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An Assessment of PIER Electric Grid Research 2003-2014 White Paper

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"Research Powers the Future"

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PREFACE

An Assessment of PIER Electric Grid Research, 2003-2014 is the report for the Energy Commission project Characterization of the Electric Grid, Issues, and Challenges (contract number 500-10-055, work authorization number WA007: White Paper on An Assessment of the Impacts of the Electric Grid Research Program, 2003-2014), conducted by the California Institute for Energy and Environment. The information from this project contributes to PIER's Energy Systems Integration Program.

ABSTRACT

This white paper describes the circumstances in California around the turn of the 21st century that led the California Energy Commission (CEC) to direct additional Public Interest Energy Research funds to address critical electric grid issues, especially those arising from integrating high penetrations of variable renewable generation with the electric grid. It contains an assessment of the beneficial science and technology advances of the resultant portfolio of electric grid research projects administered under the direction of the CEC by a competitively selected contractor, the University of California's California Institute for Energy and the Environment, from 2003-2014.

Keywords: California Energy Commission, research, public interest, renewables, efficiency, performance metrics, electric grid, transmission, distribution, Smart Grid.

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Executive Summary

Introduction

In 2000-2001, California experienced high electricity prices and consequential severe financial problems, along with electric power shortages and rolling blackouts. These crises demonstrated the public interest value of the electric grid, along with its inadequacies and vulnerabilities, prompting the California Legislature to pass the Reliable Electric Service Investments Act of 2000. Other similar state policy actions reflected these concerns over the readiness of California's electric grid, and provided the guidance for PIER-funded research and development for that critical infrastructure. The state began an expanded research effort in the PIER program to develop new technologies to enhance electric power delivery capabilities. In 2002, the CEC developed the Transmission Research Program (TRP) in response to legislation. The primary objective of the TRP was to foster research that would address critical transmission issues.

The Energy Commission had responsibility for the TRP and selected a contractor to provide program vision and strategy development, to administer and facilitate the stakeholder relationships, and to deliver research results for new electric grid technologies. The California Institute for Energy and Environment (CIEE) of the University of California was competitively selected as that contractor in 2003.

An advisory system of stakeholders of the electric grid community was critical for the design and execution of the TRP, and for the transfer of the research program's results to the end users. It helped to assure that the TRP had the right portfolio of research projects, and assisted in making the research products used and useful to Californians. The TRP advisory structure brought together informally electric grid technology "research" experts from academia, national labs, architect engineers, product vendors and consultants to focus on specific grid-related problems.

"Deliver a kilowatt-hour from anywhere to anyone at any time" was the TRP Policy Advisory Committee vision statement of the ideal transmission system. Mission success depended critically on avoiding blackouts and enabling the consumer to access clean, low-cost, reliable electricity.

Challenges Facing the California Electric Grid and Shaping the PIER TRP

After 2000–2001, the electric grid in California faced the consequences of two decades of under investment in transmission, and increasing difficulty with siting, permitting and building new transmission. The results were rising electricity costs due to congestion, and later, a threat to the state's renewable energy generation goals. Attempting to increase economic efficiencies and maintain reliability, while accommodating new power markets and new generation technologies and loads, transmission operators were impaired in their ability to plan, dispatch and regulate generation. The ever-increasing reliance on long-distance multi-state transmission lines in the western U.S. electric grid increased the risk of large widespread outages, such as the 1996 blackout in the western U.S. caused by growing destabilizing dynamic power flow behaviors. Reductions in transmission capacities to provide more margins for operators to better manage instabilities, increasing economic inefficiencies and congestion. The lack of wide-area, real-time system visualization by operators was painfully apparent, which gave rise to the deployment of synchrophasors, an emerging monitoring technology that was expected to do for transmission system diagnostics what magnetic resonance imaging (MRI) did for medical diagnostics versus old-fashioned X-rays.

Extreme events, such as the cascading blackout described above, shook public confidence in electric grids. Lawmaker and regulatory actions, such as the U.S. Energy Policy Act of 2005, toughened operational requirements, creating additional complexity for grid operations and planning. New technologies, such as demand response and distributed generation, offered opportunities for improved grid operations, but only if the challenges of integrating these technologies with the distribution and transmission systems could be overcome. More recently, and most significantly, the growth in renewable energy electric generation has further challenged grid operations.

In 2006, the California legislature directed the PIER TRP to emphasize renewable energy delivery, along with reliability and costs of the power grid, to be consistent with emerging energy policy in the state, which was driven to reduce greenhouse gas emissions. Most of the problems described above facing the electric grid in California would still need to be addressed in order to facilitate the integration of renewable generation with the electric grid. In addition, the integration of many renewable generators “fueled” by variable wind and solar energy resources called for an additional new TRP focus on technology solutions for the challenges unique to these particular generators.

With the advent of variable renewable generation in the electric grid, for the first time in history electric generators did not come with built-in energy storage, namely, in the forms of stored fuel and the inertia of the rotating mass of the electric generator. Most solar and wind powered generators cannot be run with certainty and consistency. Additionally, instead of using rotating generators, solar and wind generators usually use electronic power conversion equipment which tends to ramp (i.e., increase or decrease power output) much faster than the traditional power plants for which the electric grid was designed. California’s aggressive goals to increase the fraction of electricity generated by renewables, at the transmission and, more recently the distribution levels, made these issues real, posing challenges for timely and adequate grid delivery capacity, maintaining reliability and power quality, and avoiding economic inefficiencies.

New or expanded capabilities for the grid would be needed. In the beginning, building new transmission and distribution infrastructure using traditional “wires” technology seemed sufficient, but as time passed it became increasingly clear that new technologies offered the prospect of providing a substantial portion of the new or expanded capabilities, and would be needed to supplement the traditional “build” solutions.

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

The TRP Strategy

Emerging technologies offered solutions if they could be developed and commercialized. The TRP pursued a set of evolving technology research strategies that focused on new technologies to provide faster access for new, remotely located renewable power plants by putting new transmission lines in a “better light” through streamlining of the siting process, use of advanced counductors and other measures; accommodate unique aspects of variable renewable generators through a smarter and more flexible transmission and distribution grid; and increase the transmission capacity of the grid through improved hardware and “smart grid” enhancements.

1. New Technology for Providing Access to the Grid by Putting New Transmission Lines in a “Better Light”

For many remote renewable power plants, access to the transmission system means building new transmission lines between the power plant and the existing transmission grid. The time to site and permit a new transmission project can now be around 10 to 12 years for a major line, which is longer than it takes to build the a renewable power plant, and increases costs. The major barriers to building a new transmission line are societal resistance to siting, e.g., “not in my backyard,” and benefit identification and cost allocation.

Two general approaches were taken to put new transmission in a “better light.” One helped the public, and other concerned parties and decision makers, to better understand and communicate the costs and benefits – both economic and strategic – of transmission projects. The other approach reduced the visual profile and other environmental and siting impacts of a transmission line.

1.1. Transmission Cost Allocation Methodologies

This project documented case histories for addressing the cost allocation problem and developed new methods and approaches for expanding the planning tools for making these investment decisions and sharing in the cost of transmission projects, i.e., cost allocation. There was a need to research new approaches for assessing benefit streams, beneficiaries, and quantification of benefits for cost allocation and cost recovery for new transmission investments.

Use of a screening tool can perform quick what-if screening analyses, but it is not a substitute for detailed production costing simulation for comprehensive benefit analysis. In economic transmission projects, the principle of "beneficiaries pay" should be the basis for cost allocation.

The primary benefits of transmission, such as improved network reliability, were usually well identified in most proceedings, but some other categories of benefits were not. Since the transmission system had increasingly become a public good, the use of social rate of discount, instead of allowed weighted cost of capital, was recommended for calculating the present worth of benefits of a new transmission project. Additional research was identified as needed to quantify societal benefits of transmission in providing insurance value against extreme events that are low-probability/high-impact events. (see 3.5.1. Extreme Events)

A project presentation to the California Public Utilities Commission (CPUC) led the California Division of Ratepayer Advocates (now the Office of Ratepayer Advocates) to file a motion in 2008 to supplement the record for Investigation 08-03-010/Rulemaking 08-03-009 pertaining to an Order Instituting Investigation on the Commission's Own Motion, so actively to promote the development of transmission infrastructure to provide access to renewable energy resources for California.

1.2. Demonstration of Advanced Conductors for Overhead Transmission Lines

As loading on the electric system increases, transmission lines approach their limits on the amount of power they can carry, at which point transmission line conductors are often replaced with ones of higher capacity. But there is a limit to how much greater the replacement conductor diameter can be. To avoid high costs of rebuilding the line, it could be cheaper to use advanced conductors allowing higher power flow with a form factor similar to the old conductor.

This collaborative project, led by the Electric Power Research Institute (EPRI), evaluated the operational performance of advanced High-Temperature, Low-Sag (HTLS) conductors over three years. Five specific designs of HTLS conductors were evaluated: Aluminum Conductor Steel Supported/ Trapezoidal Wire, Gap-type Aluminum Conductor Steel Reinforced, Aluminum Conductor Invar Steel Reinforced, Aluminum Conductor Composite Reinforced, and Aluminum Conductor Composite Core. Key information is provided on design, installation, operation, and maintenance of selected HTLS conductors and their hardware accessories. The project involved field trials with CenterPoint Energy, HydroOne, Arizona Public Service, and San Diego Gas & Electric (SDG&E). The report provides data and instrumentation details for each site.

The project objectives were to gain practical experience in handling, installing, and terminating new types of conductors developed by manufacturers for use in high-voltage transmission lines, and to verify in practice the claims of manufacturers regarding their performance in an operating transmission line.

This project documented stringing, sagging, and clipping in commercially available HTLS conductor systems and evaluated the actual physical behavior of HTLS conductors in operating transmission lines. The results of this work will help utility participants choose when to use such conductors, how to choose between various types, and how to avoid problems during installation and over the life of the line. CIEE acted as the coordinator for the field test at SDG&E.

Depending on the uprating situation, stress-strain models for each of the HTLS conductors are available for utility engineers to evaluate which systems are most appropriate. The best conductor choice depends on the existing clearance buffer, original design margins, environmental loading conditions, and the desired rating increase. This study shows how HTLS conductors can be successfully used to obtain thermal rating increases of at least 50 percent, thus minimizing the need for modifications or replacement of expensive structures, e.g., transmission tower.

2. New Technology for Accommodating Variable Renewable Generator Behaviors

Technologies that lessen the impact of variable renewable generation help electric grid operators react to problems such as especially fast power ramp rates characteristic of solar and wind generators, and to better forecast variable renewable behaviors.

Solar power characteristically ramps up in the morning and down in the evening with no nighttime output, but with a power profile that varies with the season. Solar photovoltaic (PV) generators use solid-state inverters without the physical inertia described earlier, and they will react much more quickly to transients. Little was known about the effects of large penetrations of these low-inertia generators on the transmission and distribution systems.

Wind power tends to be higher at night in California and also is subject to short-term variability from changes in wind speed. The dynamic behavior of wind generators is different from typical thermal generators and generally has lower inertia. Generator models used for transmission planning did not accurately model wind generator behavior in the transmission system, and increased the level of uncertainty for the operator and threats to reliability.

The power ramp rates for both solar and wind generators are faster compared with conventional utility generators, and can pose challenges in maintaining reliability, power quality, and low regulation and ancillary costs.

The TRP focused on developing “smart” technologies that would help operators reduce uncertainty and minimize costs by forecasting the future state of the grid. The TRP also advanced the development of an analytical modeling tool to reduce the costs of managing renewable generation through the optimum shared use of resources such as energy storage, demand response and distributed generation among control areas over a wide region. Likewise, research was done to improve and update load and generator models used for planning in the WECC and California electric grid thereby improving the capability to maintain reliability.

2.1. Critical Operating Constraints Forecasting for California Independent System Operator Decision Support

When transmission resource margins become very short, knowing in advance when and how severe various transmission operating constraints become of significant value to the grid operators. During the 2005 summer season, the California Independent System Operator (CAISO) encountered conditions of very tight resource margins and serious congestion problems in Southern California. In anticipation that conditions in future summers could likely be much worse due to increasing demand for electricity and the limited transmission capacities into Southern California, this research project was initiated. Avoiding a blackout can potentially save Californians hundreds of million dollars or more. The risk of blackouts will likely increase in the future with the high penetration of renewable generation, power markets and new electric customer appliances and equipment, so improvements in forecasting critical operating constraints could yield significant cost savings, help achieve California's policy goals for CO_2 reduction, and provide reliable and low cost electricity to the State's power consumers with minimum environmental impacts.

The main goal of this research project was to provide CAISO with the decision support capability to look ahead for the next 24 hours and predict whether the system will be able to get through the day without running into critical operating constraints. Specific objectives were to enable the simulation of various scenarios of power importation or other alternatives such as load reduction to find the best way to avoid such problems and to provide a functional specification for the development of a commercial version of the tool.

This project consisted of the development of a prototype tool based on the Electric Power Research Institute (EPRI) Community Activity Room that was evaluated using historical data and its predictions were compared with actual observations. The results of the research were presented in a workshop November 7, 2007 in Folsom, California, with the intent to make this technology available to any commercial software developer who wished to turn this method into a commercial product.

This project successfully developed the methodology for Critical Operating Constraint Forecast (COCF) tool, and used it in a prototype with support from CAISO for testing and demonstration. The results showed that this method is capable of forecasting loading of transmission paths over the next 24 hours, using current data on the transmission paths flows and assumptions about where the generation deficit would be supplied for the rest of the day.

The significance of this project is that a technically viable tool can be developed by commercial vendors of Energy Management Systems, using the functional specifications in a companion report of this project, which was presented and made available at the workshop mentioned above. The knowledge for developing such a decision support tool is now in the public domain.

EPRI continues to use the techniques of the COCF work in developing an industry tool for Visualization of Operating Boundaries and conducting research in support of on-line analysis and situation awareness in the control center. The research results were also used in a PhD thesis at Stanford, and in numerous professional presentations and publications.

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

To facilitate more economical high penetration of renewable resources without compromising system reliability, three tools were developed for the CAISO power grid operators to predict and display operational impacts of uncertainties in forecasts of loads and renewable generation. The first tool ("Ramping Tool") addressed real-time capacity and ramping requirements, the second ("Transmission Tool") addressed voltage stability and transmission congestion, while the third tool ("Day Ahead Regulation Tool") predicted capacity, ramping rate and ramp duration requirements of regulation, including upward and downward requirements, for each operating hour of a day. The Ramping Tool became an industry-grade product connected to the CAISO systems and operated in real time in the CAISO Control Center. The Transmission Tool and the Day Ahead Regulation Tool have been developed to the prototype stage.

2.2.1. Transmission Forecasting Tool

This work was to develop a prototype tool to identify transmission problems posed by the variability of wind and solar generation, 1 to 3 hours ahead, and inform operators about potential risks for the purposes of early warning and preventive control. The transmission tool prototype demonstrates the key features and advantages of the methodology developed, but development and integration with vendor-supported software at CAISO are necessary for deployment.

After the start of this project, CAISO implemented a PIER-funded real-time voltage stability analysis tool (see 3.2.1. CAISO Real-Time Voltage Security Assessment (VSA)), and advanced visualization and data processing tools. Based on the recommendation of the CAISO project support team, a decision was made to develop a transmission tool prototype and a methodology integrate it with the VSA and visualization tools already installed and used by CAISO. The connectivity issues were addressed in this effort from the methodology and system model perspective to provide future connectivity of the future industry-grade applications with the CAISO systems.

The developed methodology was based on statistical simulations and analyses of various sources of uncertainty that can impact the transmission network. The developed methodology also included a linear 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. 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 module, forecast error module, probability congestion module and interface module, were also demonstrated. Future work needed is to install and test the tool in a real control center using actual system models and data.

2.2.2. Ramping Forecasting Tool

The power system process that balances supply and demand, which includes scheduling, real-time dispatch (load following), and regulation processes, is traditionally based on deterministic models.

Uncertainties in forecasting the output of variable resources such as wind and solar generation, as well as system loads, were not reflected in existing energy management systems 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 as well as to the reliability of a power grid. Without knowing the risks posed by the uncertainties, system operators had limited means to weigh the likelihood of occurrence and the magnitude of problems to mitigate adverse impacts caused by them. Some important questions needed 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 from renewable generation. Providing the ability to forecast generation ramping requirement s made this research project a significant step forward toward the objective of incorporating wind, solar, load, and other uncertainties into power system operations.

A probabilistic algorithm was created to assess the capacity and ramping requirements, and a simulation was performed using the CAISO system model and data. Innovative methodology and software tools were developed to evaluate future generation requirements, including the required capacity, ramping capability, and ramp duration capability. 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.

As stated earlier, this tool has been put into routine use at the CAISO.

2.2.3. Day Ahead Regulation Requirement Prediction Tool

Regulation provides minute-to-minute system balance by adjusting power output of units connected to the automatic generation control system. At the time of this research effort, the annual price of regulation exceeded $120 million in California. CAISO is concerned that the increasing penetration of variable renewable resources in California could add to the amount of regulation needed. The loss of the regulation capability from the retirement of “once-through cooling ” generating units located along California’s Pacific coast was expected to compound the situation. (Unknown at the time, the later shutdown of the San Onofre Nuclear Generating Station exacerbated this problem.)

These challenges motivated CAISO to obtain a tool capable of predicting the needed procurement of up- and down-regulation services in the day-ahead market.

This project developed an approach for procuring regulation capacity that would minimize the regulation capacity required during some operating hours without compromising CAISO's control performance characteristics. Three methods were developed that differed by the approach used to calculate the regulation requirement and by the type of control performance criteria used. All three methods use historical information, obtained prior to the analyzed operating day (a moving window for a user-specified period). A prototype tool for estimating regulation requirements accommodating the new control performance standard was developed and simulations showed that CAISO regulation requirements could be substantially reduced.

The project identified next steps that would increase the robustness and performance of the prototype tool, while handling imperfect information typically available in control centers.

The results of these three research efforts just described have been used for numerous follow-on or related funded efforts (about $4 million) that complement the PIER funding. The CAISO is modifying the Ramping Tool to move it to production level for 24/7 operation in the Control Center. Building on this research, AWS Truepower (project manager), CAISO, Southern California Edison (SCE), and Siemens are participating in a DOE SunShot project, "Comprehensive Solutions for Integration of Solar Resources into Grid Operations," to demonstrate integration of uncertainty information into grid system operations and probability-based controls. Based on the Ramping Tool development, a Dynamic Interchange Adjustment tool (DINA) was developed for Independent System Operator-New England (ISO-NE). This probability-based tool predicts the secure range of intra-hour interchange adjustments to trading balancing capacity with the neighbors. ISO-NE intends to move the tool to a production level. Some key concepts developed in this research just described will be used for new research projects in predictive state estimation being done by Pacific Northwest National Laboratory, who was the principal investigator and developer for these three tools with Bonneville Power Administration (BPA) and DOE.

Use of some of the tools for online analysis and visualization of operational impacts of variable renewable generation demonstrated the capability to eliminate real-time market price spikes. For example, ISO-NE will be able to show other ISOs that its balancing capacity can be traded with its neighbors without compromising its grid performance and reliability.

2.3. Wide-Area Energy Storage and Management System (WAEMS) to Balance Intermittent Resources in the California ISO

The higher penetration of variable renewable generation resources in the CAISO and BPA control areas may require expensive additional fast grid balancing services and fast up and down power ramps in the electric supply system. The successful use of wide-area energy storage to reduce the need for more expensive fast acting balancing services depends, due to statistical fluctuations, on the collective power grid regulation of the two control areas being less than the sum of individual area needs. This issue was addressed through the exchange of variable renewable energy between the participating control areas and the use of energy storage, dispatchable load, and distributed generation resources.

The goal of the multiphase effort was to develop principles, algorithms, market integration rules, functional design and technical specifications for a wide-area energy storage and intermittent energy exchange management system to mitigate unexpected rapid changes in wind generation power output. The results of this phase provided specific numerical information necessary for a detailed wide-area design system design.

An evaluation showed excellent performance of the 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 has the same fast-response characteristic (within six seconds) as that provided by flywheel energy storage alone, the fast acting energy storage used in this project, and reduces wear and tear to allow the hydro unit to operate more effectively.

The break-even price for flywheel energy storage to provide bi-directional service (1 MW regulation-up and 1 MW regulation-down) at the time was $20.37/MW. Because the average bi-directional regulation price of the CAISO balancing authority was $11.95/MW (January-July, 2010) and that of the BPA balancing authority was $9.38/MW (2010), regulation service provided by a stand-alone flywheel energy storage was projected not be economical unless the regulation price increased or the fast regulation service would be paid at a higher rate. Assuming that the minimum regulation price of regulation provided by a hydro power plant was $4/MW, the breakeven price of the combined flywheel-hydro regulation service was calculated to 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 was expected to become economical in the CAISO and BPA balancing authorities soon.

The technology developed potentially enables a 50 percent or more reduction in the regulation capacity requirement when implemented. Utilization of this approach by utilities is currently pending. This research resulted in almost a dozen professional publications.

2.4. Improved Generator and Load Models

It is important for grid planners and operators to be able to forecast how various electric grid components will behave under stressed conditions. Generator and load models are used in computer simulations of the electric grid to predict power flows and dynamics under different circumstances. Variable renewable generators and new types of consumer appliances, as well as distributed generators, connected to the electric grid are rendering the old generator and load models inadequate. This situation threatens the planning and operation of a reliable and cost-efficient electric supply and delivery system.

2.4.1. WECC Wind Generator Modeling

Older wind turbine models used in transmission system planning and reliability analyses were inaccurate, and did not represent the new generation of wind machines correctly, adversely affecting economic and reliable operations.

Proprietary models of wind turbine manufacturers for specific generators were not appropriate for use in a collaboratively controlled transmission system such as the WECC, including California, creating a need for developing standard, non-proprietary wind turbine models. While the models were designed specifically to meet WECC modeling requirements, the results could also be used by the industry as a whole throughout the world, thereby advancing the deployment of wind power globally.

This research project, which was a joint effort of the California PIER TRP and DOE's National Energy Renewable Laboratory (NREL), improved transmission planning and operating modeling tools needed to better prepare the transmission grids in western North America to accommodate growth in wind power generation to meet Renewable Portfolio Standard goals, especially California's. These are the first-ever accurate, non-proprietary models of the various types of wind turbines in commercial use today, and are now in the permanent library of software for General Electric's Positive Sequence Load Flow, Siemens Power Technologies International's Power System Simulator for Engineering (PSSE), and PowerWorld's Simulator, used by grid managers around the world. The widespread adoption of these models developed and validated in this research helps assure a competitive source of commercially available software compatible with California's electric grid needs, and its on-going maintenance and updating. This project also developed an equivalencing methodology, validated by Hydro Quebec, to aggregate individual wind generators into a model that represents an entire wind power plant.

This research created far-reaching interactions among many entities in the wind generation industry around the world.

CAISO is benefiting in its studies of integration of renewables into the California grid. It also helped to build a bridge between the power engineering and wind energy communities to improve California's ability to add renewables reliably to the grid.

This research has been identified by the National Energy Reliability Corporation (NERC) as an area of significant need in the report of the NERC Integrating Variable Generation Task Force as being in the national interest by providing a secure power grid. The result of this work are in line with FERC Order 661 and 661A and are in the national interest in providing a secure and reliable power system grid.

These wind generator dynamic models formed the foundation of other renewable energy dynamic models. For example, the WECC PV dynamic model was developed based on the Type 4 Wind Turbine Generator dynamic model developed and validated in this research project. The dynamic model of Adjustable Speed (AS) Pumped Storage Hydro (PSH) power plant was developed based on the Type 3 Wind Turbine Generator dynamic model.. This AS-PSH model is currently being implemented as a "user defined model" on the PSSE software platform before moving to the permanent PSSE library. These dynamic models were also implemented, with some technical support from NREL, on the PSCAD ® platform by NREL and implemented on the RSCAD ® platform, which is the main interface for Real Time Digital Simulation used by SCE.

Education has also benefited from this research project. The Equivalencing Wind Power Plant method developed is being used in Power System courses. These dynamic models have been implemented by the national Power Systems Engineering Research Center (PSERC) and its academic members as planning tools, research tools, and teaching materials for power engineering students.

Because of the widespread impacts this research has had, numerous follow-on research projects have been spawned around the world. The DOE Office of Energy Efficiency and Renewable Energy has funded subsequent works related to Solar/PV dynamic modeling (NREL and Sandia National Laboratory) and Adjustable Speed Pump Storage Hydro AS-PSH (NREL, Idaho National Laboratory, and Argonne National Laboratory) in both positive sequence dynamic modeling and electromagnetic transient modeling. The WECC Renewable Energy Modeling Task Force continues with extension of the WECC Wind Generation Modeling. As a follow on project, the WECC Renewable Energy Modeling Task Force has developed "Specification of the Second Generation Generic Models for Wind Turbine Generators" prepared under Subcontract No. NFT-1-11342-01 with NREL (collaboration between NREL, Sandia, EPRI, and WECC). Tutorials on dynamic modeling for renewable energy are offered periodically to the members of the WECC, which included California utilities. Numerous workshops and professional publications have been based on this research. All of these works have benefited and have leveraged the previous work of the PIER-funded WECC Wind Generator Modeling research.

2.4.2 .Load Modeling Transmission Research

Existing dynamic load models do not correctly represent actual observed modern load behavior. For example, the dynamic effects of the addition of residential and commercial solar photovoltaic generators on nearby customer loads are largely unknown. Fault Induced Delayed Voltage Recovery (FIDVR) caused by the stalling of residential air conditioners after a brief power instability, was another important modern load behavior occurring in Southern California and the U.S. Southwest not adequately modeled that urgently needed resolution because it threatened the security of the California and WECC grid.

This research addressed the voltage instability in Southern California that occurred after a brief voltage disturbance in the electric grid. Load modeling improvement resolves this problem through better predictability of damping and stability issues related to the California-Oregon Intertie critical to the security of the California and entire WECC system. Better understanding of anticipated network behavior aided in planning for the appropriate deployment of electric grid infrastructure investments. It sought to improve the accuracy of dynamic load models used in power system analysis and simulation tools by providing (1) an accurate model of residential air conditioners, (2) potential solutions to FIDVR, and (3) tools and methodologies for determining the mix and balance of different types of electrical loads. This project also included a scoping study that investigated the impact of increasing penetration of residential and commercial photovoltaic systems on load modeling accuracy. This research was a coordinated effort by members of the WECC to enhance the understanding of the behavior of loads, especially air conditioners, and to improve simulations of dynamic behavior of the power system. Because of the prevalence of this problem in Southern California, SCE was one of the leaders of this research, with PG&E and SDG&E as significant contributors. Significant staff time was provided by a number of utilities and grid operating entities in the Western Interconnection in reviewing and implementing the composite load model. Two major project participants, SCE and BPA, made in-kind contributions of approximately $170,000 and more than $1M, respectively.

Extensive testing of single-phase residential air conditioners, under various voltage and frequency transients, resulted in both an accurate dynamic model and confirmation of air conditioners as the cause of FIDVR. A new load composition tool to help build load models for simulations was developed. An uncertainty analysis was completed that led to a recommendation for future load monitoring to validate the tool. Manufacturing standards were recommended to deal with the issue in the long term.

Dissemination of project results was accomplished via the WECC Load Modeling Task Force, conference presentations, technical papers, and interactions with utilities and air conditioning unit manufacturers.

This research paved the way for the development and implementation of the composite load model – the most significant grid modeling advancement of the last decade, and has been implemented in all major commercial grid simulators used in North America (see 2.4.1. WECC Wind Generator Modeling). The model has been approved for planning and operational studies in the WECC, including California, which are used to make capital investments in the power grid and compliance with NERC Reliability Standards. The operating studies are used to set system operating limits. The electric grid planning and operations in California and the WECC are better prepared with the potential to reduce large-scale system outage caused by FIDVR.

3. New Technology for Increasing Transmission Capacity by Optimizing the Grid for Greater Power Flow

Underinvestment in transmission infrastructure in the latter decades of the 20th century had resulted in congestion and threats to reliability, and was a barrier to meeting California’s renewable energy goals.

Transmission lines have physical limits on the amount of power that can be transmitted, which depend on the conditions of that particular line and the broader wide-area transmission grid. There are two fundamental classes of limits, thermal and stability, the latter of three types: voltage, transient and dynamic. The technological sophistication of situational monitoring was never accurate or precise in the past, conservative static operating limits had been set that were often far below the physical limits, which in effect de-rated the capacity of a line, often by 20 to 50 percent or more.

Emerging technologies could reduce the margins of operating limits required for safety, and even raise the physical limits, thereby adding substantial “new” capacity without building new transmission lines or reducing reliability. These capabilities would prove vital to meeting renewable energy goals if building all needed transmission capacity falls short, especially in dense urban load centers. It might be preferred as a cheaper way to get greater transmission capacity through optimizing operations for greater power flow.

3.1. New Capacity Thermal Capability

Thermal limits are static constraints imposed on the amount of power or current a line can carry, under all anticipated conditions, before reaching limiting temperature, above which excesive line sag or physical damage may occur. The TRP explored ways to relax the conservative static limit by enabling current flows closer to the real physical limit through real- time “thermal” rating monitoring, yielding incremental capacity increases. It also sought to increase the physical thermal limits through new line conductor material technologies. These new materials could handle considerably higher temperatures without excessive sagging or damage. They did, however, require some special handling during installation because of a greater susceptibility to damage from excessive bending. New connectors and special splices were required in some situations. TRP monitored a field demonstration of one of these new conductors at a California Independently Operated Utility (see 1.2. Demonstration of Advanced Conductors for Overhead Transmission Lines).

3.1.1. Multi-area Real-Time Transmission Line Rating Study

Prior PIER research showed that thermal limits and voltage limits interact to cause combined dispatch restrictions in California’s transmission network. This project focused on finding solutions to this problem, using the Sacramento area as a test bed because thermal limitations in the Sacramento area interacted with voltage constraints to restrict economy energy imports into the area.

The objectives of this project were to identify conditions where combined constraints restricted dispatch, and to investigate prediction of line ratings in the timeframe that would be useful for dispatch purposes.

The project found that one of the key limitations on economy power imports into the Sacramento area was the thermal static line rating of the O’Banion-Elverta 230 kV circuits, which resulted in at least three curtailments of the Sutter hydro generation facility during the time period of the study. Increasing the thermal rating above the static limit of the O’Banion-Elverta circuits by 20 MW with real-time thermal ratings, the minimum possible during the curtailment periods, could increase import capacity to the area by over 250 MVA, or by about ten times, due to increased flow now allowed on adjacent circuits in addition to the O’Banion-Elverta lines.

