

Energy Storage for Wind Integration, a Conceptual Roadmap for California

Edward Cazalet, *MegaWatt Storage Farms, Inc.*, Charles Vartanian, *Southern California Edison*,
Stephanie Hamilton, *Southern California Edison*, Benjamin Coalson, *Southern California Edison*

Abstract— This paper presents a conceptual policy-level roadmap for promoting beneficial participation of energy storage to help integrate intermittent wind generation. The California wholesale electric market operated by the California Independent System Operator (CAISO) provides both a market structure and an electrical system model which the authors describe and extend upon to explore 1) desirable market and regulatory structures to incent bulk energy storage, and 2) potential system performance benefits from bulk energy storage. Specific market and regulatory enhancements are identified, relative to existing rules in California. This paper also presents illustrative electrical simulation results to demonstrate the potential operational benefits of energy storage on an electrical transmission system that hosts a significant amount of wind generation capacity. For the system simulations, energy storage is applied to the modeled CAISO system to demonstrate incremental changes in system dynamic performance. North American Electric Reliability Corporation (NERC) planning criteria are used as a benchmark for assessment of simulated system performance in this paper.

Index Terms—Energy Storage, Wind Generation, Wind Integration, Intermittent Renewable Resources

I. INTRODUCTION

California leads the United States in the use of renewable resources to meet our aggregate electrical energy needs. In anticipation of maintaining this leadership, California, and in particular Southern California Edison anticipates a significant increase in the amount of wind generation to be added to our transmission system. Energy storage will be a key element of the future solution. Successful integration of significant additional renewable wind generation with energy storage presents market, regulatory and technical challenges.

The California Independent System Operator (CAISO) in November 2007 released its final study report on the integration of renewables on the California grid [1]. The report emphasizes the challenge of integrating about 6700 MW of wind to meet the goal of 20% renewables goal by 2010. The report did not address the much greater challenges in meeting higher renewable targets in the future.

The CAISO study concludes that “Additional storage capability would be of considerable benefit with the integration of large amounts of renewables, especially intermittent renewables”. The study recommends “a California ISO project for storage technology with the goal of

removing technical and economic barriers to the deployment of the technology.” The study further recommends “stakeholder meetings and workshops to explore market mechanisms for financially compensating storage facilities for the benefits they could provide such as regulation services, other ancillary services, transmission loading relief and voltage support. This is in addition to their ability to shift off-peak energy production to energy delivery on-peak.”

II. MARKET AND REGULATORY ROADMAP TO ENERGY STORAGE

Energy storage in the form of grid scale batteries is a fast responding, two-way resource that provides generation, load, and transmission-like services. Existing ISO markets for energy and ancillary services and longer term resource adequacy requirements may need enhancement to support the development of 1000s of MW clean bulk storage on the grid necessary to meet higher renewable targets.

A. Role of Battery Storage on the Grid

A well designed multi-MW battery storage system with four quadrant power electronics can address the increased CAISO needs for (1) ramping and energy balancing, (2) time shifting of wind generation to higher load periods, (3) over generation, (4) frequency regulation, (5) dynamic system support at the sub-second level, (6) system capacity, and (7) local reliability and power quality. Batteries may be the only technology that can provide all these capabilities from a single resource. Most thermal and other storage cannot respond as fast as batteries and flywheels. Flywheels typically have more limited storage duration and therefore may address only the short-term needs.

Battery storage is often viewed as relatively costly. However, cost needs to be evaluated in the context of alternatives such as new generation and transmission investments that can also be costly and much more difficult to site and build quickly. Battery storage can often be installed in urban locations with no air emissions and other significant impacts.

The full AC to AC cycle efficiency of some battery systems is 75% or higher, which is comparable to most pumped storage.

Battery storage is a readily available solution (RAS) that can be deployed incrementally and moved if necessary. Lead times for battery storage installation are short in comparison to most generation and transmission alternatives.

Battery storage is a clean technology that can enable the integration of more intermittent renewables on the grid without the need to build as much new thermal for backup or to retain as much existing thermal for the same purpose.

The CAISO report states “Market incentives may be required to secure the flexibility needed to operate the system with large amounts of renewables.” We now consider what incentives might be necessary and justified.

