale bushings installed in a newly designed generic testing rig simulating the transformer tank cover and examining interaction issues and strength capacity measurements; (iv) mathematical modeling of bushings using finite element analysis and developing simplified practical models; (v) evaluating and verifying current and proposed standards; and (vi) developing and recommending integrated procedures for qualification and design.

The research identified weaknesses of the current qualification procedures that ignore the as-installed conditions and also minimize the importance of strength capacity-demand issues. Through adequate quantification, this study highlights key measurement and protocol requirements for qualification of bushings, so that bushings can withstand predicted levels of seismic events when installed in service. Recommendations were developed for consideration by the IEEE Working Group tasked with revising or updating IEEE Standard 693.

Such recommendations for changes to the current qualification procedures for bushings include the following: (1) Develop qualification procedures that compare the strength demands to strength capacities in mechanical terms; (2) Determine the strength capacity of bushings by either testing them to failure, statically or dynamically, or by strength computations by manufacturers; (3) Test the bushings to generate seismic strength demand using seismic simulators (shake tables) according to a desired severity (qualification level); (4) Determine the desired severity of seismic demand including the identified dynamic properties of bushings and mounting conditions, through use of interaction factors or simplified analytical models; (5) Modify the design requirements for transformer tank covers to reduce or eliminate the interaction issues; and (6) Further develop methods of reducing seismic demands on all components of transformers by using protective systems.

The first three recommendations can be implemented using revisions to the existing IEEE Standard 693 with cooperation from bushing manufacturers and the electric utility industry. The last three issues require further basic research and development, building upon the findings from this project to develop additional tools, procedures, models and specifications for the qualification of transformer bushings. The additional research results will provide even greater benefits to manufacturers, utilities and regulatory bodies as they work in partnership to improve the earthquake reliability of the electric power system.

CHAPTER 4: Seismic Insulator Analysis

This project was performed by University of California, Berkeley, Pacific Earthquake Engineering Research (PEER) Center. The Principal Investigator was Khalid Mosalam.

4.1 Introduction

Disconnect switches are a key component of power transmission and distribution systems that either control the flow of electricity between all types of substation equipment or isolate the equipment for maintenance. To mitigate the vulnerability of new disconnect switches and other electrical substation equipment to earthquakes in the United States, the Institute for Electrical and Electronics Engineers (IEEE) is developing guidelines for seismic qualification and testing of disconnect switches on shaking tables by the means of an IEEE 693 spectrum-compatible ground motion at desired high performance levels.

The motivation for determining the dynamic properties and seismic behavior of the disconnect switches and other equipment, with a special focus on the insulator components, is the severe damage that has been experienced in different electrical substation equipment over the past years caused by earthquakes. To avoid any possible energy dissipation, power leakage or substations shut downs due to earthquake damages, the IEEE guidelines for seismic testing and qualification of disconnect switches are in continuous development and update.

If the disconnect switch or its support structure did not qualify according to the IEEE guidelines, modifications of the switch design such as adding braces to increase the lateral stiffness of the support structure should be performed. This process, of repeating the shaking table test for the disconnect switch, after such design modification, is time-consuming, expensive, and sometimes not practical. This is the motivation for developing a new testing approach that can easily accommodate performing such required modifications in the disconnect switch or its support structure. The approach used here is based on the concept of real time hybrid simulations using a small shaking table for testing only a single insulator post with an online computational model for the support structure. The main advantage of the hybrid simulation (HS) approach lies in the flexibility of evaluating any support structure as a numerical simulation model. This implies that there will be no need for conducting expensive large shaking table tests for every time a modification in the support structure is made. Only a simple modification in the computer model will suffice. The hybrid simulation testing is the essence of the experimental testing program conducted in this study.

The study presented in this report aimed at developing an experimental framework, conducting finite element (FE) simulations and providing recommendations to IEEE 693 for seismic qualification of different types of high voltage electrical substation disconnect switches. The experimental framework consisted of static and dynamic testing with complimentary material characterization and resonance-search tests. The FE simulations included linear and nonlinear static and dynamic analyses of a single insulator post. The static tests were conducted for 230 kV and 550 kV porcelain insulator posts. These tests included ramp cyclic-loading tests to obtain the force-displacement relationship of the insulator posts and fragility tests to determine the failure cantilever loads, displacements, and maximum strains. Six cylindrical specimens were prepared from the broken 230 kV insulator parts for material testing. In addition, the vibration properties of the single porcelain insulator post were determined using hammer impact (resonance-search) tests.

The dynamic testing included two types of substructured tests in addition to the HS tests. First, a 550 kV substructured switch without support structure was tested on the earthquake simulator at PEER. Different combinations of uniaxial, triaxial, and rotational signals, referred to as offline signals, were generated from previous full switch tests. The results of the substructured and full switch tests were compared to demonstrate the validity and limitations of the concept of substructuring and to study the effect of the out-of-plane rotations in switches supported on flexible structures in the out-of-plane direction. The second substructured test focused on a 230 kV single insulator post with and without live parts on the uniaxial shaking table at the Structures Laboratory of UC Berkeley. The performance of that shaking table was characterized and the table was upgraded to minimize uplift during dynamic tests. Similar to the 550 kV case, uniaxial offline signals were generated from a previous 230 kV full switch test and used in single insulator tests. Comparison of full and substructured switch tests verified the use of the substructuring concept in HS testing.

Part of the experimental study focused on developing a complete HS system (HSS) for testing single insulators on the small shaking table in real time using a computational model of the support structure. The developed HSS adopted a single-degree-of-freedom model of mass-spring-dashpot system that used the measured force feedback to compute and apply the input to the shaking table in real time. A comparison with previous 230 kV full switch test validated the developed HSS for testing 230 kV single insulator posts.

An application of the developed HSS that included 230 kV hollow core composite insulators was also considered in the experimental program. A complete set of static pull-back and snap-back tests were conducted for the composite insulators before and after the HS dynamic tests. An experimental parametric study was carried out using the HS testing method where different stiffness values for the computational support structure model were considered. The varied stiffness reflected different configurations for the 230 kV disconnect switch support structure. The parametric study was conducted for the 230 kV switches including both porcelain and composite insulators, where the test results were compared for the performance evaluation of both types of insulators mounted on support structures with various structural configurations. In addition, a HS testing framework is proposed for decision making on insulator types and support structure configurations.

The computational study in this research project aimed at developing accurate computational FE models for a single 230 kV porcelain insulator post. These models were used to conduct eigenvalue, linear, and nonlinear static and dynamic FE analyses. The FE model developed for nonlinear analyses was also used to conduct a parametric study focusing on ranking the different sources of uncertainties that affect the structural response of the insulator posts. Different model parameters were varied to study how the force and corresponding displacement at failure were affected. A Tornado diagram analysis was used to illustrate and summarize which model parameters affect the behavior more. The outcome of this Tornado diagram analysis is a representation of the important candidates to focus on in future research to reduce uncertainties in the computational modeling of insulator posts.

The nonlinear FE model was used to conduct dynamic analyses using the same signal applied for the 230 kV substructured tests. The base excitation was applied at different scales to capture the insulator failure under dynamic loading which was not possible to experimentally determine due to shaking table limitations. The computational study was concluded by obtaining the maximum response nonlinear curves for the different scales used in the analysis for a single porcelain insulator post used in 230 kV electrical substation disconnect switches.

4.2 Purpose

The main purpose of the study is to develop a simple HSS for testing a single insulator post that can be used in making design decisions on suitable insulator types and support structure configurations to minimize the probability of switch failure in earthquakes. The study focuses also on conducting linear and nonlinear static analyses to rank the sources of uncertainties in porcelain insulators computational modeling, and dynamic analyses to determine failure load under earthquake loading. The final conclusions drawn from the experimental study and the FE simulations were used to provide recommendations to IEEE 693 for seismic qualification of high voltage electrical substation disconnect switches.

4.3 Objectives

The following are the main objectives of the presented study:

1) Determine the dynamic properties of 230 kV and 550 kV porcelain insulator posts;
2) Determine porcelain material mechanical properties;
3) Construct a database for the porcelain static tests conducted at UC Berkeley;
4) Conduct shaking table tests for 550 kV disconnect switch insulator phase at PEER shaking table;
5) Conduct uniaxial shaking tests for a single 230 kV insulator post at small shaking table at UC–Berkeley;
6) Compare the substructured dynamic tests with full switch tests to demonstrate the validity of the concept of substructuring;
7) Develop, implement, and validate a complete single-degree-of-freedom (SDOF) HS system for testing single porcelain insulator post in real time;
8) Determine the dynamic properties of 230 kV hollow core composite insulator posts;
9) Conduct HS dynamic tests for composite insulator post;
10) Develop accurate computational FE models of a single 230 kV porcelain insulator;
11) Conduct linear and nonlinear static analyses and sensitivity study to rank the sources of uncertainties in the computational modeling of insulators posts; and
12) Conduct linear and nonlinear dynamic analysis to determine when the insulator posts fail under dynamic loading.

4.4 Conclusions

The following are the main conclusions of the presented study:

- The force-displacement and force-strain relationships of both 230 kV porcelain and composite insulator posts are very close to linear until failure. Porcelain insulator post showed a very brittle mode of failure in fragility tests. On the other hand, the mode of failure of the polymer insulator is a separation between the tube and the metallic flange at the insulator base (tube pull out) leading to higher residual displacements. In addition, the load capacities of both insulators are comparable, while the stiffness of the porcelain insulator post is approximately 2.8 times that of the polymer post.
- The grout packing of disconnect switch supports was found insignificant in increasing the support structure stiffness. The structural properties of the 550 kV disconnect switch columns remained unaltered for the cases of with and without the grout packing.

- The rotations of the switch support structure contribute to approximately 25% of the recorded response quantities during earthquake loading. Thus, including the rotation component in the substructured dynamic tests of the 550 kV switches as a part of the input signal resulted in better match with the full switch test. It can be concluded consequently that eliminating the support structure rotations should reduce the straining actions developed in insulators during earthquakes.
- Uniaxial single-component earthquake excitations are sufficient for the full switch seismic qualification instead of triaxial three-component signal since substructured tests showed that the in-plane and out-of-plane behaviors of switch are almost uncoupled. Accordingly, developing a HS system (HSS) for uniaxial testing of a single insulator of a 230 kV switch is a suitable approach. The HS testing approach was successfully utilized, and the HSS has been developed and validated for testing a 230 kV single porcelain insulator post on the upgraded shaking table at the Structures Laboratory of UC Berkeley.
- The structural properties of the polymer insulator determined from static tests remained unchanged after numerous dynamic and HS tests. This indicates that a polymer insulator can maintain its structural properties without any degradation after earthquakes as long as no failure is initiated.
- One major advantage of the developed HSS is that the conclusions drawn for single insulator testing can be reasonably accepted at the full disconnect switch level in the open-open configuration. Another important advantage of the HSS is the major savings in time and cost.
- An extensive experimental parametric study was conducted using HS to evaluate and compare response of different insulator types and different support structural configurations. The polymer insulators have an acceptable seismic behavior that is very comparable to the porcelain insulators in terms of the developed acceleration and displacement time histories. However, the absolute forces and strains were different because of the different mass and material. Also, the peak strain normalized by the failure strain obtained from the static tests was found useful for the response evaluation of both insulators types and design of their support structures. Stiff support structures with fundamental frequency greater than 9 Hz lead to the optimum insulator response when used for 230-kV disconnect switches.
- The use of simplified Finite Element (FE) models that do not consider the complex insulator geometry and metallic cap zones can be sufficient for determining the vibration frequencies and mode shapes, linear analyses, and lateral stiffness estimates. However, accurate models are necessary for determining static and dynamic failure behavior using nonlinear analyses. From the conducted sensitivity study that aimed at ranking the sources of uncertainties using a tornado analysis framework in insulator computational modeling, the porcelain fracture energy density and tensile strength were found to be significantly affecting the failure behavior. The effect of other sources of uncertainty on the nonlinear FE model was also evaluated.
- FE nonlinear dynamic analysis was sought for determining the failure load under earthquake loading which was not possible to determine experimentally. The determined dynamic failure load was 2.2 times the load capacity determined from static tests and analysis due to the distributed mass of the insulator that leads to distributed forces along insulator height.