Extensive studies of various available rating prediction algorithms were conducted. None of the algorithms were found to have acceptable accuracy for predicting ratings in the targeted time range of 4-24 hours. The day-to-day rating patterns usually exhibited a high degree of similarity, especially during the summer, but the actual predictability of rating values varied greatly. The O’Banion-Elverta circuits had a median real-time rating of approximately150 percent of the static rating, but only a 110-115 percent capability with a probability of 90 percent during the most critical loading periods (late afternoon – early evening). Conversely, the lowest real-time ratings could occasionally be slightly below the static rating. Ratings were always safely over the static rating at night, but the circuits were never heavily loaded.

Ratings had “persistence” even though they were not sufficiently predictable to be used for daily dispatch purposes. That is, ratings could increase rapidly during a storm, for example, but ratings could not decrease rapidly, which would require either a rapid increase in ambient temperature or an abrupt reduction of kinetic energy in the atmosphere. Persistence of ratings could have a major impact on the management of contingency events in the network. It could increase operating economies because operators could either avoid changes in system dispatch, or minimize them via other available remedies. It could also substantially increase system reliability, especially during times of high system loads.

3.2. New Capacity Voltage Stability Capability

Operators may not know how susceptible the system is at any given time to undesirable voltage changes as a function of power transfer, which could lead to voltage collapse and a resulting blackout. Voltage stability constraints on power flow capacities of lines are intended to provide margins for safety in the absence of precise knowledge. The TRP developed and demonstrated a predictive analytic and modeling voltage security analysis tool for improving situation awareness and permitting smaller, better defined, constraint margins. Rights to the technology were obtained by a vendor that commercialized the new tool.

3.2.1. California ISO Real-Time Voltage Security Assessment (VSA)

Analysis of over two dozen blackouts indicated a need for developing real-time tools for monitoring system voltage security margins under normal and contingency conditions. Use of real-time security monitoring on a regional scale would prevent future voltage collapses. Following the June 2-3, 1996, major blackout in the WECC system, including California, DOE recommended that the WECC should consider the use of real-time security monitoring on a regional scale to prevent future voltage collapse events. The WECC pursued a security monitoring and analysis tool that would enable operators to identify potential problems and take corrective action.

This project was to provide CAISO with a prototype voltage security assessment tool that runs in real-time within CAISO’s reliability and congestion management system. The project developed a prototype that incorporated state-of-art algorithms (such as the continuation power flow, direct method, boundary orbiting method, and hyperplanes) into a framework most suitable for operations. A functional specification was prepared for a commercial grade system that CAISO has used to procure a production-quality tool that is now a part of a suite of advanced computational commercial tools provided by Bigwood Systems, Inc., a developer and vendor of software tools for power grid assessment, monitoring, analysis, operation, control and optimization, located in Ithaca, NY (headquarters) and San Francisco, CA.

3.3. New Capacity Transient Stability Capability

The time frame for the transmission grid to regain its equilibrium after a transient disturbance, such as a line fault or generator trip, is typically milliseconds to seconds. Generator and load models are used to plan the operating configuration of the electric transmission system to anticipate and better handle transient behaviors. But if the models are inaccurate, then the operating plans might not be able to address certain transient behaviors potentially leading to reliability and power quality problems. The TRP improved the generator models for wind generators, and the load models for new air conditioner technologies. These models are now in use in California. (see 2.4. Improved Generator and Load Models)

3.4. New Capacity Dynamic Stability Capability

Dynamic stability is the ability of the transmission grid to regain its equilibrium over 1-30 minutes. Problematic instabilities can manifest in a number of different behaviors, with low frequency oscillations being one of the most egregious in the Western grid as a reason for transmission line capacity de-ratings. Low-frequency oscillations, which cause power to surge back and forth through wide areas of the grid, typically have a period of a few seconds and can build over periods of minutes to hours. They have been identified as the initiating event of some costly major multi-state blackouts, such as the widespread blackout in the western United States and Canada in 1996. The root causes of these dynamic instabilities were not all well known and research was needed. There is a growing concern that these dynamic instabilities might be exacerbated by changes to the electric system, such as renewable energy sources that reduce system inertia and add more uncertainty, and energy efficient loads that introduce new dynamics, as well as uncertainty (see 2.4. Improved Generator and Load Models).

The TRP conducted a significant number of research efforts to develop and demonstrate stability operating tools based on synchrophasor measurements, which were new current and voltage measurement devices using time-stamping that for the first time enabled wide-area real-time status and event monitoring, detection, alarming, analysis, and visualization. The resulting tools enhanced the operator awareness for greater reliability and promised the transmission system the ability to use smaller dynamic margins. In conjunction with certain control technologies, for example energy storage, these tools might be used to mitigate dynamic instability threats, such as to damp oscillations.

The TRP conducted a business case study for the use of synchrophasor measurements that examined applications and their economics, and include a roadmap for technology development (see 3.8.1. A Business Case Study on Applying Synchrophasor Measurement Technology and Applications in the California and the Western Electricity Coordinating Council Grid). This study provided guidance for California. It encouraged TRP research in synchrophasor measurement based tools for rapid oscillation detection, analysis and mitigation; enhanced state estimation; smart adaptive relaying to prevent protection system actions from aggravating cascading blackouts; and voltage angle changes for stress indication. The TRP also contributed to the development of the platform for gathering and managing synchrophasor measurement data, and enabling application deployment. Much of this research has resulted in commercial products and uses.

3.5. New Capacity Transmission Expansion Planning Capability

Traditional deterministic planning tools increasingly became inadequate to support accurate expansion planning in a future of growing uncertainty and complexity, which was expected partly because of the growing use of variable renewable generation. The TRP anticipated that new planning tools based on probabilistic, multivariate statistical, risk assessment, and other advanced analytical science and mathematical techniques, along with faster computational tools, would be needed.

3.5.1. Extreme Events

A small initial power system disturbance can cascade into a complicated chain of dependent failures leading to a widespread blackout. Although such extreme events are infrequent, they can disrupt commerce, vital infrastructure and societal security with economic costs to society potentially in the billions of dollars for each event. Current planning practice for assuring the reliability of a large electric grid interconnection, such as the WECC, is to plan the configuration and operation of the grid for all contingencies involving the failure any one of these components, known as an “N-1” planning analysis. The computational logistics of studying all possible contingencies of two or more simultaneous component failures is highly impracticable or even impossible, even with today’s supercomputers. Another, more efficient, approach is needed. Recall that one of the recommendations of the Transmission Cost Allocation Methodologies project described earlier was the Quantification of Extreme Event Benefits (Insurance Value) (see 1.1. Transmission Cost Allocation Methodologies).

The TRP took on the challenge to develop just such a planning tool for cascading blackouts, aiming for new and innovative methodologies to simulate extreme events, and to determine the remedial actions that would allow system operators to keep the power system from collapsing and planners to enhance the grid’s resistance to cascading outages. This research pursued multiple approaches in order to better determine the strengths and weaknesses of both existing methods and the new methods, e.g., probabilistic, multivariate statistical forecasting, developed in the project, and produced encouraging results that these techniques would work to better characterize the resistance to cascading outages for a given or planned grid infrastructure configuration.

The “Extreme Events” research project developed and tested in a small-scale network model, the science and conceptual framework and advanced mathematical techniques needed for the complexity of multiple component and system failures in a transmission system, such as the "N-20" equivalent analysis. Results included identification of critical corridors, event frequency and probability, and superior operational response strategies. Phase II applied Phase I methodologies to realistic network models to test their practicality.

The project achieved a number of firsts in the analysis of large interconnections and cascading outages:

- Developed the first, full-size WECC model for cascading analyses using TRELSS, an EPRI software package for bulk power transmission system reliability evaluation using contingency enumeration as an expansion of traditional deterministic analysis.

- Developed a methodology and extensive sets of initiating events for cascading analyses in the Western Interconnection.
- Performed a total of 33,000 simulations to analyze the WECC system vulnerability to cascading events, that provided:
  - a ranking of initiating events by severity
  - an identification of the most frequent sequences of cascading outages (critical events corridors)
- Developed a reduced, 1500 bus WECC model that has been the basis of several other analyses.

The DOE Office of Electricity subsequently funded $1.25 million to the Pacific Northwest National Laboratory (PNNL), the principal investigator for the PIER-funded “Extreme Events” project, to conduct a new project, “Dynamic Contingency Analysis Tool” (DCAT) that will leverage the experience from the “Extreme Events” project and will overcome several of the gaps that were identified in the that effort. The purpose of the project is to develop a dynamic extreme events analysis tool to evaluate the risk of load loss due to extreme events, identify the most probable and impactful events, and evaluate the impact of system reinforcements. This tool should strengthen the capabilities of grid planners to assess the impact of extreme contingencies and potential cascading events across their systems and interconnections. The project directly supports new NERC “Standard TPL-001-4 Transmission System Planning Performance Requirements” to be enforced in 2015 and 2016, and a similar “Transmission System Planning Performance WECC Regional Criterion TPL-001-WECC-CRT-3” currently under development in the WECC system.

The “Extreme Event” project resulted in numerous professional publications.

3.6. Transmission Congestion Assessment and Probabilistic Forecasting

Congestion costs in California can be high and mitigating these costs involves long term planning and expensive upgrades to the grid, such as new transmission lines. In 2004, the CAISO’s gross congestion and Reliability Must Run Generation (RMR) costs were estimated to be $1 billion annually, with congestion accounting for approximately half of the total, which did not include congestion on non-CAISO transmission facilities. Improved understanding of the nature of California’s congestion issues is a necessary precursor to effectively managing the problem. Improvements in congestion management will help achieve the State’s goals for CO_2 reduction and renewable generation deployment, and to provide reliable and low cost electricity with minimum environmental impacts.

3.6.1. California Transmission Congestion Assessment

This project documented the scope and magnitude of the congestion problems facing California and reported the challenges in forecasting.

The scoping study found that the CAISO congestion cost data understated the congestion. It captured information related only to schedules attempted, and not the full economic potential for transactions. Inter-zonal congestion caused higher prices for all energy within the zone. RMR was the largest single component of congestion costs. Without the construction of new local generation, RMR costs could only be reduced by expanding the transmission capabilities into constrained local areas. Congestion could be avoided by planning and constructing sufficient transmission in advance to manage remaining congestion costs to acceptable levels. Metrics would be needed to identify and classify congestion costs as actionable, manageable, or to be monitored.

3.6.2. Probabilistic Transmission Congestion Forecasting

There are many factors that combine to determine how electricity flows on an interconnected power grid, and the uncertainties of these factors compound the difficulty of forecasting transmission congestion for any particular transmission path. This difficulty will be more pronounced with high penetrations of variable renewable generation in California. Making forecasts under high uncertainty often means using probabilistic methodologies.

This research developed new probabilistic forecasting methods for short term and long-term transmission congestion in California, for use in transmission planning and forecasting tools that recognize uncertainties created by independent market participants. The mathematical models and the time frames of the simulation differ between the short term (24 hours) and the long term (10-20 years), therefore two computer models were developed. This research determined and specified how to model the key input assumptions in order to derive valid confidence levels of the forecasted congestion variables.

For long term probabilistic forecasting, the quality of results was highly dependent on load forecasts and future resource projections, but probabilistic forecasting gave significant information regarding incremental improvements and timing of future transmission upgrade requirements. Short term simulations also showed a strong dependence on load forecasts and on generation dispatch. It was found that high variability in daily wind patterns that affect wind generation, would increase congestion and the uncertainty of forecasts.

This project developed an approach that accounts for significant uncertainty caused by load and generation forecasts as well as random unplanned equipment outages. CAISO reports that annual congestion costs on the California-Oregon Intertie path increased to $12 million in 2006 from $6.7 million in 2005, with costs expected to increase. Improvements in congestion management would save costs and help achieve California’s goals for reducing greenhouse gas emissions and providing reliable and low-cost electricity to California consumers with minimum environmental impacts.

Building on this start, EPRI, the principal investigator, has continued development of probabilistic forecasting capabilities, including for wind power integration. Many of the forecasting and hedging techniques developed in this connected collection of research are available to ISOs, energy traders, and utilities.

3.7. New High Power Managing Capability

Increasing the power flow capacity of transmission lines raises the risk of grid equipment damage, injury, and greater security and reliability vulnerabilities from more power being concentrated in fewer pathways. The TRP research in extreme event analysis (see 3.5.1. Extreme Events) addressed the latter threat in part. Protecting the grid and people from higher fault currents, however, required new hardware development because in many cases anticipated fault currents threatened to exceed the ability of existing circuit breakers to safely and reliably interrupt the faults. This required a new class of higher capability circuit breakers that are not readily available from vendors, are expensive, or are of uncertain reliability. New types of equipment called fault current controllers were currently in the RD&D phase, with several manufacturers testing prototypes in the 15 kV class. Prototype devices needed to be demonstrated in actual utility systems in order to identify implementation issues and utility resource requirements, and to provide the requisite field experience to refine the designs for utility acceptance. The TRP developed a project to test prototypes in the field with SCE as the host for the demonstration.

3.7.1. Development of Fault Current Controller Technology

Overall electric current loading on the transmission system has been rapidly climbing due to the growth in demand for electricity, which has increased the potential fault current magnitudes at locations throughout the transmission system. Fault currents, in many instances, may exceed the capability of existing protection systems (circuit breakers) to interrupt the faults safely and reliably, and represent an imminent threat to electrical equipment and the safety of utility workers and the public. Consequently, utilities must either upgrade their circuit breakers and associated equipment, or reconfigure their systems to reduce the potential fault current. Both solutions are costly, and frequently reduce system reliability and power transfer capability. Application of fault current controller (FCC) technology, also frequently referred to as fault current limiter (FCL) technology, has been identified as a viable solution for managing fault currents to keep them within the existing short circuit capacity ratings of the system.

This project developed and evaluated two prototype designs of FCC technologies. The work established criteria for FCC performance and tested the new designs against those criteria. The ultimate program goal was to enable the commercialization of FCC technology for the benefit of California and the United States.

When the project started, there were no industry standards for such a device, complicating the development of testing protocols. There were significant engineering challenges in developing the prototypes to withstand the currents and voltages in the field. Finally the prototype FCCs had to meet SCE’s specifications for field demonstration on their system. The FCCs had to demonstrate the ability to withstand live circuit events and severe environmental conditions.

The project was a focused effort to develop a workable test plan, which needed to incorporate engineering standards for electrical apparatus. Zenergy Power worked closely with Georgia Tech's National Electric Energy Testing, Research and

Applications Center and several of its member utilities, including SCE, to implement a detailed FCC test program based on selected IEEE and CIGRE standards and protocols for transformers and reactors. The EPRI/Silicon Power team created their plan based on ANSI C39.09-1999 and ANSI C37.06-2000, covering the entire spectrum of possible tests that needed to be carried out on their FCC, including component level factory tests, system level factory tests, acceptance tests, and system field tests.

This project led to the successful field demonstration of the Zenergy Power high-temperature superconducting (HTS) FCL, marking a milestone event in the history of FCL development. The experience gained from the research contributed to a more reliable controller, a dramatic reduction of the FCL's size (with a slight increase in weight), and the replacement of liquid nitrogen cryogenic refrigeration by a low-maintenance, dry (i.e., non-HTS) cooling system for increased reliability and reduced maintenance.

HTS FCL technology is being improved to reduce basic device manufacturing cost, and it is being scaled up for higher voltages and currents. The latter may be more important in terms of value. Larger renewable power generators will connect to the transmission system, and high-voltage tie-lines have become more common as more power comes from long distances and as grid interconnections occur to improve reliability and better control power flows. Higher-rated components cannot be retrofitted in the available space, leading to lengthy and costly major upgrades of grid infrastructure. Economic studies and performance models show that at current performance levels and price points, FCC technologies can be very cost-effective compared to major upgrade projects at high voltages.

The Zenergy Power HTS FCL project has already led to a scaled-up design for a transmission-level 138 kV FCL application, which Zenergy is actively marketing to utilities around the world.

The EPRI/Silicon Power Solid State FCL represents another potentially cost-effective solution to the rapidly increasing fault current levels in utility systems. One advantage of this type of FCL is the flexibility to be configured as either interruptive (i.e., to act as a "solid-state circuit breaker") or as simply limiting the fault current (and leaving the fault interruption to existing protective devices), with only minor design differences. A solid-state FCL may be used to limit the current of superconducting cables to enable the use of smaller cable sizes. The solid state FCL also has a unique capability to limit inrush currents, even for capacitive loads.

The EPRI/Silicon Power team identified some potential thermal management issues in their initial design. An improved system design was completed, and the major technical design challenges, such as the thermal management system, and the control circuit architecture and timing issues, were resolved. The cost to construct the device was constrained by the project budget. Thus, this FCL prototype was not able to advance to the laboratory test and field demonstration stages under this project.

The FCC technology is a cost-effective alternative to the capital-intensive upgrades of the power system. The demonstration projects in this phase have already resulted in two test plans and two full FCC designs, and have contributed to one commercial sale and one migration to a transmission-level application.

Advanced development of FCC technology is strongly recommended and should be put on a fast-track to maintain the required levels of electric system availability and reliability. Significant amounts of investments in capital upgrades are potentially avoidable, if suitable FCC technologies are made available to California utilities. An accelerated program of FCC technology focused on reducing the cost, improving the reliability, and increasing the voltage and current ratings of FCC technology is needed.

3.8. Real-Time System Operations

3.8.1. A Business Case Study on Applying Synchrophasor Measurement Technology and Applications in the California and the Western Electricity Coordinating Council Grid

Phasor measurement units (PMUs) collect time-synchronized grid data to provide real-time information about the status of a point on the grid, and the development of synchrophasor measurement-based technologies is needed for securely and reliably operating the modern electric transmission system under growing uncertainty, such as created by high penetrations of variable renewable generation connected to the electric grid.

The value of synchrophasor measurements is proportional to their deployment throughout California and the WECC, because of the heavy reliance California places on having access to power imported from states throughout the West. Transmission owners and operators will usually deploy new technologies only if a business case can be made. This business case study provided sound rationales for the investment needed to obtain the benefits of these tools.

This “business case” study evaluated the potential benefits, costs and understanding of who benefits and who bears the cost of expanded deployment of synchrophasor-based technologies, and what are the best research and development opportunities to advance the most promising applications of this technology for the benefit of electricity consumers and the electric industry. It provided organized consolidated information for use by the electric industry, policy makers, and researcher planners. This study was conducted to identify economic and financial barriers to commercial deployment, and technology development gaps. Especially important in this case, it also sought to obtain information to help develop technology transfer strategies and educate potential users for increased adoption of these technologies. It found that synchrophasor measurements would enable improvements in planning, operating, and maintaining the electrical grid that would otherwise not be possible.

It identified a large number of existing and potential applications of synchrophasor measurement technology.

Two key areas would benefit from applying synchrophasor measurement technology:

- Analyzing and avoiding power outages that can lead to catastrophic blackouts. Synchrophasor measurement applications can improve early warning systems to detect conditions that lead to catastrophic events, help with restoration, and improve the quality of data for event analysis.
- Improving market and system operations. Synchrophasor measurement applications help facilitate congestion mitigation through better system margin management. They also allow real time knowledge of actual system conditions as opposed to conditions defined by system models that may not reflect current conditions. In addition, state estimation solutions can be improved significantly for use in locational marginal pricing calculations, thereby improving the overall accuracy of the calculations and the associated energy clearing charges.

The results of this study served as a base to develop a near-, mid-, and long-term development and deployment roadmap. This roadmap and the process to transition PMU technology to full commercial application in California and the WECC, were key outcomes of this study that helped California, the WECC and the overall industry benefit from PMU technology.

The study raised industry awareness of the benefits of using PMU technology to improve grid reliability and support various grid applications. This report communicated both to industry executives and technical leaders that PMU data are the foundation on which various wide-area monitoring, protection and control applications, including wide-area situational awareness, could be built.

DOE used results of this report to identify and justify needs for Smart Grid investment in Transmission. A majority of funding for transmission was related to the synchrophasor technology for the DOE Smart Grid Investment Grant, and sections from the report were used in the DOE solicitation. Investments co-funded by DOE plus other private entities (such as SCE and SDG&E) resulted in deployment of approximately 1,700 PMUs by 2013. SCE has used the results of the report to justify investment in PMUs for their rate case, which was approved. SCE has invested heavily in order to deploy synchrophasor technology. The North American Synchrophasor Initiative, initially funded by DOE and later by NERC, used the PIER synchrophasor roadmap as a base for their roadmap.

It is believed that vendors have used the report results and the roadmap to guide their deployment. Utilities and RTOs have used the report results and the roadmap to guide their plans. Researchers in academia have used the results as guidelines for research initiatives. Activities initiated by this report have influenced international research and deployment of synchrophasors. Concrete examples from a number of countries around the world include Brazil, Columbia, and India.

3.8.2. Real-Time Applications of Phasors for Monitoring, Alarming and Control

The efforts funded for this project represent one phase of a multi-project RD&D activity that was being coordinated by the Consortium for Electric Reliability Technology Solutions (CERTS) for the Energy Commission’s TRP. The overall goal of the synchrophasor applications project was to accelerate adoption and foster greater use of new, more accurate, time-synchronized phasor measurements by conducting research and prototyping applications on the CAISO's synchrophasor platform that provided previously unavailable information on the dynamic stability of the grid. This platform is called the Real-Time Dynamics Monitoring System (RTDMS).

The key result of this project was the development of the RTDMS. Feasibility assessment studies utilizing synchrophasor measurements validated and improved existing stability nomograms, evaluated small-signal stability monitoring algorithms, conducted frequency-response analyses, and obtained real-time sensitivity information on grid-stress directly from synchrophasor measurements. The project successfully developed prototype applications offering a rich set of features for wide-area monitoring and analytics, which were factory- and field-tested at the CAISO and at BPA. In addition, two new dedicated displays for measurement-based angle sensitivity and voltage sensitivity were developed as key indicators of grid-stress and proximity to instability.

This led the CAISO to adopt time-synchronized phasor measurements for real-time applications in the WECC, and also made significant investments in the underlying hardware and supporting maintenance practices to host the prototypes and enable needed future research to develop functional specifications to facilitate acquisition of commercially-supported, production-quality tools. The project team recommended continuing RD&D for prototype applications towards development of functional specifications that CAISO can use to acquire production-quality tools from commercial vendors. The funding for this research came from three sources: U.S. DOE, the Energy Commission/PIER, and the Electric Power Group (EPG) in Pasadena, CA. EPG continued to invest in RTDMS after the Energy Commission/PIER and DOE funding ceased.

Since this research was done, the RTDMS and applications have been deployed at, in addition to CAISO, other major independent system operators, including PJM, New York ISO, the Electric Reliability Council of Texas and many utilities including Duke, Dominion, Lower Colorado River Authority, Salt River Project, ONCOR Electric Delivery Company, SCE, Los Angeles Department of Water and Power, HydroOne, and the Southern Company.

RTDMS has been deployed at different universities such as UCLA Smart Grid Energy Research Center, University of Illinois, Clemson, and Texas Tech University. It has been integrated with Intel technology for cyber security protection of critical infrastructures and demonstrated as integrated software (RTDMS with Security Fabric) at Texas Tech University. Three patents have come from the work: US 7,233,843 B2, dated June 19, 2007, US 8,060,259 B2, dated November 15, 2011, and US 8,401,710 B2 dated March 19, 2013. SCE has utilized RTDMS in their RTDS Lab in Westminster, CA.

Here are some examples of cases where the RTDMS has been used:

- Detection and corrective action for Pacific DC Intertie Integration with EMS/SCADA systems.
- Detection and mitigation of oscillations from wind power plants' faulty controller settings.

- Simulation and replay of system events for use in training.
- Wide-area situational awareness monitoring by ISOs covering large regions.
- Monitoring of dynamic metrics – phase angles, oscillations, damping, voltage and angle sensitivities, frequency instability.

- Automated event analyzer displays for diagnostics of events in real time to guide operator actions.

Numerous presentations and papers presented in different industry forums, such as WECC Joint Synchronized Information Subcommittee, NASPI, and IEEE.

3.8.3. Real-Time Oscillation Detection, Analysis and Mitigation

Electromechanical oscillations occur frequently on power grid systems that often die out on their own, oscillations can lead to grid instability and potentially large-scale blackouts costing billions of dollars (also see 3.4. New Capacity Dynamic Stability Capability). In August 1996 a western system breakup resulted from undamped system-wide small-signal oscillations. About 7.5 million customers (24 million people) lost their power supply for several minutes to 6 hours, principally in 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.

Therefore, significant efforts have been devoted in the past few decades to monitoring system oscillatory behaviors from real-time measurements. The relatively recent development and deployment of PMUs have provided the capability to obtain in real-time over the entire interconnection, high-precision time-synchronized data needed for estimating oscillation modes. A mode is the characterization of an oscillation in terms of its (modal) frequency and shape used to communicate the nature of an oscillation to grid operators and engineers.

The methods and tools developed in these two projects described here provide grid planners and operators the potential to have significant impact on power grid operation, as it will improve reliability and avoid significant economic losses, especially under high penetrations of variable renewable generation. This research laid the foundation for achieving the goal of not only the rapid detection and analysis of oscillations but also their control through proscribed grid operations to change inter-area oscillation modes and achieve a new grid operating state so as to mitigate threats.

The first project was a tool to improve real-time situational awareness of oscillation problems in the Western Interconnection by developing an intelligent algorithm for oscillation detection and analysis, evaluate its performance and usefulness using field measurement data, build a prototype graphical user interface, and then develop a real-time prototype tool for monitoring and analyzing power grid oscillations. This oscillation tool development was a major breakthrough in that it significantly lowers false and missing alarms, as well as shortening detection time by applying oscillation detection and analysis algorithms properly.

Recall that the California power grid is in 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. The second project was to advance modal analysis beyond detection to action, by developing a method and establishing a modal analysis for grid operation (MANGO) procedure to provide recommended actions (such as generation re-dispatch), and aid grid operation decision making for mitigating inter-area oscillations.

A MANGO procedure was established with practical considerations. The key step in the procedure is the modal sensitivity. A method for estimating relative modal sensitivity was formulated and studied with promising results from a medium-size system and the full WECC system, and the impact of topology change on damping was studied. The simulation studies were conducted with commercialized software, and the resulting experience and data paved the road for large-scale MANGO application.

Due to limited synchrophasor measurement availability, all the tests were performed with simulated data, thus further testing needs to be done with actual synchrophasor measurements once the installation underway of an additional 250+ PMUs in the WECC is completed.

This PIER research was supplemented and continued by more than $500,000 of funding from the DOE Office of Electricity and Energy Reliability through the administration of the CERTS program. The technology developed has been well received by the electric grid community as state-of-the-art and the basis for follow-on research. Part of the work was included in an IEEE special publication, which was supported by a special IEEE Task Force.

The intellectual property of this technology has been protected for commercialization through two software copyrights: (1) MANGO version 1.0, and Oscillation Detection version 1.0. The BPA has installed the Oscillation Detection software for testing, and discussions regarding testing the MANGO software tool are ongoing with several power companies.

This research has resulted in twenty professional publications.

Potentially, with these two tools, the transfer capabilities of stability-limited transmission lines can be increased, which in turn would increase asset utilization and free up transmission capacity for the California electric grid.

3.9. Advanced Protection Systems Using Wide Area Measurement

3.9.1. Scoping Study of Intelligent Grid Protection Systems

This study explored the state of the art of synchrophasor (phasor measurement unit, or PMU) technology and of remedial action schemes and special protection schemes (SPSs), and the transmission constraints of importing power into California. It recommended appropriate projects to further explore the applications of synchrophasor technology in electric grid protection systems in California.

The purpose of this project was to analyze transmission system protection issues, identify state-of-the-art technical protection solutions and their value for an intelligent system, and develop stakeholder-supported recommendations for a technology program.

The project found that almost all protection and control schemes on the grid today are local in nature, which means that the sensing of faults and tripping of equipment take place in one substation, typically telecommunications between adjacent substations to coordinate the protection to some limited extent. The particular benefit of applying synchrophasors is because of the intelligence gathered over a wide area to detect stressed system conditions, which cannot be done on a local basis. Some potential applications that hold promise are wide area voltage control, small signal stability control and transient/dynamic stability control.

Special protection schemes are the primary means of wide area control today, although some are used for local problems as well. However, presently SPSs are prescriptive in nature, in that typically load flow and transient stability studies must be done assuming worst case conditions to ensure that there is adequate protection during those times. Since worst case conditions are by definition rare, this means that most of the time system capacity will be underutilized or remedial actions will be more severe than usually necessary.

The next step should be to develop methods to control transient stability that are less dependent on off-line studies and use more on-line computation. Techniques using pattern recognition, neural networks and expert systems hold great potential for developing feasible and effective control actions that are proactive in nature rather than reactive: action could be taken ahead of time to prevent outages from occurring in the first place.

Synchrophasor technology has proven to be extremely valuable in post-disturbance analysis, providing unique insight into finding the root causes for major system disturbances, including the August 10, 1996 and August 14, 2003 Western blackouts. A demonstration project employing synchrophasors for protection applications would provide the needed experience to advance real-time reliability methods.

3.9.2 Advanced Protection Systems Using Wide Area Measurements

Protection systems for electric grids can operate in an unanticipated fashion during times of transmission system stress, and such operations are often an important contributing factor in the sequence of events leading to cascading outages. This has been documented as “the hidden-failure” phenomenon in protection systems. Other contributing factors to catastrophic failures are unexpected power system configurations that were not foreseen when protection systems were set, errors in setting and calibration of relays, or undiscovered design flaws in the protection systems.

The project objective was to research, develop and evaluate the use of advanced technologies, specifically synchrophasor data and data mining algorithms, in the monitoring, supervision, and modification of protection systems in real time, for increased electric system reliability, security and situational awareness.

The project focused on four tasks:

1. Development and validation of an equivalent California transmission system model.
2. Development of an algorithm for adaptive adjustment of dependability and security during conditions of system stress, in which false trips might contribute to further system deterioration.
3. Development of an alarm for potential load encroachment upon the trip zone of impedance relays.
4. Development of a more intelligent out-of-step relaying tool.

The results of the project were:

- Model Validation: A reduced West Coast power system model was developed based on the California model provided and the WECC system information provided by PG&E. This model was proven to reflect the behavior of the full WECC model for the major disturbances considered for this project.
- Adaptive Security/Dependability Balance: An algorithm based on Heavy Summer and Heavy Winter decision trees using synchrophasor data from key PMU locations was developed. Performance evaluation of the algorithm with new test cases created by simulating circuit element outages was performed to assess the robustness of the decision trees to topology changes. The misclassification rates for topology changes were found to be acceptably low. A functional analysis of the proposed system determined that it can be implemented with available commercial PMUs, computers and data concentrators, provided the communication links are available at the selected PMU locations.
- Alarms for Encroachment of Relay Trip Characteristics: A reduced West Coast power system model was developed and validated. Analysis showed that this model reflects the behavior of the full WECC model for the major disturbances considered for this task. A supervisory boundary, which is a concentric circle with a radius 50 percent larger than the radius of the relay trip zone, was established as the point at which alarms would be set. Contingency analysis of the Heavy Winter and Heavy Summer models revealed that for no combinations of outages and three phase faults did either the power swing or the post-disturbance load flow cause encroachment of distance relays on critical 230 kV and 500 kV lines in California.
- Adaptive Out-of-step Relaying: A reduced West Coast power system was developed and validated; generator coherence detection algorithms were developed. Alarms for out-of-step relays were set based on identifying contingencies that cause significant changes in the location of the swing center and the size and speed of stable swings at the location of the out-of-step relay. An algorithm was developed to determine the contingencies that make out-of-step relays lose their ability to differentiate stable swings from unstable swings. The performance of the algorithms was evaluated; none of the stable swings were tagged as unstable and all unstable swings were properly identified as such.