B. Spot Market Energy Pricing for Storage

In the CAISO markets there are few direct incentives for individual wind developers to install storage. Wind production credits and most wind contracts pay primarily for total MWh produced with little regard for when it is produced. CAISO market rules place the responsibility for managing the intermittency of wind and solar resources largely on the CAISO markets. Since the wind generation at dispersed wind farms connected by adequate transmission will typically have a lower overall volatility, it makes sense for the CAISO to assume responsibility for managing the overall volatility of the wind resources because it would be much more expensive for each wind farm to do so. End use customers for electricity ultimately bear the costs of wind integration assumed by the CAISO.

CASIO market clearing prices for energy services provide a primary economic driver for revenues to support the development and operation of grid connected storage to respond to the aggregate renewables intermittency. Increased penetration of intermittent renewables will increase the volatility of wind generation and energy prices. Increased energy price volatility will increase the opportunities for storage to buy energy when the price is low and sell it when the price is high. This will increase the revenues to storage projects and help to encourage their construction. However several market rules depress such energy storage revenues.

Energy prices in the CAISO are currently capped at \$400 per MWh, rising to \$1000 per MWh over the next few years. Caps on energy prices reduce the revenue opportunities for storage. Capacity payments to storage may be necessary to compensate for lost revenues from a higher price cap on energy.

CAISO market rules permit emergency out-of-market purchases at higher than the price cap depriving storage of the opportunity to get the same compensation. Also, CAISO markets pay thermal generation to start up and standby at minimum generation and thereby lower energy clearing prices and storage revenues. Currently storage would not be eligible for such start up payments and other compensation for storage availability may be necessary.

During over generation periods the CAISO report suggests that the CAISO may go also out-of-market to export over generation energy especially during the night, or require the wind plants to curtail output. Such actions are necessary, because the minimum price on energy has a floor of -\$30 per MWh. Forced curtailment of wind wastes wind generation

that might otherwise be stored for later use. A solution would be to change the price floor from -\$30 per MWh to a much lower limit.

It has been suggested that load following be established as a new ancillary service to assure that the CAISO has a sufficiently deep stack of 5-min energy bids to support renewables integration. Storage and generation would then be paid a market capacity price to submit sufficient buy and sell bids into the CAISO 5-min energy markets. This would provide an incentive for the deployment of storage and fast response generation.

C. Regulation Markets for Storage

The CAISO study estimates that 20% renewables will increase “Up Regulation” by 170 to 250 MW and “Down Regulation” by 100 MW to 500 MW. The study also estimates a need for an increase in regulation ramping rates.

Battery and flywheel storage are ideal for providing regulation services because they can immediately ramp to full charge or discharge whereas hydro and thermal generations have a much slower response time.

Faster response by storage to regulation signals should reduce the amount of regulation capacity that the CAISO would have to purchase. Such storage devices should therefore receive a higher price per MW for regulation services. Or alternatively, a new fast regulation service could be established

D. Forecasting Issues

Forecasting lead times and hence forecasting error could also be reduced by the use of fast responding storage to fully increment or decrement 5-min dispatches immediately after a forecast is published and the dispatch computed, with no ramping necessary. Storage should be compensated for this faster response and reduced forecast error.

E. Capacity and Local Reliability Benefits of Storage

If 1000s of MW of storage are developed on the grid to integrate higher levels of renewables, much of that storage could be located in urban areas close to the load. Local resource adequacy rules need to be developed to properly compensate different types of storage for the local and system capacity resources they provide. Additionally such storage can be integrated into a smart grid to provide additional reliability including “intentional islanding from the main grid” and power quality.

F. Grid Services Performance Contract

The CAISO report suggests “The first commercial deployments of new storage technology will probably need some type of a grid services performance contract to share the financial risk. This will help the owner/operator get financial backing for the new venture and a chance to validate the business economics of the system. Part of the services they provide could still be market based and part could be contract performance based similar to RMR contracts.” Such a

contract could also compensate storage for providing the system stability services addressed in the next section.

III. SYSTEM IMPACT EXAMPLE, WIND GENERATION WITH AND WITHOUT STORAGE

This paper illustrates one, of several, potential beneficial services that a large advanced energy storage system could provide to the integrated electrical system. The ability of energy storage to help match wind resource output to integrated transmission system need/demand over relatively longer timeframes (2 minutes to 24 hours) is simpler to understand and quantify over longer time periods. Several energy storage vendors and advocates posit that using a fast-acting (sub-second timeframe) grid-interface can allow an energy storage system to address additional system challenges¹. The relatively more time-aggressive and dynamic capabilities from energy storage systems are more difficult to understand and quantify through simple accounting of loads, resources, and delivery-system capacities. Additional analyses are needed to understand and define system dynamic requirements, and possible solutions. For this paper, we perform a simple exploratory study to demonstrate the modeling of dynamic power stability with and without energy storage.

