PIER Project 500-07-020

Intelligent Agents for Integration of Renewables and Storage

Project

Final Report

Prepared for:

Jamie Patterson

CEC Project Manager

California Energy Commission

1516 Ninth Street, MS-43

Sacramento, CA 95814

Prepared by:

Gerald L. Gibson, PE

Alternative Energy Systems Consulting, Inc.

5927 Balfour Court, Suite 213

Carlsbad, CA 92008

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ACKNOWLEDGEMENTS

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Finally, we would like to thank all of the members of the AESC project team. These include Gerald Gibson, Donald Pratt, Eliseo Sandoval, Mary Kruse and Dorothy Campbell.

Preface

The Public Interest Energy Research (PIER) Program was initiated in 1998 and supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $XX million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following ten RD&D program areas:

- Buildings End-Use Energy Efficiency
- Climate Change Program
- Energy Innovations Small Grant Program
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally-Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Natural Gas Research
- Renewable Energy Technologies
- Transportation Research

What follows is the final report for the Intelligent Software Agents for Integration of Renewables and Storage Project, Project: 500-07-020 conducted by Alternative Energy Systems Consulting, Incorporated (see table below for a breakdown of contract costs).

The final report is entitled "Intelligent Software Agents – Effective Integration of Renewable Energy Resources and Storage into the California Transmission System". This project contributes to the Energy Systems Research area under the Energy Systems Integration program. For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Contract Amount Detail

Contractor Name	Contract Amount	SubContract Amount
Alternative Energy Systems Consulting, Inc.	$	--
BPL Global Limited	--	$
Beacon Power Corp.	--	$

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1. EXECUTIVE SUMMARY

This Project Final Report was completed as part of a California Energy Commission PIER research and development project titled, “Intelligent Software Agents for Integration of Renewables and Storage”. The overall project goal was to demonstrate that applying agent technology could expand the potential delivery of renewable energy and use of existing transmission facilities for the benefit of the consumers in California. More specifically, the project objective was to address delivery of wind generation resources located in the Tehachapi wind resource area in California.

The Tehachapi area grid consists of a 66 kV sub transmission system that connects to a 230 kV system (see Figure E1). Both the 66 kV and 230 kV systems are owned and operated by Southern California Edison (SCE). Control of the 230 kV transmission system falls under the authority of the California ISO (Cal ISO) while control of the 66 kV sub transmission system is provided by SCE

The Tehachapi grid currently has over 340 MW of installed wind energy generation and only approximately 80 MW of local load that is primarily concentrated in two large industrial users. The grid is characterized as a “weak grid” where the connected induction machine kW rating exceeds 40% of the short-circuit rating of the gateway substation (15% is the threshold for considering a grid “weak”). VAR transport and voltage control are major considerations in weak grids such as Tehachapi.

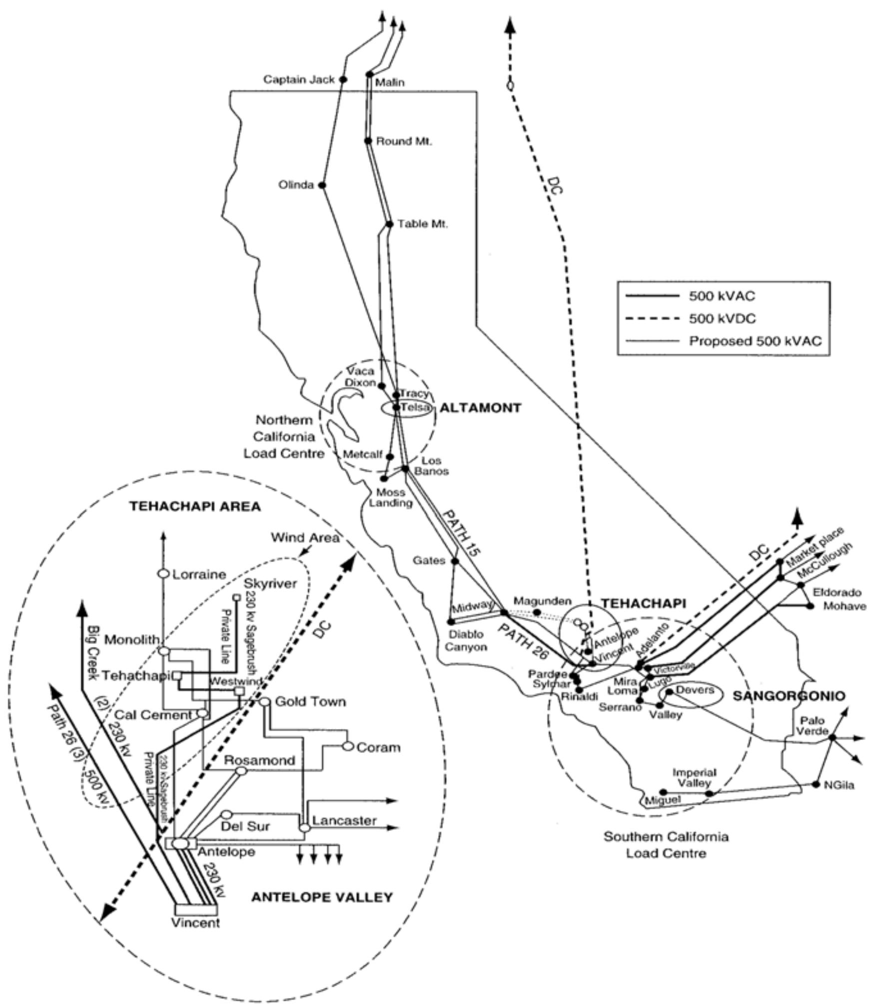

Figure E1 California and Tehachapi Area Grid

(Source: “Wind Power in Power Systems”, T. Ackerman, page 258)

Coordination of VAR

support provided by multiple wind farms with utility VAR resources or by storage assets with similar and additional capabilities is a significant consideration. The Tehachapi region is characterized by variable wind conditions, which further complicates the process. Coordination/control of local VAR assets therefore requires a level of distributed decision-making and control that could be a potential match for agent-based control technology. Improved voltage and VAR control has the potential of increasing the overall transmission capacity of the existing system, which would in turn fulfill the primary project objective.

The complexity of both the problem and the potential solution dictated a two-phase approach. In the first phase, the problem was characterized along with the requirements of the agent-based system that could address the problem. The second project phase then provided for implementation and demonstration testing of the agent-based system.

Early on in the project, a Stakeholder Working Group (SWG) was formed in order to incorporate project input from industry leaders. The SWG was comprised of the group of active Project Team members along with a group of advisory level members (see Table E1). In this arrangement the Project Team members worked together to help develop project deliverables with advisory level members providing valuable feedback through their review of these deliverables prior to final release.

Table E1 Stakeholder's Working Group

Organization	Participant
Project Team Members	
AESC	G. Gibson
California Energy Commission	J. Patterson
California ISO	D. Hawkins, H. Sanders
Southern California Edison	T. Dossey, J. Castaneda
Beacon Power	J. Arseneaux
BPL Global, Ltd.	V. Frisina, A. Vallow
Western Wind Energy	J. Ciachurski, S. Mendoza, PE
Advisory Level Members	
AES Corporation	D. Kylyshpekov
Bonneville Power Authority	J. Pease
California Energy Commission	M. Gravely
Dept. of Energy	I. Gyuk
EPRI	Dr. R. Schainker
Lawrence Berkeley National Lab	C. Marnay
Mega Watt Storage Farms	Dr. E. Cazalet
Oak Creek Energy Systems	H. Romanowitz, S. Pasapulati
Desert Research Institute	T. Surles
Oak Ridge National Lab	J. Kueck

The Phase 1 effort was successful in that the Project Team, with input from a Stakeholder's Working Group, was able to:

- Identify a project "target" with a quantifiable economic benefit and that appeared "doable" given the limited scope and resources of the project. An existing SCE operating order that provides for Tehachapi area wind generation curtailments due to thermal overload of a 66 kV sub transmission system path in the area was identified as the best near-term opportunity.
- Develop a System Requirements and Test Plan that identified more specific system requirements.
- Conduct feasibility testing of AESC agent technology on BPL Global's CentryWCC hardware platform confirming that operation of agents on the WCC was feasible.
- Define a multi-agent based system (MAS) that utilizes a Bayesian Belief Network (BBN) to monitor and evaluate the status of the 66 kV sub transmission system using a combination of SCE and CAISO provided data.
- Refurbish and successfully test the Beacon Power flywheel storage system in preparation for installation and operation during the demonstration period.

The Project's Phase 2 effort began with configuration and development of the agent-based system and associated hardware (Task 8). During this task, AESC, Beacon Power, and BPL Global confirmed the ability of the agents to successfully:

- Gather and process the needed SCE SCADA data,
- Communicate with one another to coordinate their actions
- Recommend action related to capacitor bank & storage system operation,
- Generate a frequency regulation signal using the Cal ISO ACE and convert this to the necessary power command for use by the Beacon Flywheel storage system.
- Communicate with the Beacon Power flywheel storage system with testing to confirm that the flywheel storage unit accepted agent generated commands for charging and discharging of energy along with absorption or injection of reactive power.

The demonstration test period officially began on December 1, 2010 at 4 p.m. and ended on February 11, 2011 at 5 p.m. Overall, the agent-based system performed well during the demonstration period, during which:

- Data were collected at 5 second intervals over the 1753 hour period, representing a total of 1,244,880 five second intervals with an overall data collection rate of 95.7%.

- Wind generation levels, when compared with the region's 349 MW installed capacity, were relatively low during much of the demonstration period, which required minimal use of the area capacitor bank resources (six or fewer of the thirteen total available capacitor banks were on-line over 90% of the time).

- Overall, agent availability exceeded 99% during the demonstration period with the exception of the Storage GRA, which experienced lower availability due to outages of the cell modem based communications (unique to Storage GRA). Other than the cell modem issues, the primary factors affecting agent availability were messaging issues associated with use of a centralized server-based messaging system and errors associated with retrieval of SCE SCADA data. It is important to note that both of these factors would not be evident with a system that had been fully integrated into the SCE network.

- The Bayesian Belief Networks (BBN) used by the agents to detect and predict abnormal system conditions operated successfully during the demonstration period. These BBNs were initially configured with the help of simulated sub transmission system operating data developed using the output of a power load-flow model developed by the Cal ISO and refined by Quanta Technology. Investigation of specific events that occurred during the demonstration period showed that the BBN performed well given the limitations of the configuration and training efforts. BBN performance was optimized over a limited range specific to operation when curtailment of area generation was most likely. BBN operation within this range was characterized by detection of system conditions either in step with, or in advance of operator actions. And, while additional analysis is needed, results appear to indicate that dynamic operation of the system during a known curtailment period (December 10-11, 2010) could have resulted in a significantly shorter overall curtailment period.

- Two powerful BBN capabilities were also demonstrated; first, was ability of the BBN to “learn” from actual operating data and the second was the ability to operate in the presence of unknown data.

- The BBN was able to operate successfully outside of the original configuration range as a result of additional BBN training using data collected prior to and during the demonstration period (as opposed to simulated data created using the power load flow model). However, BBN performance outside of the original configuration range was less consistent. Additional modeling and associated statistical analysis is needed in order to configure and train the BBN to operate consistently across the full range of potential sub transmission system operation.

- The Beacon Power storage system operated under Storage GRA control continuously during the demonstration period. The storage system operated in Frequency Regulation mode 97% of the time with just 3% of overall operation in Hybrid mode (frequency regulation with modified reactive power output at the request of the STAs).

To summarize, this CEC PIER project was highly successful. During the project, the project team successfully identified a significant opportunity to demonstrate the feasibility of the agent-based approach. The system that was subsequently configured and implemented performed well during the demonstration although it was constrained by the limits of the initial modeling and configuration effort.

The following additional effort is therefore recommended in order to more fully demonstrate the concept and prepare it for commercial application.

- Complete the effort to fully integrate the agent-based system into the SCE communication network in order to enhance system reliability. This would eliminate the need for cell modem based communication as well as the need for server-based SCADA data retrieval.

- Complete the effort to implement a true Peer-to-Peer communication capability in order to eliminate the need for centralized server-based communications.

- Enhance agent processing capabilities to include monitoring of sensor data quality in order to both establish a “normal” baseline for all inputs as well as identify and deal with bad or unknown sensor data.

- Implement automated BBN training in order to more readily accommodate changing area conditions.

- Review all communication protocols for compliance with newly emerging IEEE standards such as IEEE 61850 and IEEE 1613, which are applicable to substation based networks and communication devices.

2. INTRODUCTION

This Project Final Report was completed as part of a California Energy Commission PIER research and development project titled, "Intelligent Software Agents for Integration of Renewables and Storage". The overall project objective was to demonstrate that applying agent technology could expand the potential delivery of renewable energy and use of existing transmission facilities for the benefit of the consumers in California. More specifically, the project objective was to address delivery of wind generation resources located in the Tehachapi wind resource area in California.

2.1. Tehachapi Grid Background

The Tehachapi area grid consists of a 66 kV sub transmission system that connects to a 230 kV system (see Figure 1). Both the 66 kV and 230 kV systems are owned and operated by Southern California Edison (SCE). Control of the 230 kV transmission system falls under the authority of the California ISO (Cal ISO) while control of the 66 kV sub transmission system is provided by SCE

The bulk of Tehachapi wind energy is transmitted via the 66 kV gateway substation located at Cal Cement. The Cal Cement substation connects to a 230 kV substation at Antelope, which is in turn connected to the 500kV Vincent substation thus providing access to the 500 kV transmission system via Path 26.

The Tehachapi grid currently has over 340 MW of installed wind energy generation and only approximately 80 MW of local load that is primarily concentrated in two large

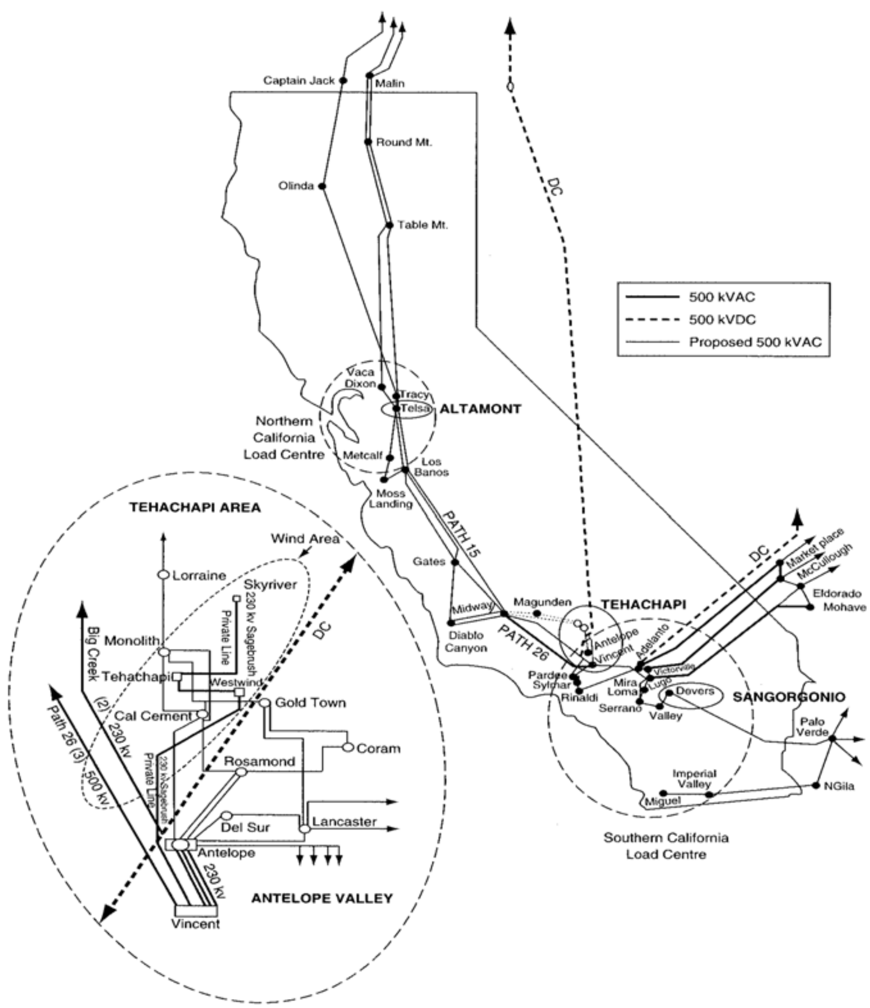

Figure 1 California and Tehachapi Area Grid

industrial users. The grid is characterized as a "weak grid" where the connected induction machine kW rating exceeds 40% of the short-circuit rating of the gateway substation (15% is the threshold for considering a grid "weak"). VAR transport and voltage control are major considerations in weak grids such as Tehachapi.

New Type 4 wind turbines equipped with solid-state inverters have greatly enhanced the ability of windfarm operators to directly contribute to grid VAR control. However, coordination of VAR support provided by multiple wind farms with utility VAR resources is a significant consideration. The Tehachapi region is characterized by variable wind conditions, which further complicates the process. Coordination/control of local VAR assets therefore requires a level of distributed decision-making and control that could be a potential match for agent-based control technology. Improved voltage and VAR control has the potential of increasing the overall transmission capacity of the existing system, which would in turn fulfill the primary project objective.

Upgrades to the Tehachapi area grid are underway as part of the Tehachapi Renewable Transmission Project. This project provides upgrades necessary to accommodate the anticipated long-term installation of new wind generation capacity in the Tehachapi region. Planned upgrades include reconfiguring portions of the 66 kV and 230 kV systems to relieve congestion and provide more direct access to the 500 kV system, which will include three new 500 kV transmission lines.

2.2. Intelligent Agent Technology

Intelligent agent technology has been identified as a key element of the DOE Smart Grid initiative. At its most basic level, an "agent" is simply an entity that acts on behalf of its user. More specifically, a "software agent" is a software construct that can act on behalf of the user. Of course, under this definition virtually any software program that performs a useful function could conceivably be cast as a "software agent". Thus the definition must be refined further to include critical functionality. For purposes of this discussion we assume that an intelligent software agent:

- Executes autonomously & operates in real-time
- Communicates with other agents or users
- Is able to exploit domain knowledge
- Exhibits goal-oriented behavior

A wide variety of agents have been identified and studied since agent research began in the late 1970's. Of the variety of agent types, the following five represent the most applicable to our project.

<u>Mobile agents</u> have the ability relocate and execute on different platforms as compared with agents that are static or remain fixed in one place. Mobile agents are autonomous but do not typically rely on direct cooperation with other agents to perform their tasks.

Reactive agents employ a basic stimulus/response type of behavior to perform their tasks. Reactive agents are only concerned with the present state of their environment and do not rely on collaboration with other agents to perform their tasks.

Deliberative Agents perform their tasks based on their own analysis of the environment. Unlike reactive agents, deliberative agents rely on analysis and planning to perform their tasks.

Collaborative Agents emphasize cooperation (via communication and collaboration) with other agents to perform their tasks.

Hybrid agents combine traits of two or more other agent types to perform their tasks. It is easy to envision a collaborative agent that is also deliberative or a reactive agent that is mobile.