The results of this project were further developed and used in field demonstrations by a subsequent research project, Application of Advanced Wide-Area Early Warning Systems with Adaptive Protection (see below). That project adapted two of the algorithms developed in this project, Security/Dependability Balance and Relay Zone Encroachment Alarms, for field implementation and demonstration by two California utilities, PG&E and SCE.

3.9.3. Application of Advanced Wide Area Early Warning Systems with Adaptive Protection

The primary goal of this project, co-funded by the DOE, the Energy Commission and the project participants, was to demonstrate, in real-world utility systems and with the participation of practicing utility engineers, three specific high-value applications in adaptive protection technology.

First, synchrophasor data were used as input to a Security/Dependability Balance algorithm. Modern grid protection systems use redundancy, i.e., multiple sets of independent relays, to ensure reliable fault clearing ("Dependability"). However, the probability of "false trips" is somewhat increased, which is usually not a problem if system conditions are normal. However, when the system is not healthy, false tripping can exacerbate the conditions leading to system collapse, i.e., blackouts. By using synchrophasor data in an algorithm that is trained to recognize such abnormal system conditions, a supervisory logic can be quickly implemented to require a "voting" scheme for the relays, in which at least two of the multiple sets of relays must agree there is a fault before tripping is implemented. Thus, system "Security" can be maintained even when the system is in a weakened condition.

Second, synchrophasor data were used as input to an Impedance Zone Encroachment algorithm. Impedance relays are set to detect conditions when the impedance they "see" in the system drops into an unacceptably low range, usually at a low point of a dynamic oscillation due to a major disturbance, and the relay trips to avoid unstable system swings. Over time, as system conditions such as loading or equipment additions are made, the relay's setting will no longer correspond to previous conditions, and the relay may operate for stable swings, an undesirable outcome. The Zone Encroachment algorithm sets up a buffer zone around the relay's normal zone, and when system swings start to encroach on the buffer zone, an alarm and display message is sent to the system operator, who can relay the warnings to the protection engineer, who can then re-evaluate, and if necessary re-program, that relay's settings to avoid undesired operations.

And third, in order for utility engineers to absorb synchrophasor data quickly so as to facilitate the required real-time responses, this project developed methods for display and visualization of protection system data and validated those methods with utility engineers in interactive interviews and workshops.

Each of the three applications of protection systems described above were demonstrated using a three-part technical process: research and development; pilot demonstration; and field demonstration.

In the R&D phase, university researchers at Virginia Tech adapted both the Security/ Dependability Balance and Zone Encroachment algorithms from previously developed, non-real-time research versions, with the necessary modifications to allow them to run in real time with streaming synchrophasor data. Researchers at

Mississippi State University built upon previous research to develop new visualizations of synchrophasor data.

In the Pilot Demonstration phase, the Security/Dependability Balance and Zone Encroachment algorithms were first implemented in Virginia Tech's laboratory using relaying and synchrophasor devices similar to that used by utilities; then they were exported to the proof-of-concept laboratory facilities at utilities PG&E and SCE, to verify correct performance and instruct utility engineers in their use. A Data Evaluation Plan was developed as a protocol for evaluating the performance of the algorithms against real data, to be collected in the final, Field Demonstration Phase. The synchrophasor visualizations developed in the R&D phase were presented to PG&E and SCE engineers and technicians in interactive workshop settings and interviews; feedback and comments were elicited; and further refinement were made to the visualizations.

In the Field Demonstration phase, the two adaptive relaying algorithms were implemented into utility operations systems by the utilities themselves, using the same devices, equipment, personnel and systems that would be used in actual practice, with the difference that the systems were in “monitor” mode, i.e., the systems were fully functional but did not impact actual relay operation prior to validation with field data. Data collected over several months were evaluated by the project team according to the Data Evaluation Plan. The data visualizations were modified according to the utility feedback received in the Pilot Demonstration phase, and a second round of interviews and workshops were conducted with the revised visualizations to ensure operator and engineer acceptability.

This project was, arguably, the first real-world utility demonstration of the use of synchrophasor data in advanced protective relaying applications, one that should inspire other researchers and utilities to implement the applications described here, as well as applications in other areas of electric grid operations and planning. The project demonstrated a feasible approach for implementing the Security/Dependability Balance algorithm in a real-time operations environment. In fact, two somewhat different approaches were used by PG&E and SCE in terms of the specific hardware used and where the algorithm software was installed, but achieving the same result: an adaptive protection system using synchrophasor data to enhance the reliability and security of a major transmission path.

The project also demonstrated an economical and feasible approach to implementing an Impedance Zone Encroachment system to inform protection engineers via on-screen alarms and notifications when impedance relay settings should be re-evaluated and/or updated for increased system security.

Important knowledge was gained from practicing utility engineers, operators and technicians regarding methods of visualizing synchrophasor-based protection system data. The prototype visualization tools were developed and vetted to meet the demands of utility personnel for clear and concise representations that can be quickly absorbed, allowing problems to be efficiently analyzed, and decisions formulated and carried out expeditiously.

4. New Cross-cutting Technology for Improving the Transmission System Reliability, Flexibility and Resiliency

Some of the TRP research cut across several of the strategies described above, such as seismic damage resistance and another was energy storage.

Because much of the California electric system is in active seismic regions, post-earthquake functioning of utility systems is a vital need for rapid response, recovery and preservation of public health and safety. Building an electric system that is more resistant to seismic motion damage will reduce the consequences and costs of electric service disruptions caused by strong ground motions. The TRP conducted analyses, simulations and lab tests on substation post insulators and transformer bushings.

4.1. Increased Seismic Robust Performance of Transmission Substation Components

Some of the TRP research was conducted on technical topics or areas that cut across several of the strategies described above. One such area was seismic damage resistance and another was energy storage.

4.1.1. Evaluation of the Seismic Performance of High-Voltage Transformer Bushings

Prior research has identified several areas of high-value seismic research that can lead to a more reliable, robust and resilient electric system, in particular the dynamic interactions between the high voltage transformer bushings and other components in large substation transformers due to seismic motions. 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.

Currently accepted standards for certifying the seismic performance of transformer bushings, based on IEEE Standard 693-2005 protocols, are not valid. Procedures used by the electric equipment industry do not properly account for the dynamics of the as-installed bushing/transformer combination in practice. This project determined the seismic response of the combined transformer-bushing interaction and to enable more accurate analysis and physical seismic qualification of bushing-transformer systems.

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. This work highlighted 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.

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.

These proposed revisions to the IEEE Standard are currently before the appropriate IEEE Task Forces and Working Groups for approval.

4.1.2. Seismic Performance of Substation Insulator Posts for Vertical-Break Disconnect Switches

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, there are guidelines for the seismic qualification and testing of disconnect switches.

A new testing approach to accommodate required modifications in the disconnect switch or its support structure 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 hybrid simulation testing is the essence of the experimental testing program conducted in this study.

The research conducted finite element (FE) simulations and provided 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 tests.

The project aimed at developing accurate computational FE models for a single 230 kV porcelain insulator post. These models were used to conduct eigen-value, 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 determine experimentally 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.

The study also focused on conducting linear and nonlinear static analyses to rank the sources of uncertainties in porcelain insulator computational modeling, and on 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 proposed revisions to the IEEE 693 Standard for consideration by the IEEE Standards Working Groups and Task Forces for seismic qualification of high-voltage disconnect switches.

4.2 Energy Storage

Energy storage is expected to play a larger role in generation resource management, integration of variable resources, and peak management applications. On September 29, 2010, Governor Arnold Schwarzenegger approved Assembly Bill 2514, Skinner, Energy Storage Systems. This bill required the CPUC to determine appropriate targets, if any, for privately owned electric utilities to procure viable and cost-effective energy storage systems. For public utilities, the bill required the Energy Commission to review and approve plans to determine appropriate targets and procure viable and cost-effective energy storage systems to meet the targets. Also, the bill recognized that despite many benefits of energy storage, there are significant barriers to obtaining the benefits of energy storage systems. To assist in the decisions to be made, the Energy Commission charged the TRP to conduct a strategic analysis of energy storage technology, called the Energy Storage Vision 2020. It reviewed the technical status and the remaining research and development needs of current storage technologies, developed a strategic vision of how California might best implement its energy storage needs over the next 10 years.

5. Electric Distribution System and Renewable Generation Integration

In 2010, with the expectation of 12,000 MW of new distributed generation, mostly solar PV, to be installed in California by 2020, attention on renewable energy integration with the grid shifted toward electric distribution. Largely in the form of small photovoltaic generators located at or near electric customers' facilities, distributed generation represented unprecedented challenges for the distribution system.

Conventional distribution systems are largely radial, designed for one-way power flow, while transmission systems are networked and designed for power flows in different directions at different times. Another significant difference between transmission and distribution is the degree of monitoring capability, with transmission systems being heavily monitored compared to distribution systems in spite of smart meter penetration late in the 2000–2013 period. Anticipation of high penetrations of variable solar PV distributed generation has raised concerns about islanding, relay desensitization because of being designed for one-way power flow, voltage regulation and flicker, and the increased need for line and transformer replacements.

Because so little is known about the distribution system, this project began with an effort to characterize the distribution system in sufficient detail to assess the effects of high penetrations of distributed PV. This project collected and analyzed data to define the requirements for an intentional monitoring plan to characterize the electric distribution system in California for high penetrations of distributed PV.

Some distribution circuits are underground (insulated cables) rather than the more typical overhead (lines and poles). Underground circuits provide higher reliability for electric customers, and many more circuits might be placed underground if the construction costs could be reduced and the cost and difficulty of locating and repairing failures in cables could be mitigated. The following research projects begin to address these issues.

5.1. Advanced Monitoring of Distribution Systems

A difference between transmission and distribution is the degree of monitoring capability. Transmission systems have become more monitored compared to distribution systems beyond the distribution substation, despite increased penetration of smart meters.

Anticipation of high penetrations of variable solar PV distributed generators have raised concerns about islanding; relay desensitization; voltage regulation and flicker; increased line and transformer replacements; and resonant conditions.

Because little is known about the distribution system, CIEE began to characterize the distribution system in sufficiently to address the effects of high penetrations of distributed PV. This project collected and analyzed available data, then defined the requirements for an intentional monitoring plan to characterize the electric distribution system for high penetrations of distributed PV.

5.1.1. Distribution System Field Study with California Utilities to Assess Capacity for Renewables and Electric Vehicles

A significant and growing amount of new renewable generation is being installed at the distribution level of the electric grid, accompanied by the proliferation of technologies such as plug-in hybrids and electric vehicles (EVs). There is thus a need for information about the impacts of these technologies, and data to support the analysis and control of distribution systems in the future. “One-size-fits-all” solutions, such as the 15 percent rule of thumb for installation of distributed generation on a feeder, are rapidly becoming unacceptable

The purpose of this project was to advance the state-of-the-art in electric distribution systems by supporting safe and reliable operation with a substantially increased presence of renewable generation, distributed generation, EVs, and other new technologies and applications.

Most of the distribution system monitoring activities by the utilities are “ad hoc” efforts that focus on specific behaviors, e.g., of PV systems, energy storage installations, EV charging, microgrid demonstrations, smart meter implementations, and demand response programs. There was considerable variation found in data quality and analytical methods. Evaluation of the overall monitoring situation gave a reasonably good picture of the baseline monitoring practices used in distribution systems today, and the gaps that need to be filled in order to manage and operate distribution systems effectively, both today and in the future.

A Data Repository was established at the University of California San Diego Supercomputer Center for the secure storage of utility data, and it is hoped that this effort be continued and expanded in a Phase 2 research project. The project acquired system data, of both physical feeder models and the associated measured data, to validate the feeder models. Utility validation of their system models is not consistent, but it is a necessary requirement to perform planning studies, to know or estimate what the actual system conditions are, or to operate the system reliably and efficiently.

The supplied data had missing data, bad data, “outliers,” and non-uniform sampling intervals requiring additional evaluation and processing before the data could be analyzed. The project was able to develop methods for dealing with these anomalies so that analysis could be efficiently performed.

The blueprint for an Advanced Monitoring Plan (AMP) was developed, which is the basis for follow-on research on the current gaps in available data and in data monitoring practices, as well as the future needs based on high levels of new technologies, such as renewable and EVs. The results from the first part of the project provided information on current needs and monitoring practices. The project included a survey of distribution engineers and experts to explore and expand the design and features of the AMP. The product is a practical basis from which to learn more about distribution systems in California.

This collaborative research effort was the first systematic look at a representative sample of distribution circuits across California. The primary benefits of this project include increased visibility of the distribution system, resulting in more reliable and efficient operations, better planning for system upgrades and expansions, and proactive detection, analysis and mitigation of the potential impacts of new technologies and applications on distribution systems.

5.2. Reliability of Underground Distribution Systems

Underground distribution circuits increase electric reliability. Despite the cost, more circuits would be underground if the cost and difficulty of reducing, predicting and locating failures could be reduced. CIEE has administered research projects on underground cable for that purpose. One project investigated three methods for detecting, in advance of failure, a common degradation of cable insulation (known as “water trees”). These methods can be applied while the cable is in service. Two methods showed promise. Another project investigated four methods for online diagnosis of underground power distribution cable from in situ measurements of cables. Two looked promising.

5.2.1. Underground Cable Diagnostics Miniaturization Research, Development, Field Test, and Commercialization

The aging and in-service deterioration of underground distribution cables is a major issue for electric utilities in California and throughout the U.S. There are over 100,000 miles of underground power distribution cables in and around the West Coast area. Older cables have a higher probability of failure due to development of defects in the cables because of aging and exposure to the elements. These defects can lead to catastrophic cable failures that are not only hazardous to the community around the location of the failure, but can result in large economic costs to affected businesses that lose power from the time of the cable failure to restoration of power.

This project addressed two primary causes of failure in underground cables:

- Broken or corroded concentric neutral (CN) wires. This research provided the foundation for the design of an advanced sensing mechanism, a device termed the “Grabber,” which utility technicians simply push onto the energized cable using an industry-standard “hot stick.” Pivoting jaws close to form a ring around the cable, with 10 to 12 micro-sensors arrayed around the cable to sense the magnetic fields from the CNs. Sensor data from the grabber is transmitted wirelessly via Bluetooth to the technician’s laptop, tablet or smart phone. The Grabber easily releases the cable when the technician pulls back on the hot stick. The technician can then review the sensor data, quickly assess the cable’s health, and determine if a cable replacement or further testing is necessary.
- Failure of the polyethylene insulation due to “water trees.” The research team determined that a technique using radio frequency (RF) coupling in the cable was the most promising method. This technique requires the insertion of an RF generation source at one end of the cable and a detector at the input end to detect reflections, or at the other end of the cable coupling. By comparing the cable’s attenuation and other characteristics with the characterization of a “healthy” cable, technicians can quickly identify the presence of water trees or other cable abnormalities. Armed with this knowledge, utilities can replace cable sections before they fail, as well as avoid unnecessary cable replacements.

The primary benefits of this knowledge are that utility personnel have advance warning that a cable may fail and cause an outage; customers will experience more reliable service; utilities will avoid excess costs due to emergency replacements and repairs, and will be able to better control their available maintenance dollars; and improved safety of utility maintenance personnel. A Commercialization Plan was developed to assure transfer of the developed technologies to the private sector. Discussions were held with technology firms and promising commercialization partners were identified. A patent application was submitted for the RF technique for detecting water trees in energized cables, and the patent was issued. A provisional patent application for the Grabber device for detecting faults in concentric neutrals was also submitted.

Concluding Statements

The research projects included in this white paper were chosen as representative of the Transmission Research Program and other PIER-funded electric grid research, led, administered, managed, and/or conducted for the Energy Commission by the California Institute for Energy and Environment at the University of California. Some of the research projects were not explicitly included, but still accounted for, because they were precursors to projects of continuing efforts included here. Other research efforts not explicitly described here were of research planning, including characterization, issue definition, technology solution identification, gap analysis and technology roadmaps.

Public interest energy research lies at the nexus of service quality, environmental imperatives, and economic objectives. At the intersection of these three objectives, integration of renewable resources throughout the electric grid to meet these goals has been a guiding theme during 2000–2013. Work sponsored through PIER systematically sought to expand the grid's technical hosting capacity for various types of renewable and distributed resources through a diverse range of approaches. The remarkable progress on renewable and DER integration would not have been possible without the contributions of PIER. While the explicit charge of PIER is to serve the interests of California, the success of the California experiment in the context of the present status of global climate negotiations, and the long-term public benefit even beyond our State's borders, cannot be overstated.

Introduction

The start of the 21st century in California was a turning point for electric grid technology research funded by the California Energy Commission (CEC) Public Interest Energy Research (PIER) program. The California electric grid entered the new millennium during the California Electricity Crisis of 2000-2001, an outcome of California's restructuring and deregulation of the regulated electricity industry in 1998. By 2000, and into 2001, as an unintended consequence of deregulation, California and its utilities were experiencing very high electricity prices and severe financial problems, along with electric power shortages and rolling blackouts—really, two crises in one. These crises demonstrated the public interest value of the electric grid, along with its inadequacies and vulnerabilities, prompting the California Legislature, with Senate Bill (SB) 1194 and Assembly Bill (AB 995), to pass the Reliable Electric Service Investments Act of 2000. Other similar state policy actions reflected these concerns over the readiness of California's electric grid, providing the bases and important guidance for PIER-funded research and development for that critical infrastructure. In summary, the state began an expanded research effort in the PIER program to develop new technologies to enhance electric power delivery capabilities.

The Beginnings of the CEC's PIER and TRP

Until 2000, although electric system reliability was included among the possible core areas for research in the public interest identified by legislation, the PIER program mainly emphasized the underrepresented core areas seen as not being adequately pursued by entities with competitive or regulated interests. This left much of the research on transmission and distribution technologies to be pursued by the California investor owned utilities (IOUs) and similar entities.

The inadequacies of the electric grid experienced during the California Electricity Crisis of 2000 -2001, however, raised doubts that research on the electric grid, especially transmission, was being done at an adequate level. In 2002, SB 1038 revised PIER legislation by adding an emphasis for transmission research. The CEC developed the Transmission Research Program (TRP) in response to this legislation, as well as other related state administration and agency policies. The primary objective of the TRP was to foster research that would address critical transmission issues.

While the CEC maintained responsibility and overall decision-making for the TRP program and reported results to the California Legislature, a program administrator contractor was selected to provide program vision and strategy development, to administer and facilitate the stakeholder relationships and interactions, to conduct certain project administrative functions, and to supply staff, namely, the TRP director, an executive assistant, and research coordinators with electric utility industry and R&D management experience. The California Institute for Energy and Environment (CIEE) of the University of California was selected as that contractor by a competitive solicitation in 2003.

The design and use of an advisory system of stakeholders of the electric grid community were key success factors for a practical strategy, design and execution of the TRP, and for the timely and effective transfer of the research program's results to the end users, particularly California electric utilities and the California Independent System Operator (CAISO). It helped to assure that the TRP had the right portfolio of research projects, and assisted in making the research products used and useful to Californians. The TRP Policy Advisory Committee (PAC) was a high level advisory committee chaired by an Energy Commissioner and populated by a variety of transmission stakeholders such as senior management of the California IOUs, namely Pacific Gas and Electric Co. (PG&E), San Diego Gas and Electric Co. (SDG&E) and Southern California Edison (SCE), and by the CAISO, the California Public Utilities Commission (CPUC), renewable advocacy groups, and U.S. federal agencies such as the Department of Energy's (DOE's) Office of Electricity and Bonneville Power Administration (BPA). The TRP PAC provided guidance on strategy development and priorities, reviewed the TRP performance, and, just as importantly, participated in the "paths to market" for the research products. Subordinate technical advisory committees, consisting of similar stakeholder representation as the TRP PAC, but at the engineering manager and practitioner levels, offered technical advice to help design the most productive and effective research projects, and reviewed the performance of the projects underway. They too enhanced technology transfer through active participation of the members. Each of these advisory committees typically met three or more times a year.

A hallmark activity of the TRP advisory structure was to bring together informally the advisory committee members and electric grid technology "research" experts from academia, national labs, architect engineers, product vendors and consultants to focus on specific grid-related problems. Through iterative interactions these teams would better define the problem, and identify possible technology solutions and the research needed to close any technology gaps. The ultimate result of these exchanges was a TRP portfolio of research projects tailored to solving specific high-importance problems with the best and latest technologies. Another hallmark activity was the increased incidence of research projects that were hosted at advisory committee member grid facilities, thus greatly enhancing the effectiveness and timeliness of technology transfer.

"Deliver a kilowatt-hour from anywhere to anyone at any time" was the TRP PAC vision statement of the ideal transmission system. It provided a rich strategic context and an "asymptotic" long-term goal for the TRP. Inherent to the vision, the electric system was seen as a critical infrastructure for efficient markets, public good and national security, where the generators and consumers were clients of the transmission grid's services. The term "generator" included central and distributed resources, and the term "consumer" encompassed a spectrum from local distribution companies to individuals. Accordingly, the TRP saw the mission of a transmission system as one to serve the public interest by delivering adequate, affordable, reliable, safe and environmentally-sound electricity from any generator to any consumer. Mission success depended critically on avoiding blackouts and enabling the consumer to access clean, low-cost, reliable electricity. At the time these two critical success factors were the ones most likely to cause transmission policy makers, planners, owners and operators to lose sleep during the early beginnings of the TRP.

The Challenges Facing the California Electric Grid and the Shaping of the PIER TRP

Coming out of the electricity crises of 2000–2001, the electric grid in California faced a number of challenges. Under investment in transmission during the last two decades of the 20th century, and increasing difficulty with siting, permitting and building new transmission, were resulting in rising congestion costs and threatening to hamper attainment of the state's renewable energy generation goals. In the attempt to increase economic efficiencies and reliability, while also accommodating power markets along with new generation technologies and loads, transmission operators found their ability to plan, dispatch and regulate generation impaired – especially with a growing dependence on the wide-area interconnection in the western area of North America, known as the Western Electricity Coordinating Council (WECC). Inadvertent changes to the dynamic behavior of the grid led to greater operational risk, reduction in transmission capacities to provide more margins for managing voltage and dynamic instabilities, and increasing economic inefficiencies and congestion. The growth in variable renewable generation was creating rapid ramp-rates, which further challenged grid operations.

The ever-increasing reliance on more long-distance multi-state transmission lines in the interconnection to the large, fragile power grid in the WECC was increasing the risk of large widespread outages. Past wide-area outages, such as the 1996 blackouts in the western U.S and the 2003 Northeast blackout, had revealed deficiencies in system protection that aggravated the extent of blackouts. Meanwhile, the inadequate capability for wide-area, real-time system visualization by operators was becoming painfully apparent. This motivated the deployment of synchrophasors, also called phasor measurement units (PMUs), an emerging monitoring technology which, compared to the typical state-of-the-art supervisory control and data acquisition (SCADA) systems, was expected to do for transmission system diagnostics and situational awareness what magnetic resonance imaging (MRI) did for medical diagnostics versus old-fashioned X-rays.

Extreme events, such as the cascading blackouts described above, and storms, such as "Katrina," were shaking public confidence in the ability of government and private institutions to provide robust and resilient infrastructure systems throughout much of the U.S. The transmission-related effects of the U.S. Energy Policy Act (EPACT) of 2005, such as transmission corridors and the Electric Reliability Organization (ERO) Enterprise reliability compliance, were creating complexity for grid operations and planning. Power market competition and budget constraints and increasing replacement costs were leading to aging infrastructure, raising concerns about power system reliability. New public policies and "consumer" technologies such as demand response (DR) and distributed generation (DG) offered opportunities for improved grid operations, but only if the challenges of integrating these new technologies with the existing grid could be overcome.

In 2006, the California legislature passed SB 1250 that contained PIER program funding reauthorization, and direction for electric transmission research to emphasize renewable energy delivery, along with reliability and costs of the power grid, to be consistent with emerging energy policy in the state, which was driven to reduce greenhouse gas emissions. An evaluation of the PIER TRP in the context of SB 1250 showed that the majority of the TRP strategy and portfolio were consistent with new legislative direction. Most of the problems described above facing the electric grid in California would still need to be addressed in order to facilitate the integration of renewable generation with the electric grid. In addition, the integration of many renewable generators “fueled” by variable wind and solar energy resources called for an additional new TRP focus on technology solutions for the challenges unique to these particular generators.

With the advent of variable renewable generation in the electric grid, for the first time in history, electric generators did not come with energy storage built-in, i.e., in the forms of stored fuel and the inertia of the rotating mass of the generator. Without the fuel-based energy storage, most solar and wind powered generators cannot be dispatched with much certainty and consistency, thus limiting their capacity value. Without the latter characteristic of rotating inertia, solar and wind generators using electronic power conversion tend to ramp (i.e., increase or decrease power output) much faster than the traditional power plants on which the electric grid was designed to rely, and often in a somewhat random manner. California’s aggressive goals to substantially increase the fraction of electricity generated by renewables, at both the transmission and distribution levels, eventually made these issues real, posing special challenges for providing timely and adequate grid delivery capacity, maintaining reliability and power quality, and avoiding economic inefficiencies.

New or expanded capabilities for the grid would be needed. In the beginning, building new transmission and distribution infrastructure using traditional “wires” technology seemed sufficient, but as time passed it became increasingly clear that new technologies offered the prospect of providing a substantial portion of the new or expanded capabilities, and would be needed to supplement the traditional “build” solutions.

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

The TRP Strategy

Emerging technologies offered solutions if they could be developed and commercialized. To assure acceptable levels of transmission adequacy, reliability, security, affordability and environmental compatibility, and to fulfill state policies and goals, the TRP since its beginning pursued a consistent set of evolving technology research strategies ultimately focused on new technologies to:

- Provide faster access for new remotely-located renewable power plants by putting new transmission lines in a “better light” through streamlining of the siting process, use of advanced conductors and other measures;
- Accommodate unique behaviors of variable renewable generators through a smarter and more flexible transmission and distribution grid;
- Increase transmission capacity by optimizing the grid for greater power flow through improved hardware and “smart grid” enhancements.

1. New Technology for Providing Access to the Grid by Putting New Transmission Lines in a “Better Light”

For most new remotely located renewable power plants, access to the transmission system means building new transmission lines between the power plant and the existing transmission grid. By the end of the 21st century, the time for siting and permitting processes for new transmission projects had grown to take typically 10 to 12 years for a major line. This situation raised concerns that it would take longer to build the new transmission extension to a renewable power plant than it would to build the power plant. It also tended to raise costs.

The major barriers to building a new transmission line were societal resistance to siting, e.g., “not in my backyard,” and benefit identification and cost allocation. In pursuit of the strategy to provide enhanced access to transmission, technology research goals were established that (1) reduced the visual profile, and other environmental and siting impacts, of a transmission line, and perhaps other grid infrastructure, and enabled public process techniques that facilitated environmental/societal issue definition and resolution and stakeholder interactions; and (2) helped the public, and other concerned parties and decision makers, to better understand and communicate the costs and values – both economic and strategic – of transmission projects.

A wide array of research and development was being done by vendors, federal research programs, universities and others in advanced compact transmission designs, new components and materials, undergrounding of lines, and related efforts aimed at reducing the footprint and visual impacts of transmission infrastructure. These activities were tracked by the TRP team and communicated to California grid stakeholders through the Policy Advisory and Technical Advisory Committees as strategic input into the CEC’s research portfolio planning process. Also, technology research projects in the TRP portfolio that were primarily targeted toward increasing the power handling capacity of the existing electric grid infrastructure, explained and expanded upon below, could be applied to new infrastructure to enhance public acceptance of siting of new installations. Web-based interactive models were pursued to enable a broader and deeper stakeholder engagement with the siting processes for better understanding of environmental, societal and economic tradeoffs.

To facilitate investment in, and permitting of, transmission infrastructure, the second technology goal was to better understand the value, benefits and costs of a transmission project. It was clear that more transmission infrastructure would be needed, either as new installations or upgrading of existing facilities, especially to provide new generators with access to connect to the backbone transmission system. It also was clear that building new transmission lines, or even upgrading existing lines, was becoming increasingly contentious and difficult to do because of issues with identifying who got what benefits and who should pay for them. The TRP looked for science and technology-based solutions to enhance processes for permitting new transmission line corridors and reduce the approval times. To facilitate transmission investment decision-making, the TRP considered research that could develop methodologies for estimating the strategic value of new infrastructure projects, and bring some science to bear on how to allocate the investment and other costs among those stakeholders enjoying the benefits. To better understand what conditions drove the need for new investment and where to put it, the TRP conducted research in congestion management planning and extreme event modeling and management.

1.1 Transmission Cost Allocation Methodologies

This project was performed by the Lawrence Berkeley National Laboratory and the Electric Power Group, LLC. The Principal Investigator was Joe Eto.

This project documented case histories for addressing the cost allocation problem and developed new methods and approaches for expanding the planning tools for making these investment decisions and providing additional information for stakeholders involved in decisions, including sharing in the cost of transmission projects, i.e., cost allocation.

While reliability-related transmission investments were moving forward, projects which were viewed as serving an economic, market or policy objective had no clear path forward, owing in part to issues related to cost recovery and cost allocation. There was a need to research new approaches for assessing benefit streams, beneficiaries, and quantification of benefits for cost allocation and cost recovery for new transmission investments.

In early stages of the project, it was found that the use of a screening tool can be very productive to perform quick what-if screening analysis, but not as a substitute for detail production costing simulation for detailed benefit analysis. In economic transmission projects, the principle of “beneficiaries pay” should be the basis for cost allocation. The project asserted that attempts should be made to quantify primary and strategic benefits of transmission projects in a transparent way so that project participants and beneficiaries can agree on the level of benefits and who gets what share of these benefits and who pays what share of the costs.

The primary benefits of transmission, such as improved network reliability – meet reliability standards and guidelines, lower cost of energy and capacity adjusted for transmission losses as a result of reduced congestion, access to lower cost resources, and increased inter-regional power trading – were usually well identified in most proceedings, but some other categories of benefits were not.

Since the transmission system had increasingly become a public good, the use of social rate of discount, instead of allowed weighted cost of capital, calculating the present worth of benefits of a new transmission project was recommended.