4.5 Recommendations to IEEE Standard 693

Based on the conclusions drawn from the presented research, the following recommendations can be made:

- A set of material characterization tests should be planned for porcelain insulators as a part of seismic qualification process of substation disconnect switches.
- Several specimens should be used for material testing, and each test should be repeated at least five times to determine the coefficient of variation accurately and to increase the confidence of the determined mean values for the different mechanical properties and to minimize the variation in each property. High confidence about the porcelain material characterization and mechanical properties is necessary to eliminate or minimize a number of sources of uncertainties for accurate computational modeling of the insulator posts.
- A modification factor for the failure load determined from static tests should be considered for seismic qualification of the insulator posts. A modification factor of 2.0 applied to the static failure load is recommended to account for the dynamic behavior effect during earthquake excitation and seismic qualification tests of the ceramic insulators.
- The decision of packing the supports of the substations disconnect switches with grout should be taken independently from any decisions aiming to stiffen the disconnect switches support structures. The grout packing at switch base supports does not increase the lateral stiffness of the switch support structures and is insignificant in altering the support structure characteristics.
- The planar two-dimensional support structures should be avoided in substation disconnect switches whenever possible. The rotations experienced during earthquake excitations, due to the support structure out-of-plane flexibility, contribute to nearly 25% of the induced straining actions in the insulator posts.
- Uniaxial shaking table tests can be used instead of triaxial tests for seismic qualification of disconnect switches. The substructured testing of the 230 kV and the 550 kV switches showed that the in-plane and out-of-plane responses of the switch are almost uncoupled.
- For a better characterization of the substation disconnect switches, it is recommended to adopt experimental frameworks that utilize the HS testing of single insulator posts in making seismic design decisions. Two testing frameworks that reflect two different applications of the HS testing were developed. The first proposed framework aims at using the HSS in choosing the most suitable insulator type, from a structural and seismic point of view, that is less likely to fail during an earthquake when used with a particular support structure configuration. The second proposed framework aims at determining the best support structure characteristics to minimize the induced stresses in a particular type of insulator posts during earthquakes, and hence can maintain a longer lifetime. The procedures developed at the end of the study are universal and can be used for any insulator type.

CHAPTER 5: Future Transmission System Operations Research

This project was performed by the California Institute for Energy and Environment (CIEE) Electric Grid Research (EGR) group (formerly called the Transmission Research Program (TRP) Group), University of California – Berkeley. The Principal Investigator was Merwin Brown.

5.1 Introduction

California has adopted aggressive energy policy goals to significantly reduce greenhouse gases, improve energy efficiencies and increased penetration of renewable energy generation. The electric transmission and distribution (T&D) system in California is a factor in being able to meet each of these goals. Although fractionally small, there are substantial energy losses in transporting electricity, which could be reduced with efficiency improvements. While T&D *per se* contributes relatively little to increasing GHG on a sustained basis, there are opportunities to reduce emissions in design, construction, operations and maintenance. Perhaps most significantly, however, T&D is absolutely essential to meet the state's renewable portfolio standard (RPS) goals. Substantial increases in the generation of electricity from renewable resources in remote locations will be necessary to achieve the RPS goals, and must rely on adequate, economical and reliable T&D for delivering renewable electricity to consumers. The current T&D system will be challenged in performing its roles in meeting these goals.

Meeting these challenges will require new or expanded capabilities for the grid. New transmission technologies offer the prospect of providing a substantial portion of the new or expanded capabilities to supplement traditional solutions. These technologies can be classified among three broad categories: a) infrastructure, b) real time systems operation, and c) transmission planning, uncertainty analysis and environmental research. This *Future Transmission Operations Research* report addresses the second of these.

Many of these new technologies will require additional development before they can be commercially or routinely deployed. The process for identifying the research activities of most value starts with identifying the most critical issues facing the electric industry community, and matching new technologies to address those issues. However there are often gaps between the current and desired status of each technology. These gaps have been identified along with the research, development and demonstration to work toward closing the gaps. The degree of success of this process depends largely on obtaining the best and latest policy, industry and technology knowledge by engaging public and private stakeholders and technology developers.

5.2 Purpose

This report contains the approach, framework and initial plan for Task 3.0, "Transmission Operations Research Report," of the California Energy Commission Contract 500-07-037, whose objective is to identify new or expanded transmission operations research activities that:

1. Increase the transmission of electricity from renewable resources;
2. Increase the efficiency of the transmission system; and
3. Reduce the emissions of greenhouse gases (GHG) that are associated with the transmission system.

The report addresses but is not limited to a description of what future transmission operations research activities could be conducted in the context of the following:

- Technologies to provide improvements to the operation of the transmission system to increase the integration of renewables;
- Smart Grid technologies for their integration into operations to increase the transmission of electricity from renewable resources; and
- Grid operation for possible improvements in the efficiency of the transmission system and reductions in the emission of GHG that are associated with transmission operations.

This report also lists research activities identified to date for this research area.

5.3 Stakeholder Engagement

A significant amount of situational analysis, technology identification, and evaluation of research and development needs, have been, and will be, accomplished by means of meetings that include representatives of key public and private stakeholders, and research and technology developer organizations. CIEE has found that the most effective means to obtain comprehensive and meaningful information about promising new research avenues is to meet at stakeholder and researcher sites so as to be accessible to a wide array of scientific, engineering, and business personnel to solicit their viewpoints and ideas. Where feasible, this is the preferred approach. It can be augmented by telephone conversations and interviews; participation in industry conferences, symposia and workshops; and other means as appropriate and feasible.

In addition, CIEE also holds Technical Advisory Committee meetings, typically "brainstorming-types" of meeting to discuss stakeholder and CIEE perspective on new planning and environment needs. Follow-up meetings are sometimes warranted to discuss draft versions of the major findings.

The following are organizations which hold meetings that could contribute to the development of the technical information described in this report. This is not an exclusive list; indeed, many additional, unanticipated meeting and conference opportunities are expected to arise, some on relatively short notice.

- IOUs and the CAISO: Scheduled on an ad-hoc basis, as needed to meet with key engineers and researchers at stakeholder sites.
- System Stability R&D Task Force: BPA schedules these meetings with representatives from CAISO, SCE, PG&E, CIEE, DOE, and other leading researchers. Emphasis is on issues which can have a significant impact on transient, dynamic and voltage stability.
- North American SynchroPhasor Initiative (NASPI): CIEE is an active participant in NASPI Working Group Meetings and has played a significant, ongoing role in projects funded by PIER. These also represent opportunities to meet with key stakeholders, technology developers, and leading researchers that routinely attend these meetings.
- Electric Power Research Institute (EPRI): EPRI conducts workshops in a number of research program areas that directly relate to the research that the TRP is doing.

5.4 Problem Statement

Renewable resources within California are extensive and varied, and California has established aggressive RPS goals to increase the fraction of electricity made from renewable energy resources and to decrease greenhouse gas emissions under AB 32. By 2010, 20% of California's electricity is to come from renewables, and by 2020, perhaps 33%. Most of the new sources are expected to connect to the transmission system in remote locations and to exhibit properties quite different from traditional generation and loads, posing special challenges for providing timely adequate grid delivery capacity, maintaining reliability, and avoiding economic inefficiencies. We refer collectively to these challenges as the problem of Renewables Integration (RI), and it is often cited as the major barrier to achieving the renewable goals of the state. New technologies will be required to provide the functional capabilities required for success.

These new technologies can be applied in the context of providing three new or expanded broad capabilities: (1) Provide physical access for each new power plant, (2) Reliably accommodate any unique renewable generator behaviors, and (3) Increase the grid's power carrying capacity to handle the additional electric power flows. As solutions are developed through research to address the issues raised in meeting these three main state policy goals of renewable generation deployment, GHG reduction and energy efficiency improvements, the transmission community must continue to assure that transmission meets the critical requirements for adequacy, reliability, affordability, security, safety, and environmental protection.

5.5 Initial Transmission Operations Research Candidates

Examples of the types of technologies and technology platforms that would qualify for examination include (but are not limited to) the following:

- **Tools for Online Analysis, Visualization, Forecasting and Real-Time Power System Control of Operational Impacts of Wind and Solar Generation**

  The high penetration of wind, solar and other renewable energy resources present significant operating challenges for generation-load balancing, frequency regulation, and transmission grid stability. This includes all types of stability: transient, small signal, and voltage. New real-time, hour-ahead and day-ahead situational analysis, visualization, forecasting and real-time power system control tools (e.g., real time nomograms) can provide transmission grid operators with actionable information that can maximize the economic utilization of renewable energy resources, avoid congestion, avoid grid operating conditions that are likely to result in voltage and dynamic instabilities, and assist operators in mitigating operating problems if and when they are experienced.

- **Dynamic Response of WECC Transmission System with High Penetration of Wind and Solar Generation**

  The high penetration (~33%) of alternative-energy generation could significantly change the dynamic response of the WECC system to disturbances, especially low frequency grid oscillations. Research is needed to improve understanding of the dynamic response under high penetration of both centralized and distributed solar and wind resources.

- **Real-Time Synchrophasor Detection, Diagnosis and Control of Dynamic and Voltage Instabilities Resulting from Significant Wind and Solar Generation**

  Grid operators in the WECC are expanding the use of synchrophasor-based monitoring, data analysis and diagnostic systems for detecting, diagnosing the causes and responding to grid disturbances that impact system reliability.

  There is a critical need for development of new real time synchrophasor based situational analysis, diagnostic, and visualization tools that can translate synchrophasor data into real time actionable information that can be used by grid operators. Further development and expanded operator use will have increased importance for managing the integration of significant intermittent renewable energy.

- **Smart Grid Operation and Control of Distribution Systems with Extensive Penetration of Distributed Solar and Wind Systems**

  Current industry standards of net metering require that distributed generation systems disconnect from the distribution system if frequency, voltage or other operating characteristics are not within normal operating ranges.