Agent autonomy is most often defined as the ability to act alone, without the need for human guidance. While autonomy is an essential agent trait, the level of level of autonomy can vary. For purposes of the proposed project we can utilize the following three levels of autonomy.

Command driven agents act autonomously to execute commands from other agents or the end user.

True consensus agents coordinate their actions by achieving a consensus amongst the involved agents.

Locally autonomous or master agents make their own decisions and may issue commands to other agents.

Another important concept relative to agents deals with classification of agent behavior. For purposes of our effort we can define three distinct behavior levels. These include:

Physical level behaviors are “autonomic” in nature and control low-level dynamic actions (i.e., collision avoidance, etc.). Examples of likely physical level activities in our project could involve response to faults, frequency or voltage events.

Tactical level behaviors deal with short-term actions to achieve near-term goals. Power grid examples could include load balancing activities, grid reconfiguration activities, actions to prevent an impending event, etc.

Strategic level behaviors involve longer-term planning and coordination. Power grid examples could include economic dispatch of generation and scheduling of maintenance activities, etc.

An agency or group of cooperating and collaborating agents can comprise multiple agent types that in turn, can incorporate multiple behavior levels.

3. PROJECT APPROACH

The project objective, to utilize agent and storage technologies to improve the delivery of wind energy from the Tehachapi region, was too broad in scope to be able to fully define project requirements. The complexity of both the problem and the potential solution dictated a two phase approach. During the first phase of the project (Tasks 2 – 7) the problem was characterized (Task 2), basic feasibility level testing was conducted (Task 4) and an agent-based system that addresses the problem, given the available project resources, was subsequently defined (Tasks 3, 5). Coincidental with this effort, Beacon Power Systems upgraded the Generation 3 flywheel storage unit initially allocated to the project to the more commercial, Generation 4 unit with the new capability of providing reactive power (Task 6). The Phase 1 effort culminated in completion of the Phase 1 Summary report (Task 7), which summarized the earlier task results.

The Phase 2 effort began with the Task 8, System Configuration and Development effort, which required that AESC and its subcontractors prepare their respective technologies for demonstration testing. The System Integration and Testing effort (Task 9) provided for installation and testing the system, including installation of the Beacon Power storage unit in the Tehachapi area, over a planned one month period. The preliminary results of this effort were summarized in the Task 9 summary report. The results of additional data analysis (Task 10) were added to the Task 9 report to form the Final Test Report. More detailed descriptions of the various project tasks are provided in the following sections.

3.1 Task 1 – Administration

All project management and reporting tasks are included in the Task 1 effort. These efforts included:

- Meetings
    - Project Kickoff Meeting
    - Critical Project Review Meeting
    - Final Project Meeting
- Reports
    - Monthly Progress Reports
    - Project Final Outline (Draft and Final)
    - Project Final Report (Draft and Final)

3.2 Task 2 - Information Gathering / Domain Analysis

The purpose of this task was to bring together the primary stakeholders in order to characterize the issues involved and to identify potential solutions. Understanding that any potential solution must:

- Provide an identifiable benefit;
- Balance the needs of the various Project Team members such that a “buy in” can be achieved;
- Utilize the available storage asset such that project results are scalable; and
- Be achievable within the limited time and resource constraints of the project.

While the initial project objective is broad, the resources of this project are relatively limited. The relatively short timeframe of the project, approximately one year from start to finish, constrains our ability to:

- Navigate and comply with government regulations related to storage system installation as well as transmittal of transmission system information subject to Critical Energy Infrastructure Information (CEII) requirements;
- Identify, obtain and install technologies such as instrumentation/sensors that require taking transmission system assets out of service; and
- Implement changes to long-standing SCE operating procedures.

Compliance with all applicable regulations is a given, and time constraints do not excuse compliance. Instead, it was important that the Project Team be cognizant of the various requirements and structure the project in such a way as to minimize compliance issues.

During this effort AESC:

- Organized a Stakeholder Working Group (SWG) tasked with identifying the most likely applications, functions and associated benefits of an agent-based system. The SWG consisted of both active (Project Team) and advisory level members who met to discuss agent technology and the potential benefits of coordinating Tehachapi area wind generation facilities and transmission assets.
- Organized and facilitated four meetings of the Project Team including a visit to the facilities of Oak Creek Energy Systems in Tehachapi. In addition, AESC conducted a “Kick-off” meeting for the SWG advisory level members via a WebEx teleconference.
- Participated in five follow-up meetings with individual Project Team members to gather additional information specific to the project.
- Attended two conferences/workshops on topics relevant to integration of wind resources or on transmission system operation.

3.2.1 Stakeholder Working Group (SWG)

The Stakeholder Working Group was formed during this task and is comprised of a group of active Project Team members along with a group of advisory level members (see Table 1). In this arrangement the Project Team members work together to help develop project deliverables with advisory level members providing valuable feedback through their review of these deliverables.

Table 1 Stakeholder's Working Group

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Mega Watt Storage Farms	Dr. E. Cazalet
Oak Creek Energy Systems	H. Romanowitz, S. Pasapulati
Desert Research Institute	T. Surles
Oak Ridge National Lab	J. Kueck

3.3 Task 3 - Define System Operating and Test Requirements

Having identified the basic project requirements during the Task 2 "Information Gathering and Domain Analysis Effort" the goal of this project task was to develop a System Requirements and Test Plan that identifies more specific system requirements for the agent-based system. During this effort AESC worked closely with personnel from the California Independent System Operator (Cal ISO) along with Southern California Edison (SCE) and Quanta Technology to identify specific system functional requirements associated with management of sub transmission system assets in the Tehachapi region. A series of meetings with project participants was used in conjunction with analysis of SCE and Cal ISO data to identify system requirements. This analysis included development and testing of a load-flow model covering the affected 66 kV sub transmission system. The model was initially developed by Cal ISO personnel using GE Positive Sequence Load Flow (PSLF) simulation software, which is commonly used in the utility industry. Loadflow model results were verified and adjusted using system data supplied by SCE and the Cal ISO. Model results were also used in conjunction with existing SCE operating orders and discussions with SCE and Cal ISO to develop basic system and test requirements.

3.4 Task 4 – Feasibility Testing

While AESC had deployed and demonstrated agent technology previously, all previous work had been in a PC environment. For this project AESC's agent technology would be operating on a new platform, specifically a small commercially available web-based device, the Centry$_{WCC}$ (WCC) by BPL Global. While there is little question that AESC's agents can operate on the Centry$_{WCC}$ it is not clear how the more limited operating environment of the WCC unit will impact agent operation. The purpose of Task 4, Feasibility Assessment effort was therefore to install agents on WCC units in order to ascertain any limitations or fundamental problems associated with operating agents on the WCC platform. These limitations, if any could then be accounted for in the system specified during the Task 5 effort. It is important to note that this is a summary report that, due to intellectual property considerations, will not include specific operating information that could be considered proprietary to the Centry$_{WCC}$ or to AESC agent technology.

During this task AESC acquired and installed two WCC units at its San Diego offices. AESC subsequently worked closely with BPL Global personnel to obtain needed documentation and to port an AESC agent(s) to the WCC for testing purposes.

3.5 Task 5 – System Design Specification

The purpose of this task was to provide specifics of a system design that meets the project and system requirements identified in Tasks 2 & 3 with consideration given to any limitations that were revealed in the Task 4, Feasibility Testing effort.

3.6 Task 6 – Flywheel Storage System Upgrade

The original goal of this task was to rebuild and upgrade the Flywheel storage system, purchased previously by the Commission, and used on a demonstration project at the Distributed Utility Integration Test facility. The original storage system consisted of seven Gen 3 flywheel units each with a capacity of 15 kW and each with its own electronic control unit. Early on in the project Beacon Power proposed to substitute a single Gen 4 production unit with an equivalent storage capacity for the refurbished Gen 3 units since this would allow the project to demonstrate a production level unit instead of storage units that were not commercially available. Additionally, the Gen 4 Electronics Conversion Module (ECM) unit had reactive power capabilities not available from the existing Gen 3 units. This substitution was approved and the task was revised to include:

- Removal of the existing Gen 3 Flywheels from the enclosure;
- Installation of a 100 kW ECM;
- Update all ancillary equipment required to run the system;
- Refurbishment and test of a Gen 4 (25kWh/100kW) flywheel storage unit to ensure that it meets operational requirements including the ability to store and discharge 100 kW for 15 minutes.;

- Verify system ability to provide inductive/capacitive reactive power up to 100 kVAR.; and
- Prepare a test report and associated photos documenting the effort and performance of rebuilt components and the fully assembled system.

3.7 Task 7 – Phase 1 Summary Report

The Phase 1 effort culminated in preparation and completion of the Phase 1 Summary report (Task 7), which summarized the Phase 1 task results. Results of the Phase 1 effort were also presented at the project Critical Project Review meeting, which was held on March 26, 2010.

3.8 Task 8 – System Configuration and Development

The first of the Phase 2 effort tasks, Task 8 System Configuration and Development, provided for project team members to modify their respective technologies and to either directly test connectivity or simulate the systems involved so that system functionality could be verified and communication between the various system components tested in-house prior to the start of the Demonstration effort (Task 9). During this task, the Beacon Flywheel Storage system was transported from Beacon Power's Massachusetts facility and installed within Western Wind Energy Corporation's Tehachapi area wind farm.

3.9 Task 9 – System Integration and Testing

In the Task 9 effort, all hardware and software systems were fully integrated and checked out in preparation for demonstration testing. The demonstration period officially began on December 1, 2010 at 4 p.m. and lasted until February 11, 2011 at 5 p.m. During this period, AESC and its principal subcontractors, Beacon Power and BPL Global LLC monitored and documented system operation. AESC demonstrated the user interface and provided SCE operations and engineering personnel with username and password information on January 12th and 13th so that they could also monitor system operation during the demonstration period. Additionally, AESC provided a system demonstration for the remaining project participants, including the Stakeholder's Working Group, during two meetings held on January 27th and 28th, 2011. AESC compiled preliminary results of the demonstration test into the Task 9 Preliminary System Integration and Testing Report.

3.10 Task 10 – Data Analysis

The purpose of this task was to conduct additional data analysis above that done under Task 9. The Task 9 analysis was focused on summarized the overall operation and performance of the system. The more detailed Task 10 analysis effort was focused on learning more about system performance during specific events. These events include line overload events and periods when wind generation levels were ramping up or down relative to area load. The results of these more detailed analyses were summarized and used to enhance the results previously reported in the Task 9 Preliminary System Integration and Testing Report. This new compilation, the Final Test Report, was the deliverable for the Task 10 effort.

3.11 Task 11 – Develop Commercialization Strategy

Under this task, AESC worked to develop a basic commercialization strategy for this application of its intelligent agent technology. Note that the results of this task effort are proprietary and are not included in this report. Instead, results were summarized for the CEC Project Manager during the Final Project meeting.

4. PROJECT RESULTS

Project results are summarized, not by task, but instead based on the principal outcomes of the Phase 1 and Phase 2 efforts. Specifically, the progression from a relatively open project objective that called for improved integration of Tehachapi area wind resources to a set of more specific project and system objectives, a specific system design that could meet those requirements and a demonstration of that system. Note that results of the Beacon Flywheel Storage system upgrade are presented separately in Appendix A.

4.1. System Requirements

The purpose of the Task 2 effort was to gather information sufficient to identify a more specific "target" for the project given the resources, including time and budget constraints, as well as the size and nature of the available storage system.

4.1.1. Project Target

The Task 2 effort was successful in that the Project Team was able to identify a project "target" with a quantifiable economic benefit and that appeared to be "doable" within the limited scope of the project. An existing SCE operating order that provides for Tehachapi area curtailments due to thermal overload of a 66 kV sub transmission system path in the area was identified as the best near-term opportunity. During 2008 (through May 29th) this limitation had resulted in Tehachapi area curtailments totaling approximately 6.6 million kWh. Improved voltage / VAR control of capacitor banks within this area of the sub transmission system as well as improved control at the wind farm level were identified as potential applications for an agent-based control. It was decided that the project would address both of these potential applications.

4.1.2. Storage System Size

In terms of transmission system assets, the size of the storage system (100 – 105 kW) is relatively small. Use of storage as a means of "leveling" wind resources was an obvious opportunity for the project to demonstrate the benefits of integrating wind and storage assets. However the size of the storage system made this potential application impractical. The consensus was that the project should make use of the faster response capabilities of the flywheel based system in relation to other forms of storage. Improving transient response and assisting with voltage/VAR control were identified as the most likely applications of the storage system.

4.1.3. Storage System Location

The relative size of the storage system and the regulatory hurtles involved with direct connection of the storage system to the transmission system dictated the location and use of the storage system. Specifically, it was decided that the storage system would be installed "behind the meter" on a participating windfarm property.

4.1.4. Communication & Control Issues

Any agent-based control system must, as a minimum, have the ability to obtain relevant system data, such as line flows, bus voltages and capacitor status from the EMS-SCADA system since installing separate instrumentation would be both costly and time consuming. Obtaining access to EMS-SCADA data requires a lengthy process to develop a "data bridge" agreement. It was suggested that the project make use of an existing data bridge agreement involving BPL Global that was developed under a different project.

4.2. System Operating and Test Requirements

The following sections summarize the system requirements in three ways. First a discussion is provided on what must occur in order for the system demonstration to be deemed a "success", followed by sections providing more specific system requirements.

4.2.1. What Constitutes "Success"?

In any demonstration project is it important to answer the question "What constitutes success?" Based on the overall objectives of this CEC-PIER project, a successful demonstration should clearly show that:

- The agent-based system is able to identify an impending condition in a 66 kV sub transmission system and the associated actions to mitigate the condition.
- The agent-based system must operate in a robust fashion with the ability to identify and correct internal system problems and/or fail in a manner that does not impede or jeopardize operation of the sub transmission system or any of the affected assets.
- Operation of the agent-based system results (if recommended actions are taken) in improved sub transmission system operation and increased availability of Tehachapi area wind generation resources (e.g., fewer or less severe curtailments).

4.2.2. Sub transmission System Operation

The agent-based system will operate to monitor and manage voltage and VARs within the Tehachapi area 66 kV sub transmission system to:

- Continuously monitor SCE provided SCADA data and Cal ISO provided data/signals in order to identify impending violations within the 66 kV sub transmission system of SCE operating requirements for voltage, VARs and line loading.

- Develop recommended actions[1] to mitigate or prevent impending system violations, including operation of thirteen capacitor banks, the Beacon flywheel storage unit and potentially, wind generation curtailment. These actions must comply with SCE sub transmission system operating orders and procedures. Additionally, all actions must be deterministic in nature in that all recommended actions will be devised a priori with approval by SCE operating personnel and will be consistently applied during system operation.
- Display, via a secure website available to all project participants:
    - Up to date status of the agent-based system to include agent status as well as the status of all system assets to the extent possible given the availability and timing of the SCE and Cal ISO provided data.
    - A separate display of detected events and associated recommended actions along with critical operating parameters to aid personnel with interpretation of the event and the recommended action.
    - An archive of all events with associated actions that have been identified during the demonstration period.
    - An archive of SCE and Cal ISO provided data (subject to access restrictions).

4.2.3. Storage System Operation

The agent-based system will control the flywheel energy storage system to provide:

- Frequency/regulation services during "normal" operation, via receipt and processing of the ACE signal provided by the Cal ISO via the SCE SCADA.
- Short-term storage or discharge supporting "actions" recommended for operation of the 66 kV sub transmission system.
- Modification of storage system VAR output in support of "actions" recommended for operation of the 66 kV sub transmission system.
- Operation of the flywheel energy storage system that meets all requirements of the flywheel storage system manufacturer.
- A record of flywheel storage system operation including commands/signals with data confirming command implementation.

4.2.4. Other Requirements

The following additional requirements applied:

- Data utilized by the agent-based system will be limited to:

[1] The agent-based system will not directly control any system assets with the exception of the Beacon Flywheel storage unit.

  - SCE supplied SCADA data via an existing databridge between SCE and BPL Global
  - Cal ISO supplied data (system ACE signal and Tehachapi area aggregated wind generation) via SCE SCADA system
  - Existing flywheel storage system input and output data
- The agent-based system will accommodate data receipt and processing at 4 or 30 second intervals depending on the nature and use of the data.
- The agent-based system will maintain a record of all agent-agent interaction as well as individual agent generated errors.

4.2.5. Test Objectives and Approach

The test objective was to confirm and document that the agent-based system was meeting the system operating requirements as described above. As noted above, the agent-based system would not take directly control sub transmission system assets. Therefore the process of "testing" system operation was to be a combination of observing system operation during the demonstration period combined with post processing of archived data during the data analysis task.

During the demonstration period AESC personnel will monitor system operation on a daily basis to:

- Ascertain the operational status of all system agents via review of the system activity logs (agent-agent interaction, agent specific errors).
- Monitor all sub transmission system "events" flagged by the system and the associated actions to confirm that the recommended actions correspond to the identified events.
- Review the SCADA data to identify any "events" that have been missed, or mis-diagnosed by the agent-based system. Adjustments to the system states (i.e., triggering levels, etc.) may be made to "fine tune" the system.
- Monitor the quality of the SCE and Cal ISO provided data/signals to identify problems and observe the system's ability to accommodate data loss.
- Monitor operation of the flywheel storage system command signals and control system I/O to confirm that it is operating normally.

Following the demonstration period AESC personnel will analyze the archived data to:

- Tabulate and summarize operation of the agent-based system itself (i.e., agent failures, restarts, communications issues, etc.)
- Tabulate and summarize all of the "events" that were identified by the system and recommend system changes that could improve performance.

- Tabulate and summarize the identified "events" and recommended actions.
- Predict the outcome of the recommended actions, using the load-flow model in conjunction with archived SCADA data.

4.3. System Specification and Design

Ultimately, the objective of the Tasks 3, 4, 5 and 8 efforts was to define and ready a system that meets the system requirements developed earlier. The resulting system consisted of three sub transmission agents (Antelope, Bailey & Cal Cement) that monitor their respective areas of the sub transmission system and two generation resource agents (Wind and Storage) that monitor and/or manage area resources. The agent coverage areas is shown in Figure 2 and summarized in Table 2.