Additional research was identified as needed on quantification of societal benefits of transmission in providing insurance value against extreme events that are low-probability/high-impact events. These conclusions and recommendation along with others are listed next.

The research study produced five areas of key conclusions and recommendations:

1. Assessment of model based traditional benefit quantification methods commonly used in the industry, such as production cost modeling and present worth analysis, showed a number of deficiencies:
    a. Models understate benefits of long life assets (50+years) by discounting future benefits using high interest rate based on cost of capital—essentially reducing the impact of benefits beyond the first 10 years.
    b. Models utilize an expected value approach that tends to minimize the consequences of high impact but low probability (extreme) events.
    c. Models are data intensive—requiring assumptions about future generation mix, fuel prices, and transmission network.
    d. Models are static with no feedback—they assume no change in investment for new generation resulting in a zero sum benefit distribution game.
    e. Extreme market volatility and multiple contingency system events, which can be very costly and risky to society, are not captured in current models.
        i. 2001 California market dysfunction—$20–40 billion.
        ii. 2003 Northeast Blackout—$5–10 billion.
2. The CAISO's Transmission Economic Assessment Methodology (TEAM) was found to be comprehensive and incorporated many enhancements to traditional production simulation analysis.
3. Research identified several areas that are amenable to advancement in existing benefit quantification methods as well as quantification of strategic benefits including:
    a. Use a social rate of discount to present worth benefits rather than utility cost of capital.
    b. Quantifying fuel diversity benefit by taking into account the price elasticity of natural gas.
    c. Application of Delphi or other stakeholder consensus generation methods to quantify benefits of mitigating low probability high societal impact events such as major blackouts and market dysfunctions.
    d. Application of dynamic analysis.
    e. Application of portfolio analysis methods commonly used in the financial services industry.
    f. Developing model based techniques to quantify extreme event benefits.
4. With acceptance by regulators and policy makers, methods in use could be augmented to recognize additional strategic benefits in the following three areas:
    a. Public Good
       Use a social rate of discount to calculate the present value of benefits for the new transmission project.

b. Fuel Diversity
Include the benefit from a potential decrease of natural gas price due to the construction of a new transmission project that integrates a significant amount of new renewable resources which also reduces natural gas consumption and emissions.
c. Low-Probability/High-Impact (Extreme) Events
Add risk mitigation benefit to society for low probability/high impact extreme market events and extreme system multiple contingency events—scenarios or Delphi method for stakeholder consensus.

5. The study recommended additional research on benefit quantification methods in the following areas:
   a. Dynamic Analysis to recognize the impact of new transmission projects on construction of new generation capacity in exporting regions.
   b. Portfolio Analysis to assess performance of different combination of demand response, renewables and fuel based generation, transmission and energy conservation programs. Portfolio analysis methods are utilized in the financial industry but research is needed to adapt these techniques to transmission expansion planning.

   c. Quantification of Extreme Event Benefits (Insurance Value) in terms of reliability and reduced market volatility. Quantification methods to be researched include application of Value at Risk, Option Value, and insurance premium concept. Reliability benefits can be measured in terms of reducing blackout footprint due to extreme (N-n) events – for explanation, see **Extreme Events** project described below – and societal value of reduced risk and exposure to run away market prices.

A project presentation to the CPUC on April 23, 2008, made by the CIEE Senior Advisor, Virgil Rose, led the California Division of Ratepayer Advocates (now the Office of Ratepayer Advocates) to file a motion on May 28, 2008, to supplement the record for Investigation 08-03-010/Rulemaking 08-03-009 pertaining to an Order Instituting Investigation on the Commission's Own Motion to actively promote the development of transmission infrastructure to provide access to renewable energy resources for California.

A project presentation to Transmission Expansion Planning Policy Committee of the Western Electricity Coordinating Council (WECC/TEPPC) led to follow-up from DOE, Midwest ISO, Southwest Power Pool, and American Electric Power.

Publications:

- Budhraja, Vikram, "Improving Electricity Resource-Planning Processes by Considering the Strategic Benefits of Transmission," paper LBNL-2547E, Peer Reviewed, Lawrence Berkeley National Laboratory, March 15, 2010. [http://escholarship.org/uc/item/7dp8d14r]

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- Before the Public Utilities Commission of the State of California, Investigation 08-03-010, Rulemaking 08-03-009, filed February 5, 2009. [http://docs.cpuc.ca.gov/efile/RULINGS/97073.pdf]

1.2 Demonstration of Advanced Conductors for Overhead Transmission Lines

This project was performed by the Electric Power Research Institute (EPRI). The Principal Investigator was John Chan.

As the overall loading on the electric system increases, the loading on specific transmission lines can approach their steady-state thermal limits. When this happens, the preferred approach is to replace the transmission line conductors with ones of higher capacity. But there is a practical limit to the size (diameter) of the conductor that can be installed in place of the old one. Rather than incur the expense of rebuilding the line, which requires considerable capital investment in new towers, insulators, footings, wider right-of-way and upgraded substation equipment, a potentially economic approach is to use newer, higher-capacity conductors characterized by advanced materials or physical design, allowing higher power flow with a form factor similar to the old conductor.

The use of such conductors can be a highly desirable and economic alternative for utilities who need to increase power transfer through a restricted right-of-way. Typically, the new advanced conductor is physically similar in most respects to the old conductor, so environmental and permitting issues are relatively minor. Such is not the case with the alternatives, such as voltage uprating, which is much more costly, time-consuming, and requires a comprehensive regulatory review and approval process.

This project comprised a collaborative research effort to evaluate the operational performance of advanced High-Temperature, Low-Sag (HTLS) conductors through approximately three years of field experience with conductors installed in actual utility systems. Five specific designs of HTLS conductors were evaluated, including: Aluminum Conductor Steel Supported/Trapezoidal Wire (ACSS and ACSS/TW), Gap-type Aluminum Conductor Steel Reinforced [G(Z)TACSR], Aluminum Conductor Invar Steel Reinforced [(Z)TACIR], Aluminum Conductor Composite Reinforced (ACCR), and Aluminum Conductor Composite Core (ACCC). The project was intended to provide general information on installation methods and requirements; actual in-service performance vis-à-vis design specs, e.g., sagging, creep, etc.; and information about their long-term behavior at different electrical current levels and in various geographical locales. Key information is provided on design, installation, operation, and maintenance of selected HTLS conductors and their hardware accessories.

Results and Findings

The project involved field trials at four utility test sites: CenterPoint Energy, HydroOne, Arizona Public Service, and San Diego Gas & Electric. The project report includes descriptions of data monitoring systems and instrumentation for each site. The report specifically includes information on the accessories used with HTLS conductors (splices, dead-ends, and terminations) and discusses the complex process of estimating service life of HTLS conductors based on the manufacturers’ technical and laboratory test data as well as the field data obtained in this study.

Several manufacturers in United States and abroad have developed advanced new HTLS conductors for use in high-voltage transmission lines. These conductors are designed to overcome the traditional limiting factors in conductor performance in terms of strength loss and sag increase by being capable of continuous operation at temperatures above 100ºC while exhibiting low thermal elongation with temperature. The goal of this project was to gain practical experience in handling, installing, and terminating these new types of conductors and to verify in practice the claims of manufacturers regarding their performance in an operating transmission line.

This project documented specific aspects of stringing, sagging, and clipping of various commercially available HTLS conductor systems and evaluated the actual physical behavior of HTLS conductors in operating transmission lines as compared to the various manufacturer-supplied design parameters in use by utilities. The results of this work will help utility participants choose when to use such conductors, how to choose between various types, and how to avoid problems during installation and over the life of the line.

Project Conclusions:

- One of the primary limitations on high temperature operation of ordinary bare stranded aluminum conductors is loss of aluminum tensile strength. Even when the aluminum strands have a substantial steel stranded reinforcing core, continuous operation is typically limited to 100ºC or less. HTLS conductors can operate continuously at temperatures between 150ºC and 250ºC depending on the particular design and wire materials.
- Those HTLS conductors which employ annealed aluminum are observed to have a lower elastic modulus than conventional ACSR. In geographical areas which experience severe ice loadings, this type of HTLS conductor may yield sags under heavy loading conditions which are comparable or even larger than the sag at high temperature.
- If HTLS conductors with annealed aluminum strands are pre-stressed, one may expect their self-damping properties to be very favorable and initial stringing sags may be quite small without causing vibration fatigue.
- Those HTLS conductors which employ high temperature resistant alloys of aluminum (e.g., TAL and ZTAL), have an elastic modulus which is comparable to conventional ACSR of the same stranding. While the sag under heavy loading conditions observed with these HTLS conductors is likely to be less than their high temperature sag, their high elastic modulus is likely to result in relatively high structure loads.

- HTLS conductors with TAL or ZTAL aluminum are likely to yield self-damping properties which are similar to conventional ACSR.
- Limited corona testing of the various HTLS conductors indicates that these conductors are likely to yield corona noise levels similar to conventional ACSR of the same diameter.
- Each of the HTLS conductors studied appears to have suitable connectors and hardware available. There is no reason to suspect that these conductor systems are unreliable in the short run (up to 5 years).
- The installation of the various HTLS conductors does not appear to be a problem. The most complex conductor system to install is the Gapped HTLS (G(Z)TACSR). The simplest conductor system is probably the ZTACIR conductor since the aluminum is not subject to damage during stringing and the core is not particularly sensitive to shear forces.
- There does not appear to be a compelling reason to choose one of the HTLS conductors over the others except possibly for cost. All of the HTLS conductors studied have the following characteristics:
  - Has a low thermal elongation rate.
  - Can operate continuously at temperatures well above 100oC without any deterioration of mechanical or electrical properties.

  - Has the same or lower resistance as the original conductor of the same outer diameter.

It is less clear which of the HTLS conductors studied in this project will work best in a particular uprating situation. However, stress-strain models for each of the HTLS conductors are available and utility engineers can evaluate each of the choices in a given uprating problem.

The best conductor choice ultimately depends on the existing clearance buffer, original design margins, environmental loading conditions, and the magnitude of the desired rating increase. The case study shows how HTLS conductors can be successfully used to obtain thermal rating increases of at least 50% and minimizing the need for expensive structure modifications.

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2. New Technology for Accommodating Variable Renewable Generator Unique Behaviors

Technologies that mitigate variable renewable generation impacts help operators prepare for and react to problems such as fast ramp rates, and better forecast the variable renewable behaviors for solar and wind all supported the goal of accommodating these generators on the grid, and ultimately recruiting them for beneficial contributions.

Solar power characteristically ramps up in the morning and down in the evening with no nighttime output, but with a power profile that varies with the season. It also exhibits short-term variations due to cloud cover. Solar photovoltaic (PV) generators use solid-state inverters without the physical inertia described earlier, and therefore will react much more quickly to transients. Little was known about the effects of large penetrations of these low-inertia generators on the transmission and distribution systems.

Wind power tends to be higher at night in California and also is subject to short-term variability from changes in wind speed. The dynamic behavior of wind generators is different from typical thermal generators and generally has lower inertia, and exhibits significant differences among different types of wind turbine designs. Generator models used for transmission planning did not accurately model wind generator behavior in the transmission system, and increased the level of uncertainty for the operator and threats to reliability.

The up and down power ramp rates for both solar and wind generators tend to be much faster than those for conventional utility generators. These rapid ramp rates posed significant challenges in maintaining reliability, power quality, and low regulation and ancillary costs.

The TRP focused on developing “smart” technologies that would help operators reduce uncertainty and minimize costs by forecasting the future state of the grid and the system resource needs for handling the ramp rates and variability of renewable generators. The TRP also advanced the development of an analytical modeling tool to reduce the costs of managing renewable generation through the optimum shared use of resources such as energy storage, demand response and distributed generation among control areas over a wide region. Likewise, research was done to improve and update load and generator models used for planning in the WECC and California electric grid thereby improving the capability to maintain reliability.

2.1 Critical Operating Constraints Forecasting for California Independent System Operator (CAISO) Decision Support

This project was performed by the Electric Power Research Institute (EPRI). The Principal Investigator was Stephen T. Lee.

In California’s power market, while demand forecasting is well handled, tools for projecting the balance of energy supply and demand through the rest of the day are not adequate. When resource margins become very short, knowing in advance when and how severe various transmission operating constraints would become is tremendously valuable to the grid operators.

During the 2005 summer season, CAISO encountered conditions of very tight resource margins and serious congestion problems in Southern California. It was fortunate that Southern California had a mild summer in 2005 with peak temperature reaching only 95 degrees, far short of the possible peak of 102 degrees. In anticipation that conditions in future summers could likely be much worse due to increasing demand for electricity and the limited transmission capacities into Southern California, this research project was initiated.

Advance knowledge of even a few hours of where these constraints would appear would enable the operators to take action to mitigate the problem before it occurs. Improved forecasting of critical operating constraints in the next 24 hours can increase the reliability and efficiency of the California electricity system. With the increased levels of renewable penetration, the volatility of potential transmission constraints due to wind and solar generation will be magnified and create significant challenges for CAISO in managing the power grid. Avoiding a blackout can potentially save Californians hundreds of million dollars. The risk of blackouts will likely increase in the future with the high penetration of renewable generation, power markets and new electric customer appliances and equipment, so improvements in forecasting critical operating constraints could yield significant cost savings, help achieve California’s policy goals for CO_2 reduction, and provide reliable and low cost electricity to the State's power consumers with minimum environmental impacts.

The main goal of this research project was to provide CAISO with the decision support capability to look ahead for the next 24 hours and predict whether the system will be able to get through the day without running into critical operating constraints, such as line overloads or low voltages, under credible contingencies. Specific objectives were to enable the simulation of various scenarios of power importation or other alternatives such as load reduction to find the best way to avoid such problems and to provide a functional specification for the development of a commercial version of the tool.

This project consisted of the development of a prototype tool based on the Electric Power Research Institute (EPRI) Community Activity Room (CAR). The CAR presents constraints as boundaries in a space with the current status as a position in that space and the distance to a boundary as the margin. The prototype was evaluated using historical data and its predictions were compared with actual observations.

To promote the commercialization of this concept, the methodology of the prototype tool was specified in detail in a functional specification document. The results of the research were presented in a workshop November 7, 2007 in Folsom, California, with the intent to make this technology available to any commercial software developer who wished to turn this method into a commercial product.

This project successfully developed the methodology for Critical Operating Constraint Forecast (COCF) tool, and tested it in a prototype with support from CAISO for testing and demonstration. The results showed that this method is capable of forecasting loading of transmission paths over the next 24 hours, using current data on the transmission paths flows and assumptions about where the generation deficit would be supplied for the rest of the day. The model provided the ability to the user to try different import scenarios to simulate how to avoid the potential critical operating constraints. Knowing an approximate time when the constraints might become critical will be very useful for the grid operators to prepare for any emergency remedial actions, such as appealing for load reduction, etc. The results of the COCF tool compared well with the results of the planning study.

The significance of this project is that a technically viable tool can be developed by commercial vendors of Energy Management Systems, using the functional specifications in a companion report of this project, which was presented and made available at the previously mentioned workshop. The knowledge for developing such a decision support tool is now in the public domain.

On a normal day, such critical conditions may not occur. However a tool like this can ascertain that this is indeed the fact for the current day, and provide situational awareness of a reassuring kind. When the conditions become more stressed, e.g., when there are transmission lines on scheduled or unscheduled outages, and when loads are increasing and imports or exports are also increasing, the ability to look through the rest of the day would become critically needed. Such an emergency operation tool would pay for itself with one such use.

EPRI continues to use the techniques of the COCF work in developing an industry tool for Visualization of Operating Boundaries (VOB) and conducting fundamental research in support of on-line analysis and situation awareness in the control center.

Among the recent reports and other deliverables on this subject are:

- T. Tinoco De Rubira (2015). Numerical Optimization and Modeling Techniques for Power System Operations and Planning, PhD Thesis, Stanford University.

- R. Entriken, W. Murray, and T. Tinoco De Rubira (2015). "Linear analysis for determining and visualizing critical thermal boundaries of power systems" Proceedings of the 2015 IEEE PES Innovative Smart Grid Technologies Conference, February 2015.

- Visualization of Operating Boundaries: Case Study for ISO-NE. EPRI, Palo Alto, CA: 2014. 3002004872. Available: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002004872

- Critical Operating Boundaries: Automated Identification and Visualization of Thermal and Voltage Limits. EPRI Palo Alto, 2014. 3002002875. Available: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002002875

- Visualization of Operating Boundaries: Case Study for Southern Company. EPRI, Palo Alto, CA: 2013. 3002002496. Available: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002002496

- T. Yong, R. Entriken, and P. Zhang (2009). Program on Technology Innovation: An Investigation of the Stability Region Concept Applied to Stability-Constrained Optimal Power Flows. EPRI, Palo Alto, CA. 1018392.

While the research progress has been full of success, the research efforts are ongoing The technology is not yet mature enough for commercial use.

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

These projects were performed by the Pacific Northwest National Laboratory (PNNL). The Principal Investigator was Yuri Makarov.

Interacting wind, solar, and load forecast errors can create significant unpredictable impacts on the transmission system, including increased congestion, 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 were developed for predicting and displaying the operational impacts of uncertainties in forecasts of loads and renewable generation. The first tool ("Ramping Tool") addressed real-time (load following) capacity and ramping requirements, the second ("Transmission Tool") addressed voltage stability and transmission congestion caused by renewables resources (mainly wind power and solar power generation), while the third tool ("Day Ahead Regulation Tool") predicted 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 CAISO systems and operated in real time in the CAISO Control Center. The Transmission Tool and the Day Ahead Regulation Tool have been developed to the prototype stage.

2.2.1 Transmission Forecasting Tool

The objective of this work was to develop a prototype tool to identify transmission problems, posed by the variability of wind and solar generation, 1 to 3 hours ahead of time, and inform operators about potential risks for the purposes of early warning and preventive control. As noted before, the scope was 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 incorporated all required essential informational, analytical, and visualization functions. Further development and integration with vendor-supported software at CAISO are necessary for deployment.

After the beginning of this project, CAISO implemented a real-time voltage stability analysis (RTVSA) tool (VSA&E tool initially developed by the Consortium for Electric Reliability Solutions (CERTS) and commercialized by Bigwood Systems Company, described elsewhere in this paper), and advanced visualization and data processing tools (developed by Space Time Insight Company). In this situation, the priorities and scope for project were changed by CAISO. Development of a stand-alone, fully-functional transmission tool would have been redundant. Based on the 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 were addressed in this effort 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 was based on Monte Carlo simulations and statistical analysis of various sources of uncertainty that can impact the transmission network. The developed methodology also included 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 is to install and test the tool in a real control center using actual system models and data.

2.2.2 Ramping Forecasting Tool

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

Uncertainties in forecasting the output of variable resources such as wind and solar generation, as well as system loads, were 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 had limited means to weigh the likelihood of occurrence and the magnitude of problems to mitigate adverse impacts caused by them. Some important questions needed 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 was recognized that it is very important to address the uncertainty problem comprehensively by taking 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 made this research project a significant step forward toward the objective of incorporating wind, solar, load, and other uncertainties into power system operations.

The product estimated and incorporated uncertainty ranges for wind power generation forecasting, demand forecasting, and generation supply interruptions caused by forced outages to provide 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. A simulation was performed using the California Independent System Operator (CAISO) system model and data. The project report also presented 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 were 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 was 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."

2.2.3 Day Ahead Regulation Requirement Prediction Tool

Regulation is a process of providing minute-to-minute system balance by adjusting power output of units connected to the automatic generation control (AGC) system. Regulation is an expensive resource; the annual price of regulation at the time of this research significantly exceeded $120 million in California. At the time of this project, the regulation capacity was calculated by the CAISO on a day head basis, for each operating hour of the next day. There is a growing concern at the CAISO that the increasing penetration of variable renewable resources in California could result in additional regulation needs.

Most of CAISO's "once-through cooling (OTC)" 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 later unexpected shutdown of the San Onofre Nuclear Generator exacerbated this problem.) The consequent decline in available regulation resources could potentially increase the price of regulation as more regulation procurement is needed. These challenges motivated CAISO to obtain a tool capable of predicting the needed procurement of up- and down-regulation services in the day-ahead market.

The goal of this project was to minimize the cost of regulation by developing an operational tool for providing a more scientific forecast of the CAISO's regulation requirement on the day-ahead basis for some operating hours without compromising CAISO's control performance characteristics. The tool can be used to calculate the regulating capacity, ramping and ramp duration requirements for each operating hour of a day, separately for the power upward and downward generation requirements.

The objective of this project was 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 predicted 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 2, (CPS2), which limits ten-minute averages of the area control error (ACE) to below a certain value, "L10," 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 was based on a new standard that was 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) was developed in this project. Simulations showed 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 was 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.

The project identified next steps that would increase the robustness and performance of the tool while handling imperfect information typically available in control centers. These steps include:
- Improving the probabilistic models to additionally reduce regulation requirements
- Adding model components reflecting new sources of uncertainty

- Putting more emphasis on the regulation requirements posed by the new NERC control performance standards
- Deploying the tool in the CAISO control center, and potentially in the IOUs' and other control centers in California.

The results of these research efforts have been used for some follow-on developments:

- The CAISO is modifying the Ramping Tool to move it to production level for 24/7 operation in the Control Center. The Ramping Tool predicts potential deficiencies of the balancing capacity in the system.
- Building on this research, AWS Truepower (project manager), CAISO, Southern California Edison (SCE), and Siemens are participating in a DOE SunShot project: "Comprehensive Solutions for Integration of Solar Resources into Grid Operations," to demonstrate integration of uncertainty information into grid system operations and probability-based controls.
- Based on the Ramping Tool development, a Dynamic Interchange Adjustment tool (DINA) was developed for ISO-New England (ISO-NE). This probability-based tool predicts the secure range of intra-hour interchange adjustments to trading balancing capacity with the neighbors. ISO-NE intends to move the tool to a production level.

- In new PNNL projects with BPA and DOE, some key concepts developed in this research will be used for predictive state estimation.

There have been a number of follow-on or related funded efforts that complement these PIER-funded projects just described:

- FY2010: DOE Office of Energy Efficiency and Renewable Energy (EERE) project "Incorporating Wind Generation and Load Forecast Uncertainties into Power Grid Operations," $700 K.
- FY2012-FY2013: Internal PNNL Use at Facility Funds (UAFF) project "Ramp and Uncertainty Tool," $75 K.
- FY2013-FY2014: DOE OE project "Stochastic Operations and Planning," $100K.
- 2012-2013: ISO New England (NE) project "Analysis of ISO NE Balancing Requirements: Uncertainty-based Secure Ranges for ISO New England Dynamic Interchange Adjustments," $90K.
- 2014: CAISO project "Ramping Tool Modification," $60K.
- FY2013-FY2015: DOE OE project "Probabilistic Methods for Planning and Operations," $700 K.
- FY2014-FY2015: DOE EERE SunShot Initiative project "Comprehensive Solutions for Integration of Solar Resources into Grid Operations," led by AWS Truepower, $820K.
- FY2013-FY2015: Internal PNNL Laboratory-directed Research and Development (LDRD) project "Operations and Planning Fusion," $612K.
- FY2014-FY2015: BPA/DOE/Alstom project "Faster Than Real Time State Estimation with Forecast for Multiple Contingency Analysis," $800K.

These projects bring about $4M additional funding to advance this technology area.

Use of some of the tools for online analysis and visualization of operational impacts of variable renewable generation demonstrated capability to eliminate real-time market price spikes. ISO NE will be able to trade its balancing capacity with its neighbors without compromising its performance and reliability. A cost/benefit analysis is part of the DOE OE project “Probabilistic Methods for Planning and Operations” described above.

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2.3 Wide-Area Energy Storage and Management System (WAEMS) to Balance Intermittent Resources in the California ISO

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

The higher penetration of variable generation resources (including wind and solar generation) in the Bonneville Power Administration (BPA) and California Independent System Operator (CAISO) control areas raises 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. The premise of wide area energy storage is that, due to statistical fluctuations, collective power grid regulation needs are less than the sum of individual area needs. This issue was addressed through the exchange of variable renewable energy between the participating control areas and the use of energy storage, dispatchable load, and distributed generation resources. This project was the second phase of a three-phase project funded by multiple parties. In the first phase, proof of concept work was completed. The results of this second phase provided specific numerical information necessary for a detailed wide area design system design.

The goal of the multiphase effort was to develop principles, algorithms, market integration rules, functional design and technical specifications for a wide-area energy storage and intermittent energy exchange management system to mitigate unexpected rapid changes in wind generation power output. The goal of this specific project, which was the second phase of the larger project, was to determine the extent that energy storage technologies can mitigate the impact of the “variable and fast ramping” nature of wind generation upon the transmission system managed by CAISO.

Because of the existence of Beacon Power Flywheels in California, and hydro plants in BPA’s area, field experiments were done on the flywheels, and then an evaluation of the combined flywheel and hydro system was done. It concluded that a combined system could effectively provide the fast regulation service of a standalone flywheel without its strict energy limit constraints, while offering a cost approaching that of conventional regulation resource. The operation over two control areas (BPA and CAISO) also reduced the total regulation requirements.

In general, the performance evaluation showed 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 could reduce wear and tear on the hydro unit and allow the hydro unit to operate closer to its preferred operating point.

The break-even price for flywheel energy storage to provide bi-directional service (1 MW regulation-up and 1 MW regulation-down) at the time was $20.37/MW. Because the average bi-directional regulation price of the CAISO balancing authority was $11.95/MW (Jan.-July, 2010) and that of the BPA balancing authority was $9.38/MW (2010), regulation service provided by a stand-alone flywheel energy storage was projected not be economical unless the regulation price increased or the fast regulation service would be paid at a higher rate. Assuming that the minimum regulation price of regulation provided by a hydro power plant was$4/MW, the breakeven price of the combined flywheel-hydro regulation service was calculated to 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 was expected to become economical in the CAISO and BPA balancing authorities soon.

As explained above, this effort was multiphase and multi-funded. Thus, in addition to the PIER funding for this particular project, it leveraged other resources provided by BPA: Phase I, $130 K, Phase II, $191 K. In June, 2014, U.S. Patent No. 8,754,547 – Controller for Hybrid Energy Storage – was issued.

The technology developed potentially enables a 50 percent or more reduction in the regulation capacity requirement when implemented. Utilization of this approach by utilities is currently pending.

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2.4 Improved Generator and Load Models

Electric grid planning and operating decisions rely on simulations of dynamic behavior of the power system. Both technical and commercial segments of the industry must be confident that the simulation models and database are accurate and up to date. Having realistic models is very important to ensure reliable and economic power system operation. A power system model consists of generation, transmission power flow and load models.

The ways that electric generators and customer electric loads behave under varying situations on the electric grid greatly affect the reliability and power quality of the entire electric supply and delivery system, such as the WECC, of which the California electric system is a subset. So it is important for grid planners and operators to be able to forecast how the various electric grid components will behave especially under conditions when the grid is stressed, for example, when there is voltage sag for some reason. Generator and load models are used in computer simulations of the electric grid to predict power flows and dynamics under different circumstances. For decades, generator and load behaviors in response to fluctuations in the electric grid did not change much, so the models for them did not need to change much. In modern times, however, new generators, such as variable renewable generators and new consumer appliances, such as modern air conditions and computerized equipment, being connected to the electric grid are increasingly rendering the old generator and load models inadequate. Allowed to continue, this situation threatens the ability to plan and operate a reliable and cost-efficient electric supply and delivery system.

2.4.1 WECC Wind Generator Modeling

This project was performed by the National Renewable Energy Laboratory. The Principal Investigator was Eduard Muljadi.

At the time of this research project, the wind turbine models that were being used in transmission system planning and reliability analyses were known to be inaccurate, and did not represent the new generation of wind machines correctly. Incorrect or uncertain analyses of the impacts of wind power generators dynamic behaviors on the grid could adversely affect both planning, and economic and reliable operation, of the California electric delivery system.

Proprietary models written by turbine manufacturers for specific generators existed, but in many cases were not readily available, and typically required a non-disclosure agreement (NDA), which constrained their use in a collaboratively controlled transmission system such as the WECC.

The WECC assigned the task of developing standard, non-proprietary wind turbine models to their Wind Generator Modeling Group (WGMG), and chose four specific generic types of wind turbine machine designs that were believed to represent the vast majority of the utility-scale wind turbine generators in the market. Utilizing WECC funding, the WGMG completed the research and development of each of these four models for use in WECC system simulation studies. While the models were designed specifically to meet WECC modeling requirements, the results could also be used by the industry as a whole.

The PIER-funded research project was cost shared with and managed by the National Renewable Energy Laboratory (NREL). The overall result of this research was to improve transmission planning and operating modeling tools needed to better prepare the transmission grids in California and western North America to accommodate the expected growth in wind power generation in order to meet Renewable Portfolio Standard goals, especially California's relatively aggressive ones. This research and development effort produced the first-ever accurate, non-proprietary (generic) models of the various types of wind turbines in commercial use today. The specific objectives of this project were to validate the new WECC wind turbine models, and to develop aggregation methods to use the individual models to develop an equivalent, aggregated model of an entire wind farm. The models are now included in the permanent library of software for General Electric's (GE) Positive Sequence Load Flow (PSLF), Siemens Power Technologies International's (PTI) Power System Simulator for Engineering (PSSE), and PowerWorld's Simulator.

The project collected and monitored data from several wind power plants representing the four types of wind turbine models developed. Validation of the models was done through two processes. First, dynamic model predictions were compared to the field measurement transient data collected from operating wind power through collaboration with Public Service of New Mexico, Bonneville Power Authority, and many other resources. Additionally, model performance was compared to available high order proprietary models from manufacturers. The dynamic models for each of the four types of wind turbines were successfully validated

The project also developed an equivalencing methodology to aggregate individual wind generators into a model that represents an entire wind power plant by an equivalent single turbine representation or, if necessary, with a small number of turbine representation. This method enables representing hundreds of wind turbine generators into a single or several turbine generators. Two guide books, "Wind Power Plant Power Flow Modeling Guideline," prepared by WECC-WGMG (2008), and "Wind Power Plant Dynamic Modeling Guide," prepared by WECC- Renewable Energy Modeling Task Force (REMTF) (2010), for doing this aggregation, the former for power flow and the latter for dynamic modeling, were produced to provide guidelines and recommended practices for wind turbine model and wind power plant representation. This equivalencing method has been validated by Hydro Quebec.