Dynamic VAR devices including SVCs and STATCOMs already provide dynamic VARs (Q) for voltage stability through a variety of commercial products. Several advanced energy storage systems' addition of rapidly modulated real power MW (P) could provide the additional benefit of rotational, or *Power* stability. SCE has previously built and successfully demonstrated a true four-quadrant energy storage system with our former 10 MW Chino Battery that used advanced power electronics to modulate both Q and P for providing stability support to the grid. The basic technologies of energy storage and power electronics are not in question. What are of interest to the authors are the grid-side impacts of adding large scale energy storage, and its possible value to the future interconnected system.

The authors have used a simplified dynamic stability study; simplified form of study as would be performed for a transmission planning study. Our study evaluates P-stability impact to the integrated grid from addition of a large advanced energy storage system. The simulations and their results are discussed below.

A. P-Stability Study Scenario

The electrical system simulations described in this paper were conducted with GE PSLF/PSDS software, using a power flow case modified by SCE from CAISO's 2015 peak summer load forecast case. The 14,800-bus case models both single units and equivalents for nearly 3,000 wind turbine generators, representing a combined total of over 4,000 MW of new wind generation in the Tehachapi Mountains area of southern California. All projects that were present in SCE's interconnection queue before May 2006 were considered in

this case, as well as the transmission system upgrades required to implement the planned generation.

Area	Number of Generators	Total Generation (MW)	Total Load (MW)	Total Import (MW)	Total Losses (MW)
SCE Service Territory	433	19,482	28,514	9,808	776
WECC System	2,964	182,251	175,610	N/A	6,641

Table 1: System model key statistics by area

The modifications to this original transmission planning case developed by SCE with CAISO oversight were kept minimal and limited to addition of the modeled storage device and the interconnecting busses and transformers. FIGURE 1 illustrates the portion of the future-expanded Tehachapi system where we have modeled the storage device.

A set of dynamic simulation runs were executed for this outage scenario, with a range of energy storage system output capacities: 0 MW, 250 MW, 500 MW, and 750 MW. The modeling of the energy storage used available model components to simulate performance metrics and advanced energy storage system. Specifically,

REAL POWER MW, is modeled via a constant real power load whose magnitude is user-defined. Pre fault the desired power level is set at -50 MW (charging). Post-fault (10 cycles after transmission system fault is cleared) the desired power level is step-changed to the target output amount, +250 to +750 MW.

REACTIVE POWER MVAR is modeled using a combustion turbine-driven synchronous machine with +/- 50 MVAR reactive limits, and nominal 0 MW real power output. This machine is modeled in continuous operation pre- through post-fault. The dynamic VARs in this modeling implementation support local voltage as seen by the energy storage system. More aggressive scenarios are recommended for future studies to assess impact and ability to provide area-wide dynamic reactive support.

The system outage scenario used to demonstrate dynamic-P support is: N-1 loss of a single 230 kV transmission line that isolates and drops 700 MW of (future expected) wind generation in the Tehachapi area. The specific switching sequence modeled is:

- At 60 cycles (1 sec.): Fault FWINDTAP 230 kV bus
- At 65 Cycles: Clear Faulted Bus,
Drop FWINDTAP-TYPICAL1 230 kV line
- At 70 Cycles: Trip FUTWIND1 and FUTWIND2 gens
- At 70 Cycles: Step-Change battery output from -50 MW to target post-fault output (250, 500 or 750 MW).

(see Figure 1 for illustration of the relative placement of these referenced busses & devices)