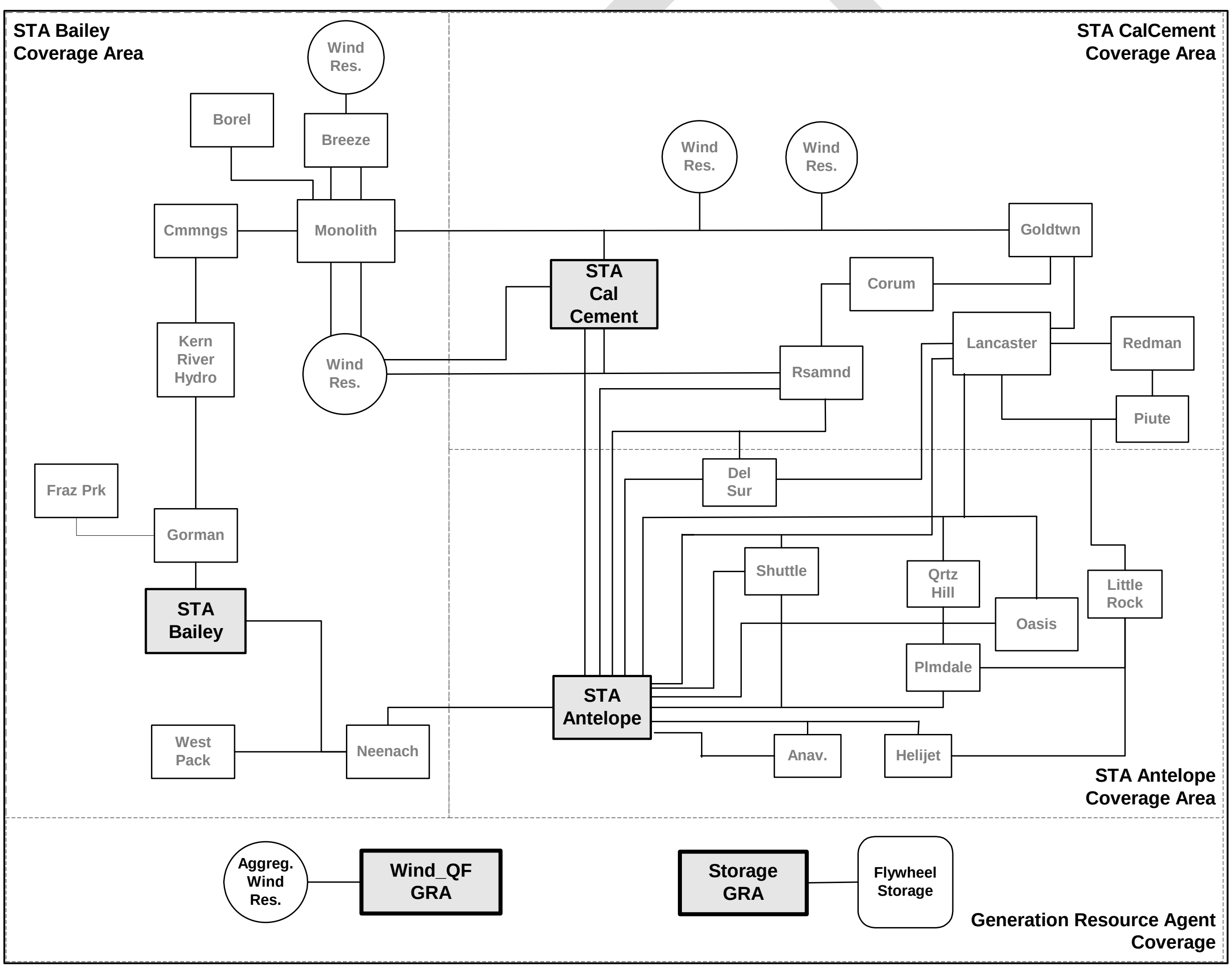


Figure 2 Agent Coverage Summary

Table 2 Agent Coverage Summary

Agent	Substations	Capacitor Banks	Generation Assets
STA Antelope	9	5	0
STA Bailey	9	4	3 [1]
STA Cal Cement	7	4	2 [1]
GRA Storage	0	0	1 [2]
GRA Wind	0	0	1 [3]

Notes:
1. Wind farm and hydro assets that lie within the agent coverage area but not directly under agent control.
2. Beacon Power Flywheel storage unit
3. Cal ISO Wind QF (aggregated Tehachapi area wind assets monitored by agent).

4.3.1. Agent Functional Description

Agent functionality, regardless of agent type, can be divided into four primary areas: operating system, data acquisition, data processing, and communications. In the case of the proposed system the agents must each successfully accomplish all necessary functions within a 5 second "window" as dictated by the SCADA data update rate. Speed of execution and timing are therefore critical operating parameters for the various agents.

Sub Transmission Agent (STA)

Each STA has control over assets that impact the sub transmission system within the confines of its physical environment. Each STA continuously monitors key parameters associated with its own physical environment (resource states, interconnect states, etc.) and uses these parameters in conjunction with a Bayesian Belief Network (BBN) to determine if action is warranted. Once an STA has identified that an actionable condition exists, the nature of the action will be dictated by the action table. Action may take the form of direct control of local assets within its physical environment or a request to other STAs for their action. In this way, any individual STA can initiate action that is both consistent and predefined.

STA operation can be characterized into three basic functions: Data Acquisition, Data Processing and Communication.

Data Acquisition -- The primary source of data used by the agents is the SCADA data provided by SCE. For purposes of this demonstration, these data were routed via an eDNA data bridge set up between an SCE eDNA server and a corresponding eDNA server located at BPL Global's offices. Every five seconds each agent independently queries the BPL Global eDNA server for the specific data that it needs in order to carry out its duties. Note that use of a databridge connected indirectly to SCE SCADA data is a convenience for purposes of the demonstration project only. Under "normal" circumstances, the agents would be communicating directly via the host utility's network and would gather data directly from the sensors.

Data Processing -- In the case of the STAs the data are processed into the inputs needed for operation of the Bayesian Belief Network (BBN). BBN inputs are comprised of both local conditions (e.g., specific instances of buss high or undervoltage, line overloads, etc.) and "shared" states. Shared states are inputs related to the general status of an STA's coverage area (e.g., single or multiple undervoltage, single or multiple high voltage, etc.). These states are communicated to STAs with coverage areas that are physically connected. In the case of the Tehachapi system, all three STAs have physical connectivity with one another and as such all three STAs communicate their general status inputs with one another prior to executing the BBN.

Having executed the BBN, each STA then examines the BBN outputs, also known as "global effects" (e.g., single high voltage, multiple high voltage, etc.) each with an associated probability that the condition exists. If the probability of any global effect exceeds the action threshold then the STA takes action. All STA's work from the same basic action table of possible actions so that actions will be consistent and repeatable. These actions were developed based on standing SCE operating order, input from SCE operations personnel, or are based on load flow modeling results. Recommended actions may entail modification of flywheel system operation or notifying the operator that capacitor bank changes are needed. Action, involving the flywheel storage unit is communicated directly to the GRA Storage agent for implementation. All action is communicated along with overall agent status information to the PowerSG/enerView system for display and archival.

Communication -- Each agent communicates with other agents as well as with BPL Global's PowerSG/enerView system used for data display and archival. Time and budget constraints required that we utilize a third-party product that relies on a single communications server to monitor and control agent communications. Reliance on a single server was a significant compromise since it requires that all communication be routed through a single point. Time constraints did not allow for implementation of true peer to peer communications in this limited duration demonstration period but any future system would certainly implement peer to peer communications.

Generation Resource Agent (GRA)

GRA data collection and processing requirements are significantly lower than for the STAs. Each of the two GRAs collects data in the same manner as the STAs with the exception of the Storage GRA, which communicates with the flywheel storage unit control using the

CentryWCC. In the case of the Wind GRA the data (Cal ISO Area Aggregated Wind Generation) are used to forecast the area wind generation for 15 and 30 minutes into the future. This information is communicated to the STAs for use in conjunction with the BBN to anticipate changes that may be needed. In the case of the Storage GRA the data (Cal ISO ACE) are used to generate a frequency regulation command for use in controlling the flywheel storage unit during "normal operation" when other types of operation (as dictated by STAs that are monitoring local conditions) are not needed.

4.3.2. Bayesian Belief Network (BBN)

A BBN is a system of interconnected cause and effect nodes, each with multiple potential states, that represent, or model, the possible states of a given domain. The network associates a "conditional probability table" with each node (the probability that a node has a given state based on the states of any parent nodes.) In addition, each node can have its current state set based on observations of the system being modeled. Given a "mix" of node states and probabilities, Bayes Rule is used to determine the probability of any given state being true within the network; hence the name Bayesian Belief Network. The probabilistic nature of the BBN affords it the ability to operate with uncertain or even missing data. For this reason it provides a more robust solution compared with deterministic methods, such as expert systems where uncertain or missing data can be problematic.

BBN conditional probability tables can be developed using a variety of methods that include "training" using actual or simulated data as well as manually setting values using domain expertise (operator expertise). In this way, the BBN network is able to encode complex probabilistic relationships between the node states that incorporate both domain expertise and relationships derived from actual operating data. In our case, power-load flow modeling was used to predict the existence of abnormal voltages or line loading at forty-two points within the Tehachapi area sub transmission system. This model was initially developed by the Cal ISO for use in the project and was later refined by Quanta Technology. Based on modeling results, as well as the availability of SCE SCADA data, a subset of points was identified for each of the three STAs for use in both monitoring local conditions as well as for use by the BBN to predict local operating conditions. In this way, the BBN size could be limited while allowing each BBN to predict abnormal operating conditions associated with buses or lines that were not being monitored directly. Figure 3 illustrates the resulting BBN that was configured for the STA Antelope coverage area.

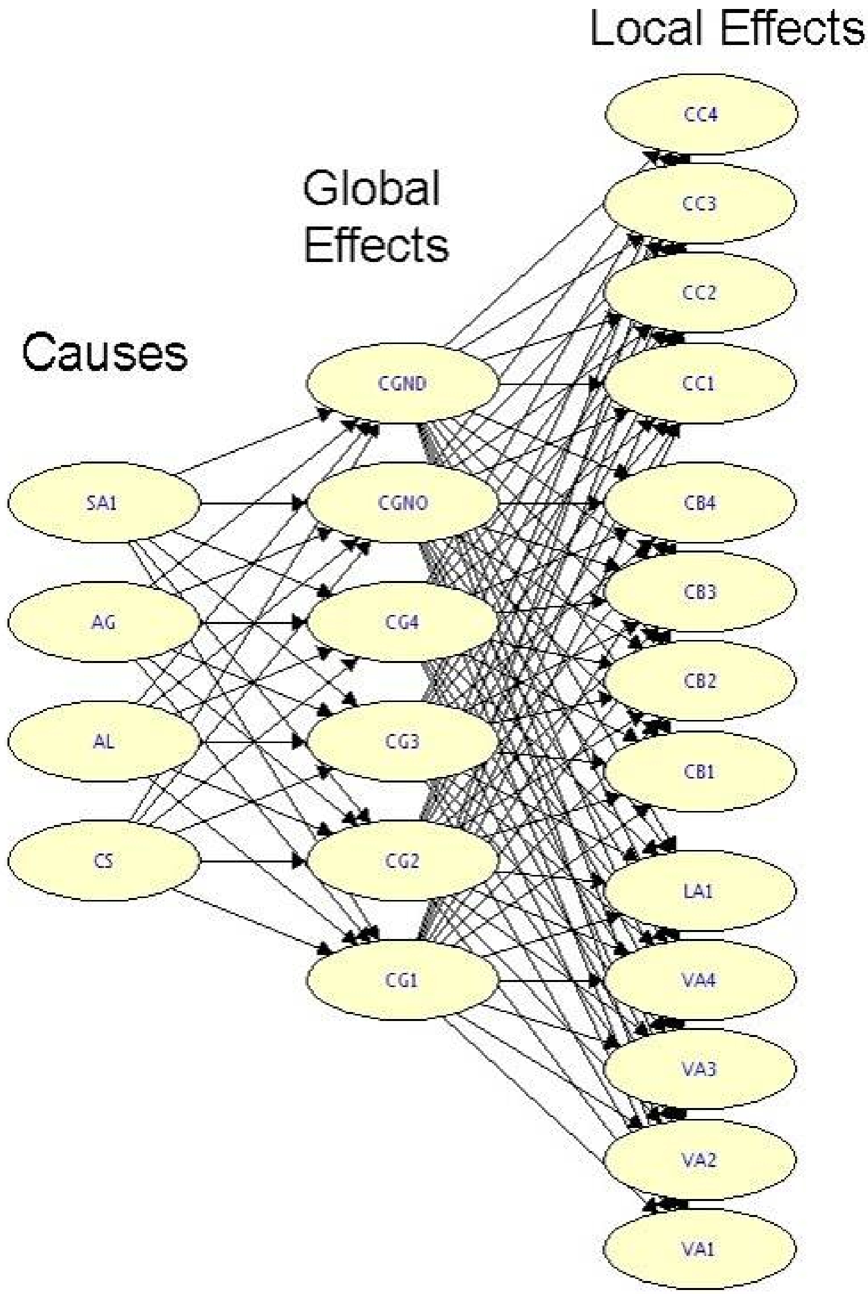


Figure 3 Example BBN -- STA Antelope

It is important to note that a BBN operates by developing probabilities associated with "discrete states". In our case, discrete output states or Global Effects are limited to the existence of abnormal operating conditions while BBN inputs, "Causes" and "Local Effects" are states related to the operating status of the specific STA coverage area.

In order to develop these discrete operating states, we again used the power load flow modeling results to develop “bins” representing significant areas of operation for each of the BBN inputs (causes and local effects).

Table 3 summarizes the most significant of the inputs that were common to each of the STA BBNs. It is important to note that BBN use of “discrete” input states (i.e., area load is less than 260 MW, etc.) is fundamentally different than systems that operate using analog, or “real number” values. Binning or grouping of inputs into states representing areas of operation provides an additional opportunity to encode important relationships into the BBN while at the same time filtering out minor fluctuations in system variables, resulting in more stable operation. The downside is that system operation is limited, in part, on the range and resolution provided by the various bins. Relative to the states shown in Table 2, it is apparent that the agent based system was configured for operation with:

- 5 or more capacitor banks on-line;
- 260 MW or more of area load; and
- 116 MW or more of area generation.

This is not to say that the system will not operate outside of these bounds, but that performance of the system was focused on operation during periods of potential area generation curtailment. The consequences of these operating limitations were evidenced during the demonstration as described further in Section 5.

Table 3 STA Belief Network Cause and Shared Local Effects Summary

CS Node Capacitor Status (5 states)	AL Node Area Load (MW) (9 states)	AG Node Area Generation (MW) (4 states)	CA, CB, CC Nodes Shared STA Status (24 states*, N, S, M)
5 or fewer	260 or less	116 or less	High Voltage
7 or 8	261 – 313	117 - 173	Very High Voltage
9 or 10	314 – 365	174 - 231	Under Voltage
11 or more	366 - 417	232 or more	Line Overload
	418 - 470		
	471 - 522		
	523 - 574		
	575 - 626		
	627 - 762		

** - where three states are possible none (N), single(S), or multiple (M); each with an associated probability.*

4.3.3. Targeted Operating Scenarios

System requirements state that the agent-based system will operate to monitor and manage voltage and VARs within the Tehachapi area 66 kV sub transmission system and develop recommended actions to mitigate or prevent impending system violations, including operation of the sub transmission system capacitor banks, the Beacon flywheel storage unit and potentially, wind generation curtailment. During the Task 5 effort these requirements were further refined to include the following targeted operating scenarios:

- Impending thermal overload of a key sub transmission line in the region in order to reduce the need for wind generation curtailments, and
- Existing or impending limitation due to N-1 operating conditions (due to potential loss of another key sub transmission line in the region).
- In both of the targeted operating scenarios, improved VAR / voltage control through management of the existing capacitor banks, wind generation curtailment and/or potential use of storage assets can be used to mitigate the effects of the targeted operating scenario.

4.3.4. Other Design Specifications

The following sections provide design information related to additional aspects of system design or operation.

Hardware

All system agents (3 – STA, 2 – GRA) will operate on BPL Global's Centry$_{WCC}$ Web Communication Controller (WCC). The WCC is a 586-grade platform with a 400 MHz AMD processor equipped with dual LAN ports for web-based communications as well as two RS-232 and two isolated RS-232 / 422 / 485 ports for communication with local controllers.

Data Requirements

Collection, use and archival of data is required during the course of the demonstration for two reasons. First, the agents require data during normal operation, which is subsequently converted into BBN state information (in the case of the STAs) and used to detect, and act on, the targeted operating scenarios. Second, data is collected and routinely analyzed both during the initial start up phase and during normal operation to monitor (and potentially refine) system performance. Additionally, archived data are used during post demonstration analysis to confirm system operation for reporting purposes. These data were provided from two sources; the Cal ISO and SCE SCADA system and are summarized in Table 4 below.

Table 4 Data Communication Summary

Data Type	Rate	Comments
SCE SCADA	5 secs	Per SCE – BPL Global "data bridge" agreement
Cal ISO Area Control Error (ACE) and Tehachapi area aggregated wind generation	4 secs	Directed from Cal ISO to SCE SCADA for subsequent transmittal via data bridge
Flywheel Storage Data	4 secs	Flywheel status and output characteristics

Communication

Web-based communications using standard XML protocols (conforms to IEEE 1547.3) and BPL Global's secure communications schema will be used during the demonstration for purposes of:

- Delivery of SCE SCADA data from SCE to BPL Global's server located in Rochester, NY. ;
- Delivery of Cal ISO data (ACE and aggregated wind generation) to BPL Global's server via SCE SCADA/BPL Global data bridge;
- Delivery of data to/from the BPL Global server and the system agents (STAs and GRA); and
- Communication between AESC and individual system agents for monitoring and maintenance purposes.
- Browser based display of information for project participants using BPL Global's **PowerSG enerView** product.
- Communication between Beacon Power and the flywheel storage unit (cell phone modem based connection)

Speed of Execution

The system specification required that all data must be communicated and processed within the 5 second SCADA data transmittal window. These actions include:

- Transmittal of data from BPL Global to the appropriate agents,
- Agent data conversion to BBN input states,
- Agent execution of BBN,
- Agent interpretation of BBN output, and
- Agent implementation of recommended actions (e.g., transmittal of recommended actions for display/reporting or delivery/receipt of flywheel storage unit command signal).

Display / Reporting

BPL Global's PowerSG enerView product[2] was accessible by authorized project participants to view:

- Status information on all system assets including agent status as well as the status of all system assets (e.g., capacitor banks, flywheel storage system, and wind generation) to the extent possible based on the available SCADA data. Information will be displayed on a system schematic with additional display features as provided by the PowerSG enerView product. The system will display "snapshot" data, which will be updated at 1 minute intervals.
- "Operating scenarios" will be identified using enerView functionality associated with "alarms", which will allow examination of data associated with the alarm condition.
- Archived data (event records) associated with alarm events.
- Archived agent generated data (agent log data)

4.3.5. Storage System Description

The Beacon Power, 100 kW, 25 kWh flywheel based storage system was installed "behind the meter" on a Tehachapi area wind farm. (see Figure 4). Storage system controls and the inverter were housed in a cargo-type container (white container in the figure) with the flywheel storage unit itself located in a concrete structure (blue cylinder in figure) adjacent to the control enclosure.

Figure 4 Storage System Installation

[2] BPL Global configured and maintained enerView during the course of the project; ownership of which remained with BPL Global.

4.3.6. Storage System Operation

As noted previously, storage unit operation was managed by the Storage GRA. The Storage GRA software operated on a compact fanless computer (labeled Power SG in Figure 5) and communicated with the other system agents via a cellular modem.

Figure 5 Storage System Control

Storage GRA functionality included:

- Collection of SCE SCADA data including Cal ISO ACE,
- Generation of frequency regulation signal for operation of storage system during "normal" operation
- Communicate with the STAs to:
  - Provide flywheel storage unit status information; and
  - Receive short term flywheel storage system operating instructions as indicated by the system action table. These actions would include discharge/charge and modification of VAR output.
- Generation of flywheel storage system commands for either frequency regulation or other short term operating modes that stay within storage unit operating limits as defined by Beacon Power Corporation.