This research created far-reaching interactions among many entities in the wind generation industry, stretching from California to around the world involved in model development and use, electric grid integration, standards, and the like:

- Electric utilities, through the WECC Wind Generator Modeling Group and WECC Renewable Energy Modeling Task Force: SCE, PG&E, CAISO, Puget Sound Electric, and BPA.
- Wind turbine manufacturers and wind generating plant developers: Mitsubishi, Vestas, Siemens, GE, Nordex, RePower, and Oak Creek Energy Systems
- Software vendors for power flow and dynamic models for the use of wind power in the electric grid: GE, Siemens PTI (PSSE), PowerWorld, Operation Technologies, and Power Tech Lab.)
- Industry consultants and associations, and National labs and university researchers: EnerNex, Operation Technologies Inc., Power Tech Lab, Utility Variable-Generation Integration Group (UVIG), , Electric Power Research Institute (EPRI), NREL, Sandia, PNNL, University of Michigan - Ann Arbor, and University of Texas – Austin

- Professional and international agencies: Institute of Electrical and Electronics Engineers (IEEE), International Electrotechnical Commission (IEC), International Energy Agency (IEA), and International Council on Large Electric Systems (CIGRE)

This research also has had many regional, national, technical and educational impacts. Before this work, there were no wind plant models. The new models for wind generators are being used to address numerous questions related to electric system dynamic behavior. Accordingly, CAISO is benefiting in its studies of integration of renewables into the California grid. It also helped to build a bridge between the power engineering and wind energy communities in California and elsewhere and it has helped to improve California's ability to add renewables reliably to the grid. It helped to increase the level of understanding of this important topic, which is still not well understood, throughout the industry; and this activity provided education on the subject matter for many people. WECC continues to be a leader in the development of the models.

Nationally, this research has since been identified by NERC as an area of significant need in the report of the NERC Integrating Variable Generation Task Force (IVGTF 2009). The results of this work are in line to support FERC Order 661 and 661A and are in the national interest in providing a secure and reliable power system grid.

This research also had a number of important technical impacts on wind generator modeling. The initial work was done on the software platforms of PSLFTM (vendor: General Electric) and PSSETM (vendor: Siemens PTI). Subsequently, other software vendors implement these WECC dynamic models in the development of wind generator models on their own software platforms (PowerWorld Simulator, ETAP, TSAT, etc.) using the same specifications described on the block diagrams in the final report. These dynamic models are part of the software library and are no longer in the form of a "user defined model." The widespread adoption of the models developed and validated in this research helps assure a competitive source of commercially available software compatible with California's electric grid needs, and its on-going maintenance and updating.

These wind generator dynamic models formed the foundation of other renewable energy dynamic models. For example, the WECC PV dynamic model was developed based on the Type 4 Wind Turbine Generator dynamic model developed and validated in this research project. These models were implemented in PSLF, PSSE and Power World Simulator software. The dynamic model of Adjustable Speed (AS) Pumped Storage Hydro (PSH) power plant was developed based on the Type 3 Wind Turbine Generator dynamic model. This AS-PSH model is currently being implemented as a "user defined model" on the PSSE software platform before moving to the permanent PSSE library. These dynamic models were also implemented, with some technical support from NREL, on the PSCAD platform by NREL and implemented on the RSCAD platform, which is the main interface for Real Time Digital Simulation (RTDS) used by Southern California Edison.

Education has also benefited from this research project. The method of Equivalencing Wind Power Plant (from hundreds of wind turbine generators) developed as part of this project, is currently being used as part of the curriculum in Power System courses. These dynamic models have been implemented in PSSE, PSLF, PowerWorld, TSAT, and many other modeling platforms, and has been used by the industry members [www.pserc.wisc.edu/about/industry_members.aspx] of the Power Systems Engineering Research Center (PSERC) [www.pserc.org] and the university members of PSERC [www.pserc.wisc.edu/about/university_members.aspx] as planning tools, research tools, and teaching materials for power engineering students. PSERC is National Science Foundation Industry-University Cooperative Research Center. Finally, various research publications by university professors and graduate students have been published utilizing the WECC dynamic models.

As one might suspect from the widespread impacts this research has had, a number of new follow-on research projects have been spawned. The DOE EERE has funded subsequent works related to Solar/PV dynamic modeling (NREL and Sandia) and Adjustable Speed Pump Storage Hydro AS-PSH (NREL, Idaho National Laboratory, and Argonne National Laboratory) in both positive sequence dynamic modeling and electromagnetic transient modeling. All of these works have benefited and have leveraged the previous work of the WECC Wind Generator Modeling.

The International Electrotechnical Commission (IEC) TC88 Working Group 27 (Wind turbines – Electrical simulation models for wind power generation – Chair: P. Sorensen, Denmark Technical University) also uses the WECC (generic) dynamic models as a foundation to define standard dynamic simulation models: the IEC 61400-27-1 (PART 1) generic wind turbine models, and IEC 61400-27-2 (PART 2) generic wind power plant models specified to be independent of any software simulation tool.

The Utility Variable-Generation Integration Group (UVIG) – led by V. Zheglov of Enernex – has developed a “wind-wiki,” a resource (similar to Wikipedia) related to renewable energy dynamic models which disseminates information regarding publications, and the validation and dynamic modeling efforts related to the WECC Wind Turbine Generator project.

The WECC Renewable Energy Modeling Task Force (REMTF), chaired by A. Ellis, Sandia, continues with extension of the WECC Wind Generation Modeling. As a follow on project, the WECC Renewable Energy Modeling Task Force has developed “Specification of the Second Generation Generic Models for Wind Turbine Generators” prepared under Subcontract No. NFT-1-11342-01 with NREL (collaboration between NREL, Sandia, EPRI, and WECC). This specification is currently being implemented in the PSLF, PSSE, and PowerWorld Simulator software. Tutorials on dynamic modeling for renewable energy are offered periodically to the members of the WECC, which included California utilities.

The IEEE Dynamic Performance of Wind Generation Working Group – Chair: P. Pourbeik, EPRI continues these efforts. The Working Group organizes panel sessions related to the dynamic modeling of wind turbine generators and offers tutorials at the IEEE PES General Meetings and IEEE Power System Conference and Expositions. The tutorial is currently being planned (with the title “Renewable Energy Systems Modeling and Dynamic Performance”) for the IEEE PES-General Meeting, July 2015, to be held in Denver, CO.

NERC IVGTF has embarked with “Task 1-1: Standard Models for Variable Generation Scope, with the emphasis on attributes such as “standard, valid, generic, non-confidential, and public”. It covers power flow and stability models (variable generation) to be developed to enabling planners to maintain bulk power system reliability, and to make recommendations and to identify changes needed to NERC's MOD Standards.

Workshops:

- WECC – 2009 Generator Model Validation Workshop, held at Tristate Generator and Transmission Association, Westminster, CO May 18-19, 2009
- WECC – 2009 Modeling Workshop for Planning Engineers, held at PG&E, San Francisco, CA, April 16-17, 2009.
- IEEE Dynamic Performance of Wind Power Generation Task Force (DPWPGTF) "Tutorial on Wind Generation Modeling and Controls," IEEE PSCE Conference, Seattle, WA, USA, March 2009.
- Tutorial: "Wind Energy Boot Camp," organized by New Mexico State University, PNM, and NREL at Albuquerque, NM, Nov 12-14, 2008.
- IEEE Dynamic Performance of Wind Power Generation Task Force (DPWPGTF), "Tutorial on Wind Generation Modeling and Controls," IEEE PES General Meeting, Pittsburgh, PA, USA, July 2008.
- "WECC Wind Generator Modeling Project," Policy Advisory Committee, California Energy Commission (CEC), Irwindale, CA, August 20, 2007, and Kickoff Meeting for the WECC Wind Generator Modeling Project, Los Angeles, CA, August 21, 2007.
- "Wind Generator Modeling", CEC/PIER TRP Technical Advisory Committee Meeting, Sacramento, CA, October 3, 2006.

- "Equivalencing Large Wind Power Plants," WECC 2006 Modeling Workshop, Las Vegas, NV, June 14-15, 2006.

Publications:

- Brochu, J., Larose, C., Gagnon, R., "Generic Equivalent Collector System Parameters for Large Wind Power Plants," IEEE Transactions on Energy Conversion, Volume: 26, Issue: 2, 2011, pp. 542 – 549.
- Brochu, J., Larose, C., Gagnon, R., "Validation of Single- and Multiple-Machine Equivalents for Modeling Wind Power Plants," IEEE Transactions on Energy Conversion, Volume: 26, Issue: 2, 2011, pp. 532-541.
- D. Burnham, S. Santoso, E. Muljadi, "Variable Rotor Resistance Control of Wind Turbine Generators," submitted to the IEEE Power Engineering Society, General Meeting, Calgary, Alberta, Canada, July 26-30, 2009.
- M. Singh, K. Faria, S. Santoso, E. Muljadi "Validation and Analysis of Wind Power Plant Models Using Short-Circuit Field Measurement Data," IEEE Power Engineering Society, General Meeting, Calgary, Alberta, Canada, July 26-30, 2009.
- E. Muljadi, T. Nguyen, M.A. Pai, "Transient Stability of the Grid with a Wind Power Plant," IEEE Power System Conference and Exposition, Seattle, WA, Mar. 15-18, 2009.
- E. Muljadi, T. Nguyen, M.A. Pai, "Impact of Wind Power Plants on Voltage and Transient Stability of Power Systems," IEEE Energy2030 conference, Atlanta, Georgia, Nov. 17-18, 2008.

- A. Ellis, E. Muljadi, ”Wind Power Plant Representation in Large-Scale Power Flow Simulations in WECC,” IEEE Power Engineering Society, General Meeting, Pittsburgh, PA, July 20-24, 2008.
- E. Muljadi, A. Ellis,” Validation of Wind Power Plant Dynamic Models,” invited panel discussion presented at the IEEE Power Engineering Society, General Meeting, Pittsburgh, PA, July 20-24, 2008.
- E. Muljadi, Z. Mills, R. Foster, J. Conto, A. Ellis, “Fault Analysis at a Wind Power Plant for a One Year of Observation,” presented at the IEEE Power Engineering Society, General Meeting, Pittsburgh, PA, July 20-24, 2008.
- E. Muljadi, S. Pasupulati, A. Ellis, D. Kosterov,” Method of Equivalencing for a Large Wind Power Plant with Multiple Turbine Representation,” presented at the IEEE Power Engineering Society, General Meeting, Pittsburgh, PA, July 20-24, 2008.
- R. Zavadil, N. Miller, A. Ellis, E. Muljadi, E. Camm, and B. Kirby, “Queuing Up,” the IEEE Power and Energy Magazine, November/December 2007
- E. Muljadi, C.P. Butterfield, B. Parsons, A. Ellis, ”Characteristics of Variable Speed Wind Turbines Under Normal and Fault Conditions,” presented at the IEEE Power Engineering Society, Annual Conference, Tampa, Florida, June 24-28, 2007.

- M. Behnke, A. Ellis, Y. Kazachkov, T. McCoy, E. Muljadi, W. Price, J. Sanchez- Gasca, “Development and Validation of WECC Variable Speed Wind Turbine Dynamic Models for Grid Integration Studies,” presented at the Windpower 2007, WINDPOWER 2007 Conference & Exhibition, Los Angeles, CA, June 24-28, 2007.

Sources:

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- “WECC Wind Generator Modeling,” Fact Sheet. [http://uc-ciee.org/images/downloadable_content/electric_grid/WGM_FactSheet.pdf]
- Personal Communications: Muljadi, Eduard, a Principal Author and the Project Manager, National Renewable Energy Laboratory, Golden, CO.

2.4.2 Load Modeling Transmission Research

This project was performed by the Lawrence Berkeley National Laboratory, the Pacific Northwest National Laboratory, Southern California Edison Co., the University of Wisconsin – Madison, and others. The Principal Investigator was Bernard Lesieutre.

The situation today is that existing load models in dynamic programs do not correctly represent the actual load behavior observed in the system under many system conditions. The dynamic effects of the addition of residential and commercial solar photovoltaic (PV) generator systems on nearby customer loads are largely unknown. One particular phenomenon known as Fault Induced Delayed Voltage Recovery (FIDVR), generally understood to be caused in this case by the stalling of residential air conditioners after a brief period of power instability, had become of increasing importance and was not reflected in current load models.

The primary problem addressed, which was not adequately represented in the load models being used, was voltage instability in Southern California, and the U.S. Southwest in general, after a brief voltage disturbance in the electric grid. Improving load modeling was one method of addressing this problem through improved predictability of damping and stability issues related to the California- Oregon Intertie and other major interties, critical to the security of the California and entire WECC system. The improved models would lead to more reliable operation of the grid in the West, and reduce the risk (and costs) of widespread blackouts. Moreover, a better understanding of anticipated network behavior would aid in planning for appropriate deployment of capital investments, including new controllers, protection, generation and transmission.

Therefore, the ultimate objective of this research was to improve the accuracy of dynamic load models used in power system analysis and simulation tools. Specific objectives included the development of:

- An accurate model of residential air conditioners,
- Potential solutions to FIDVR,
- Tools and methodologies for determining the mix and balance of different types of electrical loads, and
- A scoping study for the impact of increasing penetration of residential and commercial photovoltaic systems.

This research was a coordinated effort by members of the WECC to enhance the understanding of the behavior of loads, especially air conditioners, and to improve simulations of dynamic behavior of the power system. Because of the prevalence of this problem in Southern California, SCE was one of the leaders of this research, with PG&E and SDG&E as significant contributors. Specific tasks included testing of residential air conditioners and development of an accurate model, testing and analysis of possible solutions for FIDVR, development of improved load modeling techniques including methodology and tools for load composition, evaluation of the merits of future load monitoring and development of a monitoring placement plan, development of an uncertainty analysis for load modeling, and a scoping study to assess solar generation characteristics and associated impacts on load modeling. Technical oversight was provided by the WECC Load Modeling Task Force in cooperation with a significant number of utilities, national laboratories, and system operators.

Extensive testing of single-phase residential air conditioners, under various voltage and frequency transients, resulted in both an accurate dynamic model and confirmation of air conditioners as the cause of FIDVR. Load models that match the testing results were constructed. A new load composition tool to help build load models for simulations was developed. An uncertainty analysis was completed which led to a strong recommendation for future load monitoring to validate the tool. Potential FIDVR solutions at the system level were analyzed and some existing devices that could be solutions at the HVAC unit-level were tested. None were found to be completely satisfactory. Manufacturing standards were recommended to deal with the issue in the long term. In anticipation of high penetrations of distributed PV electric generators, a scoping study of inverter models was included in this research. It was determined that, as penetration increases, distributed PV could have significant impact on the grid. No suitable inverter models for use in load modeling currently exist, but a candidate approach was proposed. It was recommended that testing of inverters be done. Load monitoring, uncertainty analysis, and motor protection were some other areas identified in this project where additional research was needed.

Specifically, a number of ground-breaking results were obtained through this work. These included:

- Measurements that showed the characteristics of single-phase air conditioning units under stall conditions (high reactive power draw)
- Measurement of the speed of stalling in single-phase air conditioning units (3 to 5 cycles)
- Determination of voltage levels causing single-phase air conditioning unit to stall (60 – 70% of nominal voltage depending on outside air temperature and design of unit)
- Construction and validation of single-phase air conditioning unit models (against AC unit test data) for use with GE Positive Sequence Load Flow (PSLF) model.
- Examination and laboratory testing of potential solutions to the air conditioning stalling problem (most of which would help the immediate problem of low voltage, but would cause an uncontrolled high voltage transient a short time later)

- Analysis of load composition – regional and seasonal load composition values for system studies

Dissemination of project results was through the WECC Load Modeling Task Force, conference presentations, technical papers, and interactions with utilities and air conditioning unit manufacturers. Some examples of these are:

- Numerous presentations at meeting of the WECC Load Modeling Task Force attended by engineers from several western US utilities
- Presentations at conferences and meetings:
  - IEEE Conference, special session on Load Modeling
  - EPRI PQ Applications Conference 2007 and 2008
  - AHRI Unitary Small Equipment Engineering Committee Meeting 2008 (AC manufacturers association)
  - Background for two SCE IEEE Conference papers in 2013/2014 on FIDVR
- Contribution to NERC Transmission Issues Subcommittee paper on FIDVR (2009)

- Provided background for two DOE/NERC-sponsored workshops on FIDVR/ AC Stalling (2008 and 2009)

In addition to the specific technical benefits just described, based on supplied guidelines, there were a number of other benefits of this research as well. Although difficult to quantify since these FIDVR/AC events are low-probability/ high-impact events, based on professional experience and judgment, there were a number of reliability and economic benefits to ratepayers. The electric grid planning and operations in California and the WECC are better prepared with the potential to reduce large-scale system outage caused by FIDVR.

Significant staff time was provided by a number of utilities and grid operating entities in the Western Interconnection in reviewing and implementing the composite load model. Two major project participants, SCE and BPA, made in-kind contributions of ~ $170k and >$1M, respectively.

This CEC PIER work paved the way for the development and implementation of the composite load model – the most significant grid modeling advancement of the last decade. The composite load has been implemented in all major commercial grid simulators used in North America – General Electric's PSLF, Siemens PTI PSS®E and PowerWorld (See discussion on the "WECC Wind Generator Modeling" project described elsewhere in this paper.). The model has been approved for planning and operational studies in the WECC, which are used to make capital investments in the power grid and compliance with NERC Reliability Standards. The operating studies are used to set system operating limits.

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- Personal Communications, Kosterev, Dmitry, a Primary Author and Contributor, Bonneville Power Administration, Vancouver, WA

3. New Technology for Increasing Transmission Capacity by Optimizing the Grid for Greater Power Flow

Underinvestment in transmission infrastructure in the latter decades of the 20th century, when transmission capacity did not expand at the same rate as growth in power demand, resulted in congestion and threats to reliability. Although this capacity limitation affects any power plant connected to the grid, it certainly represented a barrier to meeting California's renewable energy goals.

Any transmission line has physical limits on the amount of power that can be transmitted. Which particular limit is the dominant factor constraining the capacity of a given line at a given time depends on the conditions of that particular line and the broader wide-area transmission grid. Because the technological sophistication of situational monitoring was never particularly accurate or precise in the past, conservative static operating limits had been set which were often far below the physical limits, which in effect de-rated the capacity of a line, often by 20 to 50% or more.

There are two fundamental classes of limits, thermal and stability.

- Thermal Limits: The amount of power or current a line can carry, under all anticipated conditions, before reaching its limiting temperature. The primary source of heat (known as I^2R heating) comes from the interaction between the electrical resistance (R) of the line material and the electric current (I) flowing through it. If driven above its limiting temperature, a line may excessively sag due to thermal expansion, creating a safety hazard or an outage, or be damaged by irreversible stretching. Because the assumed environmental conditions are extremely conservative (typically 109ºF and 2 ft/sec wind) when establishing thermal limits, real-time ambient information could allow substantially increased capacity limits in operations.

- Stability Limits: Poor voltage support and dynamic and transient instabilities can result in lower capacity limits, even substantially below the thermal limits in some situations, especially for long transmission lines. It is not unusual for a major interconnection path to be operationally limited by instabilities to half its rated static thermal limit. This effect imposes severe constraints on the amount of renewable power that can be imported into California, and into major load centers within the state.

There were emerging technologies that could, in principle, provide the capabilities to reduce the margins of operating limits required for safety, and even raise the physical limits, thereby adding substantial "new" capacity without building new transmission lines or reducing reliability. These capabilities would prove vital to meeting renewable energy goals if building all of the new transmission capacity needed falls short, especially likely in dense urban load centers, and might be preferred as a cheaper way to get greater transmission capacity.

3.1 New Capacity Thermal Capability

The TRP explored two avenues for mitigating thermal limits. One was to relax the conservative static limit by enabling current flows closer to the real physical limit through dynamic (real time) "thermal" rating monitoring, yielding incremental capacity increases. TRP conducted a number of assessment and deployment studies, and demonstration, of monitoring devices and data management and analysis. The second approach was to increase the physical thermal limits through new line conductor material technologies. These new materials could handle considerably higher temperatures without sagging or damage, and without the use of larger heavier cables that required new poles or towers. They did however require some special handling during installation because of a greater susceptibility to being damaged from excessive bending. Also, new connectors and special splices were required in some situations. TRP monitored a field demonstration of one of these new conductors at a California IOU.

3.1.1 Multi-Area Real-Time Transmission Line Rating Study

This project was performed by The Valley Group. The Principal Investigator was Tapani Seppa.

Prior PIER research recognized that both thermal limits and voltage limits interact to cause combined dispatch restrictions in California's transmission network. The analysis from that project concluded that a solution was required for the combined restrictions that were limiting power dispatch in the Sacramento area. The objectives of this project were to: 1) identify conditions where combined constraints restricted dispatch; 2) quantify the magnitude and cost of such restraints; and 3) investigate prediction of line ratings in the timeframe that would be useful for dispatch purposes.

In terms of lesson learned, coordination of schedules with the three utility participants became complex and difficult. Each faced a different set of limitations regarding funding availability, availability of engineering manpower, contractual negotiations, communications systems, communications interface to supervisory control and data acquisition (SCADA) systems, confidentiality requirements, scheduling constraints and priorities. Different SCADA and communications systems required modification of data collection and analysis systems for all three participants, which in turn required significant modifications in software. This complicated and prolonged the data analysis process.

There were thermal limitations in the Sacramento area that interacted with voltage constraints and limited the energy imports to the area. One of these limitations was the O'Banion-Elverta static line rating, which resulted in at least three curtailments of the Sutter generation facility; the actual real-time capability of the circuits during peak loading periods was at least 20 MW higher than the static rating. Increasing the thermal rating of the O'Banion-Elverta circuits by 20 MW with real-time ratings could increase import capacity to the area by over 250 MVA.

Extensive studies of various available rating prediction algorithms were conducted. None of the algorithms were found to have acceptable accuracy for predicting ratings in the targeted time range of 4-24 hours. The day-to-day rating patterns usually exhibited a high degree of similarity, especially during the summer, but the actual predictability of rating values varied greatly. The O'Banion-Elverta circuits had a median real-time rating of approximately 150 percent of the static rating, but only a 110-115 percent capability with a probability of 90 percent during the most critical loading periods (late afternoon – early evenings). The lowest ratings could occasionally be slightly below the static rating. Ratings were always safely over the static rating at night, but the circuits were never heavily loaded.

The original objective was to identify prediction methods that could be used in daily dispatch. It became increasingly clear as market rules changed and tightened during the project that there were no opportunities for economic dispatch that were applicable to "probable" capacity since operation of present-day markets was based only on firm capacity.

Ratings had "persistence" even though they were not sufficiently predictable to be used for daily dispatch purposes. That is, ratings could increase rapidly during a storm, for example. Ratings could not decrease rapidly, however, as it would require either a rapid increase in ambient temperature or an abrupt reduction of kinetic energy in the atmosphere.

Persistence of ratings could have a major impact on the management of contingency events in the network. It could increase operating economies because operators could either avoid changes in system dispatch or minimize them. It could also substantially increase system reliability, especially during times of high system loads.

Results of the analysis showed that dispatch constraints in the Sacramento area changed significantly over the time frame of the project. Several of the voltage constraints were alleviated by the installation of volt-ampere reactive (VAR) support. Further changes in system configuration and operations impacted the applicability of this project's results.

The indications of real time ratings persistence provided a template for application of real time ratings in California. This could increase operating economies and could also substantially increase system reliability by managing contingencies, especially during times of high system loads. The study of the combined constraints in the Sacramento area also provided an excellent example of how real time ratings could be used to mitigate import constraints to a large area.

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3.2 New Capacity Voltage Stability Capability

Operators may not know how susceptible the system is at any given time to undesirable voltage changes as a function of power transfer, which could lead to voltage collapse and a resulting blackout. Voltage stability constraints are intended to provide margins for safety, in the absence of precise knowledge. TRP developed and demonstrated a predictive analytic and modeling voltage security analysis tool for improving situation awareness and permit smaller, better defined, constraint margins. Licensing rights to the technology were obtained by a vendor that commercialized the new tool (see 3.2.1 California ISO Real-Time Voltage Security Asessment).

3.2.1 California ISO Real-Time Voltage Security Assessment (VSA)

This project was performed by the Lawrence Berkeley National Laboratory, Consortium for Electric Reliability Technology Solutions. The Principal Investigator was Joe Eto.

Analysis of over two dozen blackouts that had occurred in various places around the world indicated a need in developing real-time tools for monitoring system voltage security margins under the normal and contingency conditions. Regarding the June 2-3, 1996, major blackout in the WECC system, including California, the U.S. Department of Energy recommended that the WECC should consider the use of real-time security monitoring on regional scale to prevent future voltage collapse events. The WECC accepted this recommendation later in 1996 by deciding it would pursue a security monitoring and analysis tool that would enable operators to identify potential problems and take corrective action.

The goal of the California ISO Real-Time Voltage Security Assessment (VSA) project was to provide CAISO with a prototype voltage security assessment tool that runs in real time within CAISO's reliability and congestion management system. The project conducted a technical assessment of appropriate algorithms, developed a prototype incorporating state-of-art algorithms (such as the continuation power flow, direct method, boundary orbiting method, and hyperplanes) into a framework most suitable for an operations environment. A functional specification was prepared for a commercial grade system. CAISO has used the functional specifications to procure a production-quality tool that is now a part of a suite of advanced computational commercial tools provided by Bigwood Systems, Inc. (BSI), a developer and vendor of software tools for power grid assessment, monitoring, analysis, operation, control and optimization, located in Ithaca, NY (headquarters) and San Francisco, CA.

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3.3 New Capacity Transient Stability Capability

Transient stability is the ability of the transmission grid to regain its equilibrium in the event of a transient disturbance, such as a line fault or generator trip. Time frames are typically milliseconds to seconds. Generator and load models are used to plan the operating configuration of the electric transmission system to anticipate and better handle transient behaviors. But if the models are wrong, then the operating plans might not be able to address certain transient behaviors potentially leading to reliability and power quality problems. TRP conducted research and demonstration to improve the generator models for wind generators, and the load models for new air conditioner technologies. These models are now in use in California, the WECC, and other parts of the world. (See elsewhere in this paper, "Improved Generator and Load Models," under "New Technology for Accommodating Variable Renewable Generator Unique Behaviors.")

3.4 New Capacity Dynamic Stability Capability

Dynamic stability is the ability of the transmission grid to regain its equilibrium over time frames of 1 minute to as much as 30 minutes. Problematic instabilities can manifest in a number of different behaviors, with low frequency oscillations being perhaps the most egregious in the Western grid as a reason for capacity de-ratings. Low-frequency oscillations, which cause power to surge back and forth through wide areas of the grid, typically have a period of a few seconds and can build over periods of minutes to hours. They have been identified as the initiating event of some costly major multi-state blackouts, such as the widespread blackout in the western United States and Canada in 1996. The root causes of these dynamic instabilities were not all well known and research was needed. There is a growing concern that these dynamic instabilities might be exacerbated by changes to the electric system, such as renewable energy sources that reduce system inertia and add more uncertainty; and energy efficient loads that introduce new dynamics, as well as uncertainty. These all change system oscillation behaviors and make it more difficult to manage through traditional modulation control tuned with a system model.

TRP conducted a significant number of research efforts to develop and demonstrate stability operating tools based on synchrophasor measurements, which were new current and voltage measurement devices using time-stamping that for the first time enabled wide-area real-time status and event monitoring, detection, alarming, analysis and visualization.

The resulting operator tools considerably enhanced the operator situational awareness for greater reliability and promised enable operation of the transmission system with smaller dynamic margins. In conjunction with certain control technologies, perhaps energy storage, the tools might be used to mitigate dynamic instability threats, such as to damp oscillations. The TRP conducted a business case study for the use of synchrophasor measurements that examined applications and their economics, and include a roadmap for technology development. This study provided guidance for California and for many other entities across the nation. It encouraged TRP research in synchrophasor measurement based tools for rapid oscillation detection, analysis and mitigation; enhanced state estimation; smart adaptive relaying to prevent protection system actions from aggravating cascading blackouts; voltage angle changes for stress indication; etc. TRP also contributed substantial to the development of the platform for gathering and managing synchrophasor measurement data, and enabling application deployment. Much of this research has resulted in commercial products and uses.

3.5 New Capacity Transmission Expansion Planning Capability

Although reasonably precise, the traditional deterministic planning tools were increasingly becoming inadequate to support accurate expansion planning in a future of growing uncertainty and complexity, which was expected partly because of the growing use of variable renewable generation. The TRP anticipated that new planning tools based on probabilistic, multivariate statistical, risk assessment, and other advanced analytical science and mathematical techniques, along with faster computational tools, would be needed. Recall that a recommendation of the Transmission Cost Allocation Methodologies project described earlier was the Quantification of Extreme Event Benefits (Insurance Value) in terms of reliability using an insurance premium concept. Reliability benefits can be measured in terms of reducing blackout footprint due to extreme (N-n) events and societal value of reduced risk of a power supply disruption.

3.5.1 Extreme Events

The TRP took on the challenge of developing a planning tool for cascading blackouts caused by extreme events. A small initial power system disturbance can cascade into a complicated chain of dependent failures leading to a widespread blackout. On August 10, 1996, a blackout started in the Northwest USA and spread by cascading to disconnect power to about 7,500,000 customers, including millions of customers in both Northern and Southern California. The blackout of August 14, 2003 on the East Coast affected 50 million people and caused an estimated $10 billion in economic losses in the USA. Although such extreme events are infrequent, the direct costs are estimated to be in the billions of dollars, disrupting commerce and vital infrastructure. These blackouts also incur indirect costs including those from socioeconomic disruptions.

A current practice for reasonably and routinely assuring the reliability of a large electric grid interconnection, such as the WECC, which might have well over 10,000 components that could fail, is to plan the configuration and operation of the grid for any one of these components to fail without an electrical disruption. The short hand expression for this practice is the N-1 analysis, where “N” is the number of nodes (components) in the interconnection and “1” represents one of these nodal components failing. The N-1 reliability analysis is done repeatedly for the failure of each nodal component in turn. Traditional direct analytic approaches using N-1, or even selected N-2, contingencies do not even begin to provide the capability to analyze cascading blackouts, which have been characterized as “N-20” contingency events, because many components usually fail in a given large spread electric system outage event.

Performing extreme event analysis for an interconnection such as the WECC using the traditional approaches and the fastest computers in the U.S. was estimated for even an N-3 to take many months, and an N-4 analysis to take over a thousand years. Clearly the traditional analytical tools would not suffice for extreme event modeling. Hence there was a need to develop new and innovative methodologies to simulate power systems to address the extreme events using practical power systems and come up with remedial actions that would allow system operators to keep the power system away from collapse, and designers to enhance the resistance to cascading outages. This research pursued multiple approaches in order to better determine the strengths and weaknesses of both existing methods and the new methods, e.g., probabilistic, multivariate statistical forecasting, developed in the project, and produced encouraging results that these techniques would work to better characterize the resistance to cascading outages for a given or planned grid infrastructure configuration.

The “Extreme Events” research project developed, and tested in a small-scale network model, the science and conceptual framework and advanced mathematical techniques needed for the complexity of multiple component and system failures in a transmission system, such as the "N-20" equivalent analysis. Results included identification of critical corridors, event frequency and probability, and superior operational response strategies. Phase II applied Phase I methodologies to realistic network models to test their practicality.