¹ CAISO, p. 93-94

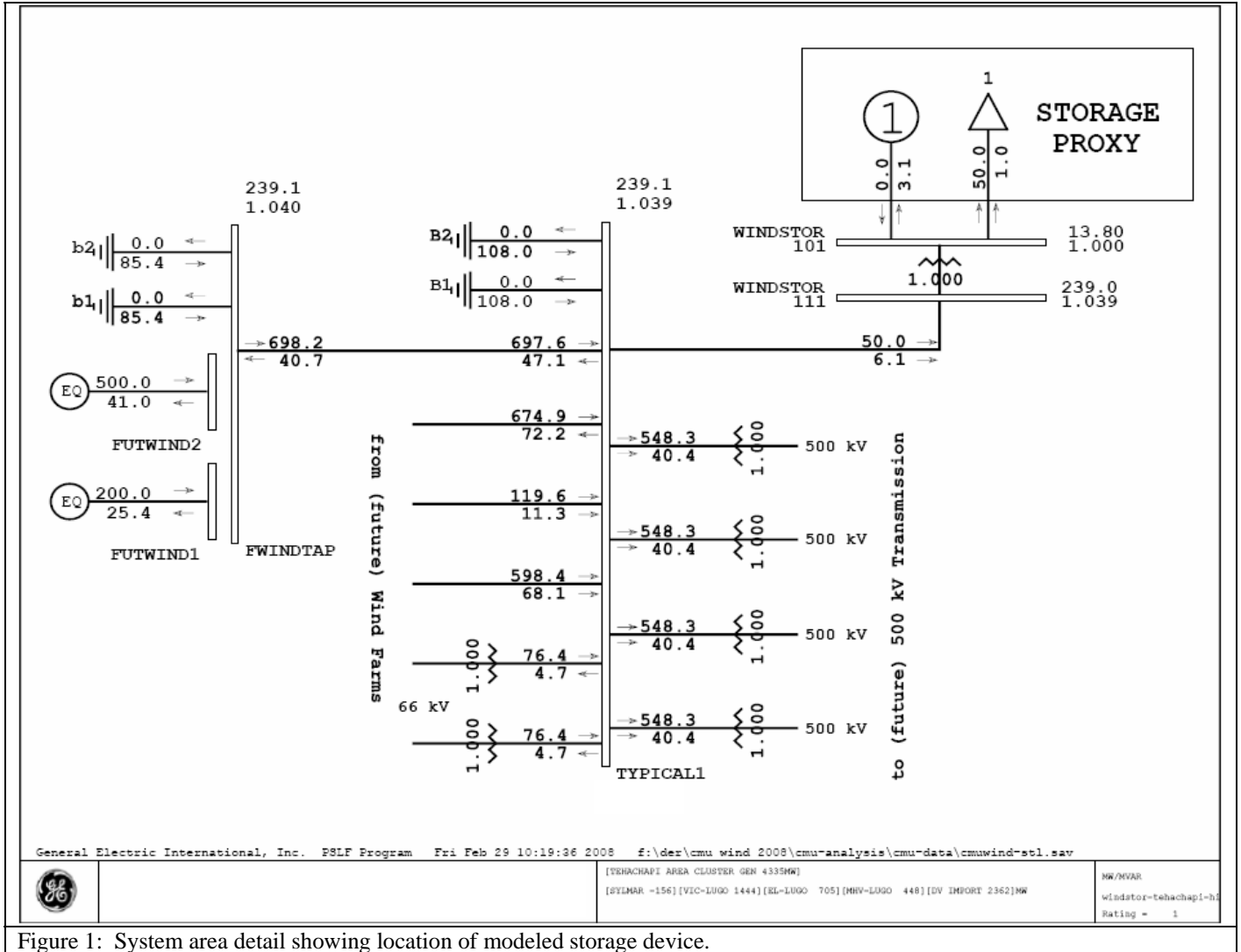


Figure 1: System area detail showing location of modeled storage device.

Use of this outage scenario starts to help address a key element of SCE’s comments to the draft CAISO Renewable Integration Report, i.e., the need to understand the system’s response to, and interaction with, large quantity of wind generation. The aggregate wide-area system response simulated and presented in this paper is the aggregate response of existing conventional technologies, responding to sudden loss of wind generation. This concern, explored at a very high level here, is the system’s response to the presence of large amounts of wind. Two extracts from SCE’s comments to the CEC on the CAISO’s Renewable Integration Report illustrate concerns regarding system-side characteristics and response, and the relevance to power stability (note mention of inertia):

“The Draft Report does not appear to address a number of technical issues. These issues are critical to understanding how integrating intermittent resources affect SP15. Such issues include

- a. Impacts of large amounts of wind resources on the Southern California Import Transmission (SCIT) nomogram since wind generation does not contribute significant amounts of inertia to the electric system.”²

And,

“SCE would like the CAISO to perform a scenario with maximum wind generation online, with minimum imports, and minimum thermal generation on-line, to determine how the system will perform if the wind speed drops down to a minimum value where all the wind output is shut-off in a 10 minute window. This might require keeping more units on automatic generation control (AGC) to pick up the lost generation.”²

The authors would like to reiterate the general need for deeper understanding of these system-focused (versus device level) aspects of integration of intermittent renewable generation. Technical solutions exist, and it will serve all stakeholders to better understand the various options, their capabilities, and also costs. A complete exploration of the topic of system response to loss of large amounts of renewable resources is beyond the scope of this study, but is recommended to future research as a desirable and technically rich area of exploration.