4.4. Demonstration Test

In the Task 8, System Configuration and Development effort, the project team members modified their respective technologies and subsequently either directly tested connectivity or simulated the systems involved so that system functionality could be verified and communication between the various system components tested prior to the start of the demonstration period. The demonstration took place during the Task 9, System Integration and Test effort, during which, all hardware and software systems were fully integrated and operated continuously. During this time AESC and its principal subcontractors, Beacon Power and BPL Global LLC monitored and documented system operation.

4.4.1. Demonstration Period

The demonstration test period officially began on December 1, 2010 at 4 p.m. and ended on February 11, 2011 at 5 p.m. Contractually, the project initially required a one month demonstration period but this period was eventually extended to a total of seventy-three days in order to provide project participants with additional time to observe system operation. The additional demonstration time also provided more opportunities to observe system operation during periods of higher wind generation since wind generation typically increases in spring and early summer.

4.4.2. Data Collection

During the demonstration period data were collected at 5 second intervals over the 1753 hour period, representing a total of 1,244,880 five second records. Some loss of data occurred as a result of server outages, consisting primarily of a multi-day outage that occurred at the start of the New Year. Overall, a data collection rate of 95.7% was achieved during the demonstration period. A monthly breakdown of data collection performance is provided in Table 5.

Table 5 Data Collection Summary - % of Total Data Collected

December	January	February	Overall
98.6%	91.3%	100.0%	95.65%

4.4.3. Generation and Area Load Summary

Total generation and load levels were monitored for the area served by the Tehachapi sub transmission system. Area generation was estimated by adding the net power flowing into the area via the 230 kV transmission system and the aggregated wind generation as monitored by the California Independent System Operator (Cal ISO). The output of a small hydropower installation (approximately 10 MW) that operates in the region was also included in the calculations. A monthly summary of area generation and load in MW is provided in Table 6. As the table shows, both area load and generation varied significantly during the demonstration period. Total area generation peaked at similar levels each month with December showing the highest overall generation levels during the demonstration.

Table 6 Area Load and Generation

	Total Generation (MW)	Total Load (MW)
December		
Max	268.95	401.24
Avg	80.22	189.46
January		
Max	264.16	419.34
Avg	59.37	203.79
February		
Max	237.86	279.64
Avg	55.44	187.35
Overall		
Max	268.95	419.34
Avg	67.82	194.99

The distribution of Tehachapi area wind generation (as aggregated by Cal ISO) experienced during the demonstration period is shown below in Figure 6 Area Wind Generation Distribution. Wind generation levels, when compared with the 349 MW installed capacity, were relatively low during the majority of the demonstration period. During the demonstration period, wind generation was below 20 MW 55% of the time and exceeded 200 MW just 5.5% of the time.

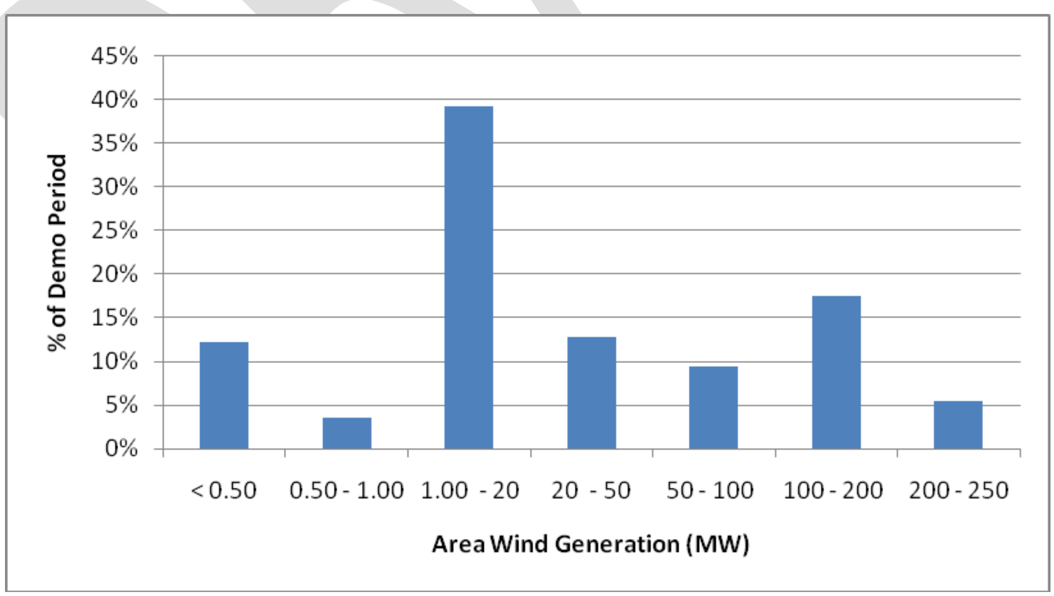


Figure 6 Area Wind Generation Distribution

4.4.4. Sub Transmission System Operation

Capacitor bank operation is the principal means of dealing with increased wind generation in the Tehachapi region. In general, SCE operators observe the voltage and reactive power at the principal substation in the area and increase or decrease the number of capacitor banks to maintain a minimum level of reactive power as well as minimum voltage levels. Automated tap changers are also operating continuously to maintain substation voltage levels as well. Occasionally, the operator will "block" the tap changers temporarily while making capacitor bank changes but this is not always the case. Thus, in many instances operators are working in conjunction with the tap changers to maintain system voltage and reactive power levels. In general, increased use of capacitor banks to control system voltages is an indication that wind generation levels are impacting system operation. Compliance with CEII restrictions prevents any discussion of individual capacitor banks however it is informative to look at the amount of time during the demonstration period when significant numbers of capacitor banks were on-line. During normal operation each of the sub transmission system agents monitored the status of the regional capacitor banks in order to develop the BBN inputs and to help devise an appropriate course of action; when BBN output indicated that action was needed. Capacitor status, as monitored by the agents is summarized in Table 7.

Table 7 Capacitor Status Summary

Capacitor Status	December	January	February	Overall
5	77.9%	91.1%	92.8%	**85.6%**
6	6.8%	3.3%	3.4%	**4.8%**
7 or 8	10.3%	5.1%	3.7%	**7.1%**
9 or 10	3.4%	0.6%	0.1%	**1.7%**
11 or 12 or 13	1.6%	0.0%	0.0%	**0.7%**

As the table shows, there were 6 or fewer capacitor banks on-line over 90% of the time. December experienced the highest level of activity relative to capacitor bank use, which corresponds with the previously noted higher generation levels that occurred during December. Further review shows that there were twenty-two days during the demonstration period when more than 6 capacitor banks were in use. These dates are summarized in Table 8.

Based on feedback from SCE personnel, issues associated with system operation in response to wind generation are primarily associated with the amount of wind generation relative to area load as opposed to wind generation levels alone. SCE operators take action based on existing operating orders, some of which provide designated operating ranges of both reactive power and system voltage for various levels of area load and area generation. Thus increased use of the capacitor banks during December, when the amount of generation was higher overall relative to the area load reflects this relationship. Although it is important to note that overall, the amount of wind generation and any associated operating issues were relatively minor during the demonstration period.

Table 8 Operational Dates of Interest

December	Max Caps	January	Max Caps	February	Max Caps
12/9/2010	10	1/8/2011	10	2/1/2011	8
12/10/2010	10	1/9/2011	10	2/7/2011	10
12/11/2010	13	1/13/2011	10		
12/14/2010	11	1/14/2011	8		
12/15/2010	13	1/30/2011	8		
12/16/2010	8	1/31/2011	10		
12/19/2010	10				
12/20/2010	10				
12/23/2010	8				
12/26/2010	8				
12/27/2010	8				
12/29/2010	8				
12/30/2010	8				
12/31/2010	8				
Totals:	**14**		**6**		**2**

Wind Resource Curtailment Events

Information on the number and duration of wind resource curtailments initiated by SCE during the demonstration was not made available. However, AESC became aware of one such occurrence that began on December 10th and lasted through part of December 11th and the circumstances of this event are discussed in Section 5 in more detail.

4.4.5. Agent-Based System Performance

The following sections summarize the performance of the agent-based system in terms of both the availability and functionality of the agents.

Agent Availability

Agent availability was measured based the agents ability to accomplish its overall mission. Agents were considered "unavailable" if they were either down (software had stopped functioning or was reset) or were otherwise unable to complete their data retrieval and processing functions functioning (software was otherwise functioning normally). Based on these broad criteria, the agents still achieved a high level of availability. With the exception of the GRA Storage agent, the agents were available over 99% of the time (see Table 9 Agent Availability).

Table 9 Agent Availability

Agent	December	January	February	Total Availability
STA Antelope	99.6%	99.0%	99.8%	**99.4%**
STA Bailey	99.5%	99.0%	99.7%	**99.3%**
STA Cal Cement	99.6%	99.0%	99.6%	**99.4%**
GRA Wind	99.9%	99.3%	100.0%	**99.7%**
GRA Storage	93.1%	83.4%	99.46%	**90.1%**

Agent availability was affected by a number of factors. The lower overall availability evidenced in January was the result of a multiple day outage of the PowerSG servers. This was a onetime event associated with the New Year. Short outages were necessary on a daily basis in order to retrieve and reset log files used to document agent actions during the demonstration period. These log file resets accounted for approximately 0.03% of the downtime. Additional outages were experienced on a daily basis due to issues associated with use of the Active MQ messaging system. These outages were only associated with receipt of messages (sending of messages was unaffected). The GRA Wind agent only sends messages, and was therefore able to achieve a higher overall availability relative to the other agents for this reason. Additional downtime also resulted from issues associated with agent retrieval of SCE SCADA data via the eDNA servers. Retrieval of the large number of points accessed by the STAs required a different retrieval method than for the GRA Wind agent, which required far fewer points. The higher overall availability achieved by the GRA Wind agent relative to the STA agents was also attributable to this eDNA related issue.

GRA-Storage Agent Availability was significantly lower than the other agents. This lower availability was the direct result of issues associated with the cell modem that was necessitated by the remote location. It should be noted that in many instances, the GRA Storage was deemed “unavailable” due to the extended length of time required for it to obtain SCADA data from the eDNA server. So, while it was officially unavailable, it was still able to receive messages from the STAs and status information from the storage unit itself.

It is worth noting that the primary factors affecting agent availability, Active MQ messaging, eDNA data retrieval, the onetime Power SG server outage and cell modem based communications would not be factors in a commercial system. True peer-to-peer communications and direct data retrieval from local sensors via a local area network would eliminate these issues in a commercial system and result in availabilities approaching 100% (as experienced by the GRA Wind agent in December and February).

Bayesian Belief Network (BBN) Performance

As noted previously, the BBN employed by the STAs to detect and predict abnormal system conditions was initially configured with the help of load-flow modeling conducted by Quanta Technology. Essentially, the load-flow model was used to predict system parameters (i.e., voltages and line loads, etc.) that were then used to “train” the BBN. As one would expect, during the course of the demonstration period the BBN occasionally encountered a combination of system parameters (input states) that were not initially modeled. When this situation occurred the BBN output, which corresponds to the probability of a given global effect, would become equal to zero. This zero value is subsequently detected by the associated STA and an alarm was generated. In this way, AESC personnel were quickly notified. Recorded data points for the suspect period of time were then used to “train” the BBN and update the BBN configuration, off-line. The updated configuration was then uploaded to the affected agent(s). Updating of the BBN configuration offline was required a total of 14 times during the demonstration. Twelve of the configuration events were associated with the Antelope and Cal Cement STA, and only two were associated with the Bailey STA.

It is important to note that encountering new combinations of input states did not cause the BBN to stop functioning or impact other agent functionality. In all instances, the duration of these events was short lived and the BBN resumed normal operation as soon as the BBN encountered known state conditions. Also, it should be noted that the use of off-line BBN training was necessitated by the short demo period and that automated BBN training would be implemented in a commercial system. Thus, a BBN could receive model based training for the most infrequent operating scenarios and then “learn” the more common system operating characteristics during a “start up” or training phase.

Definitions of the Local and Global conditions detected by the three STAs along with the allowable duration (Delay) of an excursion before any recommended actions are summarized in Table 10 while events or instances of these conditions that occurred during the demonstration are summarized in Table 11.

Table 10 Local and Global Conditions Summary

Condition	Threshold	Delay (secs)
Line Overload	> 1 P.U.	60
Very High Voltage	> 115%	15
Under Voltage	< 95%	60
High Voltage	> 105.9%* (66kV) > 110% (12kV)	120
N-1 Overload	NA	30
N-1 Violation	NA	30
** - changed from 105% on 1/24/2011*		

Table 11 BBN Detected Local and Global Effects

Global Effect	December		January		February	
	Instances	%	Instances	%	Instances	%
Line Overload						
STA.ANTELOPE	92	0.02%	373	0.08%	0	0.0%
STA.BAILEY	0	0.00%	0	0.00%	0	0.0%
STA.CAL CEMENT	26	0.01%	373	0.08%	0	0.0%
Very High Voltage						
STA.ANTELOPE	0	0.0%	0	0.0%	0	0.0%
STA.BAILEY	0	0.0%	0	0.0%	0	0.0%
STA.CAL CEMENT	0	0.0%	0	0.0%	0	0.0%
Under Voltage						
STA.ANTELOPE	88851	17.3%	19129	4.0%	1323	0.7%
STA.BAILEY	4	0.0%	0	0.0%	0	0.0%
STA.CAL CEMENT	10372	2.0%	0	0.0%	0	0.0%
High Voltage						
STA.ANTELOPE	164513	32.0%	75703	15.6%	19948	10.8%
STA.BAILEY	8623	1.7%	2	0.0%	0	0.0%
STA.CAL CEMENT	14381	2.8%	3992	0.8%	0	0.0%
N-1 Overload						
STA.ANTELOPE	0	0.0%	0	0.0%	0	0.0%
STA.BAILEY	0	0.0%	0	0.0%	0	0.0%
STA.CAL CEMENT	0	0.0%	0	0.0%	0	0.0%
N-1 Violation						
STA.ANTELOPE	0	0.0%	0	0.0%	0	0.0%
STA.BAILEY	0	0.0%	0	0.0%	0	0.0%
STA.CAL CEMENT	0	0.0%	0	0.0%	0	0.0%

As Table 11 shows, there were no instances (an instance is one 5 second record) of Very High Voltage, N-1 Overload or N-1 Violation effects during the demonstration period. This is not unexpected in that these represent serious operating issues. A very limited number of Line Overload instances were recorded, primarily in January. But the duration of these instances were less than 8 minutes total in December and 31 minutes in January. Additional discussion of these instances is provided in Section 5.

Undervoltage events in December were primarily the result of one or more sensors that were isolated when operators removed associated lines or buses from service. A software change in early January corrected this situation as evidenced by the decrease in January and February. Remaining instances of undervoltage occurred during periods of increasing wind generation and these events are discussed in more detail in Section 5.

Instances of High Voltage were evident in all three months. High Voltage events were often associated with the 12 kV buses. SCE operating personnel confirmed in early January that it is normal for some of the 12 kV buses to operate at or above the 5% limit. Additionally, it was learned that some of the 66 kV buses also have a tendency to operate near the limit. For this reason, the High Voltage limit was increased for both the 66 kV and 12 kV buses during January. It should also be noted that use of fixed thresholds was also a convenience of the demonstration project. A commercial system could easily track and learn what is "normal" for each bus thus eliminating this type of "false" alarm.

Early in the demonstration period it was discovered that one of the high voltage indications was the result of a faulty bus voltage sensor, which had failed leaving a constant indication of a high voltage condition. An alternate eDNA sensor point was not available so the affected agent simply entered the BBN input associated with this sensor as "unknown". The BBN was then able to continue to operate normally using the remaining "known" inputs. This demonstrated a very powerful feature of the BBN; the ability to operate in the absence of data or with uncertain data. In this case, discovery of the faulty sensor and reprogramming of the agent was done offline but this could easily be implemented as an automated process in a commercial system.

Recommended Actions

As noted previously, each STA monitors its local region and uses both local and shared information in conjunction with the BBN to identify high probability actionable conditions (as shown previously in Table 8). The actionable conditions, their relative priority and the associated potential agent actions are summarized in Table 12. Each STA addresses conditions singly, in that action associated with a higher priority condition will supersede action related to a lesser priority condition (e.g., the STA always puts out the biggest "fire" first). In this way, the STA will always attempt to correct the highest priority condition first. Thus if an N-1 condition is detected in the absence of any other actionable condition then the STA will recommend that the operator "consider action".

Table 12 Recommended Actions

Global Effect	Priority	Potential Actions (in order of occurrence)
Line Overload	1	Curtail Wind, Storage – Absorb Energy
Very High Voltage	2	Deactivate capacitor bank, Storage - Absorb Max VARS
Under Voltage	3	Activate capacitor bank, Storage – Inj VARS
High Voltage	4	Deactivate capacitor bank, Storage – Hybrid Mode, Storage – Absorb Max VARS
N-1 Overload	5	"Consider Action"
N-1 Violation	5	"Consider Action"

STA operation of the capacitor banks, when indicated, is accomplished via a capacitor bank loading order that was developed based on a combination of existing SCE Operating Orders and load-flow modeling results. The STAs utilize one of two different activation orders, a "Local Area Activation" order when a condition is limited to a single STA and a "General Activation Order" when multiple agents have detected an abnormal condition (see Table 13).

For instance, if multiple agents detect an undervoltage condition in their individual coverage areas then this constitutes a "general" undervoltage situation and the next available capacitor bank in the "General Activation Order" list is activated. If however the undervoltage condition is only indicated in a single coverage area then the next available capacitor bank associated with that specific coverage area is activated sequentially (i.e., A1, A2, ...A5, etc.).

Table 13 Capacitor Bank Activation Order

<----Activation	Local Area Activation Order	General Activation Order	<----Deactivation
	A1	1	
	A2	2	
	A3	3	
	C1	4	
	B1	5	
	B2	6	
	C2	7	
	B3	8	
	C3	9	
	C4	10	
	A4	11	
	A5	12	
	A6	13	

** - capacitor bank names have been excluded due to CEII restrictions.*

Each STA monitors the status of all available capacitor banks and all agents utilize the same activation order. Thus any agent can take an action that addresses either a local or a general condition and the actions of any given agent are both consistent and repeatable.

Capacitor bank operation during the demonstration period is summarized below in Table 14 Capacitor Bank Operation Summary. It is important to note that system "actions", with the exception of actions associated with the storage system, were recommendations. Thus capacitor bank operation shown in the table is the result of operator actions, which may or may not correspond with system recommendations. That being the case, it is still interesting to note that capacitor bank operation does follow the basic "local" activation order that was utilized by the system. For instance, the capacitor designated as C1 experienced the highest amount of operation relative to the other "C" designated capacitor banks. However, there are many exceptions, which could be related to the existence of "general" vs. "local" conditions. Overall, the capacitor banks were only lightly used during the demonstration period, which is another indication that wind generation, and issues associated with control of the system in the presence of high wind generation, were uncommon.