A joint industry, national laboratory, and university team addressed the challenges of large blackouts caused by cascading failure by a combination of modeling, simulation and analysis techniques. Multiple approaches were pursued in order to better determine the strengths and weaknesses of both existing methods and the new methods developed in the project.

The project developed transmission grid models for cascading failure at several levels of detail for the California grid. These grid models were used with both industry and research-grade software to simulate the sequence of cascading events when there are one or several initial disturbances in the power grid. These simulated cascades were then analyzed and methods developed to detect critical elements and conditions and recurring sequences of events. The project analyzed historical data on blackouts, analyzed simulated blackouts statistically, studied the grid as an evolving complex system, and suggested factors that influenced the risk of cascades and ways to measure these factors. The understanding and methods developed can be applied to future studies to identify grid vulnerabilities, investigate the effectiveness of mitigation techniques, and quantify and explain the blackout risk.

The project achieved a number of firsts in the analysis of large interconnections and cascading outages:

- Developed the first-ever, full-size WECC model for cascading analyses using TRELSS, an Electric Power Research Institute (EPRI) software package for bulk power transmission system reliability evaluation using contingency enumeration as an expansion of traditional deterministic analysis.
- Developed a methodology and extensive sets of initiating events for cascading analyses in the Western Interconnection.
- Performed a total of 33,000 simulations to analyze the WECC system vulnerability to cascading events, providing:
  - A ranking of initiating events by severity
  - Identification of the most frequent sequences of cascading outages (critical events corridors)
- Compared results obtained in Phase II against reduced models
- Developed a reduced, 1500 bus WECC model that has been the basis of several other analyses, such as: Benjamin Carreras et al., "Validating OPA with WECC Data," 46th Hawaii International Conference on System Sciences, January 2013.

- This model was provided under a non-disclosure agreement (NDA) to Oregon State University for use by staff and students.

The U.S. Department of Energy's Office of Electricity (DOE-OE) subsequently funded at $1.25M the Pacific Northwest National Laboratory (PNNL), the principal investigator for the "Extreme Events" project, to conduct a new project, "Dynamic Contingency Analysis Tool" (DCAT) that will leverage the experience built in the extreme event project and will overcome several of the gaps that were identified in the previous effort. The purpose of the project is to develop a dynamic extreme events analysis tool to evaluate the risk of load loss due to extreme events, identify the most probable and impactful events, and evaluate the impact of system reinforcements. The goal of this project is to strengthen the capabilities of grid planners to assess the impact of extreme contingencies and potential cascading events across their systems and interconnections. This project will develop the necessary models and methods for analysis and identification of cascading events in the context of large dynamic systems. The project directly supports new NERC "Standard TPL-001-4 — Transmission System Planning Performance Requirements" to be enforced in 2015 and 2016, and a similar "Transmission System Planning Performance WECC Regional Criterion TPL-001-WECC-CRT-3" currently under development in the WECC system.

Publications, Presentations and Industry Interactions:

- Presented "Extreme Events Analysis in the full WECC System – Methodologies and Results" to the WECC Reliability Subcommittee on January 14, 2011.
- Provided sample results to Project Advisory Committee (PAC) members from Idaho Power and PG&E to further examine simulation results.
- Verified a limited set of actual cascading events from WECC disturbance reports in TRELSS and compared the results.

- Y.V. Makarov, N. Samaan, R. Diao, M. Kumbale, Y. Chen, R. Singh, and M.P. Morgan, “Assessment of Critical Events Corridors through Multivariate Cascading Outages Analysis,” 2011 PES General Meeting, 24-29 July 2011, Detroit, Michigan, USA. (Panel paper)
- Active participation in the IEEE Task Force on Understanding, Prediction, Mitigation and Restoration of Cascading Failures, that resulted in several publications such as: Papic M, K Bell, Y Chen, I Dobson, L Fonte, E Haq, P Hines, D Kirschen, X Luo, S Miller, NA Samaan, M Vaiman, M Varghese, and P Zhang. 2011. “Survey of Tools for Risk Assessment of Cascading Outages,” IEEE Power and Energy Society General Meeting, July 24-29, 2011. Detroit, Michigan.
- Submitted and published in IEEE Transactions: Vaiman, M.; Bell, K.; Chen, Y.; Chowdhury, B.; Dobson, I.; Hines, P.; Papic, M.; Miller, S.; Zhang, P., “Risk Assessment of Cascading Outages: Methodologies and Challenges,” Power Systems, IEEE Transactions on , vol.27, no.2, pp.631-641, May 2012.

- Presented at the 2011 IEEE PES General Meeting: Vaiman, M.; Bell, K.; Chen, Y.; Chowdhury, B.; Dobson, I.; Hines, P.; Papic, M.; Miller, S.; Zhang, P., “Risk Assessment of Cascading Outages: Part I – Overview of Methodologies,” IEEE Power and Energy Society General Meeting, vol., no., pp.1-10, 24-29 July 2011.

Sources:

- Extreme Event Research Fact Sheet: http://uc-ciee.org/images/downloadable_content/electric_grid/EE_FactSheet.pdf
- Extreme Events (Contract Number 500-02-004, UCMR-076), conducted by Pacific Northwest National Laboratory, University of Wisconsin-Madison, Electric Power Research Institute, BACV Solutions, Southern Company, CIEE, University of Alaska–Fairbanks. CEC-500-2013-031, March 2011. [http://www.energy.ca.gov/2013publications/CEC-500-2013-031/CEC-500-2013-031.pdf

- Personal Communications: Mark Morgan, Project Manager, Pacific Northwest National Laboratory, Richland, WA.

3.6 Transmission Congestion Assessment and Probabilistic Forecasting

Congestion costs in California can be very high and mitigating these costs generally involves long term planning and expensive upgrades to the grid in the form of new transmission lines or expansion of existing ones. In 2004, California Independent System Operator (CAISO) gross congestion and Reliability Must Run Generation (RMR) costs were estimated to be in the neighborhood of $1 billion annually, with congestion accounting for approximately half of the total. This figure did not include congestion that may be experienced on the California transmission facilities operated separate from CAISO. The problems of congestion also have an adverse impact on reliability, environment, and efficiency. Improved understanding of the nature of California’s congestion issues is a necessary precursor to effectively managing the problem. Improved forecasting of transmission congestion in both the short term and the long term can increase the reliability, efficiency and long term of the California electricity system. Improvements in congestion management will help achieve the State's goals for CO2 reduction and renewable generation deployment, and to provide reliable and low cost electricity with minimum environmental impacts.

3.6.1 California Transmission Congestion Assessment

This project was performed by the Electric Power Group. The Principal Investigator was Jim Dyer.

The purpose of this project was to perform a scoping study to document in explicit detail the scope and magnitude of the congestion problems facing the state of California and to report the challenges in forecasting. The specific objective was to develop a primer document on congestion on the California grid that would:

- Explain the problem of congestion
- Identify the key metrics and thresholds for establishing critical levels of congestion.
- Present historical congestion patterns
- Discuss the challenges of forecasting congestion
- Describe the current transmission system sources of information regarding congestion and identify sources of inconsistencies.

The project consisted of two primary approaches to gathering information – data collection and interviews. The data collection process was to obtain historical data on congestion from a number of California transmission control area operators as well as the California Energy Commission. Interviews were then conducted with several California transmission control area operators to obtain their inputs and assessments.

The scoping study found that the CAISO congestion cost data understated the amount of congestion that exists. It captured information related only to schedules attempted, as compared to the full economic potential for transactions. Inter-zonal congestion caused higher prices for all energy within the zone. This price impact was not captured in current congestion cost assessments. Reliability Must Run (RMR) was the largest single component of congestion costs. Without the construction of new local generation, RMR costs could only be reduced by expanding the transmission capabilities into constrained local areas. Congestion could only be avoided by planning and constructing sufficient transmission in advance to manage any remaining congestion costs to acceptable levels. Metrics would be needed to identify and classify congestion costs as actionable, manageable, or to be monitored. In general, the findings provided an essential building block for developing a congestion planning methodology in future research.

Sources:

- Dyer, Jim; John Ballance. (Electric Power Group, LLC). 2007. California Transmission Congestion Assessment. California Energy Commission. Publication number: CEC-500-2011-007.

[http://www.energy.ca.gov/2011publications/CEC-500-2011-007/CEC-500-2011-007.pdf]

- “California Transmission Congestion Assessment,” Research Project Fact Sheet. [http://uc-ciee.org/images/downloadable_content/electric_grid/TCAM_FactSheet.pdf]

3.6.2 Probabilistic Transmission Congestion Forecasting

This project was performed by the Electric Power Research Institute (EPRI). The Principal Investigator was Stephen T. Lee.

Because there are many factors that combine to determine how electricity flows on an interconnected power grid, the uncertainties of these factors, for example random loss of a generator or a transmission line, a load coming on or dropping off line, or the variability of a renewable generator, compound the uncertainty and the difficulty of forecasting transmission congestion for any particular transmission path. This difficulty will become even more pronounced with the advent of high penetrations of variable renewable generation in California. Making forecasts under high uncertainty often means using probabilistic methodologies.

This research developed new probabilistic forecasting methods, for both short term and long-term transmission congestion in California, for use in transmission planning and forecasting tools that recognize uncertainties created by independent market participants, especially variable renewable resources, and distributed generation, and by consumer participation, particularly demand response. The mathematical models and the time frames of the simulation differ between the short term (24 hours) and the long term (10-20 years), and therefore two computer models were developed to address the two time frames. An important aspect of this research was that it determined and specified how to accurately model the key input assumptions in order to derive valid confidence levels of the forecasted congestion variables. Methodology was demonstrated using the equivalent model of the WECC system, with focus on the impact of such congestion on the California power grid and consumers

For long term probabilistic forecasting, the quality of results was highly dependent on load forecasts and future resource projections, but probabilistic forecasting gave significant information regarding incremental improvements and timing of future transmission upgrade requirements. Short term simulations also showed a strong dependence on load forecasts and on generation dispatch. It was found that high variability in daily wind patterns affecting wind generation would increase congestion and the uncertainty of forecasts.

This project developed an approach that accounts for significant uncertainty caused by load and generation forecasts as well as random unplanned equipment outages. Meeting California’s Renewable Portfolio Standard goals will increase the volatility of congestion due to wind generation and present tremendous challenges for the CAISO in managing the power grid. The CAISO reported that annual congestion costs on the California-Oregon Intertie (COI) path increased to $12 million in 2006 compared to $6.7 million in 2005. Congestion costs will likely increase even more with the higher penetration of wind power, so improvements in congestion management could yield significant cost savings and help achieve California's goals for reducing greenhouse gas emissions and providing reliable and low-cost electricity to California consumers with minimum environmental impacts.

The successes of this PIER funded project were built upon by EPRI in follow-on research:

- The EPRI P40 (Grid Planning) members continued one year funding support in 2008 and development of a software package based on this CEC/CIEE research project: Probabilistic Transmission Congestion and Constraints Forecast (PCF) Version 1.0 (1015997) Available: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001015997

- Some of probabilistic modeling approaches developed through the CEC/CIEE research project were also applied to address wind integration, which was supported by EPRI P173 members (Renewable Integration). The final report is Advanced Planning Method for Integrating Large-Scale Variable Generation. Available: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001017903 Congestion Risk Assessment, EPRI, Palo Alto, CA. 1013809. Available: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001013809

Other research conducted by EPRI built upon this CEC/CIEE research project:

- Probabilistic Transmission Congestion and Constraints Forecast (PCF) Version 1.0 (1015997): Available: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001015997
- Hedging the Long-Term Transmission Price Risks Associated with Generation Investments. Available: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001010693
- Transmission Price Risk Management. Available: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001012475
- Managing Transmission Risk. Available: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=TR-114276
- Managing Transmission Curtailment Risk Through Forecasts of Transmission Loading Relief Calls. Available: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001015871

Many of the forecasting and hedging techniques developed in this connected collection of research is available to ISOs, energy traders and utilities.

Sources:

- Lee, Stephen, December 2012. Probabilistic Transmission Congestion Forecasting. California Energy Commission, PIER Program. CEC-500-2013-120. Available: http://www.energy.ca.gov/2013publications/CEC-500-2013-120/CEC-500-2013-120.pdf
- "Probabilistic Transmission Congestion Forecasting," Research Project Fact Sheet, Available: http://uc-ciee.org/images/downloadable_content/electric_grid/TPCF_Fact Sheet.pdf
- Personal Communication: Robert Entriken and Liang Min, Electric Power Research Institute, Palo Alto, CA

3.7 New High Power Flow Managing Capability

Increasing the capacity of transmission lines, however, brings with it the threats of substantial grid equipment damage and injury to humans from higher fault currents, and greater security and reliability vulnerabilities from more power being concentrated in fewer pathways. These threats needed to be addressed along with achieving increased power capacities in the grid. The TRP research in extreme event analysis described above addressed in part the latter threat. Protecting the grid and people from higher fault currents required hardware development because in many cases anticipated fault currents threatened to exceed the ability of circuit breakers to safely and reliably interrupt the faults. Aside from undesirable solutions such as installing substation neutral reactors, splitting substation buses, or derating circuit paths, what was needed was a new class of devices to control the fault currents by keeping them within the capabilities of the available circuit breakers. Fault current controllers were currently in the RD&D phase, with several manufacturers testing prototypes in the 15 kV class. Prototype devices needed to be demonstrated in actual utility systems in order to identify implementation issues and utility resource requirements, and to provide the requisite field experience to refine the designs for utility acceptance. The TRP developed a project to test prototypes in the field with a California utility as the host for the demonstration.

3.7.1 Development of Fault Current Controller Technology

This project was performed by the Electric Power Research Institute (EPRI), SC Power Corp. (later Zenergy Corp.), and the University of California - Irvine. The Principal Investigator was Carl Blumstein, CIEE.

Overall electric current loading on the transmission system has been rapidly climbing due to the growth in demand for electricity. The resulting higher electrical energy levels have increased the potential fault current magnitudes at locations throughout the transmission system. Fault currents, in many instances, may exceed the capability of existing protection systems (circuit breakers) to interrupt the faults safely and reliably, and represent an imminent threat to electrical equipment and the safety of utility workers and the public. Consequently, utilities must either upgrade their circuit breakers and associated equipment, or reconfigure their systems to reduce the potential fault current. Both solutions are costly, and frequently reduce system reliability and power transfer capability. Application of fault current controller (FCC) technology, also frequently referred to as fault current limiter (FCL) technology, has been identified as a potentially viable solution for managing fault currents to keep them within the existing short circuit capacity ratings of the system, in order to expand and extend the transmission system's capacity and service life while minimizing capital costs. This approach allows utilities to continue to meet the growing demand for electricity reliably and cost-effectively.

This project developed and evaluated two prototype designs of FCC technologies. The goals of the proposed research were to establish the desired criteria for FCC performance and to test the two prototype FCC technologies against those criteria by means of controlled laboratory testing and field demonstration in a commercially operating Southern California Edison Co. (SCE) distribution system. The overall objective of this project is to facilitate the improved, safe and reliable operation of the power system by advancing FCC technology as a cost-effective and environmentally-preferred option to breaker upgrades or system reconfiguration, and by evaluating the realistic potential of this technology to mitigate fault current levels at higher voltages in the electric system through real-world utility testing. The ultimate program goal is to enable the commercialization of FCC technology for the benefit of California and the United States.

The objectives of the proposed research were to:

- Establish an FCC test plan including test criteria, test protocol, test site selection, test scheduling, data collection plans, and interface requirements for both the laboratory testing and field demonstration.
- Develop two prototype FCCs, one saturable-core type developed by Zenergy Power plc, and one solid-state type developed by the Electric Power Research Institute (EPRI) and Silicon Power Corp. team.
- Conduct laboratory testing of the two FCCs against the criteria, including pre-connection high-voltage insulation tests, normal operation tests, and fault current limiting tests.
- Install the FCCs on the SCE distribution system and perform field demonstration for a minimum of six months.
- Complete the evaluation of the technologies on the basis of performance, respective strengths and weaknesses, costs, reliability, installation, operation and maintenance issues, and potential for development to high-voltage design.

A project team was formed, in which the California Institute for Energy and Environment (CIEE) as the Performing Institution was responsible for overall project direction, coordination and administration; University of California, Irvine (UCI) as the Principal Investigator was responsible for project technical management, coordination, and contractor oversight; Southern California Edison Co. (SCE) was the host utility for the field demonstration and support; and Zenergy Power, plc and the EPRI/Silicon Power team were engaged to prototype and field-test a passive-type FCC and an active-type FCC, respectively. In addition, a Project Advisory Group (PAG) was assembled with experts from utility companies, national laboratories, regulatory boards, and other relevant stakeholder organizations to provide technical guidance and evaluation of project results.

The project started in September 2007. This was not the first attempt in the United States to develop a distribution-level FCC and demonstrate it on an operating power system. However, none of the earlier efforts had led to a successful field demonstration in the US. The obstacles to be overcome were challenging. First, there were no industry standards for such a device, complicating the development of testing protocols. Second, there were significant engineering challenges in developing the prototypes to withstand the currents and voltages in the field. Third, the prototype FCCs had to meet SCE’s specifications for field demonstration on their system. Finally, the FCCs had to demonstrate the ability to withstand live circuit events and severe environmental conditions.

An important step taken in the early stages of the project was a focused effort to develop the test plan acceptable to SCE and workable for the teams. This test plan needed to incorporate, to the extent possible, the relevant engineering standards that apply to electrical apparatus. Zenergy Power worked closely with Georgia Tech's National Electric Energy Testing, Research and Applications Center (NEETRAC) and several of its member utilities, including SCE, to implement a detailed FCC test program based on selected IEEE and CIGRE standards and protocols for transformers and reactors. The EPRI/Silicon Power team created their plan based on ANSI C39.09-1999 and ANSI C37.06-2000, covering the entire spectrum of possible tests that needed to be carried out on their FCC, including component level factory tests, system level factory tests, acceptance tests and system field tests. Many technical issues related to laboratory test and field demonstration interfacing were resolved via a series of meetings with knowledgeable SCE engineers. Both teams completed their test plans, which provided valuable design and testing guidelines.

Zenergy Power completed the design, construction, and testing of an FCC prototype based on the saturable-core concept. This type of FCC is basically a coil wound on an iron core and connected in series with the power line. In the normal state, the core is biased into magnetic saturation by a dedicated DC electromagnet, so that the inductance of the magnetically saturated coil and the corresponding voltage drop across the coil terminals are negligible. Therefore, the coil has no deleterious effect on the system during normal operation. However, in the event of a fault, the magnetic core is driven out of saturation by the fault current. Consequently, the coil becomes highly inductive, effectively inserting a large impedance into the power circuit and limiting the fault current, without any need for active sensing or switching. A key enabling feature of the Zenergy Power HTS FCL is the use of a high-temperature superconducting (HTS) winding for the DC bias circuit, which reduces bias circuit power loss while increasing the intensity of the bias field; thus the Zenergy Power device is referred to as an HTS FCL.

The prototype HTS FCL went through a series of rigorous laboratory tests in BC Hydro's Powertech Laboratory in Surrey, BC, Canada. A total of 65 separate tests were performed, including 32 full-power fault tests with first peak fault current levels up to 59 kA at the rated voltage. Fault tests included individual fault events of 20-30 cycles duration, as well as multiple fault events in rapid sequence (to simulate automatic re-closer operation) and extended fault events of up to 82 cycles duration, simulating primary protection failure scenarios. The HTS FCL passed the test criteria in all cases. Only minor modifications to high-voltage isolation layout were needed. The unit was then transferred to the SCE Westminster High-Voltage Test Facility for acceptance tests by SCE per IEEE Standard C57-12.01-2005 (Attachments III-VI).

Upon the successful completion of the acceptance tests, the HTS FCL was installed in SCE's Avanti Circuit of the Future and operated from March 2009 through October 2010. The unit was integrated into SCE's SCADA system and operated in real time to provide protection to the distribution circuit during its field demonstration. A monitoring and data acquisition system was installed to archive performance data of the HTS FCL throughout the field testing period.

During the course of the field demonstration, several deficiencies in the original design and construction were revealed, including a PLC RAM overflow programming issue, HVAC shutdown due to excessive ambient temperature, helium leaks in the cryogenic coolers, nitrogen pressure instabilities associated with the liquid nitrogen cooling system, and a terminal block short. These events provided valuable learning experiences for the team to identify design weaknesses and make necessary corrections along the way, resulting in significant design and implementation enhancements.

The immediate research benefits obtained from the Zenergy Power HTS FCL's operational experience included validation of the importance of a more compact, more reliable, and easier to maintain non-HTS design for the FCL, and one which is scalable to transmission voltages. Operations manuals for the device are provided as Attachments VII-IX.

The field demonstration has been instrumental in furthering the development of FCL technology and contributing to Zenergy Power's first commercial sale of a medium-voltage device. Furthermore, Zenergy Power has extended the research results to prototype development and applications at the transmission voltage level.

The Electric Power Research Institute (EPRI) and Silicon Power Corp. team completed an initial design for an FCL based on solid-state circuit technology employing their Super GTO (SGTO) thyristor switches. The FCL design consists of a set of standard building blocks (SBB), each containing an SGTO-based circuit designed for 5 kV voltage blocking and 2000 A continuous current ratings. The SBBs are used in multiples to form standard power stack (SPS) assemblies rated for 50 kV voltage blocking and 2000 A continuous current ratings. One SPS per phase is required for the 15kV-class system.

Three SPSs are then housed in an oil-filled tank to form a complete three-phase FCL, referred to as the Solid State FCL (SSFCL) unit. In the normal state, the SGTO switches are turned on, which allows continuous rated current to flow through the circuit; upon detection of a fault, the control circuits open the SGTO switches to insert a current limiting reactor (CLR) into the circuit to limit the fault current.

The 15kV, 1200A SSFCL was designed for outdoor use according to the C57.12.00-2010 IEEE Standard for General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers. The overall SSFCL package is physically similar to a typical substation transformer tank with an external radiator bank for the cooling system. A comprehensive test plan was also developed for the SSFCL.

During initial simulation of the thermal performance of the SSFCL design, less than optimal thermal performance was predicted, which could have led to undesirable effects on the stability and reliability of the final, manufactured SSFCL. The designs of the thermal management system and the control boards were therefore modified during the course of the project, to provide a more efficient thermal management system and to improve the noise immunity of the controls. An unfortunate result of this necessary re-design was a much higher projected construction cost than allowed by the available project budget; therefore, this part of the project was terminated by mutual consent of the CEC, CIEE and EPRI at the conclusion of the design stage. EPRI was able to incorporate this and other lessons learned into a newer SSFCL design, to be developed within their normal program funding structure and demonstrated at some point in the future.

Conclusions:

The research in this project has led to the successful field demonstration of the Zenergy Power HTS FCL, marking a milestone event in the history of FCL development in the United States. The experience gained from the research contributed to a more reliable controller, a dramatic reduction of the FCL’s size (with a slight increase in weight), and the replacement of liquid nitrogen cryogenic refrigeration by a low-maintenance, dry (non-HTS) cooling system for increased reliability and reduced maintenance requirements.

The first-generation “Spider-core” HTS FCL design had a dry-type transformer (air dielectric) structure, total overall dimensions of 19’x19’x7’, and weighed approximately 50,000 lb. The second-generation “Compact” HTS FCL that followed from this demonstration employed innovative core architecture and oil dielectric transformer construction techniques that led to a much more compact size of approximately 8’x10’x11’ and a somewhat increased weight of approximately 67,000 lb. The Compact FCL has a power rating similar to the Spider-core FCL, but with a much higher fault current limiting performance. The new Compact FCL design is an improved option for applications where real estate is limited, albeit with somewhat increased weight.

Regarding cost-effectiveness, as the first-generation device had a relatively low power rating, on the order of 25 MVA, the present manufacturing cost may not represent a high value proposition. This issue is being addressed on two fronts: HTS FCL technology is being improved to reduce basic device manufacturing cost, and it is being scaled up for higher voltages and currents. The latter may be more important in terms of cost-effectiveness and value proposition, considering the fact that higher voltage substations can often be more crowded and have fewer options for expansion, and higher voltage components (switchgear, insulators, transformers, bus-work) are exponentially more expensive than their low-voltage counterparts. Furthermore, the larger renewable power generators will most likely desire to connect to the transmission system, and high-voltage tie-lines have become increasingly more common as more power is wheeled from long distances and as grid interconnections occur to improve reliability and better control power flows. All of these factors are projected to continue to increase energy levels within the grid, leading to potentially unsafe fault current levels. In some cases, higher-rated components cannot be retrofitted in the available space, leading to lengthy and costly major upgrades of grid infrastructure. Economic studies and performance models show that at current performance levels and price points, FCC technologies can be very cost-effective compared to major upgrade projects at high voltages.

A key area for improvement identified during the field testing was the liquid nitrogen cooling system, which required periodic maintenance of the cryostat, including drying, establishing vacuum, and refilling the liquid nitrogen. This may not be practical, considering the fact that the unit would typically be installed in a high-voltage substation area. However, this issue was resolved in the second-generation FCL design by replacing the liquid nitrogen HTS system with a cryogen-free, “dry-type” conductive cooling system, available as a commercial off-the-shelf unit, resulting in a more reliable and robust system requiring less maintenance.

Overall, the Zenergy Power HTS FCL project is considered to have been an important success and it has already led to a scaled-up design for a transmission-level 138 kV FCL application, which Zenergy is actively marketing to utilities around the world.

The EPRI/Silicon Power SSFCL represents another potentially cost-effective solution to the rapidly increasing fault current levels in utility systems. One advantage of this type of FCL is the flexibility to be configured as either interruptive (i.e., to act as a “solid-state circuit breaker”) or simply limiting the fault current (and leaving the fault interruption to existing protective devices), with only minor design differences. Also, a solid-state FCL may be used to limit the current of superconducting cables to enable the use of smaller cable sizes. The solid state FCL also has a unique capability to limit inrush currents, even for capacitive loads.

The EPRI/Silicon Power team identified some potential thermal management issues in their initial design. An improved system design was completed, and the major technical design challenges, such as the thermal management system, and the control circuit architecture and timing issues, have been resolved. However, the resulting cost increase to actually construct the device was constrained by the project budget. Thus, this FCL was not able to advance to the laboratory test and field demonstration stages under this project.

According to the design predictions, the system size and weight would be 6.5’x12’x12’ and weight would be 62,000 lb. with oil cooling. These size and weight specifications would have been considered acceptable for utility applications.

The SSFCL employs a modular and scalable design. The SSFCL designed for the 12 kV line in this project period is composed of 10 SBBs in series. A future consideration with this design is that voltage sharing to maintain all the SBBs under the blocking voltage under dynamic conditions may be a technical challenge for transmission level applications where the voltage level is above 100 kV.

Overall, the EPRI/Silicon Power team made a substantial amount of progress in the design, development and improvement of the SSFCL concept. During the project period, many engineering challenges were identified and a new design was completed.

Recommendations:

Fault Current Controller (FCC) technology is a potentially cost-effective alternative to the capital-intensive upgrades of the power system that would ordinarily be required to meet growth in electrical demand. The demonstration projects in this phase have already resulted in two test plans and two full FCC designs, and have contributed to one commercial sale and one migration to a transmission-level application.

Further fast-paced and more advanced development of FCC technology is strongly recommended. As the demand for electrical energy rapidly increases, particularly in response to renewable power and “green technology” initiatives, and in the absence of better alternatives, substantial investments in system upgrades would have to be made on a fast-track basis in order to maintain the required levels of electric system availability and reliability. Significant amounts of these investment are potentially avoidable, if suitable FCC technologies are available to California utilities, and if California utilities are given reasonable incentives to deploy the new technologies. An accelerated program of FCC technology focused on reducing the cost, improving the reliability, and increasing the voltage and current ratings of FCC technology is needed in order for California utilities and ratepayers to reap the benefits. New and promising technologies are also important for economic recovery and the creation of new jobs.

Sources:

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3.8 Real-Time System Operations

3.8.1 A Business Case Study on Applying Synchrophasor Measurement Technology and Applications in the California and the Western Electricity Coordinating Council Grid

This project was performed by KEMA, Inc. The Principal Investigator was Damir Novosel.

Phasor measurement units (PMUs) collect time-synchronized grid data to provide real-time information about the status of a point on the grid. The development of new synchrophasor measurement-based technologies for analysis, modeling, visualization and control can produce previously unavailable, greatly needed tools for securely and reliably operating the modern electric transmission system under growing uncertainty, such as created by high penetrations of variable renewable generation connected to the electric grid.

Synchrophasor measurements can potentially transform the way the electric grid is operated, reducing costs, improving reliability, and reducing the number and scale of major power outages. Some observers have likened its ability to improve grid situational awareness as akin to the medical diagnostic advancements in moving from x-rays to MRIs.

The value of synchrophasor measurement applications to California electric customers is largely proportional to the degree they are deployed throughout

California and the Western Electricity Coordinating Council (WECC), because of the heavy reliance California places on having access to power imported from states throughout the West. Transmission owners and operators, who have the means to purchase, install and operate phasor-based applications, will usually deploy new technologies only if a business case can be made. While policy can have a strong influence on the degree and timing of deployment, policy makers need to know the high-value public benefits, and economic and financial barriers to commercial deployment. While the potential applications of synchrophasor measurements were recognized by many, some industry professionals and policymakers remained uninformed or unconvinced of the financial soundness of the investment. This business case study provided sound rationales for the investment needed to obtain the benefits of these tools.

This “business case” study evaluated the potential benefits, costs and understanding of who benefits and who bears the cost of expanded deployment of synchrophasor-based technologies and what are the best research and development opportunities to advance the most promising applications of this technology for the benefit of electricity consumers and the electric industry. It provided organized consolidated information for use by the electric industry players, policy makers and researcher planners. This study was conducted to identify economic and financial barriers to commercial deployment, and technology development gaps. Especially important in this case, it also sought to obtain information to help develop technology transfer strategies and educate potential users for increased adoption of these technologies.

This “business case” analysis and R&D roadmap were developed through a consensus process by the Principal Investigator in cooperation with major California utilities, the California Independent System Operator, and other electric power stakeholders.. The project identified applications, benefits, business rationales, and development and deployment barriers. It also created a roadmap for technology development and deployment. Results were obtained through collaboration with stakeholders, from interviews, group meetings, literature, and high-level analysis. An industry workshop was held to assist in publicizing the project results.

This study found that synchrophasor measurements would enable improvements in planning, operating, and maintaining the electrical grid that would otherwise not be possible. It identified a large number of existing and potential applications (either already deployed or under development) of synchrophasor measurement technology. Additionally, the study demonstrated that significant financial benefits may potentially be realized in using PMUs in market operations, such as more accurate locational marginal pricing-based clearing price calculations and improved congestion management through accurate detection of transfer capabilities. Some new applications also were identified, such as real-time system model adjustment for fault location calculations and monitoring phase unbalance with state estimation applications.