  For high penetration of distributed renewable energy systems, utilities and grid operators are very interested in the development and deployment of distributed interconnection equipment that is capable of automated restoration of service and reliable situational awareness information while addressing distribution protection requirements.

- **WECC Load Modeling Including Distributed Solar Systems and Real-Time Control of Voltage Instabilities**

  Based on PIER, DOE and member funding support of Phase 1 efforts, WECC transmission and distribution system planners and operators are now using significantly improved end use load models for establishing the transfer limits of major transmission interties and managing distribution and transmission voltage instabilities caused by typical residential air conditioners. Potential options for mitigating these voltage instabilities that are being evaluated by utilities included improved air conditioner retrofit controls and transmission system controls.

Current preliminary research is focused on understanding the impact of distributed solar systems on dynamic and voltage stability. Future research will explore potential options for improving the voltage and dynamic stability performance of these systems and how they might be designed to address voltage and dynamic instability problems.

- **Smart Grid Restoration of Distributed Solar and Other Renewables**

  Current industry standards of net-metering and other small-scale distributed renewable interconnection equipment require that these systems disconnect from the distribution system if frequency, voltage or other operating characteristics are not within normal operating ranges. Utilities and grid operators are very interested in the development and deployment of distributed interconnection equipment that is capable of automated restoration of service and reliable information while addressing distribution protection requirements.

5.6 Benefits to California

This work benefits California by addressing how new technologies can be developed for helping the electric transmission and distribution system (T&D) perform its role in meeting the three main state policy goals of renewable generation deployment, GHG reduction and energy efficiency improvements, while continuing to assure that transmission meets the critical requirements for adequacy, reliability, affordability, security, safety, and environmental protection. California has adopted aggressive energy policy goals to significantly reduce greenhouse gases, improve energy efficiencies and increase penetration of renewable energy generation. The electric T&D system in California is a factor in being able to meet each of these goals, but currently faces many challenges in performing its roles in achieving them. Meeting these challenges will require new or expanded capabilities for the grid, and new transmission technologies offer the prospect of providing a substantial portion of the new or expanded capabilities to supplement traditional solutions. This report identifies the drivers and rationales that create the needs for new technologies, and describes the most promising new technologies and the research activities needed to help bring them to productive deployment and commercial reality in a manner that meets California needs in a timely fashion.

CHAPTER 6: Wide Area Energy Storage and Management System

This project was performed by the Pacific Northwest National Laboratory (PNNL). The Principal Investigator was Yuri Makarov.

6.1 Introduction

This research was conducted by the Pacific Northwest National Laboratory (PNNL), which is operated for the U.S. Department of Energy (DOE) by Battelle under Contract DE-AC05-76RL01830, for Bonneville Power Administration (BPA), the California Energy Commission, and the California Institute for Energy and Environment (CIEE).

The higher penetration of intermittent generation resources (including wind and solar generation) in the Bonneville Power Administration (BPA) and California Independent System Operator (CAISO) balancing authorities (BAs) raises the issue of requiring expensive additional fast grid balancing services in response to additional intermittency and fast up and down power ramps in the electric supply system.

6.2 Goals

The overall goal of the Wide Area Energy Storage and Management System (WAEMS) project is to develop the principles, algorithms, market integration rules, functional design, and technical specifications for an energy storage system to cope with uncertainties and unexpected rapid changes in renewable generation power output. The resulting WAEMS system will store excess energy, control dispatchable load and distributed generation, and use inter-area exchange of the excess energy between the CAISO and BPA BAs. A further goal is to provide a cost-benefit analysis and develop a business model for an investment-based practical deployment of such a system.

There are two tasks in Phase II of the WAEMS project: the flywheel field tests and the battery evaluation.

The goal of the "Flywheel Field Tests" task is to minimize the balancing effort by developing a centralized control system that operates energy storage devices in conjunction with conventional generators to provide fast balancing services that can be shared among balancing authorities. The idea is based on coordination of traditional services (provided by conventional generation) and energy storage. In Phase II of the WAEMS project, a prototype WAEMS configuration consisting of a hydroelectric plant and a flywheel energy storage system was field tested using actual area-control-error (ACE) and regulation signals provided by BPA and CAISO. The results were used to evaluate the performance and economics of the flywheel-hydro regulation service.

The goal of the "Battery Storage Evaluation" task is to investigate technical characteristics and economics of the sodium-sulfur (NaS) battery energy storage used for regulation and real-time dispatch (also called load following) services in the electricity market operated by the California Independent System Operator (CAISO).

6.3 Flywheel Field Tests Outcomes

The performance evaluation shows excellent performance of the WAEMS control algorithm, which separates the faster regulation effort provided by the energy storage from the slower one provided by a conventional regulating unit. The WAEMS combined service is not strictly constrained by energy storage limits because the hydro plant supports the desired flywheel's energy level. In addition, the WAEMS combined service has the same fast-response characteristic (within 6 seconds) as that provided by the flywheel energy storage alone. Furthermore, the WAEMS control algorithm reduces wear and tear on the hydro unit and allows the hydro unit to operate closer to its preferred operating point.

The breakeven price for flywheel energy storage to provide bi-directional service (1 MW regulation-up and 1 MW regulation-down) is $20.37/MW. Because the average bi-directional regulation price of the CAISO balancing authority is $11.95/MW (Jan.-July, 2010) and that of the BPA balancing authority is $9.38/MW (2010), regulation service provided by a stand-alone flywheel energy storage will not be economical unless the regulation price will be increased or the fast regulation service will be paid at a higher rate.

Assuming that the minimum regulation price of regulation provided a hydro power plant is $4/MW, the breakeven price of the combined flywheel-hydro regulation service would be $12.19/MW; therefore, the flywheel-hydro regulation service breakeven price is found to be slightly higher than the average CAISO ($11.95/MW) and BPA ($9.38/MW) regulation prices. Because regulation prices are expected to increase when more renewable generation resources are integrated into the power grids, the flywheel-hydro regulation service is expected to become economical in the CAISO and BPA balancing authorities soon.

6.4 Battery Storage Evaluation Outcomes

- If an NaS battery is operated for 20 years at its rated output of 4 MW, operating it at a lower depth of discharge (DOD) results in less cost with the existing lifecycle-DOD curve. If manufacturers can improve the NaS battery lifecycles at high DODs (>50%), the breakeven prices will drop significantly for high DOD cases.

- Under the pay-by-capacity scheme for regulation services, the NaS battery has a longer life and a lower cost when it runs at lower DOD. With current technology, the battery-rated power output is 4 MW. The results indicate that if the 4 MW battery provides one-directional regulation service, the high-end cost will be 26 $/MW, and the low-end cost will be 16 $/MW; therefore, the NaS battery was not profitable in either the CAISO or the BPA market when providing 1-directional regulation services.

- If the NaS battery power-to-energy ratio can be increased, the breakeven price for regulation or real-time dispatch services will drop significantly because the battery is capable of handling a broader range of signals. For example, the current power-to-energy ratio for a 4 MW, 28 MWh NaS battery is 4:28, or 1:7. If the rated power of the NaS battery can be increased from 4 MW to 8, 12, 16, or 20 MW, while its energy storage remains at 28 MWh, the power-to-energy ratio can be increased to 2:7, 3:7, 4:7, or 5:7, respectively. However, after the rated power is raised to 12 MW, the breakeven price drop is not significant, but the life of the NaS battery is shortened dramatically. Therefore, based on the existing lifecycle-DOD curve, it may be beneficial for the manufacturer to increase the rated-power output of the NaS battery up to 8 or 12 MW, which will result in a breakeven price drop of 1/2 to 1/3 compared with that of the 4 MW case.

6.5 Conclusions

From the results, we conclude that the opportunities for flywheels or other energy storage devices (ESDs) lie in the following areas:

- To avoid performance problems associated with their finite energy storage capacity, provide regulation services for system operators which would agree to manage the flywheels' energy level, or participate in alternative schemes helping to co-optimize fast acting storage devices and conventional generators to provide high-quality combined regulation services.

- Operate energy storage devices in conjunction with conventional generators to improve their response time, reduce their wear and tear, and provide compatible services that do not require modifications of the existing automatic generation control and market systems.

- To increase the capacity payment, explore opportunities for sharing regulation services among two or more balancing authorities.

- Investigate methods and tariff changes so that the fast responsive and flexible resources can be compensated for additional services such as frequency response, fast ramping, voltage and reactive power support, or damping of transmission line oscillations to prevent grid angular instability.

Based on the Phase II results, it is recommended that the next phase of the WAEMS project focus on research leading to (1) practical deployment of the WAEMS that provides balancing services (including both load-following and regulation services) to the CAISO and BPA balancing authorities, and (2) commercialization of the control algorithms developed in Phases I and II of the WAEMS project.

A near-term goal should be commercialization of a shared storage system between CAISO and BPA. A longer term goal should be development of methodologies for operating both fast and slow resources and sharing these resources over multiple control areas to facilitate the renewable integration and operate the power grids reliably and economically.

6.6 Next Steps

- Enhance the WAEMS controller so that it is more robust and can provide load following services;

- Field test more energy storage technology options, such as Li-ion battery energy storage; and

- Assist BPA and CAISO to deploy a WAEMS system between BPA (offer a hydropower plant) and CAISO (offer an energy storage device).

Another potential area of future research is the development of an energy storage evaluation toolbox that incorporates the models, algorithms, methodologies, and standardized testing signals developed or obtained in previous WAEMS tasks. This toolbox would help users find optimal configurations and assess the performance and economics of different energy storage solutions, enabling them to answer the following questions:

- Are the selected ESDs capable of providing the required services as expected?

- How much fast-regulating ESD capacity is needed for a given regulation/load-following signal?

- What is the cost of the service?

This research will provide information for power grid operators to make decisions on building an energy storage portfolio that best meets the wind-integration requirements and is most economical to implement.

CHAPTER 7: Oscillation Detection and Analysis

This project was performed by the Pacific Northwest National Laboratory (PNNL). The Principal Investigator was Yuri Makarov.

7.1 Introduction

Small signal stability problems can cause system oscillations, which are one of the major threats to grid stability and reliability in California and the western United States. An unstable oscillatory mode can cause large-amplitude oscillations and may result in system breakup and large-scale blackouts. There have been several incidents of system-wide oscillations worldwide. Of these, the most notable is the August 10, 1996 western system breakup produced by undamped system-wide oscillations.

In real time operation, it is important to get accurate and timely information about system oscillations to enable operator actions and prevent failures if oscillations occur. Additionally, power system planning establishes the dynamic stability margin to avoid system breakups caused by oscillations, which puts limits on the power transfer capabilities. Accurate and timely information about the oscillations can help optimize these transfer margin settings so that a grid operates at its full capacity, while staying within the stability boundary.

In power systems, a small-signal oscillation is the result of poor electromechanical damping. Considerable understanding and literature have been developed on the small-signal stability problem over the past 50+ years. These studies mainly utilized component-based models and eigenvalue analysis of their characteristic matrix. However, its practical feasibility is greatly limited because power system models are often inadequate in describing real-time operating conditions.