Table 14 Capacitor Bank Operation Summary

Cap Order		December		January		February		Overall Demo Period	
Gen'l	Local	% On	% Off	% On	% Off	% On	% Off	% On	% Off
1	A1	55.7%	44.3%	0.9%	99.1%	0.0%	100.0%	27.0%	73.0%
2	A2	38.9%	61.1%	56.0%	44.0%	30.4%	69.6%	44.7%	55.3%
3	A3	24.6%	75.4%	15.5%	84.5%	9.5%	90.5%	18.5%	81.5%
4	C1	100.0%	0.0%	100.0%	0.0%	100.0%	0.0%	100.0%	0.0%
5	B1	13.2%	86.8%	8.6%	91.4%	4.6%	95.4%	9.8%	90.2%
6	B2	88.5%	11.5%	52.1%	47.9%	64.5%	35.5%	69.2%	30.8%
7	C2	20.8%	79.2%	18.1%	81.9%	6.3%	93.7%	17.4%	82.6%
8	B3	7.7%	92.3%	3.7%	96.3%	4.0%	96.0%	5.7%	94.3%
9	C3	1.2%	98.8%	2.0%	98.0%	0.1%	99.9%	1.3%	98.7%
10	C4	0.0%	100.0%	0.0%	100.0%	0.0%	100.0%	0.0%	100.0%
11	A4	22.5%	77.5%	8.6%	91.4%	2.5%	97.5%	13.5%	86.5%
12	A5	11.7%	88.3%	26.1%	73.9%	6.4%	93.6%	17.9%	82.1%
13	A6	7.0%	93.0%	0.0%	100.0%	0.0%	100.0%	3.9%	96.1%
							Average:	25.3%	74.7%

Implemented Actions – Storage System Operation

As noted previously, the only recommended actions that were implemented by the agent-based system during the demonstration period were actions that involved the storage system. Under "normal" conditions the Storage GRA manages storage unit output in support of frequency regulation. The power command issued to the storage unit master control was developed by the GRA using the CAISO ACE signal and an algorithm supplied by the storage unit manufacturer. In "normal" operation the storage unit real power output can vary from a maximum discharge/charge rate of +/- 100 kW with the reactive power automatically set to by the storage unit controller to achieve a unity power factor. When an abnormal condition is detected by one or more of the STAs then a message from the affected STA to the Storage GRA causes the Storage GRA to retask the storage system in order to address the local condition. The storage unit can be retasked into one of four other operating modes. Conditions and corresponding storage system operating modes are summarized in Table 15 below. Note that with the exception of hybrid operation, the storage system was only used if no capacitor bank assets were available. While in hybrid mode the storage system continues to provide frequency regulation support but with the reactive power output modified to absorb VARS in support of local needs. In order to avoid exceeding the maximum apparent power output capability of the storage system both the reactive and real power output components were limited to a maximum of 70 kW (-70 kVAR).

Table 15 Storage System Operating Conditions

Storage Unit Action	Condition	Storage Unit Real Power (kW)	Storage Unit Reactive Power (kVAR)
Frequency Regulation	Normal Operation	-100 to 100	Varies to achieve unity PF
Hybrid Mode (Capped Freq Reg with VARS absorption)	High Voltage	-70 to 70	-70 to 0
Max Charging	Line Overload	-100	Varies to achieve unity PF
Max VARS Absorption*	High or Very High Voltage	0	-100
Max VARS Injection*	Undervoltage	0	100

** -- Storage system operation is only enabled if all capacitor bank assets have been deployed.*

Storage system operation during the demonstration period is summarized below in Table 16 and Table 17. The storage system operated in Frequency Regulation mode 97% of the time with just 3 percent of the overall operation in Hybrid mode. As noted earlier, frequency regulation was accomplished using a "pseudo" frequency regulation signal generated by the Storage GRA using the Cal ISO ACE signal. This was a relatively unsophisticated control signal in that it did not account for the state of the storage system itself. More sophisticated storage control signals either in use or proposed for use, monitor the storage system status to ensure that storage system is able to maintain some level of operation (charging or discharging) in support of frequency regulation at all times. The lack of feedback in the algorithm that was utilized is evidenced by the fact that while the storage system was tasked 100% of the time in support of frequency regulation (including Hybrid mode) it was either fully charged (4%) or completed depleted (7%) approximately 11% of the time and was therefore unable to provide support.

Table 16 Storage System Operation Summary

Operation	December	January	February	Overall Demo Period
Frequency Regulation	96.7%	97.8%	97.1%	97.0%
Hybrid Mode (Freq Reg + VARS ABS.)	3.3%	2.2%	2.9%	3.0%
Depleted (Stored Energy < 500 Wh)	6.1%	7.2%	7.0%	7.0%
Full Charge (Stored Energy > 25000 Wh)	4.6%	3.6%	2.4%	4.0%

Table 17 Storage System Operating Parameter Summary

Parameter Description	December			January			February			Overall Demo Period		
	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
Power Output Command	-1.0	1.0	0.0078	-1.0	1.0	-0.0039	-1.0	1.0	-0.0057	-1.0	1.0	0.0010
Power System Output	-105227.2	97679.5	-9118.7	-105447.0	97533.0	-9075.1	-105447.0	97386.4	-8728.1	-105447.0	97679.5	-9036.6
Stored Energy Value	0.0	27130.6	11042.6	0.0	27126.1	9750.5	0.0	27135.1	8617.3	0.0	27135.1	10093.9
Reactive Power (VAR)	-100610.6	101636.5	3303.0	-46238.4	78627.3	1837.0	-31216.4	79433.3	2619.2	-100610.6	101636.5	2610.7
Real Power (VA)	0.0	106399.6	52415.0	1685.4	106472.9	51751.1	1978.5	106253.1	51591.3	0.0	106472.9	52012.7

4.4.6. Event Analysis

As noted previously, wind generation and area load levels were relatively low during the seventy-three day demonstration period and this resulted in operation of six or fewer capacitor banks over 90% of the time. There were twenty-two days during the seventy-three day demonstration period when additional capacitor banks were operated indicating that these dates were "Operational Dates of Interest" (see Section 4.4.4, Table 8). Of these twenty-two dates, six were selected as representative examples of system performance involving line overload, high voltage and undervoltage events. These dates were examined in more detail to compare actual operation against the agent-based system's indications as well as to provide insight on operation of the three STAs relative to one another. These dates are summarized in Table 18 below along with the operating scenario(s) of interest.

Table 18 Event Analysis Dates of Interest

Date	Scenario(s) of Interest
12/10/2010	Line Overload, Wind Generation Curtailment
12/11/2010	Line Overload, Wind Generation Curtailment
12/14/2010	Undervoltage, High Voltage, Line Overload
12/19/2010	Undervoltage, High Voltage
1/30/2011	Undervoltage, High Voltage
1/31/2011	Undervoltage, High Voltage

General Observations

Prior to discussing BBN performance on the dates of interest it would be useful to review common features of the various plots as well as relevant system operating characteristics.

Discrete BBN Inputs versus Real Value Data

The fact that the BBN utilizes discrete rather than real value inputs (see Section 4.3.2) makes its performance dependent, in part, on the manner in which the "real value" input parameters are converted into discrete input states (e.g. grouping of real value inputs into discrete input "bins"). For example, as noted previously, the input node associated with capacitor bank status "bins" any instance of 5 or fewer capacitors into a single input state, "5 Caps". Thus the BBN is unable to recognize or learn about operation when fewer than five capacitor banks are on-line (since 2, 3, 4 and 5 capacitor banks on-line all have the same, "5 Caps" capacitor status input state). This is evidenced in the data by periods when the agent-based system may appear insensitive to changes in capacitor banks, area load or generation (since as far as the BBN is concerned these inputs are not changing). This limitation is merely a circumstance of the project's main focus, which was to demonstrate system operation during periods of high area generation. The focus of the load flow modeling, BBN configuration and training efforts were all directed at operating scenarios involving high area generation and there was therefore no need to carry input states that were only relevant during low wind conditions. With the benefit of additional load flow modeling or additional analysis of the input parameters, it would be relatively easy to incorporate additional input nodes and/or states to accommodate the full range of operation.

Use of Fixed Thresholds

As noted previously, the STA's collected and processed SCE SCADA data at five second intervals. Data processing primarily consisted of transforming the real values of the SCADA data into the discrete input states required by the BBN. Some of the BBN inputs were related to detection of local issues such as high or undervoltage conditions, etc. The thresholds used for this determination were fixed (see Section 0) and applied in the same fashion to each input. Thus, the BBN may appear insensitive to changes in local voltages or line loads until the changes exceed "normal" thresholds. Additional system sensitivity can be achieved by retaining fixed percentage thresholds but allowing the system to monitor and calculate what is "normal" for each parameter. Thus a voltage that typically "runs high" will not trigger false alarms etc.

Automated Transformer Tap Changer Operation

The transformers at the key substation in the Tehachapi area are equipped with tap changers that automatically work to control system voltages. The operators may, on occasion, temporarily lock these tap changers in a fixed position in order to facilitate bringing capacitor banks on or off-line; but this is not common. Thus the operator's actions may at times conflict or coincide with tap changer actions causing some swings in voltage. The agent-based system deployed during the demonstration did not have any inputs related to tap changer position. A future refinement, to add some feedback from the tap changers, could further improve system operation.

Aggregated Antelope Area Wind Generation Value

To reduce the total number of SCE SCADA point transmitted during the demonstration, the agent-based system utilized a Cal ISO aggregated area wind generation value in lieu of gathering all of the individual generator data. The Cal ISO updates this data at 15 minute intervals, which is evidenced in the area generation plots as "step" rather than continuous data. The slow update rate for this parameter relative to a 5 second update rate for other data provides for both a "choppy" plot.

December 10 & 11, 2010

According to SCE operations personnel, a Tehachapi area wind curtailment event was declared on December 10th at 18:58 and ended on December 11th at 09:49. Figure 7 contains plots of multiple parameters of interest during this time period including the voltage and reactive power at a key area substation along with the status of the capacitor banks, area load, area generation and STA Antelope BBN outputs pertaining to under, high, multiple undervoltage, multiple high voltage and line overloads. Note that the rapid variation evidenced in the station voltage and station reactive power plots is the likely result of operation of the station automatic transformer tap changers as opposed to operator initiated activity.

The sequence begins with the STA BBN flagging high voltage conditions that appear to be the result of 12 kV buses that typically run higher than normal. This situation was remedied later in the demonstration period by raising the high voltage threshold for 12 kV buses. The figure does show that the STA Antelope BBN correctly flagged the line overload event beginning at 18:45, although the overload indication was very brief in duration (3 minutes). It isn't clear from the area generation plot whether the SCE curtailment notice was effective in that the area generation continued at high and relatively constant levels following the beginning of the curtailment period.

Additional brief BBN indications of line overload, including indications of multiple line overloads (indication by more than one STA) appear sporadically during the curtailment period. It is important to note that following detection of the line overload condition the STA also correctly recommended curtailment while requesting that the storage system be retasked from frequency regulation to a maximum charging state in order to absorb energy. Additional analysis and load flow modeling could provide additional insight but it appears that an appropriately sized storage system could have been dynamically controlled to potentially minimize the overload condition. The fact that there are only sporadic indications of line overload later in the period may be indicative that an extended curtailment period could have been avoided with more dynamic control such as that provided by the agent-based system.

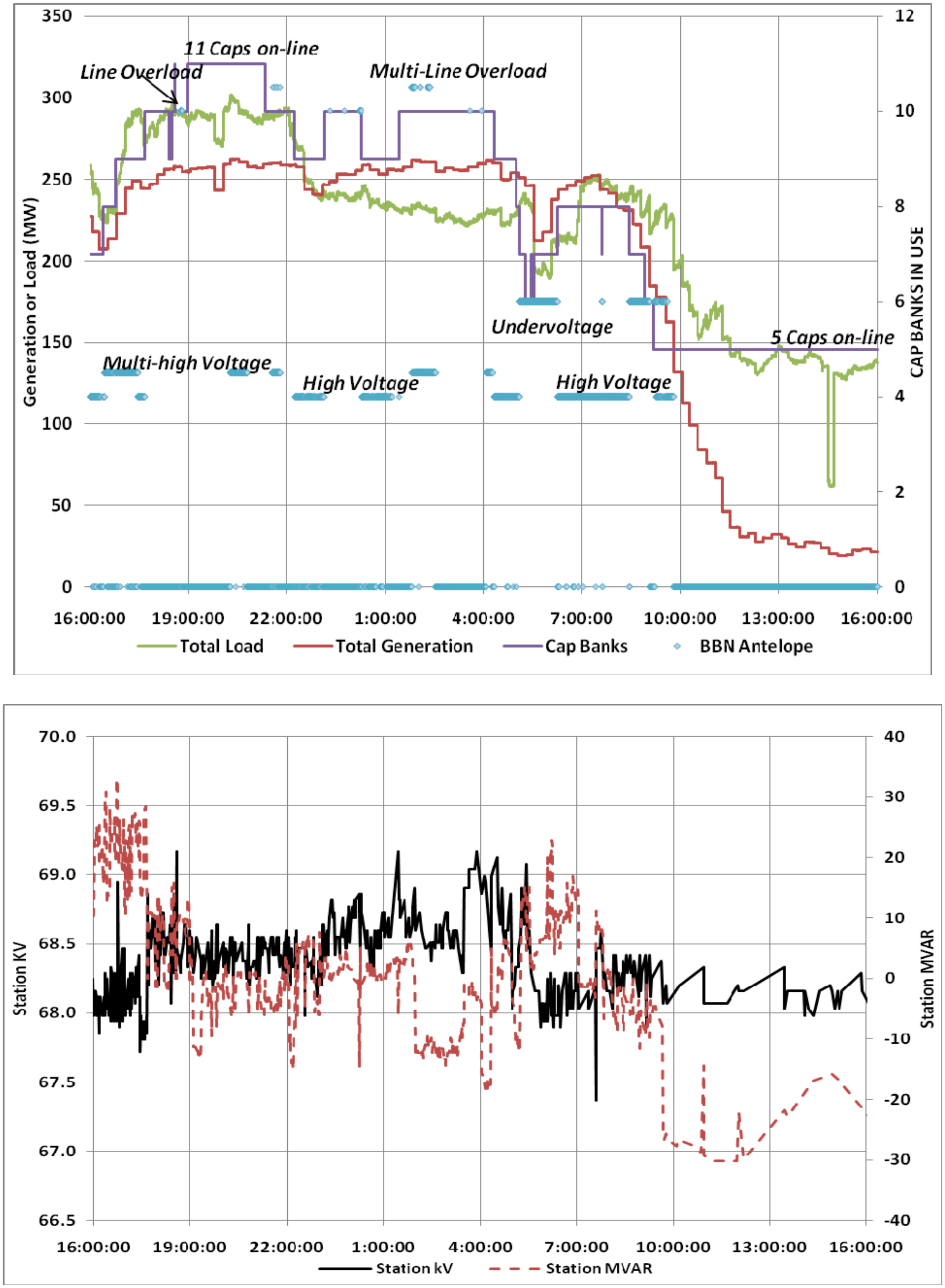


Figure 7 December 10 -11, 2010 – Parametric Comparison

December 14, 2010

The events on December 14th provide insight on BBN performance under a variety of system conditions. During this period, the STA Antelope BBN flagged multiple occurrences of undervoltage and high voltage with very short duration instances of multiple undervoltage and high voltage events along with a limited number of short duration line overloads. Figure 8 contains plots of multiple parameters of interest including the voltage and reactive power at a key area substation along with the status of the capacitor banks, area load, area generation and BBN outputs pertaining to under, high, multiple undervoltage, multiple high voltage and line overloads.

The sequence begins at about approximately 01:00 with just 3 capacitor banks on-line. Total area generation starts at a relatively low level, below 50 MW, and ramps up to approximately 250 MW in three hours time. During this same time period area load starts well above the area generation (exceeding generation by 100 MW) but the two values begin to coincide at approximately 04:30. In response to falling reactive power levels (MVAR) operators began adding additional capacitor banks. Note that operators attempt to maintain a negative reactive power level (representing excess area reactive power), at the key area substation, meaning that MVAR readings should always remain negative. The figure shows excess reactive power levels decreasing and then becoming positive (reactive power is being imported from outside of the area) during this time. The BBN is correctly flagging the probability of an undervoltage during this time with a recommendation to bring an additional capacitor on-line. This indication/recommendation does not pass until three additional capacitor banks are brought on-line (however, the recommended capacitor bank was altered by the operator's continuing actions). The operators continue to place additional cap banks in service until a total of 11 banks are eventually on-line. Note that after the ninth bank was brought on-line that the agent-based system began to flag a probable high voltage, which appears to correctly correspond with recovering reactive power levels (e.g., less banks were needed) and rising voltage levels. Thus, the agent-based system correctly identified the need for additional capacitors in advance of when the action was actually taken and correctly identified when additional banks were not needed.

The remainder of the day contains a mixture of recommendations and actions, which at times appear to be contradictory. Relative to high voltage indications, the BBN flagged a probable high voltage condition for much of the remainder of the day beginning at the time when the ninth capacitor bank was placed in service (0630). These indications appear to be a reflection of relatively high station voltage levels (+/- 69 kV) along with the return to higher reactive power levels. While these indications appeared reasonable there were also short periods when undervoltages, including multiple undervoltages were also indicated, which would appear contradictory.