The study also concluded that as this technology is deployed and applied and as users gain experience and comfort, new applications will continue to be identified. Although there are a huge number of potential applications, this study identified two key areas that would benefit from applying synchrophasor measurement technology.

The first is analyzing and avoiding power outages that lead to catastrophic blackouts. PMU technology is a paradigm shift that enables the higher levels of reliability improvement required for outage and blackout prevention. Synchrophasor measurement applications can improve early warning systems to detect conditions that lead to catastrophic events, help with restoration, and improve the quality of data for event analysis.

The second application is improving market and system operations. Synchrophasor measurement applications help facilitate congestion mitigation through better system margin management. They also allow real time knowledge of actual system conditions as opposed to conditions defined by system models that may not reflect current conditions. In addition, state estimation solutions can be improved significantly for use in locational marginal pricing calculations, thereby improving the overall accuracy of the calculations and the associated energy clearing charges.

In addition to this general analysis, very detailed analysis of key individual applications demonstrated that many applications have a major improvement impact with PMUs or cannot be implemented without PMUs. These applications include angle/frequency monitoring and visualization and post-mortem analysis (including compliance monitoring).

The results of this study can serve as a base to develop a near-, mid-, and long-term development and deployment roadmap. This roadmap and the process to transition PMU technology to full commercial application in California and the WECC were key outcomes of this study that should help California, the WECC and the overall industry benefit from PMU technology.

This study concluded that synchrophasor measurement applications offer large reliability and financial benefits for customers, society, and the California and WECC electrical grid if implemented across the interconnected grid. Therefore, it provides motivation for regulators to support deploying this technology and its applications.

The study report has raised industry awareness of the needs and benefits of using the PMU technology to improve grid reliability and support various grid applications. This report communicated both to industry executives and technical leaders that PMU data are the foundation on which various wide-area monitoring, protection and control applications, including wide-area situational awareness, could be built. Presently, those applications enable early warning of conditions that could lead to catastrophic events, facilitate system restoration, enable accurate component and system models, improve event analysis, and more.

DOE used results of this report to identify and justify needs for Smart Grid investment in Transmission. A majority of funding for transmission was related to the synchrophasor technology for the DOE Smart Grid Investment Grant (SGIG) DE-FOA-0000036 in 2009, and sections from the report were used in this FOA. Investments co-funded by DOE plus other private entities (such as SCE and SDG&E) have resulted in deployment of approximately 1,700 PMUs by 2013. SCE has used the results of the report to justify investment in PMUs for their rate case. The rate case was approved and SCE has invested significant effort to deploy synchrophasor technology. The North American Synchrophasor Initiative (NASPI), initially funded by DOE and later on by NERC, has used the PIER synchrophasor roadmap as a base for their roadmap.

It is believed that vendors have used the report results and the roadmap to guide their deployment. Utilities and RTOs have used the report results and the roadmap to guide their plans. Researchers in academia have used the results as guidelines for research initiatives. Activities initiated by this report have influenced international research and deployment of synchrophasors. Concrete examples among a number of countries around the world are Brazil, Columbia, India, and others.

This study was a collaborative effort of power system technical and business professionals, leading researchers, and academics. Success of this project was based on continued guidance and contributions by direct participants such as Bonneville Power Administration (BPA), Pacific Gas and Electric (PG&E), Sempra Utilities (SDG&E), and Southern California Edison (SCE), and by contributing participants such as U.S. DOE, CAISO, TVA, Energy, NERC, and the WECC Remedial Action Scheme Reliability Subcommittee. There were other contributors and reviewers such as PNNL, Virginia Tech, Georgia Tech, and AEP. The project was reviewed by the Eastern Interconnection Phasor Project leadership and comments were incorporated in its report.

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3.8.2 Real-Time Applications of Phasors for Monitoring, Alarming and Control

This project was performed by the Lawrence Berkeley National Laboratory, and Electric Power Group. The Principal Investigator was Joe Eto.

The efforts funded for this project represent one phase of a multi-project research, development, and demonstration (RD&D) activity that was being coordinated by the Consortium for Electric Reliability Technology Solutions (CERTS) for the Energy Commission’s TRP.

The overall goal of the synchrophasor applications project was to accelerate adoption and foster greater use of new, more accurate, time-synchronized phasor measurements by conducting research and prototyping applications on the CAISO’s synchrophasor platform that provided previously unavailable information on the dynamic stability of the grid. This platform is called the Real-Time Dynamics Monitoring System (RTDMS). Feasibility assessment studies were conducted on potential applications of this technology for small-signal stability monitoring, validating/improving existing stability nomograms (a graphical representation of two or more variables used to define critical conditions based on simulations to aid in power system operations), conducting frequency response analysis, and obtaining real-time sensitivity information on key metrics to assess grid stress. Based on study findings, prototype applications for real-time visualization and alarming, small-signal stability monitoring, measurement-based sensitivity analysis and frequency response assessment were developed, factory- and field-tested at the CAISO and at BPA.

The key result of this project was the development of the RTDMS. The CERTS team conducted feasibility assessment studies utilizing synchrophasor measurements to validate and improve existing stability nomograms, evaluated small-signal stability monitoring algorithms, conducted frequency-response analyses, and obtained real-time sensitivity information on grid-stress directly from synchrophasor measurements. These rigorous RD&D studies enabled the project team to successfully develop prototype applications offering a rich set of features for wide-area monitoring and analytics, which were factory- and field-tested at the CAISO and at BPA. In addition, two new dedicated displays for measurement-based angle sensitivity and voltage sensitivity were developed as key indicators of grid-stress and proximity to instability.

The success of this research led the CAISO to adopt time-synchronized phasor measurements for real-time applications in the WECC. CAISO also made significant investments in the underlying hardware and supporting maintenance practices to host the prototypes and enable needed future research to develop functional specifications to facilitate acquisition of commercially-supported, production-quality tools.

The project team designed RTDMS to do wide-area monitoring and analytics. Wide-area monitoring allowed operators to evaluate stability margins across critical transmission paths, detect potential grid instabilities in real time, and mitigate these problems through the system’s manual or automatic controls. The system may also be used to improve state estimations and to determine the optimal location for additional phasor measurements.

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

The funding for this research came from three sources: U.S. DOE, CEC/PIER/CIEE and the Electric Power Group (EPG) in Pasadena, CA. EPG is continued to invest in RTDMS after the CEC/PIER/CIEE and DOE funding was stopped.

Since this research was done, the RTDMS and applications have been deployed at, in addition to CAISO, other major ISOs including PJM, New York (NY) ISO, the Electric Reliability Council of Texas (ERCOT) and many utilities including Duke, Dominion, Lower Colorado River Authority (LCRA), Salt River Project (SRP), ONCOR Electric Delivery Company, SCE, Los Angeles Department of Water and Power (LADWP), HydroOne, Southern Company, and others.

RTDMS has been deployed at different Universities such as UCLA Smart Grid Energy Research Center (SMERC), University of Illinois, Clemson, and Texas Tech University (TTU). It has been integrated with Intel technology for cyber security protection of critical infrastructures and demonstrated as integrated software (RTDMS with Security Fabric) at TTU. RTDMS being used as part of a DOE-funded cost-share project with EPG, SCE and ERCOT to develop Phasor Simulator for Operator Training (PSOT). Three patents have come from the work: US 7,233,843 B2, dated June 19, 2007, US 8,060,259 B2, dated November 15, 2011, and US 8,401,710 B2 dated March 19, 2013. SCE has utilized RTDMS in their RTDS Lab in Westminster, CA.

Here are some examples of cases where the RTDMS has been used:

- Detection and corrective action for Pacific DC Intertie Integration with EMS/SCADA systems.
- Detection and mitigation of oscillations from wind power plants' faulty controller settings.
- Simulation and replay of system events for use in training.
- Wide area situational awareness monitoring by ISOs covering large regions.
- Monitoring of dynamic metrics – phase angles, oscillations, damping, voltage and angle sensitivities, frequency instability.

- Automated event analyzer displays for diagnostics of events in real time to guide operator actions.

Numerous presentations and papers presented in different industry forums such as WECC Joint Synchronized Information Subcommittee (JSIS), NASPI, and IEEE.

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3.8.3 Real-Time Oscillation Detection, Analysis and Mitigation

These two projects were performed by the Pacific Northwest National Laboratory (PNNL). The Principal Investigators were Dr. Ning Zhou and Zhenyu (Henry) Huang.

Electromechanical oscillations occur frequently on power grid systems, typically when the system is perturbed in some fashion or is otherwise stressed. While they often die out on their own, i.e., are properly damped, the oscillations can grow out of control leading to grid reliability issues and potentially large-scale blackouts with costs estimated in the billions of dollars. Of those incidents, the most notable is the August 10, 1996 western system breakup, a result of undamped system-wide small-signal oscillations, here after called “oscillations.” During the outage in 1996, about 7.5 million customers (24 million people) lost their power supply for 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.

In power systems, an 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. Because of this threat of outages, and the few options grid operators have had to detect and respond to these dynamic instabilities, transmission planners have limited the power that can be transmitted over some major interconnections to substantially less than they could otherwise handle. This practice provides a dynamic stability margin of safety but at a cost of infrastructure asset capacity to deliver power, e.g., 1000s of megawatts, which limits the ability of the California and the Western Interconnection to economically exchange power and can lead to electricity shortages.

Therefore, significant efforts have been devoted in the past few decades to monitoring system oscillatory behaviors from real-time measurements. The relatively recent development and deployment of phasor measurement units (PMU) have provided the capability to obtain in real-time over the entire interconnection high-precision time-synchronized data needed for estimating oscillation modes. A mode is the characterization of an oscillation in terms of its (modal) frequency and shape used to communicate the nature of an oscillation to grid operators and engineers.

The methods and tools developed in these two projects provide grid planners and operators the capability to detect and mitigate power grid oscillations, and they are expected to improve reliability and avoid significant economic losses, especially under high penetrations of variable renewable generation. This research laid the foundation for achieving the goal of not only the rapid detection and analysis of oscillations but also their control through proscribed grid operations to change inter-area oscillation modes and achieve a new grid operating state so as to mitigate threats.

The overall goal of the first research project was a tool to improve real-time situational awareness of oscillation problems in the Western Interconnection. To achieve this goal the project specifically had to develop an intelligent algorithm for oscillation detection and analysis, evaluate its performance and usefulness using field measurement data, build a prototype graphical user interface (GUI), and then develop a real-time prototype tool for monitoring and analyzing power grid oscillations.

The development of this tool took advantage of past work on measurement-based modal analysis, also known as a ModeMeter, which uses real-time synchrophasor 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 WECC had conducted a number of system tests in the decade before this research project was initiated. 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 had already been developed. Each is effective for certain situations, but not as effective for some other situations. For example, the traditional “Prony” algorithm analysis works well for oscillation data, but not for ambient data. However, the “Yule-Walker” algorithm was 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 relatively long time window used in the algorithm is an issue in timely estimation of oscillation modes. Because power system situations change over time, and oscillations can occur at any time, this research project developed an intelligent ModeMeter tool that could rapidly and adaptively select from these different algorithms and adjust parameters for various situations.

Testing and validation for accuracy and speed, based on both simulation data and field measurement data from various system events on the WECC power grid, were done on the new ModeMeter tool. A real-time prototype tool for monitoring and analyzing power grid oscillations was developed around this new smart ModeMeter, integrated with a GUI. Finally the prototype tool was tested with real-time streaming synchrophasor measurement data.

The resultant prototype tool can automatically detect and analyze power grid oscillations in near real time using ringdown data from synchrophasor measurement units (PMUs), i.e., early oscillatory signals resulting within seconds after large sudden disturbances on the grid, such as a power line or a power generator dropping out of service. By effectively identifying ringdown data, the algorithm can identify the oscillation modes thereby providing the necessary information to operators accurately within a short time window. This oscillation tool development was a major breakthrough in the sense that it significantly lowers false and missing alarms, as well as shortens detection time by applying oscillation detection and analysis algorithms properly.

Recall that the California power grid is in 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. The overall goal of the second research project was to advance modal analysis beyond detection (see the first project above) to action, by developing a method and establishing a modal analysis for grid operation (MANGO) procedure to provide recommended actions (such as generation re-dispatch), and aid grid operation decision making for mitigating inter-area oscillations.

The challenge of managing oscillations is growing. For example, variable renewable energy generation reduces system inertia and adds more uncertainty; energy efficient loads with lower electrical resistance 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 an acknowledged system model, which is becoming less effective as the grid evolves in the 21st century, but uses real-time synchrophasor and other synchronized measurements of the electric grid.

When an oscillation with low damping is detected using the tool developed in the first project described above, MANGO can be used by a grid operator, or automated operation schemes, to potentially utilize generator re-dispatch or responsive loads (demand response) to adjust system power flow patterns so as to increase system oscillatory damping to a benign level. MANGO can also utilize some other smart grid technologies, such as storage, distributed generation or electric vehicle charging, for power flow pattern adjustment. Therefore, MANGO can improve grid reliability and efficiency, and also help to facilitate the deployment of renewable energy, demand response, and energy storage, which has both economic and environmental implications.

The fundamental part of this work explored the relationship between low damping and grid operating conditions, and then used the relationship to develop recommended actions for grid operations for increasing damping, therefore reducing the chance of system breakup and power outages. Different from traditional power system stabilizers and other modulation control mechanisms, MANGO increase 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, leaving the system a vulnerable as before. The significance of the use of synchrophasor measurements to achieve this distinction perhaps can be seen in how the MANGO procedure works.

The MANGO procedure consists of three major steps:

- Recognition – operator recognizes the need for operating point adjustment through online ModeMeter monitoring (see the first project discussion);
- Implementation – operator implements the adjustment per recommendations by the MANGO procedure; and

- 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 the grid 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, this research project primarily focused on estimating modal sensitivity from real-time measurements. Furthermore, a new concept of relative sensitivity was proposed for this procedure. Testing with power plants in the WECC indicated strong correlation of power flow patterns to the damping, giving clear guidance on how to adjust generator outputs to improve damping.

In summary, a MANGO procedure was established with practical considerations. The key step in the procedure is the modal sensitivity. A method for estimating relative modal sensitivity was formulated and studied with promising results from a medium-size system and the full WECC system, and the impact of topology change on damping was studied. The simulation studies were conducted with commercialized software, and the resulting experience and data paved the road for large-scale MANGO application.

Please note that, due to limited synchrophasor measurement availability at the time of this research project, all the tests were performed with simulated data. To fully demonstrate the benefit of the developed MANGO method, further testing needs to be done with actual synchrophasor measurements once the installation underway of an additional 250+ PMUs in the WECC is completed. 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.

This PIER research was supplemented and continued by more than $500,000 of funding from the U.S. DOE Office of Electricity and Energy Reliability through the administration of the CERTS program.

The technology developed has been well recognized by the electric grid community as state-of-the-art and the basis for follow-on research as listed in the references below. Part of the work was included in an IEEE special publication, which was supported by a special IEEE Task Force: (See Publication #3 below.) Several of the publications listed below were invited papers at prestigious international conferences. (See Publications #2, #7, #10 below.) And several papers have been well cited by other researchers.

(See Publications #4, #8, #9, #10 below). Many of the citations were by students in performing their graduate studies.

The intellectual property of this technology has been protected for commercialization through two software copyrights: (1) (MANGO) Model Analysis for Grid Operations version 1.0, and Oscillation Detection version 1.0. The Bonneville Power Administration has installed the Oscillation Detection software for testing, and discussions regarding testing the MANGO software tool are ongoing with several power companies.

Potentially; with these two tools, the transfer capabilities of stability-limited transmission lines can be increased, which in turn would increase asset utilization and free up transmission capacity for the California electric grid, as discussed above in this paper.

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3.9 Advanced Protection Systems Using Wide Area Measurement

3.9.1 Scoping Study of Intelligent Grid Protection Systems

This project was performed by Stuart Consulting. The Principal Investigator was Bob Stuart.

This study explored the state of the art of synchrophasor (phasor measurement unit, or PMU) technology and of remedial action schemes (RAS) and special protection schemes (SPS), and the transmission constraints of importing power into California. It recommended appropriate projects to further explore the applications of synchrophasor technology in electric grid protection systems in California.

In virtually all of the major blackouts dating back to the first big New York blackout in 1965, protective relays have played a major role in either contributing to the cause of the blackout or failing to mitigate the speed of the blackout. Unusual circumstances in terms of weather and configuration of the high voltage transmission grid that was not anticipated or studied by protection and operation engineers also contributed to these blackouts.

Two major trends over the last fifteen to twenty years have had an impact on the vulnerability of the high voltage transmission grid to withstand major blackouts. Utilities have been operating the high voltage transmission grid closer to the margin, meaning a smaller difference between reliable and unreliable operation. At the same time, remedial action schemes (RAS) and special protection schemes (SPS) have become widely used to protect against multiple contingencies. While these schemes provide a safety net to protect against extreme conditions, they are prescriptive by nature. The protection and operation engineers must anticipate these conditions and set the special protection schemes accordingly. This oftentimes means taking overly cautious remedial actions, or backing off on system transfer capability, leaving transmission capacity underutilized, at increased cost of operation.

The purpose of this project was to analyze transmission system protection issues, identify state-of-the-art technical protection solutions and their value for an intelligent system, and develop stakeholder-supported recommendations for a technology program. The specific project objectives were to:

- Evaluate system protection issues, needs and opportunities in consultation with the organizations participating in the TRP Policy Advisory Committee (PAC);

- Review the state-of-the-art in intelligent system protection technologies for addressing these issues, needs and opportunities with manufacturers and suppliers of promising system protection technologies;
- Review ongoing system protection R&D, field test validation projects and industry standards activities and explore opportunities to collaborate on RD&D that is synergistic with California's system protection issues, needs and opportunities;
- Develop prioritized recommendations for intelligent system protection R&D, field test validation and other related technology transfer activities that offer the potential to yield significant reliability, increased transfer capacity and other benefits for California's electricity consumers; and

- Review and obtain feedback on this recommended system protection R&D agenda from the TRP PAC, Technical Advisory Committees, equipment manufacturers and other industry experts.

The findings of the project are as follows:

Utilities in the Western United States have been installing PMUs since the early to mid 1990s. BPA has accepted the responsibility of being the repository for most if not all of the PMU data at their Ditmer control center in Vancouver, Washington. The data are primarily used for disturbance analysis, generation modeling and data modeling. As of the writing of this report, no operator actions based on PMU data had been implemented because no engineering studies had been done to correlate phase angles to system conditions requiring remediation.

Pacific Northwest National Laboratories (PNNL) has been in the forefront of research to provide real-time displays and operator screens to enhance situational awareness for operators. They have been doing advanced research into simulating actual real-time operating scenarios at control centers to include the trending of data and an RTDM (real time display monitor).

The IEEE (Institute of Electrical and Electronic Engineers) established the first synchrophasor standard, C37.118-2005. It defines measurement convention, measurement quality and communication protocol; all PMUs must meet these requirements to be compliant. Communication latency, performance under dynamic conditions, aliasing and instrument transformer errors are areas that need to be better defined and further researched.

There are over 14 manufacturers of PMUs that can be grouped into two categories: manufacturers whose primary product lines are disturbance recorders and monitoring equipment, and who produce stand-alone PMUs; and manufacturers whose primary product lines are protective relays, and who produce a combined relay/PMU package. All equipment is high quality, but there are tradeoffs to be considered in choosing one or the other approach.

Almost all protection and control schemes on the grid today are local in nature. This means that the sensing and tripping take place in one substation, typically with some schemes utilizing telecommunications between adjacent substations to coordinate the protection. The particular benefit of applying synchrophasors is because of the intelligence gathered over a wide area to detect stressed system conditions, which cannot be done on a local basis. Some potential applications that hold promise are wide area voltage control, small signal stability control and transient/dynamic stability control.

Special protection schemes (SPS) are the primary means of wide area control today although some are used for local problems as well. However, presently SPSs are prescriptive in nature, in that typically load flow and transient stability studies must be done assuming worst case conditions to ensure that there is adequate protection during those times. Since worst case conditions are by definition rare, this means that most of the time system capacity will be underutilized or remedial actions will be more severe than usually necessary.

The next step should be to develop methods to control transient stability that are less dependent on off-line studies and use more on-line computation. Techniques using pattern recognition, neural networks and expert systems hold great potential for developing feasible and effective control actions that are proactive in nature rather than reactive: action could be taken ahead of time to prevent outages from occurring in the first place.

Synchrophasor technology has been used to date primarily as a system monitoring and analysis tool. In post-disturbance analysis it has provided invaluable insight into finding the root causes for major system disturbances including the August 10, 1996 and August 14, 2003 disturbances.

California relies heavily on imported power from both the Northwest and Southwest, and many special protection schemes determine how much power can be imported based on voltage and transient stability limits. More intelligent special protection schemes that would take action based on actual real time conditions would allow power to be imported nearer the maximum limit.

No American utility has yet implemented a synchrophasor-based application in actual practice. NERC has been very supportive of the use of the technology. It is very important to apply the technology in a real-time application as quickly as possible, to build confidence in the technology and to work out implementation issues, such as telecommunications latency and dynamic response.

Both PG&E and SCE have extensive RAS/SPS applications that impact both power imported into California as well as internal generation in California. All of these special protection schemes protect against multiple contingencies. Both utilities have installed a significant number of PMUs on their bulk transmission system and have extensive high-speed telecommunications infrastructure, and would therefore be good candidates for a demonstration project.

A demonstration project employing synchrophasors for protection application would provide the needed experience to advance real-time reliability methods. An excellent candidate would be SCE's Big Creek project; the installation of a phasor data concentrator (PDC), a centralized programmable logic controller (PLC) and the software to program the PLC as a special protection scheme would be a feasible and economical demonstration project. It would show how operating Big Creek at higher levels of generation, while backing down more costly generation, would save Californians a significant amount in generation costs with a small investment of money and effort.

In the long term, the knowledge gained from the demonstration project could be transferred to more complicated special protection schemes such as the California – Oregon RAS scheme. The potential for savings is very large assuming that more economic hydroelectric power could be imported into California at least part of the time, and more costly thermal generation in California backed down.

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3.9.2 Advanced Protection Systems Using Wide Area Measurements

This project was performed by Virginia Polytechnic Institute and State University (Virginia Tech). The Principal Investigator was Virgilio Centeno.

Protection systems can operate in an unanticipated fashion during times of transmission system stress, and such operations are often an important contributing factor in the sequence of events leading to cascading outages. Considering the very large number of relaying systems in existence (by a rough estimate over 5 million on the North American Power Grid), it is to be expected that some of these unanticipated operations are due to defective relays. This has been documented as "the hidden-failure" phenomenon in protection systems. Other contributing factors to catastrophic failures are unexpected power system configurations which were not foreseen when protection systems were set, errors in setting and calibration of relays, or undiscovered design flaws in the protection systems.

In recent years, innovations in the field of power system protection, power system operation and power system devices have made possible new proactive approaches to the supervision of protection systems so that the likelihood of catastrophic failures of the power grid are significantly reduced, the regions of the power system affected by such events are limited, and the power system restoration process can be sped up. The project objective was to research, develop and evaluate the use of these technologies in the California system to monitor, supervise, and modify the protection systems in real time based upon the information about the state of the power system provided by the phasor measurements. Three particular aspects of protection system supervision and control were selected for research, because they address the principal concerns regarding protection system responses, and are inter-related 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 R&D effort was conducted in close cooperation with PG&E, CAISO and SCE, who were key members of the Technical Advisory Group (TAG). The study system selected was from the California power grid, and the results of the research were intended to provide proofs-of-concept of the proposed project, as well as complete functional specifications for implementing these ideas on the California system. It is expected that when fully tested by the utilities the results of the research can be directly integrated into the Energy Management Systems (EMS) of the California utilities.

The project focused on four tasks:

[1] Development and validation of a California transmission system model: Develop equivalent models for the electric system outside California, and validate the operation of the California-only model with respect to the full WSCC electric system model.

[2] Development of an algorithm for adaptive adjustment of dependability and security. Determine the key locations in the California electric system where an insecure relaying operation during stressed system conditions would be detrimental to the viability of the power system, and develop a decision tree that uses synchrophasor measurements from the selected locations to determine when the system is in stressed conditions, implementing a voting scheme to supervise the relaying system logic to prevent incorrect operation during these times.

[3] Development of an alarm for potential load encroachment, using real-time wide area synchrophasor data and the existing protection system data base to determine which of the relay characteristics are in danger of being encroached upon during a catastrophic event.

[4] Development of a more intelligent out-of-step relaying tool. Determine the coherent generator groups in the California system model and use them to implement a technique that uses wide-area measurements to provide a more appropriate out-of-step decision.

The results of the project were:

- Model Validation: A reduced West Coast power system model was developed based on the California model provided and the WECC system information provided by PG&E. The model consists of 3996 buses, 1124 generators (647 with dynamic models), 1913 loads, and a single generator representing the WECC external to California. The validation process performed at Virginia Tech show that this model reflects the behavior of the full WECC model for the major disturbances considered for this project. The voltage and frequency responses of the reduced California model are consistent with the full WECC California model for the large disturbances, generation drop and line loss, considered for this project. Conclusion: For the major disturbances considered for this project, the derived California model is considered valid.
- Adaptive Security/Dependability Balance: The optimal location for the adaptive protection scheme was derived using a systematic procedure to identify and rank critical location in power systems. The critical location was confirmed, based on practical experience, by the Technical Advisory Group, to be the Midway-Vincent 500 kV transmission path. Decision trees were generated for the Heavy Winter and Heavy Summer Models with acceptably low misclassification rates. PMU locations and the signals to be monitored were determined from the decision trees to

be Los Baños, Devers, El Dorado, and Pittsburg. Performance evaluation of the algorithm with new test cases created by simulating circuit element outages was performed to assess the robustness of the trees to topology changes. The misclassification rates for topology changes were found to be acceptably low. A functional analysis of the proposed system determined that it can be implemented with available commercial PMUs, computers and data concentrators, provided the communication links are available at the selected PMU locations.

- Alarms for Encroachment of Relay Trip Characteristics: A reduced West Coast power system model, consisting of 3996 buses, 1124 generators (647 with dynamic models), 1913 loads, and a single generator representing the WECC external to California, was developed. The validation process performed at Virginia Tech showed that this model reflects the behavior of the full WECC model for the major disturbances considered for this task. Critical locations for the proposed encroachment alarm system were determined with the help of the TAG, who recommended focusing only on California's Path 15 and Path 26. The following critical locations were determined at the following transmission lines:
  - Midway – Vincent #3 500 kV
  - Midway – Vincent #2 500 kV
  - Midway – Vincent #1 500 kV
  - Los Banos – Midway #2 500 kV
  - Diablo – Midway #3 500 kV
  - Diablo – Midway #2 500 kV
  - Vaca-Dixon – Cottonwood 230 kV

  Based on the analysis of the system model and the selected critical locations, PMU placement for this class was determined at the following substation locations: Midway 500 kV, Los Banos 500 kV, Diablo 500 kV, and Vaca-Dixon 230 kV. Based on an exhaustive contingency analysis, critical relays were determined as those that are most at risk of encroachment: distance relays, loss-of-excitation relays and out-of-step relays. A supervisory boundary, which is a concentric circle with a radius 50% larger than the radius of the relay trip zone, was established as the point at which alarms would be set. Contingency analysis of the Heavy Winter and Heavy Summer models revealed that for no combinations of outages and three phase faults did either the power swing or the post-disturbance load flow cause encroachment of distance relays on critical 230kV and 500kV lines in California.

  Alarms for out-of-step relays were based on identifying contingencies that cause significant changes in the location of the swing center and the size and speed of stable swings at the location of the out-of-step relay. An algorithm was developed to determine the contingencies that make out-of-step relays lose their ability to differentiate stable swings from unstable swings. The advantage of this system is that it will be fully automated in GE-PSLF so that as the model changes or new out-of-step relays are inserted it can be easily re-run. If sufficient phasor measurement units are available it may be possible to automatically detect the N-1 or N-2 conditions for which an out-of-step relay's settings are incorrect and issue an alarm accordingly. The following countermeasures were identified for the selected relay types:

  - Shrinking or reshaping of the trip region of distance relays and loss-of-excitation relays to prevent load encroachment without impacting their security.
  - Power swing blocking for out-of-step relays can prevent false tripping when the speed of the apparent impedance trajectory indicates that it is not a fault.
  - Automatic actions depend heavily on the proper functioning of phasor measurement units, digital relays, and communication channels. Defects in any of these elements could result in false tripping or a failure to trip.
  - The alarms developed in this task call the protection engineer's attention to a potential problem. For encroachment of distance relays and loss-of-excitation relays, the trajectory of the apparent impedance before and after the encroachment should be stored by the proposed system along with all the power system variables measured at the relay's terminals. Alarms for out-of-step relays, should indicate which system condition triggered the outage, and the location of the new swing center of the system.

  A functional analysis of the proposed system determined that it can be implemented with available commercial PMUs, computers and data concentrators if the communication links are available at the selected PMU locations.

- Adaptive Out-of-Step Protection: A reduced West Coast power system was developed based on the California model provided and the WECC system information provided by PG&E. The model consists of 3996 buses, 1124 generators (647 with dynamic models), 1913 loads, and a single generator representing the WECC external to California. The validation process performed at Virginia Tech showed that this model reflected the behavior of the full WECC model for the major disturbances considered for this task. Moving-window and growing-window coherence detection algorithms were developed to detect coherent generator groups, and the following 10 PMU locations are proposed to detect and monitor coherent groups in the California system:
  - Los Baños 500 kV
  - Morro Bay 230 kV
  - Diablo Canyon 500 kV
  - Imperial Valley 230 kV
  - Magunden 230 kV
  - Kramer 230 kV
  - Mountain View 230 kV
  - Haynes 230 kV
  - Vulcan I 92 kV
  - Litehipe 230 kV

  An autoregressive model was developed to predict angle swings, and an angle difference of 150 degrees for two consecutive samples was shown to be an effective trigger for detecting unstable swings. The performance of the proposed adaptive out-of-step algorithms was evaluated. The average time between system separation and its detection is 217 ms. None of the stable swings were tagged as unstable and all unstable swings were properly identified as such. Operation of the proposed system depends heavily on the proper functioning of PMU, data concentrator, out-of-step computer and communication channels. Defects in any of these elements could result in mis-operation of the proposed system. A functional analysis of the proposed system determined that the system can be implemented with available commercial PMUs, computers and data concentrators if the communication links are available at the selected PMU locations. A preferred sampling rate of 30 samples/second is recommended for PMUs and a real-time operating system is recommended for the out-of-step computer.