Therefore, significant efforts have been devoted in the past 20 years to monitoring system oscillatory behaviors from real-time measurements. The deployment of phasor measurement units (PMU) provides high-precision time-synchronized data needed for estimating oscillation modes. Measurement-based modal analysis, also known as ModeMeter, uses real-time phasor measurements to estimate system oscillation modes and their damping. Low damping indicates potential system stability issues, which should lead to the issuance of oscillation alarms when the power system is lightly damped. A good oscillation alarm tool can provide time for operators to take remedial reaction and reduce the probability of a system breakup due to a light damping condition. To facilitate ModeMeter development and evaluation, the Western Electricity Coordinating Council (WECC) has conducted a number of system tests in the past decade. The tests include large signal tests through the insertion of the 1,400 MW Chief Joseph braking resistor, mid-level signal tests through ±125 MW modulation of Pacific DC Intertie (PDCI) real power set values, and noise probing tests through ±10-20 MW modulation of the PDCI power. Recently, the system tests have advanced towards a weekly basis for future continuous tests and real-time oscillation monitoring. Real-time oscillation monitoring requires ModeMeter algorithms to have the capability to work with various kinds of measurements: oscillation data (ringdown signals), noise probing data, and ambient data.

Several measurement-based modal analysis algorithms have been developed. They include Prony analysis, Regularized Robust Recursive Least Square (R3LS) algorithm, the Yule-Walker algorithm, the Yule-Walker Spectrum algorithm, and the N4SID algorithm. Each is effective for certain situations, but not as effective for some other situations. For example, the traditional Prony analysis works well for oscillation data, but not for ambient data. However, Yule-Walker is designed for ambient data only. Even in an algorithm that works for both oscillation data and ambient data, such as R3LS, latency results from the time window used in the algorithm is an issue in timely estimation of oscillation modes. For ambient data, the time window needs to be longer to accumulate information for a reasonably accurate estimation. For oscillation data, the time window can be significantly shorter, so the latency in estimation can be much less. In addition, adding a known input signal, such as noise probing signals, can increase the knowledge of system oscillatory properties and thus improve the quality of mode estimation. System situations change over time. Oscillations can occur at any time, and probing signals can be added for a certain time period and then removed. All these observations point to the need to add intelligence to ModeMeter applications. That is, a ModeMeter tool needs to adaptively select different algorithms and adjust parameters for various situations.

7.2 Project Goals

This project aims to develop systematic approaches for algorithm selection and parameter adjustment. The very first step is to detect occurrence of oscillations, so the algorithm and parameters can be adjusted accordingly. The proposed oscillation detection approach is based on the extended signal-to-noise ratio of measurements. Intuitively, ambient data would have a low signal-to-noise ratio, while oscillation data would have a high signal-to-noise ratio. Some additional metrics are also introduced to further reduce missing detection and false alarms. Upon detection of oscillation data, the ModeMeter algorithm can be changed to accommodate the higher density of information in the signal. The ModeMeter may use Prony analysis, or the time window of an algorithm can be greatly shortened, so the latency is significantly reduced, and the responsiveness of mode estimation is improved.

7.3 Results and Conclusions

This report describes such an oscillation detection algorithm. Combined with a recursive Prony algorithm, a tool has been implemented for oscillation data detection and analysis. A 17-machine model provides simulation data used to show the statistical performance of the algorithm. Field measured data from Wide Area Measurement System (WAMS) of the Western Electricity Coordinating Council (WECC) system is used to validate the proposed algorithm. The results demonstrate the effectiveness of the proposed algorithm. Based on the detection, Prony analysis can be applied to estimate oscillation mode timely and accurately. The method has been implemented and integrated into a graphic user interface to monitor oscillation modes in real time.

CHAPTER 8: Modal Analysis for Grid Operations (MANGO) on the Western Interconnection

This project was performed by the Pacific Northwest National Laboratory (PNNL). The Principal Investigator was Yuri Makarov.

8.1 Introduction

System oscillation problems are one of the major threats to grid stability and reliability in California and the Western Interconnection. Under-damped or un-damped oscillations can cause power grid breakups and even large-scale power outages. There have been several incidents of system-wide oscillations in the United States and abroad. Of those incidents, the most notable is the August 10, 1996 western system breakup, a result of undamped system-wide oscillations. During the outage in 1996, about 7.5 million customers (24 million people) lost their power supply for the range from several minutes to 6 hours. One of the major areas affected was California. Given the wide-area nature of oscillation problems, California sits at one end of the oscillation mass and would be an area experiencing the consequences. California is also an area that can implement control actions to mitigate oscillation problems. The challenge is how to determine when to take control actions, what control actions to take, and what effects to expect after the actions are taken. This report aims to develop a systematic method, termed "Modal Analysis for Grid Operation (MANGO)," to address this challenge.

Recent deployment of smart grid technologies poses an even larger challenge in mitigating oscillation problems. For example, renewable energy sources reduce system inertia and add more uncertainty; energy efficient loads introduce new dynamics, as well as uncertainty. These all change system oscillation behaviors and make it more difficult to manage oscillations through traditional modulation control tuned with a system model. MANGO control does not rely on a known system model, but uses real-time phasor measurements and other synchronized measurements. MANGO can potentially utilize responsive loads to adjust system power flow patterns so as to improve system damping. MANGO can also utilize some other smart grid technologies, such as storage, for power flow pattern adjustment. Therefore, MANGO can not only improve grid reliability and efficiency, but also help to facilitate the development of smart grid technologies such as renewable energy, demand response, and energy storage. This has both economic and environmental implications.

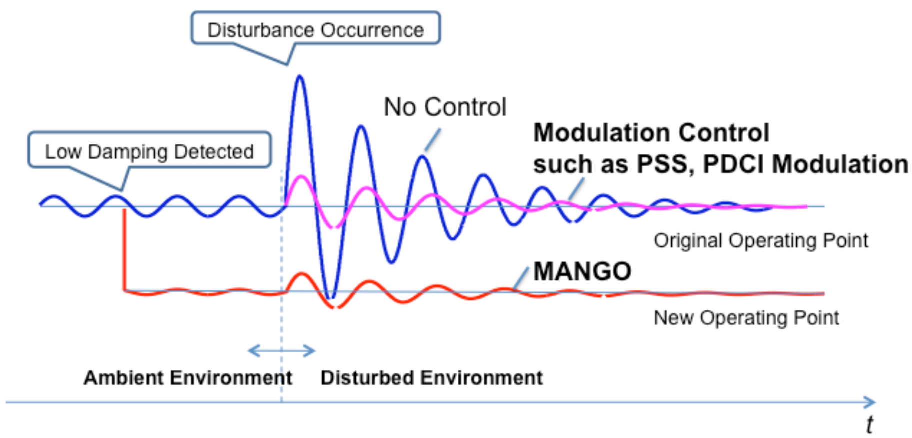
For more than 20 years, significant efforts have been devoted to monitoring system oscillatory behavior from measurements. The deployment of phasor measurement units (PMU) provides high-precision, time-synchronized data needed for detecting oscillation modes. The ongoing Western Interconnection Synchrophasor Project (WISP) will install additional 250+ PMUs in the Western Electricity Coordinating Council (WECC) system in the next three years. Measurement-based modal analysis, also known as ModeMeter, uses real-time phasor measurements to identify system oscillation modes and their damping. Low damping indicates potential system stability issues. Modal analysis using phasor measurements has been demonstrated to have the capability of estimating system modes in real time from oscillation signals, probing data, and ambient data.

With more and more phasor measurements available and ModeMeter techniques maturing, there is yet a need for methods to bring modal analysis from monitoring to actions. The methods should be able to associate low damping with grid operating conditions, so operators or automated operation schemes can respond when low damping is observed. The work presented in this report aims to develop such a method and establish a MANGO procedure to provide recommended actions (such as generation re-dispatch), and aid grid operation decision making for mitigating inter-area oscillations.

8.2 MANGO Process

The fundamental part of the work explores the relationship between low damping and grid operating conditions and then uses the relationship to develop recommended actions for damping improvement, therefore reducing the chance of system breakup and power outages. Different from power system stabilizers and other modulation control mechanisms, MANGO improves damping through operating point adjustments. Traditionally, the modulation-based methods do not change the system's operating point, but improve damping through automatic feedback control. Figure 1 illustrates the difference of these two types of damping improvement methods. MANGO, represented in red, and modulation control, represented in magenta, are complementary towards the same goal.

Figure 1: MANGO versus Modulation Control

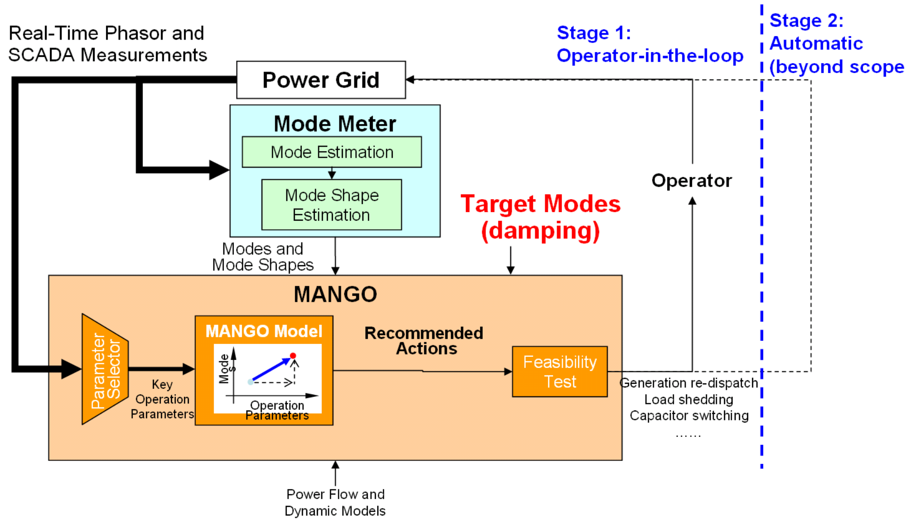


Differences between traditional modulation control and MANGO control.
Source: Pacific Northwest National Laboratory

MANGO is a measurement-based procedure, as shown in Figure 2 2. As the first stage of development, the MANGO procedure is targeted to have operators in the loop. Practical implementation is envisioned to be achieved by integrating MANGO recommendations into existing operating procedures. The MANGO model can be updated according to the current measurement and mode estimation results. Operators are included in the loop to bring in expert knowledge. In the future, after the confidence and accuracy of the MANGO model is established, it is expected that the automatic closed-loop control will be introduced to expedite the implementation and avoid human errors. The automatic process can be integrated into a remedial action scheme (RAS) system or a special protection system (SPS).

Extensive sensitivity studies based on model simulation show that damping can be controlled by adjusting operating parameters through means such as generation re-dispatch, or load reduction (as a last resort). Damping ratios decrease consistently with the increase of overall system stress levels. At the same stress level (i.e., same total system load), inter-area oscillation modes can be controlled by adjusting power flow patterns to reduce flow on the interconnecting tie line(s). The effectiveness of the MANGO control is dependent on specific locations where the adjustment is applied.