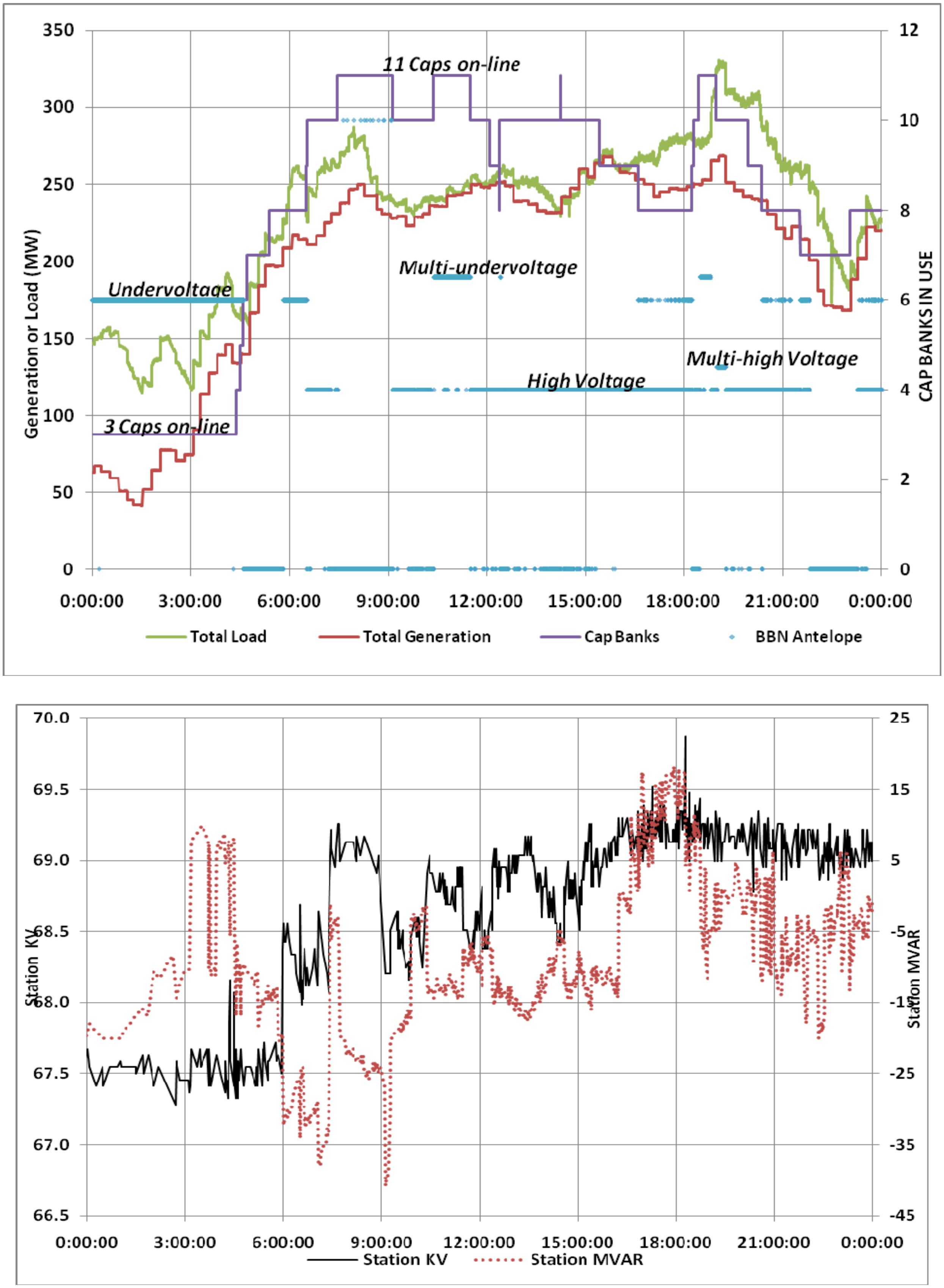


Figure 8 December 14, 2010 – Parametric Comparison

A closer inspection of the BBN input states revealed that transitions from undervoltage to high voltage etc. correspond with transitions in the BBN input states (remembering that BBN inputs are discrete states such as "5 or few capacitor banks", or "area load is less than 260 MW", etc.). As noted previously, the fact that the BBN utilizes discrete rather than real value inputs makes its performance dependent, in part, on the way in which the "real" input parameters are converted into discrete input values (e.g. grouping of real value inputs into discrete input "bins"). The BBN behavior was exemplary during the transition from low to high area generation since this was the focus of the modeling effort used for both BBN training as well as the operating scenario used to design the input states. This is an indication that additional input states (i.e., more and finer area load and area generation input states, etc.) covering the full range of operation would have improved BBN performance in other time periods.

December 19, 2010

The events on December 19th provide additional insight on BBN performance during transitions from low to high wind conditions. Figure 9 contains plots of multiple parameters of interest including the voltage and reactive power at a key area substation along with the status of the capacitor banks, area load, area generation and STA Cal Cement BBN outputs pertaining to under, high, multiple undervoltage, multiple high voltage and line overloads.

At the start of the period, the STA Cal Cement BBN indicated that there was a high probability of an undervoltage condition and was recommending that an additional capacitor bank be brought on-line. At approximately 00:40 one capacitor is brought off-line by operators, which results in both a voltage reduction and a lessening of the available reactive power. At this same time, area generation begins to ramp up resulting in further lessening of the reactive power resources until there is no longer an excess and the area begins to import MVAR through the key area substation (MVAR value becomes positive) beginning at 05:30. No additional capacitor banks are brought on-line until 14:00 following a significant drop in area load coincident with an increase in area generation. The operator then rapidly brings 5 additional capacitor banks on-line in the next twenty minutes. The BBN undervoltage indication ceases with the addition of the seventh capacitor bank but resumes again until the ninth capacitor bank is brought on-line. The BBN indications and associated recommendations for additional capacitor banks appear very reasonable in light of the need for additional reactive power resources (MVAR values at or above zero) as area generation is ramping up.

Reactive power levels recover with the addition of the eighth and ninth capacitor banks (MVAR indicates negative) and the BBN begins to indicate that a high voltage condition is probable (recommending that the ninth capacitor bank be brought off-line). The fact that the BBN indicates an undervoltage condition (recommending that the capacitor bank be brought back on-line) with the ninth capacitor bank is briefly taken off-line at 15:52 is an indication that the actual requirement may fall somewhere between 8 and 9 capacitor banks.

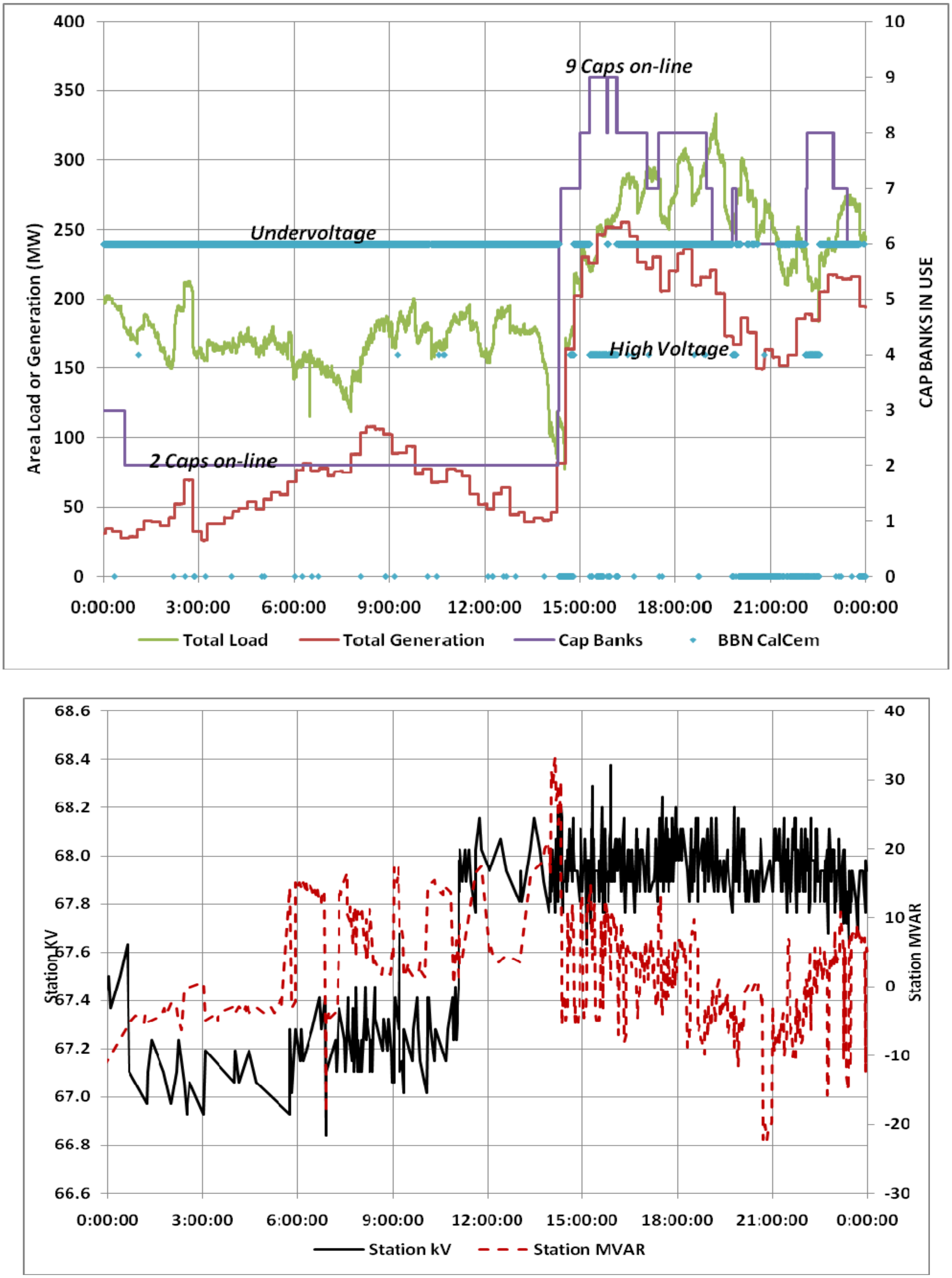


Figure 9 December 19, 2010 – Parametric Comparison

It is important to note that the agent-based system has the ability to modify the reactive power output of the storage unit while still operating it in frequency regulation mode (Hybrid operation). Thus during periods when the BBN is indicating a probable high voltage condition it is also temporarily (for instances lasting less than 5 minutes) causing the storage system to modify its reactive power output. Having the ability to control the storage system in this fashion can therefore provide more dynamic and finer control of system reactive power.

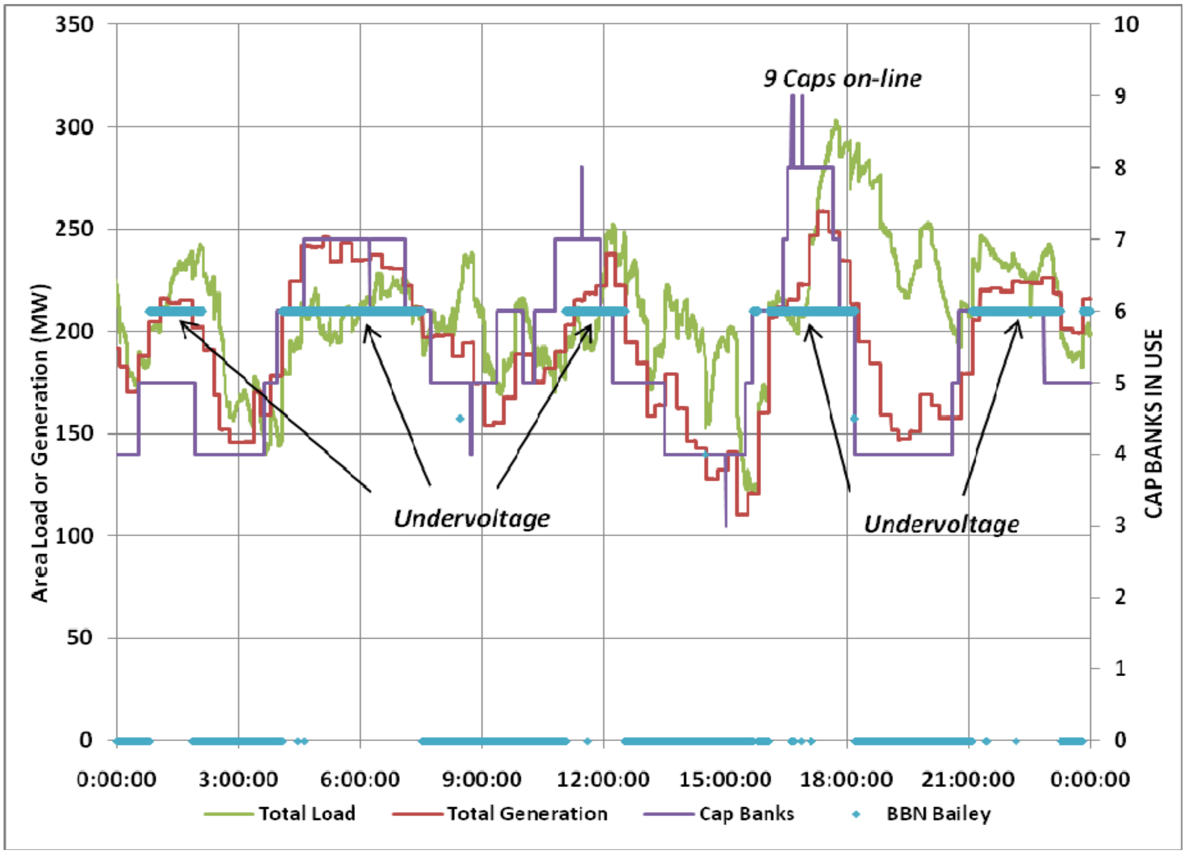
January 30, 2011

The events on January 30th provide insight on the performance of the STA BBNs relative to one another. Figure 10 contains plots of multiple parameters of interest for both the Antelope and Bailey BBN including the status of the capacitor banks, area load, area generation and BBN outputs pertaining to under, high, multiple undervoltage, multiple high voltage and line overloads. The Cal Cement BBN (not shown) was very similar to Antelope.

In general, the BBNs are consistent with one another with indications that undervoltage is probable during periods when area generation is in transition, and more specifically, when area load and area generation are close in magnitude. As shown previously, these periods require the most reactive power resources and are evidenced by increased capacitor bank activity. In the case of the Antelope BBN (bottom plot), the undervoltage indications correspond with operator operation of capacitor banks during much of the day (04:00 – 19:00). Recommendations associated with the Antelope BBN are in line with operator actions with the exception of minor variations in the timing (i.e., bring the bank on slightly sooner and remove it slightly later). A few very brief indications of high voltage also occurred, which appear to be transients related to bringing a capacitor bank on and off line. It should be noted that delays (see Section 0) built into the system would prevent these brief indications from generating any recommended actions.

In the case of the Bailey BBN, the undervoltage indications are much longer in duration and rather than differing in the timing of capacitor bank operation, instead recommends that an additional capacitor bank be placed in service during these same time periods. In addition, earlier in the day (01:00 – 02:00) the Bailey BBN was indicating undervoltage with a recommendation for an additional capacitor bank when Antelope BBN was indicating normal operation. Late in the day (21:00 – 22:00), both the Antelope and Bailey BBN were indicating the need for an additional capacitor bank.

The behavior of the BBNs on this day are a reminder that each BBN is trained separately, first, using the results of the load flow modeling and later via use of actual data. The relationships that each BBN encode within their connection weights are therefore tailored to their local environment. While the operators respond to local events (i.e., a specific line or bus event, etc.), in general, their control actions are based on the voltage and reactive power levels at the key substation. While this approach is effective in most circumstances, it does result in behavior that may differ from BBN recommendations, which have more local content.



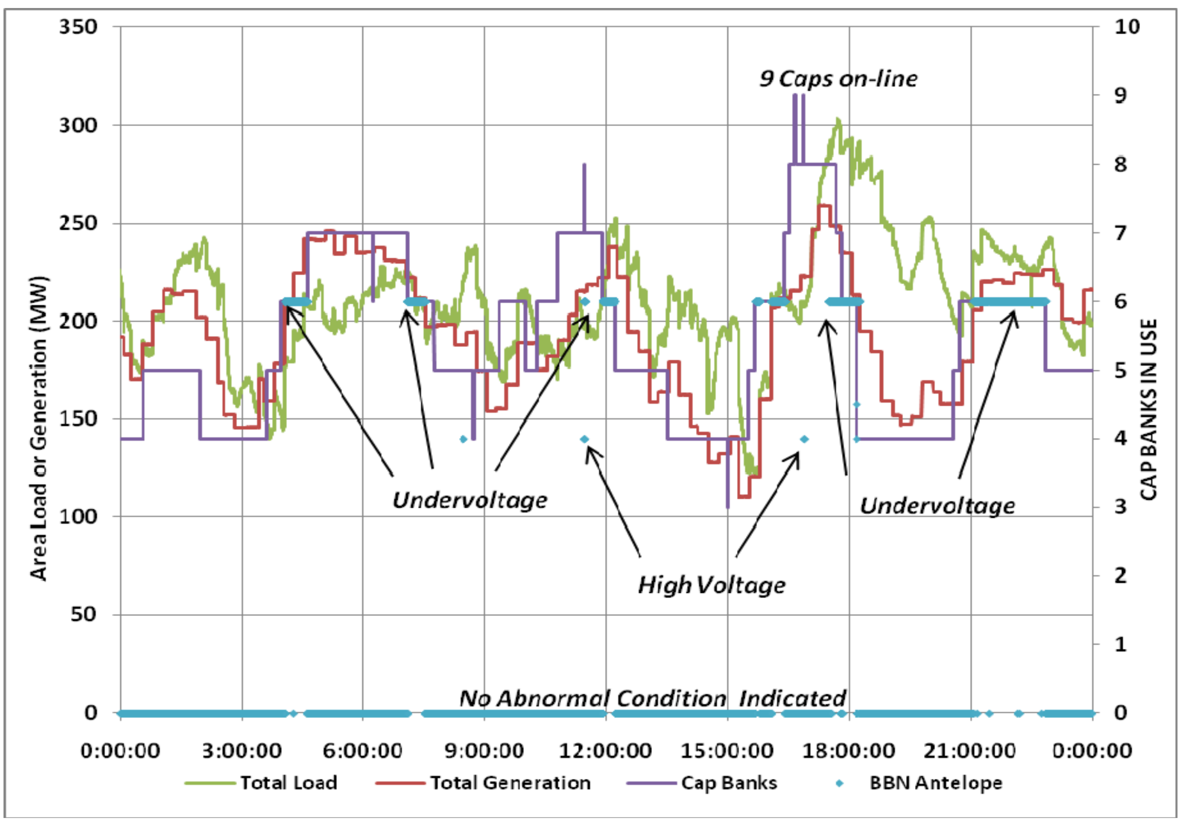


Figure 10 January 30, 2011 – Parametric Comparison

January 31, 2011

Operation on this date is illustrative of other time periods during the demonstration when operators were initiating actions while the agent-based system was indicating that the probability of an abnormal condition, warranting action, was low. Figure 11 contains plots of multiple parameters of interest including the status of the capacitor banks, area load, area generation and Antelope BBN outputs pertaining to under, high, multiple undervoltage, multiple high voltage and line overloads. As the figure shows, the operators correctly work to maintain adequate area reactive power resources (MVAR) by bringing capacitor banks on- and off-line at various times during the day. This is evidenced by operation of capacitor banks early in the day (prior to 04:30) and later in the day (after 14:30) when excess station reactive power levels are low (near zero or positive). With the exception of very brief periods (00:40, 14:30, 18:30), the BBN was indicating that the probability of an abnormal condition was low and that no action was needed.

This apparent disparity between BBN and operator performance illustrates the shortcoming of the BBN configuration and training as it relates to the range of operation that was experienced during the demonstration period. As noted previously, in Section 4.4.4, the BBN operates using discrete input states, which were developed based on load-flow modeling results. The apparent lack of BBN activity on January 31st is the result of limitations associated with the power load flow modeling and the resulting “binning” of the BBN input states. This limitation becomes apparent when the actual BBN input states are examined. Figure 12 contains the same parametric plot (top plot) of BBN inputs as was previously shown in Figure 11; these parameters represent the “raw” input data prior to its translation into BBN input states. The bottom graph in Figure 12 shows these same input states after processing into BBN input states. As the figure shows, the processed BBN input states are relatively constant during much of the day, with area load changing between the two lowest input states, and area generation changing between the three lowest generation states. And, while the actual data would indicate that the area load and generation levels are nearly equal in magnitude at different times during the day (an indication that action is likely needed) that this is not the case for the filtered data. So, it is apparent that the BBN was behaving appropriately based on its configuration and training.

The lack of activity in the BBN is the result of the lack of activity in its input states, which in turn, is a consequence of the limited modeling and training that was performed. Additional analysis and/or modeling that covered the full range of operation would provide additional resolution in the input states and allow the BBN to encode the needed probabilistic relationships through the full range of operation.