The results of this project were further developed and used in field demonstrations by a subsequent research project, Application of Advanced Wide Area Early Warning Systems with Adaptive Protection (see below). That project adapted two of the algorithms developed in this project, Security/Dependability Balance and Relay Zone Encroachment Alarms, for field implementation and demonstration by two California utilities, PG&E and SCE.

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3.9.3 Application of Advanced Wide Area Early Warning Systems with Adaptive Protection

This project was performed by the California Institute for Energy and Environment (University of California, Berkeley), Virginia Tech, Mississippi State University, Pacific Gas & Electric Co., and Southern California Edison Co. The Principal Investigator was Carl Blumstein. .

Analysis of recent blackouts of power systems has shown that unanticipated operation of protection systems can contribute to cascading phenomena that lead to blackouts. This project developed and field-tested two methods of Adaptive Protection systems utilizing synchrophasor data that are intended to avoid the unintended and undesired operation of protection systems and thereby reduce the probability of blackouts. One method detects conditions of system stress that can lead to unintended relay operation, and initiates a supervisory signal to modify relay response in real time to avoid false trips. The second method detects the possibility of false trips of impedance relays as stable system swings “encroach” on the relays’ impedance zones, and produces an early warning so that relay engineers can re-evaluate relay settings. In addition, real-time synchrophasor data produced by this project was used to develop advanced visualization techniques for display of synchrophasor data to utility operators and engineers.

Protection systems for the electric grid have evolved significantly in recent decades. Up until about the 1980s grid protection consisted of a collection of independent electromechanical relays, which were calibrated for an assumed set of normal conditions, together with power circuit breakers to “trip out” lines and generators to protect them when a fault (short circuit or other system disturbance) unexpectedly occurred. Design of such systems erred on the side of dependability (reliability in clearing actual system faults). But errors in relay operation, such as false tripping when no fault actually occurred, while hopefully minimized, nevertheless sometimes occurred, compromising system security.

Nowadays electromechanical relays have mostly been supplanted with digital relays, which, being essentially microprocessor-based, are capable of being re-set quickly, and even remotely, if real-time system information is available and the prevailing conditions call for it. Also, given wide-area system information, special relaying schemes can be implemented that can coordinate and optimize relay operations for regional or area-wide objectives that were not possible with the older technology. But, given that relay operations happen very quickly, sometimes as fast as a few milliseconds (a couple of cycles at the 60 Hz power frequency), it is necessary to time-synchronize the wide-area measurement data in order to overcome the problems of latency in data transmission, thereby ensuring correct analysis, implementation and operation of such a relaying scheme. Fortunately, here too in recent years the technology to achieve this time-synchronization has become widely and economically available: global positioning systems (GPS). By time-stamping the system measurements via the GPS clock, the resultant data being labeled as “synchrophasor” data to distinguish output from non-time-correlated (“phasor”) measurements, a multitude of advanced applications becomes possible, including adaptive relaying, as the area of protection system technology described above has come to be known. These applications can provide substantial benefits to the electric system and its customers in the form of economical, safe, reliable and resilient electric service.

The primary goal of this project was to demonstrate, in real-world utility systems and with the participation of practicing utility engineers, three specific high-value applications in adaptive protection technology.

First, synchrophasor data was used as input to a Security/Dependability Balance algorithm. One of the defining characteristics of modern grid protection systems is redundancy: in order to ensure that when a fault occurs it is dependably cleared, more than one set of independent relays is employed in every relaying application; this guarantees that, if one of the relays fails to operate, the probability that all the relays will fail to operate is extremely small (Dependability). However, every relay system also has a small probability of operating when no fault is present: this is called a “false trip.” Redundant sets of relays will have a correspondingly higher probability of false trips, which fortunately are exceedingly rare, and when system conditions are normal, i.e., the system is “healthy,” false trips are usually just a nuisance and not a significant problem, and the “Security” of the system is considered satisfactory. However, when the system is not healthy, as when several lines or generators have gone out of service for unexpected reasons, relays are more likely to false-trip because their settings do not necessarily correspond to the new conditions. And false tripping very much needs to be avoided during conditions of stress, because it will likely exacerbate the process of system collapse. By using synchrophasor data in an algorithm that is trained to recognize such abnormal system conditions, a supervisory logic can be quickly implemented to require a “voting” scheme for the relays. Simply put, this means that when conditions are stressed, the logic requires that at least two of the multiple sets of relays must agree there is a fault before tripping is implemented. Thus, by using the intelligence available from synchrophasors, the balance between Dependability and Security can be maintained even when the system is in a weakened condition. The Midway – Vincent 500 kV transmission line, jointly owned and operated by PG&E and SCE, was chosen as the test bed for this application.

Second, synchrophasor data was used as input to an Impedance Zone Encroachment algorithm. Some relays, called “impedance relays” (impedance is a quantity that combines electrical resistance and inductance), are set to detect conditions when the impedance they “see” in the system drops into an unacceptably low range, usually at a low point of a dynamic oscillation due to a major disturbance. The objective is to avoid unstable system swings. Over time, as system conditions such as loading or equipment additions are made, the relay’s setting will no longer correspond to previous conditions, and the relay may operate for stable swings, an undesirable outcome. The Zone Encroachment algorithm sets up a buffer zone around the relay’s normal zone, and when system swings start to encroach on the buffer zone, an alarm and display message is sent to the system operator, who can relay the warnings to the protection engineer, who can then re-evaluate, and if necessary re-program, that relay's settings to avoid undesired operations. The Midway terminal of the Midway – Vincent 500 kV line was chosen for this application.

And third, in order for utility engineers to absorb synchrophasor data quickly so as to facilitate the required real-time responses, this project developed methods for display and visualization of protection system data and validated those methods with utility engineers in interactive interviews and workshops.

Each of the three applications of protection systems described above were demonstrated using a three-part technical process: research and development; pilot demonstration; and field demonstration.

In the R&D phase, university researchers at Virginia Tech adapted both the Security/Dependability Balance and Zone Encroachment algorithms from previously developed, non-real-time research versions, with the necessary modifications to allow them to run in real time with streaming synchrophasor data. University researchers at Mississippi State built upon previous research to develop new visualizations of synchrophasor data.

In the Pilot Demonstration phase, the Security/Dependability Balance and Zone Encroachment algorithms were first implemented in Virginia Tech's laboratory using relaying and synchrophasor devices similar to that used by utilities; then they were exported to the proof-of-concept laboratory facilities at utilities PG&E and SCE, to verify correct performance and instruct utility engineers in their use. A Data Evaluation Plan was developed as a protocol for evaluating the performance of the algorithms against real data, to be collected in the final, Field Demonstration Phase. The synchrophasor visualizations developed in the R&D phase were presented to PG&E and SCE engineers and technicians in an interactive workshop setting, their feedback and comments were elicited, and used to further refine the visualizations.

In the Field Demonstration phase, the two adaptive relaying algorithms were implemented by the utilities themselves into utility operations systems, using the same devices, equipment and systems employed in actual practice; with the difference that the systems were in "monitor" mode, i.e., the systems were fully functional, and data collected from their performance over several months was evaluated by the project team according to the Data Evaluation Plan. The data visualizations were modified according to the utility feedback received in the Pilot Demonstration phase, and a second round of interviews and workshops conducted with the revised visualizations to ensure operator and engineer acceptability.

The project demonstrated a feasible approach for implementing the Security/ Dependability Balance algorithm in a real-time operations environment. In fact, two somewhat different approaches were used by PG&E and SCE in terms of the specific hardware used and where the algorithm software was installed, but achieving the same result: an adaptive protection system using synchrophasor data to enhance the reliability and security of a major transmission path. The project also demonstrated that periodic re-analysis of wide area system conditions and updating of the programming logic is desirable for optimum performance of the algorithm. While not possible in a research project due to time and budget constraints, utility protection engineers can perform this task on a routine basis.

The project also demonstrated an economical and feasible approach to implementing an Impedance Zone Encroachment system to inform protection engineers via on-screen alarms and notifications when impedance relay settings should be re-evaluated and/or updated for increased system security.

Important knowledge was gained from practicing utility engineers, operators and technicians regarding methods of visualizing synchrophasor-based protection system data. The prototype visualization tools were developed and vetted to meet the demands of utility personnel for clear and concise representations that can be quickly absorbed, allowing problems to be efficiently analyzed, and decisions formulated and carried out expeditiously.

The primary benefit to the public from widespread use of the Security/Dependability Balance and Zone Encroachment technologies, is a more reliable and secure electric grid, one that suffers from fewer blackouts, and therefore fewer customer outages. Residential customers will experience less inconvenience from lack of electric service; commercial and industrial customers will experience significantly lower costs in terms of production not lost and personnel not idled. Electric rates will also be lower than would otherwise be the case, due to the avoided costs of extended system outages.

This project was also, arguably, the first real-world utility demonstration of the use of synchrophasor data in advanced protective relaying applications, one that should inspire other researchers and utilities to implement the applications described here as well as others. The Phasor Business Case Study [Novosel et al., 2007] outlined numerous other potential applications that would benefit from synchrophasors, not just in the relaying area (Out of Step Relaying, Generator Protection, etc.) but in six other major areas of the utility business: Real-Time Monitoring and Control, System Benchmarking and Model Validation, Post-Disturbance Analysis, Power System Restoration, Protection and Control of Distributed Generation, and Overload Monitoring and Dynamic Rating of Transmission Lines. The use of synchrophasor data either enables or enhances applications in these areas, all of which contribute to improved power system reliability, security and economics.

Many utilities are currently in the process of procuring and installing synchrophasor infrastructure, studying the feasible business applications germane to their respective utilities, and estimating the economic benefits to be realized therefrom. Making the leap from research applications to production business applications is typically the most difficult step in the long process from original idea to real-world implementation. This project has provided a demonstration of how it can be done with synchrophasor applications.

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4. New Cross-cutting Technology for Improving the Transmission System Reliability, Flexibility and Resiliency

Some of the TRP research was conducted on technical topics or areas that cut across several of the strategies described above. One such area was seismic damage resistance and another was energy storage.

4.1 Increased Robust Seismic Performance of Transmission Substation Components

Much of the California electric system is in highly active seismic regions, including most of the large urban areas. Post-earthquake functioning of utility systems is viewed by emergency responders and society in general as an absolutely vital need for rapid response, recovery and preservation of public health and safety. Building an electric system that is more resistant to seismic motion damage will reduce the consequences and costs of electric service disruptions caused by strong ground motions. TRP conducted analyses, simulations and lab tests on substation post insulators and transformer bushings. Prior tests and field experience indicated that current qualified standards were based on inadequate tests or procedures. The TRP research resulted in better knowledge of equipment failures during seismic events for revising qualification procedures for relevant IEEE standards.

4.1.1 Evaluation of the Seismic Performance of High-Voltage Transformer Bushings

This project was performed by the Multi-Disciplinary Center for Earthquake Engineering Research (MCEER) at the State University of New York – Buffalo. The Principal Investigator was Andrei Reinhorn.

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 bushings and other components in large substation transformers (the transformer tank, tank cover, mounting turret, attached buswork and switches, etc.) due to seismic motions. 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, was that the currently-accepted standards and qualification procedures for certifying the seismic performance of transformer bushings are not entirely valid. These 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, as indicated by actual unexpected performance, including catastrophic failure during seismic events when the equipment was certified to more severe levels of seismic motion than experienced in real events.

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 was 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.

The goals were 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.

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.

These proposed revisions to the IEEE Standard are currently before the appropriate IEEE Task Forces and Working Groups for approval.

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4.1.2 Seismic Performance of Substation Insulator Posts for Vertical-Break Disconnect Switches

This project was performed by the University of California – Berkeley. The Principal Investigator was Khalid Mosalam.

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) develops guidelines for the seismic qualification and testing of disconnect switches. Due to the severe damage to electrical substation equipment over the past years caused by earthquakes, 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 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.

The main purpose of the study was to develop a simple hybrid simulation system (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 also focused on conducting linear and nonlinear static analyses to rank the sources of uncertainties in porcelain insulator computational modeling, and on 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 proposed revisions to the IEEE 693 Standard for consideration by the IEEE Standards Working Groups and Task Forces for seismic qualification of high voltage electrical substation disconnect switches.

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4.2 Energy Storage

Energy storage is expected to play a larger role in generation resource management, integration of variable resources, and peak management applications. On September 29, 2010, Governor Arnold Schwarzenegger approved Assembly Bill 2514 (AB 2514), Skinner, Energy Storage Systems. This bill required the California Public Utilities Commission (CPUC) to determine appropriate targets, if any, for privately owned electric utilities to procure viable and cost-effective energy storage systems. For public utilities, the bill required the CEC to review and approve plans to determine appropriate targets and procure viable and cost-effective energy storage systems to meet the targets. Also, the bill recognized that despite many benefits of energy storage, there are significant barriers to obtaining the benefits of energy storage systems. To assist in the decisions to be made, the CEC charged the TRP to conduct a strategic analysis of energy storage technology, called the Energy Storage Vision 2020. It reviewed the technical status and the remaining research and development needs of current storage technologies, developed a strategic vision of how California might best implement its energy storage needs over the next 10 years.

5. Electric Distribution System and Renewable Generation Integration

In 2010, in large part because of Governor Brown's Campaign Promise that included 12,000 MW of distributed – mostly renewable – generation installed in California by 2020, attention on renewable energy integration with the grid shifted toward distribution. Largely in the form of small photovoltaic generators located at or near electric customers' facilities, distributed generation represented unprecedented challenges for the distribution system.

Conventional distribution systems are still today largely radial, designed for one-way power flow, while transmission systems are networked and designed to handle power flows in different directions at different times. While transmission systems tend to "look alike," distribution circuits are very diverse and each is unique, with different lengths, amounts of above ground and underground lines, phase imbalances, types of loads, voltage regulation equipment, and so forth. Distribution circuits exhibit many local idiosyncrasies. Load profiles vary substantially among customer classes, and of course the mix of load classes vary significantly among distribution circuits. Transmission systems are more balanced among sections because of the statistics of aggregating large numbers of customers. Distribution circuits are older than most transmission systems, and more vulnerable to disruptions from weather events, accidents, animals, trees, and so on.

5.1 Reliability of Underground Distribution Systems

Some distribution circuits are underground, substantially increasing electric reliability for customers on these circuits. Despite the construction cost, many more circuits would likely be underground if the cost and difficulty of reducing, predicting and locating failures in underground lines when they do occur could be reduced. CIEE has administered research projects on underground cable for that purpose. One project investigated three methods for detecting, in advance of failure, a common degradation of cable insulation (known as "water trees") and specifically degradation of the concentric neutrals of underground power distribution cables. Importantly, these methods can be applied while the cable is in service (energized). Two methods showed promise, with one being able to detect the break in the concentric neutral at least 200 feet from the fault location. Another project investigated four potential methods for online diagnosis of underground power distribution cable from in situ measurements of cables. It concluded that of the four, two looked promising but more research would be required.

5.1.1 Underground Cable Diagnostics Miniaturization Research, Development, Field Test, and Commercialization

This project was performed by the University of California – Berkeley. The Principal Investigator was Richard White.

The aging and in-service deterioration of underground distribution cables is a looming issue facing electric utilities in California and throughout the U.S. There are over 100,000 miles of underground power distribution cables in and around the West Coast area of the United States. Older cables have a higher probability of failure due to development of defects in the cables because of aging and exposure to the elements. These defects can lead to catastrophic cable failures that are not only hazardous to the community around the location of the failure, but can result in large economic costs to affected businesses that lose power from the time of the cable failure to restoration of power. Utilities today mostly use a simple age-of-operation schedule to determine which cables to replace. This scheduled replacement method is not optimal and definitely not cost-effective; what's needed is a condition-based inspection method that functions with the cable energized (i.e., in service). The scheduled replacement method also does not solve the failure problem with new cables or replacement cables installed in the future.

The goal of this project was to address two primary causes of failure in underground cables: broken or corroded concentric neutral (CN) wires, and failure of the polyethylene insulation due to "water trees." The research team developed two scenario-specific solutions that enable grid operators to assess the health of energized cables and pre-empt catastrophic cable failures.

<u>Assessment of Concentric Neutrals:</u>

In a previous project [Paprotny et al., 2011 (3)] the fundamental methods for diagnosing failed CNs were investigated. The results of this research provided the foundation for the design of an advanced sensing mechanism, a device termed the "Grabber," which utility technicians simply push onto the energized cable using an industry-standard "hot stick." Pivoting jaws close to form a ring around the cable, with 10 to 12 micro-sensors arrayed around the cable to sense the magnetic fields from the CNs. Sensor data from the grabber is transmitted wirelessly via Bluetooth to the technician's laptop, tablet or smart phone. The Grabber easily releases the cable when the technician pulls back on the hot stick. The technician can then review the sensor data, quickly assess the cable's health, and determine if a cable replacement or further testing is necessary. The Grabber is also being designed so that it could be left attached to the cable indefinitely as a condition-based monitoring solution.

<u>Online Cable Diagnostics using RF Coupling:</u>

In a previous project [Paprotny et al., 2011 (2)] the mechanisms by which water trees develop in polyethylene were investigated. Once the fundamental science was understood, methods for diagnosing the existence of water trees in energized cables were investigated for feasibility as well as practicality in the field. The research team determined that a technique using radio frequency (RF) coupling in the cable was the most promising method. This technique requires the insertion of an RF generation source at one end of the cable and a detector at the input end to detect reflections, or at the other end of the cable coupling. By comparing the cable's attenuation and other characteristics with the characterization of a "healthy" cable, technicians can quickly identify the presence of water trees or other cable abnormalities. Armed with this knowledge, utilities can replace cable sections before they fail, as well as avoid unnecessary cable replacements.

Project Benefits:

The primary objective of this project was to diagnose the two most common problems in underground cables that indicate the cable is likely to fail in the near future. The primary benefits of this knowledge are:

1. Utility personnel have advance warning that a cable may fail and cause an outage. They can schedule the cable for immediate replacement, reducing the probability that a failure will cause customer outages.
2. Customers will experience more reliable service, and will suffer less inconvenience and the economic costs that accompany outages.
3. Utilities will avoid excess costs due to emergency replacements and repairs, and will be able to better control their available maintenance dollars.

4. The safety of utility maintenance personnel and customers will both be improved.

Technology Commercialization and Tech Transfer:

A key deliverable for this project was a Commercialization Plan that would accelerate the transfer of the developed technologies to the private sector. A number of discussions were held with various technology firms regarding licensing and marketing of the diagnostic methods developed in this project, and the most promising commercialization partners were identified. A patent application was submitted for the RF technique for detecting water trees in energized cables, and the patent was issued. A provisional patent application for the Grabber device for detecting faults in concentric neutrals was also submitted.

While these patent applications were being processed and filed, a temporary hiatus in commercialization discussions with potential companies was in place. Once the patents were filed and disclosed, permission was granted by the Berkeley Office of Intellectual Property & Industry Research Alliances to continue these discussions in pursuit of commercialization. The Berkeley team plans to resume these efforts in early 2015.

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5.2 Advanced Monitoring of Distribution Systems

Perhaps the most significant difference between transmission and distribution is the degree of monitoring capability. Transmission systems have become relatively heavily monitored over time compared to distribution systems, which seldom have had monitoring beyond the distribution substation. This is true despite the relative large penetration of smart meters late in the 2000 – 2013 period, since advanced metering generally has not yet provided much real-time data to operators.

Anticipation of, and in some local instances, experiences with, high penetrations of variable solar PV distributed generators have raised concerns about islanding (unintentional for reasons of safety, and intentional for grid resiliency); relay desensitization because of being designed for one-way power flow; voltage regulation and flicker, due in part to the variability of the solar resource and the rapid ramp rates of PV units; line and transformer replacements due to extra use and higher frequency of duty cycles; and resonant conditions.

Given how little is known about the distribution system, the CEC selected CIEE to conduct a research project to begin to characterize the distribution system in fine enough granularity to answer questions regarding the effects of high penetrations of distributed PV. This project collected and analyzed some of the available data, and will define the requirements for an intentional monitoring plan to characterize the electric distribution system in California for high penetrations of distributed PV.

5.2.1 Distribution System Field Study with California Utilities to Assess Capacity for Renewables and Electric Vehicles

This project was performed by the University of California – Berkeley, the University of California – San Diego, and the University of California – Irvine. The Principal Investigators were Carl Blumstein and Alexandra von Meier.

A significant and growing amount of new renewable generation is being installed at the distribution level of the electric grid, accompanied by the proliferation of technologies such as plug-in hybrids and electric vehicles (EVs). As a result, the need for information about the potential impacts of these technologies, and data to support the analysis and control of distribution systems in the future, is becoming clear and urgent. “One-size-fits-all” solutions such as the 15% rule of thumb for installation of distributed generation on a feeder are rapidly becoming unacceptable as a means of managing the integration of new technologies in distribution and proactively dealing with the unforeseen impacts of renewable integration. New analytical and control methodologies are being developed and used, but more and better data about the distribution system is required for these methods to be practicable.

Extensive monitoring of distribution circuits by utilities was historically not cost-effective given the lack of business need for such information, so there is little if any comparative data of sufficient quality to provide a baseline or reference for measurements on distribution feeders with and without high penetrations of renewables. Furthermore, monitoring systems capable of discovering any new unanticipated distribution system phenomena are generally not in widespread use. As a result, utility operations personnel currently have very little information, real-time or otherwise, about the status of the distribution network they are charged with operating. This situation is described as a lack of observability, poor “situational awareness,” or lack of “visibility” of the electrical phenomena resulting from new sources and users of electricity on distribution circuits, or even of normal and routine occurrences on the system. Monitoring locations today may consist of only one point per feeder: the meter measuring power flow and voltage at the distribution substation transformer. It will be increasingly important to have some knowledge of what happens beyond the substation because of the potential impacts on the reliability and economic efficiencies of the distribution system.

Goals and Objectives:

The purpose of this project was to advance the state of the art in electric distribution systems by supporting safe and reliable operation with a substantially increased presence of renewable generation, distributed generation, electric vehicles (EVs), and other new technologies and applications. By analyzing the available monitoring data from utilities, the project’s goals were to: characterize the impacts of these technologies on electric distribution system operation and performance; increase the operational visibility and situational awareness beyond the substation; provide a better understanding of the requirements for strategic upgrades and new technologies in the distribution system infrastructure and operational tools to accommodate desired levels of DG; and to inform updated DG specifications and interconnection standards that allow the increased use of distributed renewable generation resources without adverse impacts on safety and reliability.

The project technical approach consisted of two avenues of effort. First, a collaborative process of sharing data was established, using typical measurements available from existing devices installed in a number of utility distributions systems in California. Intended to establish a baseline of current monitoring practices and methodologies, analysis of these existing measurements aimed to begin characterizing distribution feeders with and without distributed energy resources (DER), validating distribution feeder models, and identifying gaps in available data. The second part of the project used the results and lessons learned from the first part, along with information from a number of other sources, including a utility survey and a workshop with invited experts and utility colleagues, to develop an Advanced Monitoring Plan (AMP), the principal deliverable of the project. Expressly designed to be a blueprint or roadmap for follow-on research efforts to this project, the AMP would expand the distribution database with measurements from new line sensors and substation monitors installed by participating utilities in collaborative efforts, for the express purpose of analyzing the impacts and requirements imposed by high levels of renewables and other new technologies in the distribution system, and informing the development of advanced applications for the planning, design and operation of the distribution systems of the future.

Project Results:

California utilities are engaged in, and have accomplished, a number of monitoring activities, indicating that that there is a general awareness that more needs to be known about the behavior of distribution systems, and especially the current and potential impacts of increased levels of renewables, EVs and other technologies. Most of these monitoring activities are “ad hoc” efforts focusing on investigating specific behaviors, e.g., of PV systems, energy storage installations, EV charging, microgrid demonstrations, smart meter implementations, demand response programs, and so forth. While mostly concerned with understanding the behavior of the individual devices, some projects also include feeder-level analysis, such as volt/VAR control algorithms. There was considerable variation found in data collection, data quality, data resolution and accuracy, placement strategies for the monitoring devices, and analytical methods employed. Evaluation of the overall monitoring situation gave a reasonably good picture of the baseline monitoring practices used in distribution systems today, and the gaps that need to be filled in order to manage and operate distribution systems effectively, both today and in the future. A sobering caveat must be offered: the current commitment of utilities in terms of human resources and budget needs to be substantially increased in order to accomplish these intended goals, which will require support and approval of both utility managements and regulatory agencies.

A Data Repository was established at the UC-San Diego Supercomputer Center for the secure storage of utility data. The data acquired from utilities was analyzed to the extent possible in terms of spatial and temporal characteristics. More data would have been desirable; indeed, considerably more data would be needed to perform the feeder characterization originally envisioned for this project, in terms of categorizing feeders by general type, by levels of renewable generation, or other key parameters. It was recommended that this effort be continued and expanded in a Phase 2 research project.

The project team did acquire enough actual system data, in the form of both physical feeder models and the associated measured data, to perform validation of the feeder models. While some utilities have made efforts to validate their system models, it is unclear how universal a practice this is, but it is a requirement that must be fulfilled. Unless the physical system model is accurate, it is not possible to perform meaningful planning studies, to know or estimate what the actual system conditions are, or to operate the system intelligently (which is to say, reliably and efficiently). Therefore, model validation will likely be the necessary first task for utilities when acquiring data from new, advanced monitoring systems, that is intended for use in advanced applications.

Data quality also needs to be addressed. The supplied data had missing data, bad data, “outliers,” non-uniform sampling intervals, and so forth, which required that additional evaluation and processing be done before the data could be used in analysis programs. Also, since there are a number of software packages marketed to utilities for analysis of distribution systems, the data supplied by the utilities varied in format. The upside is that the project team was able to develop methods for dealing with these anomalies so that analysis could be efficiently performed, which should prove to be valuable time-savers in follow-on research efforts.

Finally, the blueprint for an Advanced Monitoring Plan (AMP) was developed. The AMP is intended to be the basis for follow-on research efforts to address the current gaps in available data and in data monitoring practices, as well as the future needs based on high levels of new technologies, such as renewables, EVs, etc. The results from the first part of the project provided information on current needs and monitoring practices; additional efforts in the second part of the project included a survey of distribution engineers and experts, and an all-day interactive workshop, to further explore and expand the design and features of the AMP. The resulting product is, we believe, a practical basis for further research to learn more about distribution systems in California, and in particular the impacts of new technologies such as such renewables and EVs on the design and operation of those systems.

Project Benefits:

This collaborative research effort represented, arguably, the first systematic look at a representative sample of distribution circuits across the State of California. It began with an inventory of typical feeder data that was gleaned from existing utility instrumentation, and an evaluation of efforts that have already been made by individual utilities to improve visibility on distribution circuits. It proceeded with analysis of the received data in terms of characterization of feeders, and validation of system models. Finally, an Advanced Monitoring Plan was developed and is proposed as a potential framework for additional research in distribution monitoring, for the purpose of filling the gaps in available data and methods that will needed for the planning and operation of distribution systems now and in the future.

The primary benefits to be derived from this project and its follow-on research efforts include increased visibility of the distribution system, resulting in more reliable and efficient operations, better planning for system upgrades and expansions, and proactive detection, analysis and mitigation of the potential impacts of new technologies and applications on distribution systems.

California electric ratepayers, customers and stakeholders will benefit from distribution systems that will be better able to handle the unprecedented challenges placed upon them.

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Concluding Statements

The research projects included in this white paper were chosen as representative of the Transmission Research Program and other PIER-funded electric grid research, led, administered, managed and/or conducted for the California Energy Commission by the California Institute for Energy and Environment of the University of California. Some of the research projects were not explicitly included, but still accounted for, because they were precursors to projects of continuing efforts included here. Many of the other excluded research efforts not explicitly described in detail here were of the nature of research planning consisting of situational characterization, issue definition, technology solution identification, gap analysis and technology research roadmaps for the California electric grid. While these planning efforts usually did not result in direct benefits to the electric grid, they did help in formulating the most valuable portfolio of research projects, and making the research products used and useful in a timely fashion to Californians.

Public interest energy research is situated at the nexus of three inextricably linked, yet competing desires for electric power systems: service quality, environmental imperatives, and economic objectives. At the intersection of these three goals, the effective integration of renewable resources throughout the electric grid has been a central, challenging theme for the 2003–2014 period of this particular portfolio of research projects. Work sponsored through PIER systematically sought to expand the grid’s technical hosting capacity for various types of renewable and distributed resources through a diverse range of approaches. It would be wrong, of course, to credit PIER research with the entirety of newly connected renewables and DER during this period; nor could the most ambitious analyst assign an explicit percentage of due credit to PIER. Nevertheless, the authors feel confident in stating that the remarkable progress on renewable and DER integration seen in California in these recent years – progress that serves as an example to other states and nations around the world – would not have been possible without the contributions of PIER, at least not without some combination of electric service degradation and cost increases that in all likelihood would have made the case of California less of a poster child and more of a cautionary tale. While the explicit charge of PIER is to serve the interests of California's electric ratepayers, in fact much more is at stake. In the context of the present status of global climate negotiations, most notably with respect to China, the imperative for success of the California experiment, and the long-term public benefit even beyond our State's borders of every contribution toward this success, cannot be overstated.

GLOSSARY

AB	Assembly Bill
AC	Alternating Current
ACE	Area Control Error
AGC	Automatic Generation Control
CAISO	California Independent System Operator
CEC	California Energy Commission
CPUC	California Public Utilities Commission
DC	Direct Current
DER	Distributed Energy Resources
DG	Distributed Generation
DOE	(U.S.) Department of Energy
ED	Economic Dispatch
EIPP	Eastern Interconnection Power Pool
EMS	Energy Management System
EPACT	Energy Policy Act (2005)
ERO	Electric Reliability Organization
EV	Electric Vehicle
FERC	Federal Energy Regulatory Commission
FIDVR	Fault-induced Delayed Voltage Recovery
GHG	Greenhouse Gas
GUI	Graphical User Interface
GW	Gigawatt
HVAC	Heating, Ventilating and Air Conditioning
IEEE	Institute of Electrical and Electronics Engineers

IOU	Investor-owned Utility
ISO	Independent System Operator
MW	Megawatt
NaS	Sodium-sulfur
NERC	North American Electric Reliability Corporation
OTC	Once-through Cooling
PAC	Policy Advisory Committee
PIER	Public Interest Energy Research
PMU	Phasor Measurement Unit
POU	Publicly Owned Utility
PURPA	Public Utility Regulatory Policies Act
PV	Photovoltaic(s)
R&D	Research and Development
RMR	Reliability Must Run
ROI	Return on Investment
RPS	Renewable Portfolio Standard
SB	Senate Bill
SCADA	System Control and Data Acquisition
T&D	Transmission and Distribution
TAC	Technical Advisory Committee
TRP	Transmission Research Program
UC	Unit Commitment
VAR	Volt-Ampere Reactive
WAEMS	Wide-Area Energy Storage and Management System
WECC	Western Electricity Coordinating Council