Figure 2: MANGO Framework



General framework for the MANGO procedure and how it ties into ModeMeter technology and current operations.
Source: Pacific Northwest National Laboratory

The MANGO procedure consists of three major steps:

(1) Recognition – operator recognizes the need for operating point adjustment through online ModeMeter monitoring;

(2) Implementation – operator implements the adjustment per recommendations by the MANGO procedure; and

(3) Evaluation – operator evaluates the effectiveness of the adjustment using ModeMeter and repeats the procedure if necessary.

The recognition and evaluation steps in the MANGO procedure rely on a good ModeMeter to estimate the current modes, while the implementation step builds on modal sensitivity, i.e., the relationship of oscillation modes and operating parameters. The relationship is generally nonlinear, and it is impractical to derive a closed-form analytical solution for this relationship. Theoretically, the sensitivity can be calculated from the model of a power system, but the model is usually not able to reflect real-time operating conditions. Therefore, the work reported here has been primarily centered on estimating modal sensitivity from real-time measurement. A new concept of relative sensitivity is proposed. The relative sensitivity is formulated using least squares principles in the form that can be estimated directly from measurements. Testing has been carried out with a medium-size 34-machine system model (analogous to the WECC system) and with the full-size WECC system. The results indicate strong correlation of power flow patterns to the damping, giving clear guidance on how to adjust generator outputs to improve damping.

System topology changes the inherent dynamics in a power system, and thus changes the modal properties. Topology analysis is conducted to characterize the impact of topology change on oscillation modes. Within the WECC system, topology changes that just modify the impedance along an energy path have significantly more impact on mode damping than on mode frequency. However, there are some topology changes that completely eliminate an important path, and sometimes an entire mode. Even when the mode is not eliminated, it may reappear at a quite different frequency, though with a similar mode shape. Including topology information in the MANGO procedure is very important to its successful application. Topology impacts the MANGO procedure in two aspects: as input, it may change the sensitivity relationship between operation parameters and mode damping; as an output, topology adjustment can be another option for damping control, as shown in the results with the full WECC system. This merits further study.

8.3 Results and Conclusions

In summary, a MANGO procedure has been established with practical considerations. The key step in the procedure is the modal sensitivity. A method for estimating relative modal sensitivity has been formulated and studied with promising results from a medium-size system and the full WECC system. Impact of topology change on damping has been studied. The simulation studies were conducted with commercialized software, and the resulting experience and data pave the road for large-scale MANGO application. Due to limited phasor measurement availability, all the tests are performed with simulated data. To fully demonstrate the benefit of the developed MANGO method, further work will continue the tests with actual phasor measurements once the WISP completes the installation of additional 250+ PMUs. Other future work includes evaluation of the impact of mode meter accuracy on modal sensitivity estimation, and further enhancement of the understanding of the topology impact on oscillation mitigation measures. As MANGO aims at an operator-oriented measure, it is important to identify implementation strategies with operating procedures. Only when the MANGO measure is included in operating procedures can the benefit be actually realized in improving power grid reliability.

CHAPTER 9: Future Transmission Planning and Environmental Research

This project was performed by the California Institute for Energy and Environment (CIEE) Electric Grid Research (EGR) group (formerly called the Transmission Research Program (TRP) Group), University of California – Berkeley. The Principal Investigator was Merwin Brown.

9.1 Introduction

California has adopted aggressive energy policy goals to significantly reduce greenhouse gases, improve energy efficiencies, and increase penetration of renewable energy generation. The electric transmission and distribution (T&D) system in California is a factor in being able to meet each of these goals. Although fractionally small, there are substantial energy losses in transporting electricity, which could be reduced with efficiency improvements. While T&D *per se* contributes relatively little to increasing GHG on a sustained basis, there are opportunities to reduce emissions in design, construction, operations and maintenance. Perhaps most significantly, however, T&D is absolutely essential to meet the state's renewable portfolio standard (RPS) goals. Substantial increases in the generation of electricity from renewable resources in remote locations will be necessary to achieve the RPS goals, and must rely on adequate, economical and reliable T&D for delivering renewable electricity to consumers. The current T&D system will be challenged in performing its roles in meeting these goals.

Meeting these challenges will require new or expanded capabilities for the grid. New transmission technologies offer the prospect of providing a substantial portion of the new or expanded capabilities to supplement traditional solutions. These technologies can be classified among three broad categories: a) infrastructure, b) real time systems operation, and c) transmission planning, uncertainty analysis and environmental research. This Future Transmission Planning and Environmental Research report addresses the third of these.

Many of these new technologies will require additional development before they can be commercially or routinely deployed. The process for identifying the research activities of most value starts with identifying the most critical issues facing the electric industry community, and matching new technologies to address those issues. However there are often gaps between the current and desired status of each technology. These gaps have been identified along with the research, development and demonstration to work toward closing the gaps. The degree of success of this process depends largely on obtaining the best and latest policy, industry and technology knowledge by engaging public and private stakeholders and technology developers.

9.2 Purpose

This report contains the approach, framework and initial plan for Task 4.0, "Transmission Planning and Environmental Research Report," of the California Energy Commission Contract 500-07-037, which is to identify new or expanded transmission operations research activities that:

1. Increase the transmission of electricity from renewable resources,
2. Increase the efficiency of the transmission system, and
3. Reduce the emissions of greenhouse gases (GHG) that are associated with the transmission system.

The report addresses but is not limited to a description of what future transmission planning and environmental research activities could be conducted in the context of the following:

- Technologies that provide improvements to the upgrading, siting, construction, and installation of transmission equipment to increase the integration of renewables.
- Methodologies and analytical techniques to provide improvements to the upgrading, siting, construction, and installation of transmission equipment to increase the integration of renewables.
- SmartGrid technologies for the inclusion into the planning process for transmission to increase the transmission of electricity from renewable resources.
- Variations of transmission planning methods to improve efficiency and reduce GHG.

This report also lists research activities identified to date for this research area.

9.3 Stakeholder Engagement

A significant amount of situational analysis, technology identification, and evaluation of research and development needs have been, and will continue to be, accomplished by means of meetings that include representatives of key public and private stakeholders and research and technology developer organizations. CIEE has found that the most effective means to obtain comprehensive and meaningful information about promising new research avenues is to meet at stakeholder and researcher sites so as to be accessible to a wide array of scientific, engineering, and business personnel to solicit their viewpoints and ideas. Where feasible, this is the preferred approach. It will be augmented by telephone conversations and interviews; participation in industry conferences, symposia and workshops; and other means as appropriate and feasible.

In addition, CIEE also holds Technical Advisory Committee meetings, typically "brainstorming" types of meetings, to discuss stakeholder and CIEE perspective on new planning and environment needs. Follow-up meetings are sometimes warranted to discuss draft versions of the major findings.

The following are organizations which hold meetings that could contribute to the development of the technical information described in this report. This is not an exclusive list; indeed, many additional, unanticipated meeting and conference opportunities are expected to arise, some on relatively short notice.

- **North American SynchroPhasor Initiative (NASPI)**
  CIEE is an active participant in NASPI Working Group Meetings and has played a significant, ongoing role in projects funded by PIER. These also represent opportunities to meet with key stakeholders, technology developers, and leading researchers that routinely attend these meetings.
- **Electric Power Research Institute (EPRI) Workshops**

  EPRI has a number of research program areas that directly relate to transmission research, including:
  - Underground Transmission Technologies Workshop

    Underground Transmission Technologies have been identified as another key technology and are particularly relevant to efforts to facilitate the siting and approval of new transmission lines. CIEE TRP is in the planning stages of hosting a Workshop to assist in developing recommended new avenues of research.
  - Meetings with CEC Transmission Planning, IOUs and CAISO

    In general, meetings with these entities will be scheduled on an ad-hoc basis, as needed to meet with key engineers and researchers at stakeholder sites, to develop the information necessary for defining the needed research in transmission planning and the environment.
  - Topical Conferences and Workshops

    Public notices of workshops and conferences related to transmission planning and environment will be watched for relevant opportunities.

9.4 Problem Statement

Renewable resources within California are extensive and varied, and California has established aggressive RPS goals to increase the fraction of electricity made from renewable energy resources and to decrease greenhouse gas emissions under AB 32. By 2010, 20% of California's electricity is to come from renewables, and by 2020, 33%. Most of the new sources are expected to connect to the transmission system in remote locations and to exhibit properties quite different from traditional generation and loads, posing special challenges for providing timely and adequate grid delivery capacity, maintaining reliability, and avoiding economic inefficiencies. We refer collectively to these challenges as the problem of Renewables Integration (RI), and it is often cited as the major barrier to achieving the renewable goals of the state. New technologies will be required to provide the functional capabilities required for success.

These new technologies can be applied in the context of providing three new or expanded broad capabilities: (1) Provide physical access for each new power plant, (2) Reliably accommodate any unique renewable generator behaviors, and (3) Increase the grid's power carrying capacity to handle the additional electric power flows. As solutions are developed through research to address the issues raised in meeting these three main state policy goals of renewable generation deployment, GHG reduction and energy efficiency improvements, the transmission community must continue to assure that transmission meets the critical requirements for adequacy, reliability, affordability, security, safety, and environmental protection.

9.5 Initial Transmission Planning and Environmental Research Candidates

Examples of the types of technologies and technology platforms that would qualify for examination include (but are not limited to) the following:

- **Enhance Acceptance of New Transmission by Facilitating the Transmission Approval Process**
  New transmission siting is highly complex, with diverse stakeholders and jurisdictions, and no integrated process for generation and transmission planning currently exists. Research focusing on information and tools that facilitate the public debate which support regional planning and transmission-corridor assessment would help foster consensus among these stakeholders on major transmission projects.
- **Enhance Acceptance of New Transmission by the Deployment of New Technologies**
  A major objection to most new transmission projects is their visual and environmental impacts. Reducing the visual profile and other environmental and siting impacts can help mitigate these concerns. The value and benefits, including the impact on GHG, of applying technologies such as undergrounding, HVDC and HVDC Light, better utilization of existing right of ways (ROWs) and other methods to minimize these impacts, need to be integrated into planning tools.
- **Improve Understanding of the Value of Transmission**

  The acceptance of new transmission and technologies can be increased if their costs and values are understood. Methods to incorporate cost allocation and strategic value of transmission and new technologies such as advanced power flow devices (e.g., Flexible AC Transmission Systems (FACTS), DC transmission, etc.), energy storage, demand side options and capacity additions can help to inform decision making.
- **Market Impacts**

  Intermittent renewables are expected to increase locational marginal pricing (LMP) volatility since renewable power output is dependent on variable (e.g., wind and sun) input as well as plant economics. Market simulation and market-power analysis, application of uncertainty analysis and techniques, and economic modeling and evaluation of cost of trade across market seams may help to better characterize renewable market participation and perhaps mitigate their effects.

- **Advanced Planning**

  Advanced long-range planning tools need to incorporate the uncertainties in expanding the transmission to serve new renewable generator plants to increase reliable power transfer capacities into major customer load centers. It is also anticipated that to meet RPS goals, wind generation will be imported from outside of California and will magnify transmission congestion costs as well as impact grid reliability. High renewable penetration will require complementary energy resources for shaping and firming the variability of renewable resources.