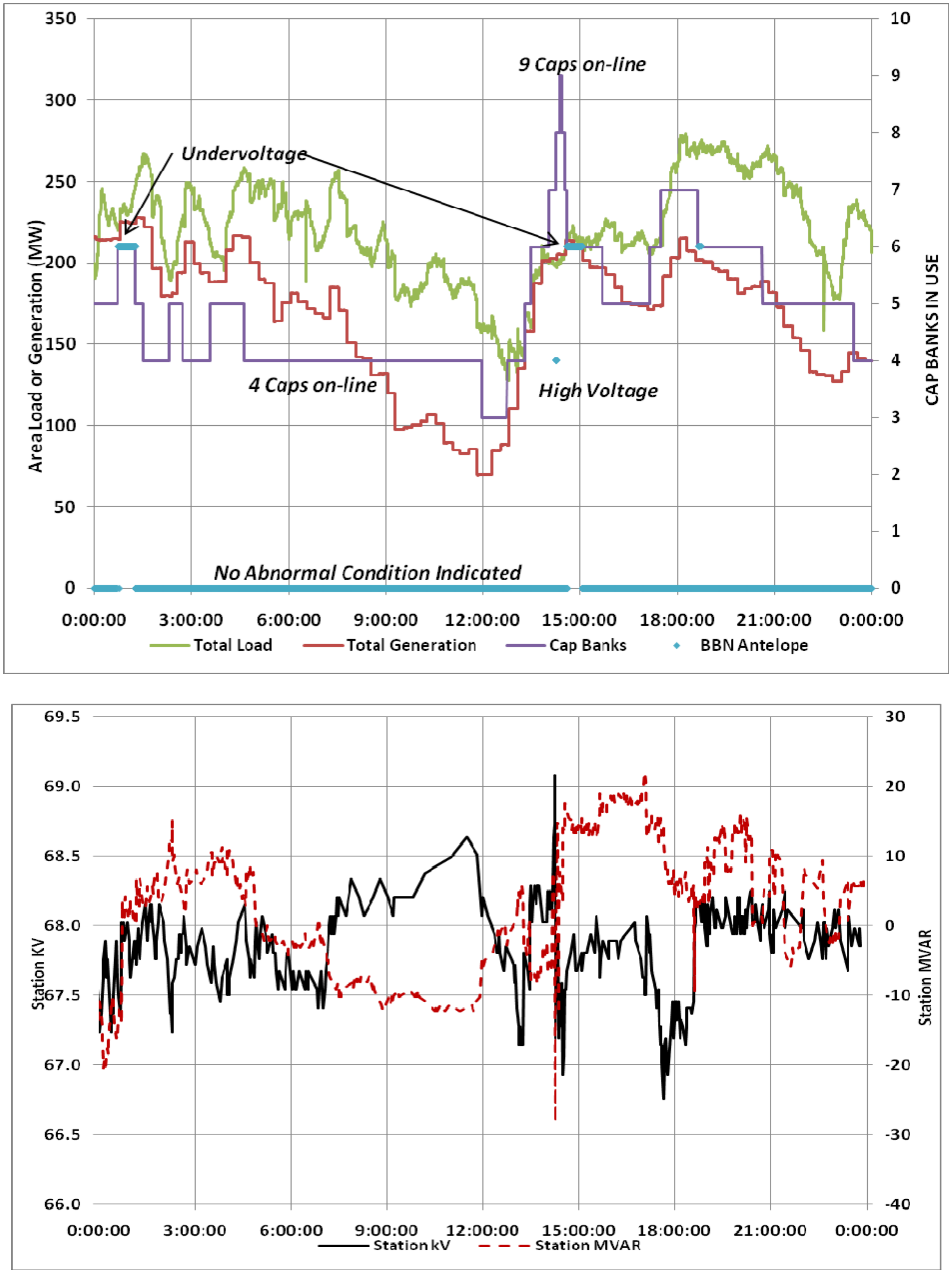
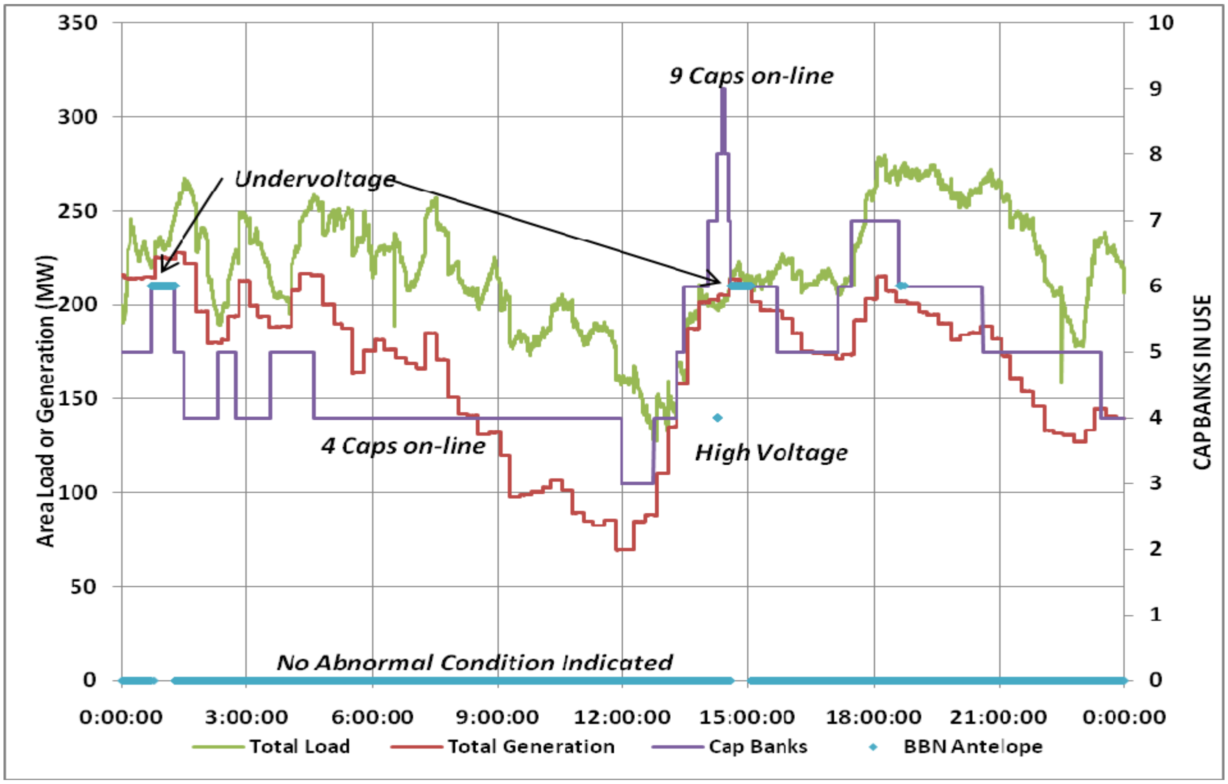


Figure 11 January 31, 2011 – Parametric Comparison



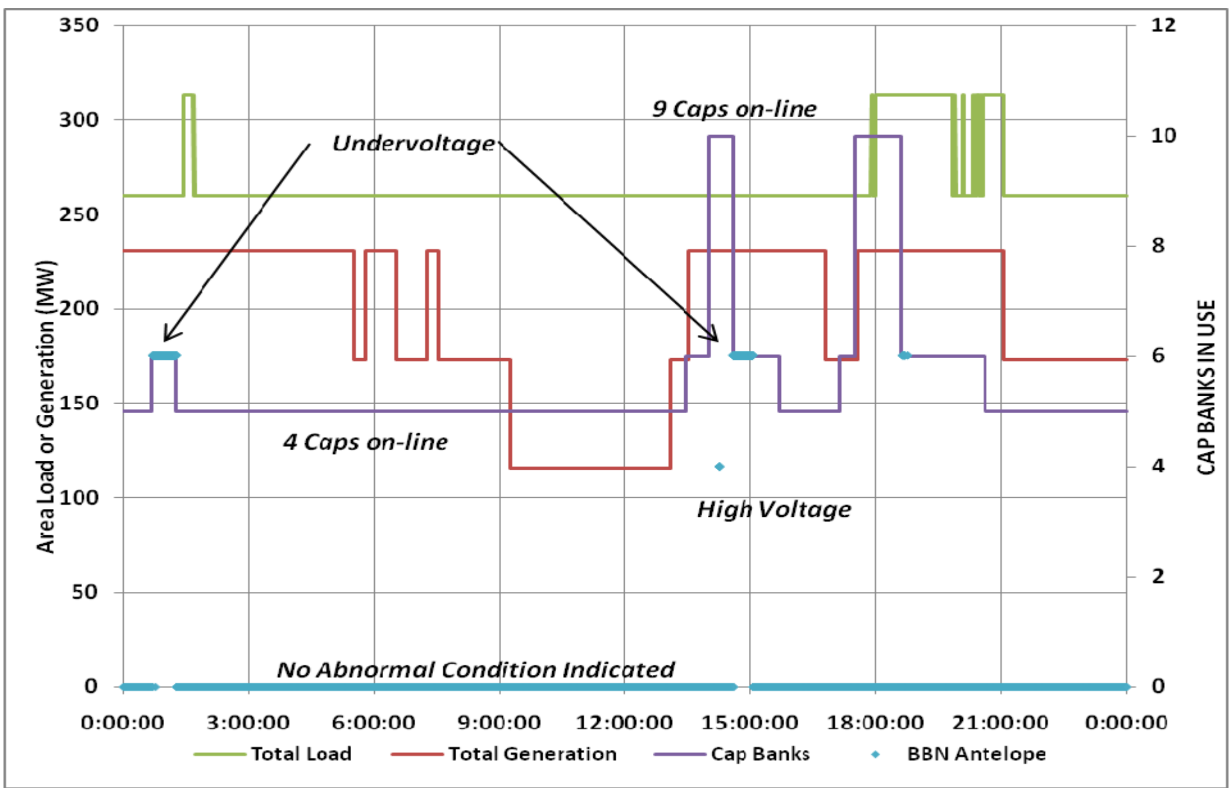


Figure 12 January 31, 2011 – Filtered Parametric Comparison

4.4.7. Demonstration Test Summary

The demonstration test period officially began on December 1, 2010 at 4 p.m. and ended on February 11, 2011 at 5 p.m. Contractually, the project initially required a one month demonstration period but this period was eventually extended to a total of seventy-three days in order to provide project participants with additional time to observe system operation.

Overall Performance / Operation

During the demonstration period, data were collected at 5 second intervals over the 1753 hour period, representing a total of 1,244,880 five second intervals. Some loss of data occurred as a result of server outages, consisting primarily of a multi-day outage that occurred at the start of the New Year. Overall, a data collection rate of 95.7% was achieved during the demonstration period.

Total generation and load levels were monitored for the area served by the Tehachapi sub transmission system. Both area load and generation varied significantly during the demonstration period. Wind generation peaked at similar levels each month with December showing the highest overall generation levels during the demonstration. Wind generation levels, when compared with the region's 349 MW installed capacity, were relatively low during the demonstration period. Wind generation was below 20 MW 55% of the time and exceeded 200 MW just 5.5% of the time.

Capacitor bank operation is the operator's principal means of dealing with increased wind generation in the Tehachapi region. Increased use of capacitor banks to enhance system reactive power capabilities in order to control system voltages is an indication that wind generation levels are impacting system operation. Data collected by the agents showed that there were six or fewer of the thirteen total available capacitor banks on-line over 90% of the time. The need for relatively few capacitor banks during the vast majority of the time is further evidence of the relatively "mild" wind generation levels that were experienced during the demonstration period. Further review shows that there were twenty-two days during the demonstration period when more than 6 capacitor banks were in use.

With the exception of the Storage GRA, agent availability exceeded 99% during the demonstration period. Agent availability was affected by a number of factors. The primary factors affecting agent availability were messaging issues associated with use of a centralized, server based messaging system and errors associated with retrieval of SCE SCADA data. A onetime data server outage and cell modem based communication outages (source of Storage GRA unavailability) were responsible for the majority of system downtime. It is important to note that both of these factors would not be evident if the system had been fully integrated into the SCE network. Full integration would allow each the three STAs (Antelope, Bailey and Cal Cement) to collect sensor information directly as well as communicate with one another via the

SCE secure network. Elimination of these issues would therefore greatly enhance agent availability.

Each STA utilized a Bayesian Belief Network (BBN) to detect and predict abnormal system conditions. Each BBN was initially configured with the help of power load-flow modeling conducted by Quanta Technology. The BBNs operated successfully during the demonstration period. BBN training was updated using actual data a total of 14 times during the demonstration in order to accommodate operating scenarios that had not previously been encountered or modeled. Twelve of the training events were associated with the Antelope and Cal Cement STAs, and only two were associated with the Bailey STA. It is important to note that encountering new combinations of input states did not cause the BBN to stop functioning or impact other agent functionality. In all instances, the duration of these events was short lived and the BBN resumed normal operation as soon as the BBN encountered known state conditions.

There were no instances (an instance is one 5 second record) of BBN prediction/detection of Very High Voltage or either of the N-1 related effects during the demonstration period. This is not unexpected in that these represent serious and uncommon operating issues. A very limited number of Line Overload instances were recorded, primarily in January. But the duration of these instances were less than eight minutes total in December and thirty-one minutes in January.

Undervoltage events in December were primarily the result of one or more sensors that were isolated when operators removed associated lines or buses from service. A software change in early January corrected this situation as evidenced by the decrease in January and February. Remaining instances of undervoltage occurred during periods of increasing wind generation and these events are discussed in more detail in Section 3. Instances of High Voltage were evident in all three months. High Voltage events were often associated with the 12 kV buses. In early January, SCE operating personnel confirmed that it was normal for some of the 12 kV buses to operate at or above the 5% limit. Additionally, it was learned that some of the 66 kV buses also have a tendency to operate near the limit. For this reason, the High Voltage limit was increased for both the 66 kV and 12 kV buses during January. It should also be noted that use of fixed thresholds was also a convenience of the demonstration project. A commercial system could easily track and learn what is "normal" for each bus thus eliminating this type of "false" alarm.

Early in the demonstration period it was discovered that one of the high voltage indications was the result of a faulty bus voltage sensor, which had failed leaving a constant indication of a high voltage condition. An alternate eDNA sensor point was not available so the affected agent simply entered the BBN input associated with this sensor as "unknown". The BBN was then able to continue to operate normally using the remaining "known" inputs. This demonstrated a very powerful feature of the BBN; the ability to operate in the absence of data or with uncertain data. In this case, discovery of the faulty sensor and reprogramming of the agent was done offline but this could easily be implemented as an automated process in a commercial system.

The storage system operated under Storage GRA control continuously during the demonstration period. The storage system operated in Frequency Regulation mode 97% of the time with just 3% of overall operation in Hybrid mode (frequency regulation with modified reactive power output).

Specific Performance / Operation

The BBN performed well given the limitations of the configuration and training efforts. BBN performance was optimized over a limited range specific to operation when curtailment of area generation was most likely. BBN performance was optimal within this training range, which consisted of Tehachapi area sub transmission system operation with:

- 5 or more capacitor banks on-line;
- 260 MW or more of area load; and
- 116 MW or more of area generation.

BBN operation within this range was characterized by detection of system conditions either in step with, or in advance of operator actions. And, while additional analysis is needed, results appear to indicate that dynamic operation of the system during a known curtailment period (December 10-11, 2010) could have resulted in a significantly shorter overall curtailment period. The agent-based system demonstrated that it could also dynamically control the flywheel storage system in response to Tehachapi area conditions. The Storage GRA successfully retasked the storage system from its normal operating mode, Frequency Regulation, to Hybrid mode consisting of a power output that supported Frequency Regulation with reactive power output modified to support local reactive power requirements.

The BBN was able to operate successfully outside of the original configuration range as a result of BBN training using data collected prior to and during the demonstration period (as opposed to simulated data created using the power load flow model). However, operation was less consistent over this wider range resulting in periods when the BBN appeared unresponsive to changes in load, generation or changes in capacitor status. This unresponsive behavior was related to the configuration of the BBN itself (number and spacing of input states), which caused the BBN to be insensitive to some changes in load, generation and capacitor status. For instance, the BBN was configured such that the BBN capacitor bank status input would be set to "5" whenever 5 or fewer capacitor banks were on-line. Thus the BBN was unable to differentiate between operation with 2, 3, 4 or 5 capacitor banks on-line. Similarly, the BBN was unable to differentiate between various generation levels below 116 MW and area load levels below 260 MW. Inconsistent operation at these lower levels was the result of both "in sensitivity" (inability to detect change) and an inability to establish the probabilistic relationships between discrete input states in these lower ranges (since only one input state existed). Additional modeling and associated statistical analysis is therefore needed in order to configure and train the BBN to operate consistently across the full range of potential sub transmission system operation. Automated training or "learning" could also be implemented in order to compensate for changing operating conditions.

The agent based system utilized alarm/action thresholds that were a fixed percentage based on a single nominal voltage (66 kV or 12 kV) or line load. Use of fixed thresholds and nominal voltages was determined to be too simplistic resulting in system operation with some buses perpetually in "alarm". This was remedied by increasing the threshold, which also resulted in some loss of overall sensitivity. Performance could be improved by continuously monitoring individual buses to establish and update "normal" operating levels in lieu of the use of a fixed nominal voltage. This modification while outside of the scope of the current project could be easily implemented in a commercial system.

5. CONCLUSIONS AND RECOMMENDATIONS

The overall project objective was to demonstrate that applying agent technology could expand the potential delivery of renewable energy and use of existing transmission facilities for the benefit of the consumers in California. More specifically, the project objective was to address delivery of wind generation resources located in the Tehachapi wind resource area in California. The complexity of both the problem and the potential solution dictated a two-phase approach. In the first phase, the problem was characterized along with the requirements of the agent-based system that could address the problem. The second project phase then provided for implementation and demonstration testing of the agent-based system.

The Phase 1 effort was successful in that the Project Team, with input from the Stakeholder's Working Group, was able to:

- Identify a project "target" with a quantifiable economic benefit and that appeared "doable" given the limited scope and resources of the project. An existing SCE operating order that provides for Tehachapi area wind generation curtailments due to thermal overload of a 66 kV sub transmission system path in the area was identified as the best near-term opportunity.
- Develop a System Requirements and Test Plan that identified more specific system requirements.
- Conduct feasibility testing of AESC agent technology on BPL Global's CentryWCC hardware platform confirming that operation of agents on the WCC was feasible.
- Define a multi-agent based system (MAS) that utilizes a Bayesian Belief Network (BBN) to monitor and evaluate the status of the 66 kV sub transmission system using a combination of SCE and CAISO provided data.
- Refurbish and successfully test the Beacon Power flywheel storage system in preparation for installation and operation during the demonstration period.

The Project's Phase 2 effort began with configuration and development of the agent-based system and associated hardware (Task 8). During this task, AESC, Beacon Power, and BPL Global confirmed the ability of the agents to successfully:

- Gather and process the needed SCE SCADA data,
- Communicate with one another to coordinate their actions
- Recommend action related to capacitor bank & storage system operation,
- Generate a frequency regulation signal using the Cal ISO ACE and convert this to the necessary power command for use by the Beacon Flywheel storage system.
- Communicate with the Beacon Power flywheel storage system with testing to confirm that the flywheel storage unit accepted agent generated commands for charging and discharging of energy along with absorption or injection of reactive power.