- **Accommodation of Distributed Renewable Energy Generation and Demand Response**

  Distributed renewable energy is generally installed at the distribution level, but there is an interaction between distributed generation, demand response and transmission. At higher penetration levels, net energy produced finds its way back to the transmission level creating unprecedented operational, protection, interconnection, reliability, and market issues. However, through integration with multiple distribution sources, systems could become a dispatchable electric supply on the transmission system. The development of a Smart Grid is a prerequisite for success of this concept.

- **Controlled/Strategic Islanding**

  When a disturbance is detected that may escalate into a wide-area cascading blackout, adaptive and corrective control strategies offers the potential to split the WECC system into self-sustaining islands.

- **Wind Generation-PHEV Partnership**

  Time of day wind generation profiles do not follow system load. Charging of plug-in hybrid electric vehicles may be conveniently managed to mitigate the minimum load issue of wind generation in the electric grid in California as well provide distributed energy storage.

- **N-1 Reliability in a Renewable Generation Environment**

  The increasing penetration of variable as well low-inertial resources from renewable generation is hypothesized to have significant impact on grid reliability. Classic N-1 reliability criteria may no longer adequately protect the grid from extreme events.

9.6 Benefits to California

This work benefits California by addressing how new technologies can be developed for helping the electric transmission and distribution system (T&D) perform its role in meeting the three main state policy goals of renewable generation deployment, GHG reduction and energy efficiency improvements, while continuing to assure that transmission meets the critical requirements for adequacy, reliability, affordability, security, safety, and environmental protection. California has adopted aggressive energy policy goals to significantly reduce greenhouse gases, improve energy efficiencies and increase penetration of renewable energy generation. The electric T&D system in California is a factor in being able to meet each of these goals, but currently faces many challenges in performing its roles in achieving them. Meeting these challenges will require new or expanded capabilities for the grid, and new transmission technologies offer the prospect of providing a substantial portion of the new or expanded capabilities to supplement traditional solutions. This report identifies the drivers and rationales that create the needs for new technologies, and describes the most promising new technologies and the research activities needed to help bring them to productive deployment and commercial reality in a manner that meets California needs in a timely fashion.

CHAPTER 10: Adaptive Relaying Technology Development

This project was performed by the Virginia Polytechnic Institute. The Principal Investigator was Virgilio Centeno.

10.1 Introduction

The 2003 Northeast blackout, the 1996 West Coast blackouts, and other recent system blackouts throughout the world have shown the importance of a reliable power system in modern societies, and the enormous economic and societal impact a blackout can cause. Blackouts are the results of a cascading phenomenon where, in a large percentage of cases, some protection system misoperates and becomes an important contributing factor in the sequence of events leading to the blackout. This is known as "the hidden-failure phenomenon in protection systems." Other contributing factors to catastrophic failures are unexpected power system configurations which have not been foreseen when protection systems were set, errors in setting and calibration of relays, or undiscovered design flaws in the protection systems. Adaptive relaying and wide area measurement has been proposed as a possible solution to hidden failures. Adaptive relaying systems use digital relays that can change their settings to adapt to changing system conditions, either automatically by sensing the proper parameters, or in response to a control signal from an operator or wide-area control system.

10.2 Purpose

This three-year research project developed and evaluated the use of adaptive protection to monitor, supervise, and modify the protection systems in real time, based upon the information about the state of the power system provided by synchronized phasor measurements. Four aspects of the protection system supervision and control were selected for research, because they address principal concerns regarding protection system responses, and are interrelated and complementary in their scope. Such measures are within the capabilities of technology available today, and when successfully applied can reduce the frequency and intensity of power system blackouts.

This Research Development and Demonstration (RD&D) effort was conducted in close cooperation with two California utilities, PG&E and SCE. The studies were conducted using a validated California Power System Model developed in a prior Virginia Tech PIER-sponsored project, and the results of the research provided proof-of-concept of the proposed approach, as well as complete functional specifications for implementing these ideas on the California system.

10.3 Objective

The objective of this project was to use real-time synchronized phasor measurement data to provide improved protection system supervision in order to make it adaptive to the prevailing system state. By using real-time wide area measurements, it is possible to determine optimum protection policies and settings for critically located relaying systems. It is recognized that primary protection of power system equipment requires high speed decision making that is incompatible with delays of even tens of milliseconds. Such protection is unlikely to be adaptive to remote inputs.This three year RD&D project addressed slow speed protection functions in which the latency involved in remote phasor measurements is not an obstacle. In particular, adaptive supervision of back-up zones, intelligent load shedding, adaptive generator loss-of-field relaying, and the use of remote phasor measurements in the design of robust damping control of low frequency oscillations were developed.

10.4 Conclusions

To fulfill the objectives the project team:

- Developed a scheme for supervising back-up zones with remote phasor measurements so that back-up protection is not allowed to operate when it is not appropriate.
- Developed a load shedding algorithm by simulating various contingency conditions on the California power system model, and assessed its efficacy at taking control action to prevent islanding.
- Developed techniques to use wide area measurement systems to adjust the generator loss-of-field relay settings automatically as the system Thévénin (equivalent-circuit) impedance changes. Algorithms were developed to determine the proper method for setting these relays. Verification of the appropriateness of the developed logic was performed with simulations.
- Developed a methodology to design a robust damping controller using remote phasor measurements on a multi-mode, multi-DC-line large system, along with suggested limits on the allowed delay. The methodology extended the results to FACTS devices and generator excitation systems as the control mechanism.

10.5 Future Work

This project was a proof of concept of four adaptive protection enhancements whose goal is to improve the reliability of the California electric grid. The Smart Grid Investment Grant (SGIG) funding provided by the recovery act of 2009 (ARRA) has accelerated the deployment of wide area measurement devices, improving the prospects for near-term feasibility and implementation of the proposed protection schemes.

This research has moved the proposed schemes from conceptual enhancements to proven concepts applicable to the California grid. The next logical step in this development is a laboratory test at the California utilities using on-line data from the real system. These tests will reveal additional details on the limitations of available commercial equipment and other possible limitations due to non-technical requirements in the availability and sharing of the required wide area data and information among the California utilities.

CHAPTER 11: Developing Tools for Online Analysis and Visualization of Operational Impacts of Wind and Solar Generation

This project was performed by the Pacific Northwest National Laboratory (PNNL). The Principal Investigator was Yuri Makarov.

11.1 Overview

Interacting wind, solar, and load forecast errors can create significant unpredictable impacts on the transmission system, including increasedcongestion, reduced voltage and reactive power stability margins, among others. These impacts will increase along with the increasing penetration levels of variable renewable generation in the Western Interconnection and California power systems. To maintain a secure system reliability level, the probability and the magnitude of the impacts should be evaluated and communicated to the system operators. Based on this information, the system power flow limits, generation dispatch, voltage levels, and available reactive power margins could be adjusted to minimize the risk of system problems and failures to an acceptable level whenever it is required.

To facilitate wider penetration of renewable resources without compromising system reliability, three tools intended for use by California Independent System Operator (CAISO) power grid operators have been developed for predicting and displaying the operational impacts of uncertainties in forecasts of loads and renewable generation. The first tool ("Ramping Tool") addresses real-time (load following) capacity and ramping requirements, the second ("Transmission Tool") addresses voltage stability and transmission congestion caused by renewables resources (mainly wind power and solar power generation), while the third tool ("Day Ahead Regulation Tool") predicts capacity, ramping rate and ramp duration requirements of regulation, including upward and downward requirements, for each operating hour of a day. The Ramping Tool is an industry-grade product connected to the California ISO systems and operated in real time in the California ISO Control Center. The Transmission Tool and the Day Ahead Regulation Tool have been developed to the prototype stage.

11.2 Transmission Tool

The objective of this work was to develop a prototype tool to identify transmission problems, posed by the intermittency and variability of wind and solar generation, 1 to 3 hours ahead of time, and inform operators on potential risks for the purposes of early warning and preventive control. As noted before, the scope is limited to developing a prototype tool that implements and demonstrates the main developed methods and models, and fully illustrates the advantages of the methodology.

The transmission tool is a standalone working prototype product that demonstrates the key features and advantages of the methodology developed. The initial design incorporates all required essential informational, analytical, and visualization functions. Further development and integration with vendor-supported software at CAISO are necessary for deployment.

Since the beginning of the project, CAISO has implemented a real-time voltage stability analysis (RTVSA) tool (VSA&E tool initially developed by CERTS and commercialized by Bigwood Systems Company), and advanced visualization and data processing tools (developed by Space Time Insight Company). In this situation, the project priorities and scope have been changed by CAISO. Development of a stand-alone, fully-functional transmission tool would be redundant. Based on recommendation of the CAISO project support team, a decision was made to develop a transmission tool prototype and its integration approach with the tools already installed and used by CAISO. The connectivity issues are addressed in this report from the methodology and system model perspective to provide future connectivity of the future industry-grade applications with the CAISO systems generally, and with the Bigwood real-time stability analysis applications, as well as with the Space Time Insight visualization tools.

The developed methodology is based on Monte Carlo simulations and statistical analysis of various sources of uncertainty that can impact the transmission network. The developed methodology also includes a linearized power flow model to calculate incremental active power flows in the transmission network caused by forecasting errors.

The prototype tool that was developed demonstrated the methodology, design considerations, system architecture, simulation results, and the graphical user interface (GUI). The power system model and the methodology to determine the probabilistic thermal congestion limits based on power transfer distribution factor were presented. The five key system modules, i.e., power flow module, power transfer distribution factors (PTDF) module, forecast error module, probability congestion module and interface module, were also demonstrated. Currently, the developed transmission tool is in a prototype stage, based on a simplified model and data. Future work could be to install and test the tool in a real control center using actual system models and data.

11.3 Ramping Tool

Because conventional generators need time to be committed and dispatched to a desired megawatt level, scheduling and load following processes use load and wind power production forecasts to achieve future balance between conventional generation and energy storage on the one side and system load, intermittent resources (such as wind and solar generation), and scheduled interchange on the other side. The power system balancing process, which includes scheduling, real-time dispatch (load following), and regulation processes, is traditionally based on deterministic models.

Uncertainties in forecasting the output of intermittent resources such as wind and solar generation, as well as system loads, are not reflected in an existing energy management system (EMS) or tools for generation commitment, dispatch, and market operation. With the growing penetration of intermittent resources, these uncertainties could result in significant unexpected load-following and dispatch problems, and pose serious risks to control and operation performance characteristics as well as the reliability of a power grid. Without knowing the risks posed by the uncertainties, system operators have limited means to weigh the likelihood of occurrence and the magnitude of problems to mitigate adverse impacts caused by them. Some important questions need to be addressed in counteracting the impact of uncertainties; for instance, whether and when one should start more units to balance against possible fast ramps in the future over a given time horizon.

It is very important to address the uncertainty problem comprehensively by including all sources of uncertainty (load, intermittent generation, generators' forced outages, etc.) into consideration. All aspects of uncertainty, such as the imbalance size (which is the same as the capacity needed to mitigate the imbalance) and generation ramping requirement, must be taken into account. The latter unique features make this work a significant step forward toward the objective of incorporating wind, solar, load, and other uncertainties into power system operations.

In this project, all uncertainties associated with wind power generation forecasting, load demand forecasting, and generation supply interruptions caused by forced outages are taken into account in the evaluation of uncertainty ranges for the required generation performance envelope including balancing capacity, ramping capability, and ramp duration. A probabilistic algorithm, based on a histogram analysis to assess the capacity and ramping requirements, is presented. Simulation was performed using the California Independent System Operator (CAISO) system model and data. This report also presents these simulation results confirming the validity and efficiency of the proposed solutions.

The work pursued the following objectives:

- Develop a probabilistic model to evaluate uncertainties of wind and load forecast errors and to provide rapid (every 5 minutes) look-ahead (up to 5-8 hours ahead) assessments of their uncertainty ranges.
- Improve existing models to evaluate uncertainties caused by generator random forced outages, failures to start up, and contingency reserve activation processes.
- Create an integrated tool that consolidates the above-mentioned continuous and discrete random factors contributing to the overall uncertainty, to evaluate look-ahead, worst-case balancing generation requirements (performance envelopes) in terms of the required capacity, ramping capability, and ramp duration.
- Build a methodology and procedures for self-validation of the predicted performance envelope for each look-ahead interval.
- Develop visualization displays to communicate information about the expected ramps and their uncertainty ranges.
- Develop a framework for integration of the tool into the CAISO's Energy Management System (EMS) and market systems.
- Use actual CAISO data to perform simulation.

The following results have been achieved in this work:

Innovative methodology and software tools have been developed that are capable of evaluating future generation requirements, including the required capacity, ramping capability, and ramp duration capability (performance envelope) in view of uncertainties caused by wind and solar generation and load forecast errors. The approach includes three stages: 1) forecast and actual data acquisition, 2) statistical analysis of retrospective information, and 3) prediction of future grid balancing requirements for specified time horizons and confidence intervals.

Assessment of the capacity and ramping requirements is performed using a specially developed probabilistic algorithm based on a histogram analysis incorporating all sources of uncertainty and parameters of a continuous and discrete nature:

- A "flying brick" method has been developed to assess the look-ahead worst-case performance envelope requirement to be able to enable the system to accommodate the uncertainties with certain specified degree of confidence. The "flying brick" concept is to simultaneously include the ramp rate, ramp duration, and capacity requirements directly in the balancing process.

- A self-validation approach has been used. The purpose of the self-validation algorithm is to verify that the uncertainty ranges predicted based on retrospective information are valid for the future dispatch intervals.
- An industrial software tool has been developed and tested.
- Simulations using actual data provided by this project's CAISO engineering support team have been carried out. Simulation results have shown that the proposed methodology is quite accurate and efficient.
- The concept of probabilistic tool integration into EMS has been developed. The concept includes three levels of integration: a passive level, an active level, and a proactive level. The passive integration level integrates wind forecast information and its visualization without introducing any changes to the EMS algorithms. On the active level, the unit commitment (UC) and economic dispatch (ED) procedures are repeated several times for every dispatch interval to determine whether the system can meet the limits of generation requirements caused by uncertainties for a certain confidence level. The system "breaking points" are communicated to the user. The proactive level required some modifications of the UC and ED algorithms in order to directly incorporate uncertainties into these procedures. In this case, the generation units will be committed and dispatched, so that these uncertainties would not create "breaking points."

11.4 Day Ahead Regulation Tool

Regulation is a process of providing minute-to-minute system balance by adjusting the power output of generators connected to the automatic generation control (AGC) system. Regulation is an expensive resource, and the annual price of regulation significantly exceeds $120 million in California.

Most of CAISO's "once-through cooling" generating units using seawater for cooling, located along California's Pacific coast, are expected to be retired or retrofitted within the next decade. These units have traditionally been used to provide balancing services for CAISO, and their retirement could potentially create a deficiency in available regulation resources. The consequent decline in available regulation resources could potentially increase the price of regulation as more regulation procurement is needed. These challenges motivate CAISO to obtain a tool capable of predicting the needed procurement of up- and down-regulation services in the day-ahead market.

The objective of this project is to develop an approach to procuring regulation capacity that would minimize the regulation capacity required during some operating hours without compromising CAISO's control performance characteristics. The chosen approach predicts CAISO's regulation requirement on a day-ahead basis by calculating the required regulating capacity, ramping rate (rate of change of the regulating units' output) and ramp duration (how long the ramp should be maintained), including upward and downward, for each operating hour of a day.

In this project, three methods were developed. The methods differ by the approach used to calculate the regulation requirement and by the type of control performance criteria used. The first and second methods are close in philosophy to the existing control performance standard, CPS2, which limits ten-minute averages of the area control error (ACE) to below a certain value, L_{10}, specified by the North American Electric Reliability Corporation (NERC).

- The first method evaluates regulation requirements based on statistical analysis of all components of the regulation requirement: forecast errors (load, wind and solar generation), uninstructed generation unit deviations, frequency errors, and metering error correction.
- The second method predicts regulation requirements based on a statistical analysis of ACE signals and actual regulation applied in the system.
- The third method is based on a new standard that is currently under trial use in the industry. It evaluates the regulation requirement in order to meet the new Balancing Authority ACE Limit (BAAL) standard, by which instantaneous values of ACE are limited by frequency-sensitive ACE limits. Like the second method, it is based on a statistical analysis of the actual ACE and frequency information.

A methodology for estimating regulation requirements taking into account the new control performance standard (BAAL) has been developed. Simulations have shown that CAISO regulation requirements can be substantially reduced because the BAAL standard allows a BA to operate in a wider ACE range compared with the previous CPS2 standard.

All three methods use historical information, obtained prior to the analyzed operating day (a moving window for a user-specified period). The performance of the proposed methods can be further improved by incorporating ramp and uncertainty information provided by the CAISO wind and solar forecast service providers.

A software tool has been developed, which includes a graphical user interface (GUI), algorithms for detecting and correcting input data outliers, an Oracle®-based database, and a self-validation procedure. The tool implements the following main features:

- Prediction of hourly-specific regulation requirements for the next operating day, which can potentially help the CAISO to save money on regulation cost;
- Detailed visualization of input data and results, making the process transparent and user-friendly to the CAISO operators and engineers;
- Flexibility (different confidence levels, moving-window sizes, etc.) allowing CAISO engineers to fine-tune the tool to their needs, including the level of compliance with the existing control performance standards;
- Self-validation of predicted results, providing a self-control feature for the accuracy of the algorithm; and
- Detection of outliers and statistical analysis of input data (distribution, standard deviation, mean value) to help in detecting and eliminating bad data.

CHAPTER 12: Technology Transfer Activities

This Task was performed by the CIEE Electric Grid Research (EGR) Group. The Principal Investigator was Merwin Brown.

12.1 Introduction

The energy sector is undergoing tremendous change as pressure increases to curb carbon emissions and create a clean energy economy. Policy drivers within the State of California are envisioned to become a catalyst for transforming the region's energy infrastructure. This includes a high penetration of renewable energy generation to meet our energy needs.

Increasing pressure to curb costs and negate environmental impacts is believed to be a factor that has slowed the pace of investment in electric grid infrastructure, resulting in a grid that is constrained and stressed. New grid technologies will be needed to make renewable generation deployment easier and less costly, especially technologies that make the grid smarter. The research, development and demonstration (RD&D) investment in advancing the maturity of these new technologies is substantial. If this investment is not to be wasted, the technology must be effectively transferred, ultimately to the end user, but also to the various participants along the technology development value chain, from technology concept through product deployment.

12.2 Technology Transfer

Transferring technology from its creator to a user often for economic benefit is known as technology transfer. Technology transfer is closely related to knowledge transfer in both transferring the intellectual property, knowledge and skills as well as the physical properties of technologies and methodologies. Key in successful technology transfer is early recognition of promising new technologies. These must be nurtured from the research through development, demonstration, and deployment. The Federal government through the Department of Energy alone invested $26.4 billion in 2011 in energy research. Other entities performing RD&D in the U.S. electricity sector such as the electrical equipment manufacturers, utilities, the Electric Power Research Institute, and state-funded agencies such as the California Energy Commission, invest hundreds of millions more each year.

12.3 Barriers to Technology Transfer

Breaking down barriers to technology transfer is essential to provide smooth and timely implementation of new technology. At every stage of the technology transfer process risks exist along the path to market adoption. Challenges come from many sources and can be from the lack of resources, including:

- Financial. Funding for an endeavor is necessary throughout its entire lifecycle. Incentives in the form of tax credits, matching funds, cost recovery policies or direct rebates to the consumer can help to offset some costs and financial risk.

- Legal and Regulatory. Without an enabling policy and regulatory framework, new technologies may have difficulties becoming adopted. Establishing a clear, transparent and consistent regulatory and permitting process across state, local and federal agencies can reduce conflict among stakeholders and speed implementations.
- Institutional and Social. Capacity is built through maintaining a strategic vision, governance and leadership, relationship building, developing resources, delivery and good management. An organization must be able to continue to maintain itself through professional interactions and industry associations to keep up with evolving technologies.
- Human. Lack of human capacity can stall adoption. Both scientific and technical expertise must be developed to install, operate and maintain new technology.

12.4 Technology Transfer Activities

To advance science and technologies through the research, development and demonstration process requires the transfer of knowledge from one party to another at various stages involving many different knowledge communities. Technology transfer covers the gamut of interactions between researchers, entrepreneurs and the end users. The following is a list of activities that can connect the communities together:

- Passive information sharing. Sharing occurs through publication of peer review journal articles and other similar sources. Research findings once published wait to be found by an entrepreneur who has a practical problem to solve.
- Active information sharing. Knowledge transfer occurs through personal interactions. Exchange often occurs in a formal setting such as a conference, workshop, seminar, discussion forum, training or consultancy. Timeliness is preserved in addressing current problems.
- Tacit information sharing. Tacit knowledge is built over time both informally and formally. Informal information sharing and relationship building may occur actively through conversations, a coffee break, or a chance exchange at a conference to grow both the participants' knowledge base and their industry networks. Formal information sharing may occur through education and training to create the next generation of scientists, engineers and technicians.
- Cooperative involvement. Stakeholder involvement in the decision making process increases the likelihood of technology transfer of being successful and timely. Stakeholder consensus helps to ease acceptance of new technologies and policies as well as to build early support by incorporating information sharing, and by communication of values and views.
- Demonstration projects. Demonstration projects are a special form of cooperative involvement. Demonstrations increase the acceptance of new technologies since the host often invests tangible resources in terms of equipment and personnel. Close involvement of industry personnel also builds tacit knowledge as they install, operate

and monitor the performance of new technology, as well as helping to build confidence in the new technology.

- Patents, licensing, and standards. The development of industry standards, usually through community involvement, is one indication of the proliferation of a new technology. An agreed information exchange protocol, communication interface, or performance standard gives added assurance that a new technology will work as expected.