In addition, AESC and BPL Global successfully configured and tested the database and associated web-based user interface needed for storage and display of data and results during the demonstration period.

The demonstration test period (Task 9) officially began on December 1, 2010 at 4 p.m. and ended on February 11, 2011 at 5 p.m. Overall, the agent-based system performed well during the demonstration period, during which:

- Data were collected at 5 second intervals over the 1753 hour period, representing a total of 1,244,880 five second intervals with an overall data collection rate of 95.7%.

- Wind generation levels, when compared with the region's 349 MW installed capacity, were relatively low during much of the demonstration period, which required minimal use of the area capacitor bank resources (six or fewer of the thirteen total available capacitor banks were on-line over 90% of the time).

- Overall, agent availability exceeded 99% during the demonstration period with the exception of the Storage GRA, which experienced lower availability due to outages of the cell modem based communications (unique to Storage GRA). Other than the cell modem issues, the primary factors affecting agent availability were messaging issues associated with use of a centralized server-based messaging system and errors associated with retrieval of SCE SCADA data. It is important to note that both of these factors would not be evident with a system that had been fully integrated into the SCE network.

- The Bayesian Belief Networks (BBN) used by the agents to detect and predict abnormal system conditions operated successfully during the demonstration period. These BBNs were initially configured with the help of simulated sub transmission system operating data developed using the output of a power load-flow model developed by the Cal ISO and refined by Quanta Technology. Investigation of specific events that occurred during the demonstration period showed that the BBN performed well given the limitations of the configuration and training efforts. BBN performance was optimized over a limited range specific to operation when curtailment of area generation was most likely. BBN operation within this range was characterized by detection of system conditions either in step with, or in advance of operator actions. And, while additional analysis is needed, results appear to indicate that dynamic operation of the system during a known curtailment period (December 10-11, 2010) could have resulted in a significantly shorter overall curtailment period.

- Two powerful BBN capabilities were also demonstrated; first, was ability of the BBN to "learn" from actual operating data and the second was the ability to operate in the presence of unknown data.

- The BBN was able to operate successfully outside of the original configuration range as a result of BBN training using data collected prior to and during the demonstration period (as opposed to simulated data created using the power load flow model). However, BBN performance outside of the original configuration range was inconsistent. Additional modeling and associated statistical analysis is needed in order to configure and train the BBN to operate consistently across the full range of potential sub transmission system operation.

- The Beacon Power storage system operated under Storage GRA control continuously during the demonstration period. The storage system operated in Frequency Regulation mode 97% of the time with just 3% of overall operation in Hybrid mode (frequency regulation with modified reactive power output at the request of the STAs).

To summarize, the CEC PIER project was highly successful. During the project, the project team successfully identified a significant opportunity to demonstrate the feasibility of the agent-based approach. The system that was subsequently configured and implemented performed well during the demonstration although it was limited by the boundaries of the initial modeling and configuration effort.

The following additional effort is recommended in order to more fully demonstrate the concept and prepare it for commercial application.

- Complete the effort to fully integrate the agent-based system into the SCE communication network in order to enhance system reliability. This would eliminate the need for cell modem based communication as well as the need for eDNA based SCADA data retrieval.

- Complete the effort to implement a true Peer-to-Peer communication capability in order to eliminate the need for centralized server-based communications.

- Enhance agent processing capabilities to include monitoring of sensor data quality in order to both establish a “normal” baseline for all inputs as well as identify and deal with bad or unknown sensor data.

- Implement automated BBN training in order to accommodate changing area conditions.

- Review all communication protocols for compliance with newly emerging IEEE standards such as IEEE 61850 and IEEE 1613, which are applicable to substation based networks and communication devices.

GLOSSARY

Critical energy infrastructure information (CEII).

California energy commission (energy commission)

Southern California Edison (SCE)

Stakeholder Working Group (SWG)

Area Control Error (ACE)

Positive Sequence Load Flow (PSLF)

Electronics Conversion Module (ECM)

Bayesian Belief Network (BBN)

BPL Global's Centry$_{WCC}$ Web Communication Controller (WCC)

APPENDIX A FLYWHEEL STORAGE UNIT UPGRADE

The original goal of Task 6 was to rebuild and upgrade the Flywheel storage system, purchased previously by the Commission, and used on a demonstration project at the Distributed Utility Integration Test facility. The original storage system consisted of seven Gen 3 flywheel units each with a capacity of 15 kW and each with its own electronic control unit. Early on in the project Beacon Power proposed to substitute a single Gen 4 production unit having an equivalent storage capacity for the refurbished Gen 3 units since this would allow the project to demonstrate a production level unit instead of storage units that were not commercially available. Additionally, the Gen 4 Electronics Conversion Module (ECM) unit had reactive power capabilities not available from the existing Gen 3 units. This substitution was approved and the task was revised to include removal of the existing Gen 3 Flywheels from the enclosure.

A.1. Installation of a 100 kW ECM

- Update all ancillary equipment required to run the system;
- Refurbishment and test of a Gen 4 (25kWh/100kW) flywheel storage unit to ensure that it meets operational requirements including the ability to store and discharge 100 kW for 15 minutes.;
- Verify system ability to provide inductive/capacitive reactive power up to 100 kVAR.; and
- Prepare a test report and associated photos documenting the effort and performance of rebuilt components and the fully assembled system.

A.2. Flywheel Storage System Test

Upon completing the refurbishment and installation tasks, Beacon Power Corporation personnel conducted a performance test of the Gen 4 flywheel storage system at their Massachusetts headquarters. The purpose of this test was to document the actual performance of the integrated system consisting of the Tehachapi Control Enclosure, Flywheel and interconnecting gear. Material for the following subsections was extracted directly from, or is paraphrased from, Beacon Power's acceptance test document, Tehachapi.Flywheel.Acceptance.Rev.doc (dated 3/10/2010).

A.3. System Shakedown

Prior to initiating the performance test the necessary sub system connections, settings and operations were verified. This shakedown encompassed the following:

- Vacuum control and monitoring
- Process cooling flow balancing and leak check
- Cooling equipment setup and operation

- Dust Control System operation
- Network communications
- System level fault monitoring and reporting
- Energy measurement configuration and operation
- Flywheel system acceptance testing
- Power and signal electrical connection verification

A.4. System Response Test – Tracking a Regulation Signal

Following shakedown, the flywheel was pre-charged to an initial speed of 5,000 rpm. A simulated frequency regulation signal was then provided to the flywheel control consisting of the following four parts:

1. **Stress test** – repetitively go to 100 kW and -100 kW holding for a minute or so at each stop.
2. **Follow a signal** – This is just a random excerpt from a modified ACE signal
3. **Full charge** – Get the Flywheel charged up to 15000 RPM
4. **Full discharge** – Discharge the FW to CUTOFF speed (8000 RPM)

The results of this test are shown in Figure A1 below.

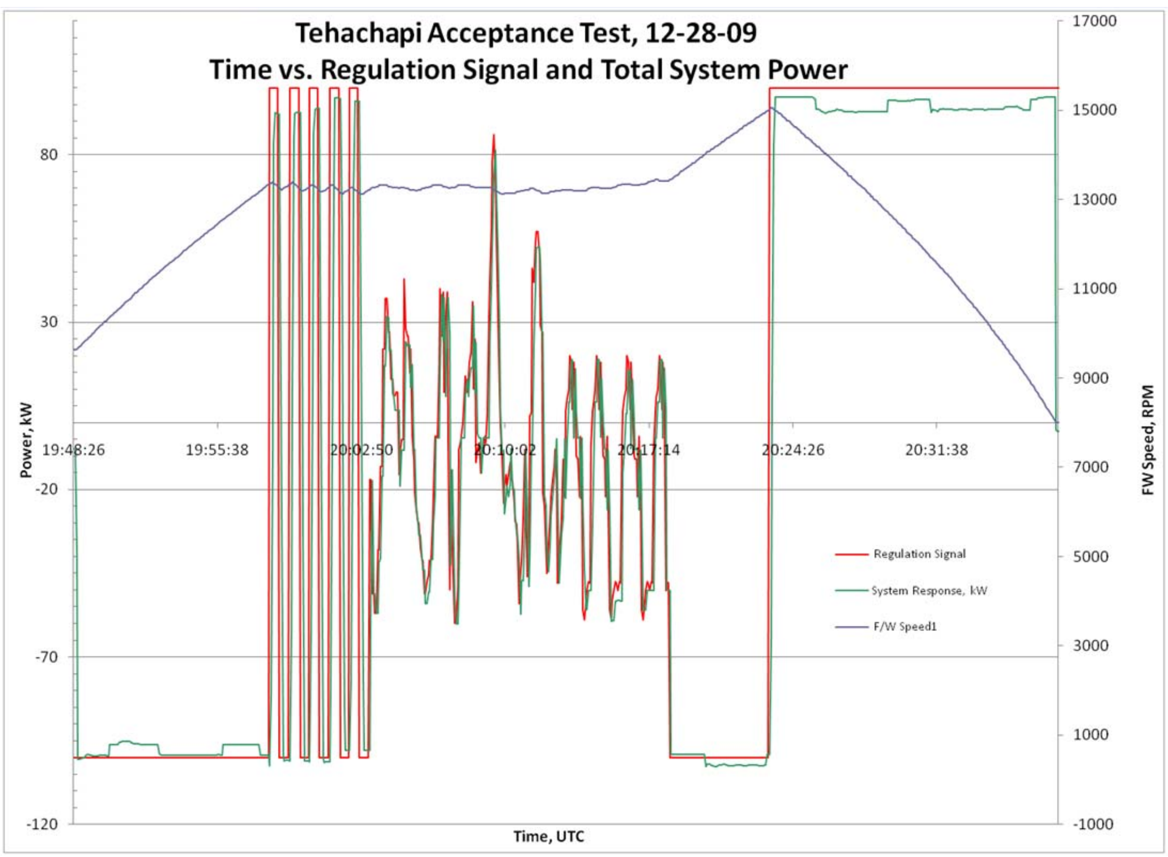


Figure A1. Actual Response to the Test Regulation Signal

- There is up to 4 seconds of dead band time due to the 4 second sample rate of the data system. This affects the response time.

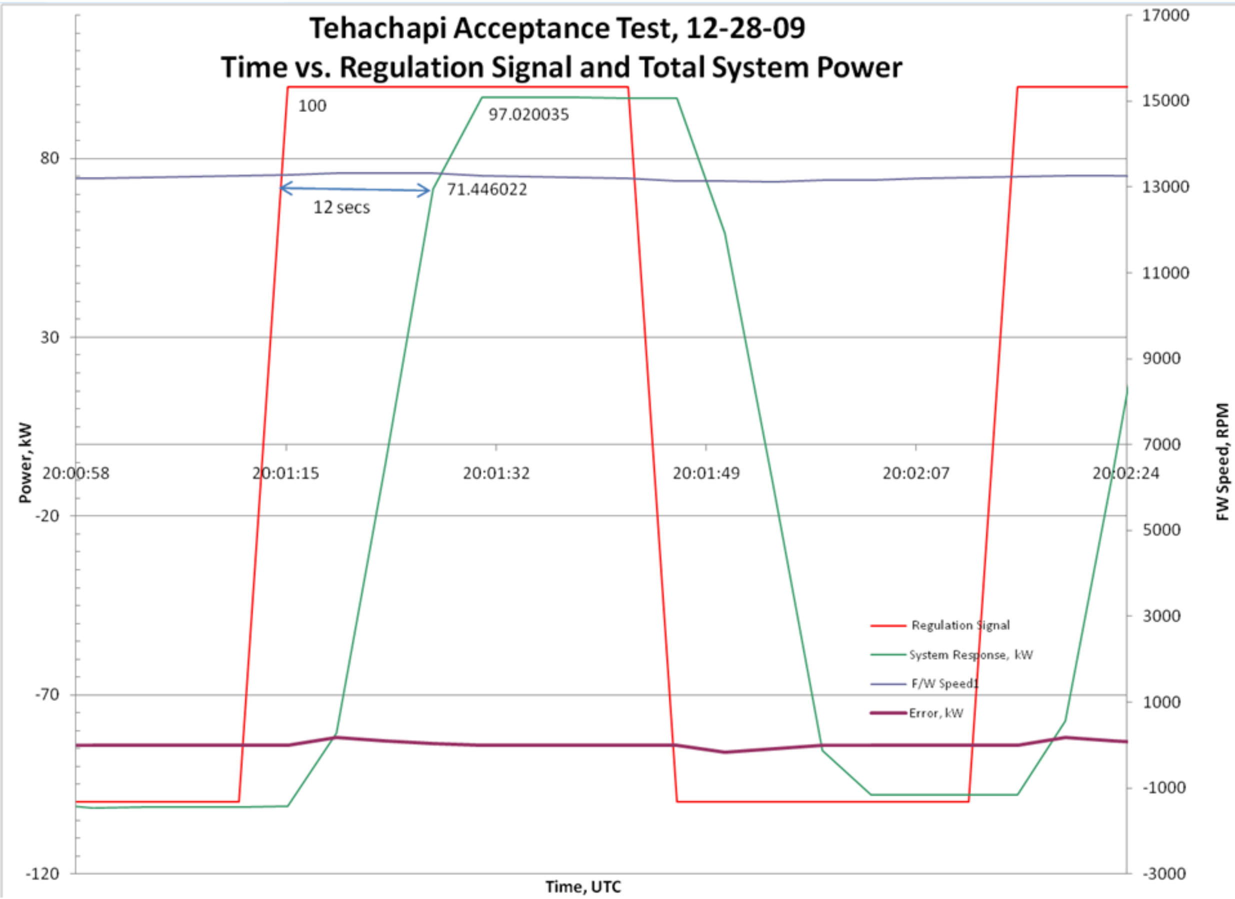


Figure A2. 12 Sec Settling Time, 2.8 % SS Error (typical for stress test phase)

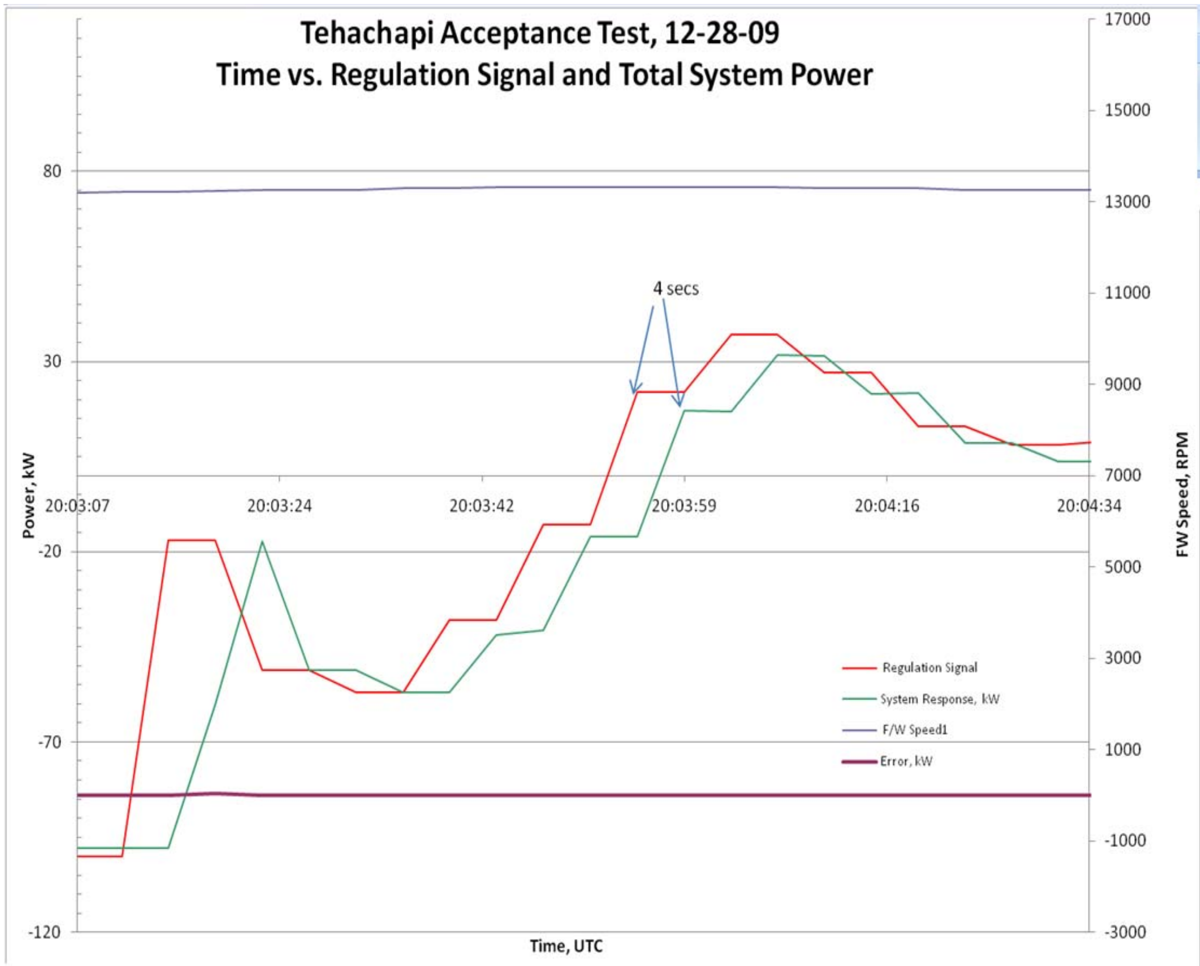


Figure A3. System Response: 0 to 5 % SS Error, 4 Sec Settling Time

Figures A2 and A3 above are plots of the system response compared to the requested signal. In these instances, system response was within 5% SS Error and well under 15 sec settling time. Overall, we calculated that the SS error (including the difference during settling) averages about 15% and at steady state, the error averages 5.5%, including plant load variation.

A.5. Additional Testing

Table A1 summarizes the additional tests that were successfully conducted on the Beacon flywheel storage system.

Table A1. Additional Testing Summary

Test Name	Purpose
Reactive Power Demonstration	Demonstrate leading and lagging reactive power settings and specifically to show that when real and reactive power are equal the measured phase is 45 + /- 5 degrees.
Fault Tests – Cause faults and demonstrate text messages	Show that when a fault occurs a test message is sent to the Beacon On-Call phone
Voltage Mode Tests (Grid Power Outage Tests)	
Manual Voltage Mode	This verifies that the main contactor opens and system can be manually put into voltage mode where the Flywheel and ECM become the voltage source for the system secondary loads such as the cooling systems.
Auto Voltage Mode	The system will open the main contactor, the flywheel will fault, then the Beacon Master Controller (BMC) will clear the faults and put ECM/Flywheel into voltage mode. The flywheel will support the loads until its speed is down to ~ 3500 RPM at which time cooling is not required. As soon as the power goes out a text message will go to the Beacon On-Call phone.

A.6. Flywheel Storage System Testing Summary

All tests were successful demonstrating that:

- The flywheel could follow a fast changing regulation signal, and store enough energy to support more than 15 minutes of full 100 kW power when charging or discharging.
- The ability to control reactive current with or without the flow of real current.
- The system responds correctly when a fault occurs.
- The system responds correctly when it encounters a Grid Power Outage.