12.5 Applications of Technology Transfer in This Contract

In application, most technology transfer activities cannot be singularly categorized. Knowledge transfer occurs in many modes depending on the complexity and purpose of the activity. Within electric grid research this is apparent as technology transfer involves many different communities and personnel within these communities at different stages within the process. CIEE's Electric Grid Research (EGR) program, through its experienced and knowledgeable staff, is active in all stages of the process. The following examples highlight applications of the different technology transfer activities that EGR carried out in the execution of this contract:

- Example 1. Knowledge Transfer Through Passive and Active Participation

  All final reports for the California Energy Commission's Public Interest Energy Research (PIER) program and Fact Sheets can be found at: http://www.energy.ca.gov/research/reports_pubs.html.

  The CIEE website, http://uc-ciee.org, contains the CIEE library – a compendium of progress toward California's energy research goals. Housed here are the CIEE work products related to sponsored projects and research development activities: draft final reports, fact sheets, published papers, case studies, white papers, conference proceedings, papers, posters and presentations, and press releases. Accessible to all, the collection is a growing framework for advancing research and policy, in California and beyond.

- Example 2. Advisory Groups

  Cooperative involvement in electric grid research in the PIER program focused on the Policy Advisory Committee (PAC) and the Technical Advisory Committees (TAC) that support it. Committee membership was composed primarily of personnel from the three major investor owned utilities (IOU) in California – Pacific Gas and Electric Co. (PG&E), Southern California Edison Co. (SCE) and San Diego Gas and Electric Co. (SDG&E) – and the California ISO (CAISO), and chaired by an Energy Commission commissioner. Additional participants were often invited to participate, to share knowledge and provide a broader perspective to the meeting's focus.

  Advisory group meetings were a forum for communication between the stakeholders and research and development community. Meetings often held several objectives to:

  - update participants on current national and state policy trends in energy;
  - educate participants about ongoing research, and sometimes findings, in the community, including results from IOUs, universities and national laboratories; and
  - provide a forum for stakeholders to participate in the decision making process by identifying their pressing problems, the potential technologies needed to address

these problems, and selecting the research activities for the highest priority technologies requiring additional development.

- Example 3. Demonstration Projects

  The IOUs often provide not only the facility for hosting a new technology but staff time to implement and monitor it. One example is the Wide-Area Energy Storage and Management System (WAEMS) Project. This project partnered private sector technology from Beacon Power Corp. with major power balancing authorities (California Independent System Operator (CAISO), Bonneville Power Administration (BPA), and a major utility, Pacific Gas and Electric (PG&E)), with research performed at a national laboratory, Pacific Northwest National Laboratory (PNNL). With access to these facilities, researchers designed and monitored experiments to determine the performance characteristics of the BPA hydro system and the Beacon Power flywheel system, and evaluated the performance characteristics of a PG&E Sodium Sulfur Battery Storage Facility. Testing scenarios were prepared in cooperation with BPA and CAISO. Participation by BPA and CAISO aided the deployment of wide area energy storage and managements systems between the two balancing authorities as well as commercialization of the control algorithms.

- Example 4. Operator Training

  Effective use of new tools depends not only on involving the end users in the development of the tools but also on training them in the tools' actual use. This is especially important in the operation of the electric grid when near real-time decision making affects grid reliability. An example of this is the Developing Tools for Online Analysis and Visualization of Operational Impacts of Wind and Solar Generation project; PNNL worked closely with CAISO in developing, testing and installing the system, as well as training the operators in its use. The project involved CAISO engineers and operators from start to finish to ensure system compatibility and to incorporate feedback for the control room operators (end user). The system is now operating in a real time environment at CAISO.

- Example 5. Standards Development

  To develop effective standards, the characteristics of the technology and its performance in actual usage must be understood. An example of this process is the Analysis of Seismic Performance of Transformer Bushings project. The approach here requires the development of highly complex modeling, and use of the most advanced seismic simulators available at the Structural Engineering and Earthquake Simulation Lab (SEESL) at the State University of New York (SUNY), Buffalo to test specimens. Through the graduate program at SUNY Buffalo, SEESL trained graduate students in the latest advancements in algorithm development, analysis and testing. This knowledge becomes further shared as these students are employed in industry and the methodology gains acceptance through familiarity. Members from PG&E, SDG&E, SCE, Western Area Power Administration and private industry including members of the IEEE 693 Standards Committee have monitored and advised on this project. Adoption of the new proposed standards will provide manufacturers with the information they need to build bushings with predictable performance, and hopefully greater survivability in seismic events, thus preventing power interruptions.

12.6 Next Steps

Next steps for individual projects are highly dependent on where each is in the research and development process. The following introduces each project funded under this contract and summarizes their next steps.

Task 2.2 Analysis of the Seismic Performance of Transformer Bushings

Further work is recommended to convert the findings from this project to specifications for the manufacturers, utilities and regulatory bodies. In addition, further studies are necessary to account more directly for the conductors connected to the bushings and the other equipment. As demonstrated here, installed conditions alter the performance of substation equipment and require complex testing and validation to ensure their survivability during a seismic event.

Task 2.3 Analysis of the Seismic Performance of Substation Post Insulators

Material characterization tests, including determination of parameters such as Young's modulus, tensile strength, compressive strength, and fracture energy density should be performed for porcelain insulators, as input to the seismic qualification process for substation disconnect switches. Further research is needed to determine the proper amplification factor for dynamic response of post insulators for "as-installed" conditions. As was done in the Seismic Bushings project, research is needed to determine the demand to capacity ratio (DCR), to characterize the strength capacity of substation insulators.

Task 3.2 Oscillation Detection and Analysis

Further work recommended includes extensive testing studies with a large amount of field measurement data and subsequent revisions and improvements of the algorithms as a result of this testing, and producing actionable information to increase damping, effectively suppressing the oscillations.

Task 3.3 Application of Modal Analysis for Grid Operation (MANGO) on the Western Interconnection

As the immediate next step, the first stage is to evaluate and improve the MANGO method with the full Western Electricity Coordinating Council system. The second stage is to test and demonstrate the MANGO method with actual measurement in a control room environment. In the third stage, as a longer term effort, the proposed MANGO method can be extended for the smart grid environment and to consider the impact of renewable energy penetration.

Task 4.1 Adaptive Relaying Technology Development and Measurements

The next step in development of adaptive relaying methods is a laboratory test at the California utilities using on-line synchrophasor data from a real system. These tests will reveal additional details on the limitations of available commercial equipment and other possible limitations due to non-technical requirements in the availability and sharing of the required wide area data and information among the California utilities.

Task 4.2 Developing Tools for Online Analysis and Visualization of Operational Impacts of Wind and Solar Generation

Next steps would increase the robustness and performance of the tool while handling imperfect information typically available in control centers, improve the probabilistic models to additionally reduce regulation requirements, add additional model components reflecting new sources of uncertainty, put more emphasis on the regulation requirements posed by the new NERC control performance standards, and deploy the tool in the CAISO control center (and potentially in the IOUs' and others' control centers in California).

12.7 Conclusions

Technology transfer is a contact sport. It cannot be done in isolation. It requires communication and contact across communities, leveraging each community's knowledge and skills. In increasingly complex and specialized research, funding and legal environments, expert knowledge has been recognized as a required element of success. State and Federal funded research plays an important role in many of the steps providing resources at every stage. In particular, California's PIER program plays a role in this by connecting researchers to end users and technology providers, and CIEE's EGR Group played an important role in this effort.

CHAPTER 13: Conclusions and Recommendations

This project was a compendium of many different tasks, with some tasks performed by the contractor (CIEE) and its subcontractors, consisting of universities and national laboratories. The common denominator was a synergistic focus on developing technologies and tools that will enable reliable and economically efficient design and operation of the electric grid under stresses such as renewable integration, markets, growing power demands and extreme natural events such as earthquakes. A number of tasks represented one phase in the overall path from laboratory to commercialization. These tasks have generally demonstrated the viability of methods and tools that can be of significant value in the face of uncertainties resulting from renewable integration and other major forces and trends in the power system.

This project was the outcome of long study by CIEE under the direction of the Energy Commission and in consultation with the key stakeholders including the major California IOUs, CAISO, and prominent researchers both within and outside of California. This study focused on identifying the important research that could provide near term value in the context of technologically enhancing the capabilities of the electric grid that would best assist California in achieving its energy policy goals. CIEE has long held a holistic approach to grid research and maintained strong relationships with stakeholders. The authors believe that these two factors are critical to ensuring that research dollars are spent on important topics and do not duplicate other research in the field.

The following are recommendations for follow-on research based on results of this project:

- Continue to the next phase of the Wide Area Energy Storage and Management System (WAEMS).

  This research offers the promise of both reducing total requirements for regulation services by combining multiple balancing areas (e.g. CAISO and BPA) and reducing the cost of services by combining expensive fast regulation (e.g. flywheels) with low cost, but slower regulation (e.g. hydro).

- Continue to the next phase of Modal Analysis for grid Operations (MANGO) on the Western Grid.

  The control of wide area oscillations is key to increasing the capacity of major transmission lines and facilitating the long distance transmission of renewable resources. MANGO provides decision support to operators to monitor and manage poor damping situations but is near but not yet at the stage of commercial development.

- Continue development of the Forecasting Tools for Online Analysis of Wind and Solar.

  Both the Transmission Tool and Day Ahead Regulation Tool provide significant forecasting assistance to manage the variable nature of renewables, but need further development to be commercially viable.

- Perform demonstrations based on Adaptive Relaying technology research and demonstration.

  Several types of protective circuits have been shown to benefit in the laboratory from the use of synchronized phasor measurements to adapt their operation to the prevailing system conditions. In order for these adaptive features to be implemented, utilities must first demonstrate their worth under field conditions. One such project under DOE auspices with California Energy Commission support is already under way, based on previous similar PIER-funded work. Similar demonstrations of other adaptive relaying applications, as developed under this contract, are also needed.

- Additional research on development and application of synchrophasor technology to electric system operations and planning.

  Further research and demonstration of applications of synchrophasor technology to electric systems should also be pursued. Aside from the aforementioned applications of synchrophasors relating to Adaptive Relaying technologies, there are numerous other areas where synchrophasor technology could provide a high level of benefits to electric system operations and planning, including real-time monitoring and control, congestion management, state estimation, post-disturbance analysis and system restoration, and model validation, to name a few.

APPENDIX A:
Future Transmission Grid Infrastructure Final Report

APPENDIX B:
Seismic Bushing Analysis Final Report

APPENDIX C:
Seismic Insulator Analysis Final Report

APPENDIX D:
Future Transmission System Operations Research Final Report

APPENDIX E:
Wide Area Energy Storage Management Systems Final Report

APPENDIX F:
Oscillation Detection and Analysis Final Report

APPENDIX G:
Modal Analysis for Grid Operations (MANGO) on the Western Interconnection Final Report

APPENDIX H:
Future Transmission Planning and Environmental Research Final Report

APPENDIX I:
Adaptive Relaying Technology Development Final Report

APPENDIX J:
Developing Tools for Online Analysis and

Visualization of Operational Impacts of Wind and Solar Generation Final Report

APPENDIX K:
Technology Transfer Activities Final Report