² Chinn, p.8, 11

B. P-Stability Study Results

Description of simulation results for the system and outage scenario described above are presented below.

To demonstrate the system-level stability, following loss of significant wind generation, major 230 kV busses across SCE's system were monitored for voltage and frequency through the simulated 10 second window. These monitored busses are:

Antelope 230 kV (proximate to wind generation)
Rector 230 kV (CA Central Valley load center)
La Fresa 230 kV (Los Angeles Basin load center)
San Onofre 230 kV (Southern border of SCE's system)
Devers 230 kV (Eastern border of SCE's system)

For each scenario, the P and Q output of the larger of the two outaged wind generators is plotted, and the P and Q output of the Energy Storage system is plotted. The local/terminal voltages and frequencies are also shown on these plots.

SCENARIO 1: 700 MW Wind Generation Lost, 0 MW Energy Storage Output Added, Figures 2a-2d below.

SCENARIO 2: 700 MW Wind Generation Lost, 250 MW Energy Storage Output Added, Figures 3a-3d below.

SCENARIO 3: 700 MW Wind Generation Lost, 500 MW Energy Storage Output Added, Figures 4a-4d below.

SCENARIO 4: 700 MW Wind Generation Lost, 750 MW Energy Storage Output Added, Figures 5a-5d below.

These plots graphically illustrate that both voltage and frequency recovery improve with addition of fast-acting Energy Storage, following modeled loss of 700 MW of wind generation in the Tehachapi area. And, that these beneficial impacts are proportional to output capacity of the added Energy Storage.

The modeling simplifications and 'proxy' aspect of the energy storage (versus the wind generators which are modeled in relatively higher detail), prevent deeper or more conclusive statements regarding impacts. But, the authors believe that the findings from this 'simplified' work do support development of more detailed and robust modeling and analysis of the potential dynamic system benefit from fast-acting energy storage systems coincident with large amounts of wind generation. In particular, GE's "UPFC" (unified power flow controller) sample model within PSLF may

provide a next-step improved 'proxy' for modeling grid-side dynamic impacts of fast-acting Energy Storage systems. However, the paper's authors' had no prior experience in attempting use of this model, and the model and its correct implementation were found to be non trivial.

This study graphically illustrated relative performance of system response to sudden loss of wind generation between scenarios without, and then with, energy storage. But, there are criteria against which modeled system dynamic performance are evaluated: the WECC/NERC Planning Criteria³. Under WECC/NERC criteria the maximum lower frequency deviation limit is 59.6 Hz, for loss of single component (NERC disturbance Category B), and any oscillations must be positively damped. For the scenario studied, the monitored busses all remained above this lower-limit threshold. BUT, positive damping is indeterminate for the outage scenario with 0 MW Energy Storage added after the outage. A longer duration stability run would be required to make a more conclusive statement about the modeled damping of the 'no storage' case, and would require additional extra analytic effort beyond this study. What is conclusive from this study's early illustrative simulations is addition of energy storage, as modeled in this study, can improve the recovery profile (speed the recovery and return to normal system frequency) of system-level frequency.

C. P-Stability Study Conclusions and Recommendations

As shown with this very simplified stability study, energy storage with the appropriate capabilities can help power stability, thus offering potential to facilitate integration of intermittent wind energy. But, regulatory and technical hurdles remain and require further development, and ultimately action, to bring energy storage's multitude of beneficial characteristics to help California meet our wind integration challenge. Designed and applied correctly, a coordinated generation/storage system can turn a system problem into a system asset.

Recommended actions that will accelerate technical understanding, and ultimately adoption of beneficial storage technologies and grid-supportive applications include:

- Develop explicit dynamic models of energy storage systems for use in transmission planning studies to illuminate device/system dynamic interaction in the 0-10 second dynamic stability transient timeframe.
- Perform further technical evaluation of system response and mitigation options for sudden loss of wind generation.

³ WECC, Part I

Figure 2: Scenario 1: 700 MW wind generation lost, no energy storage response.

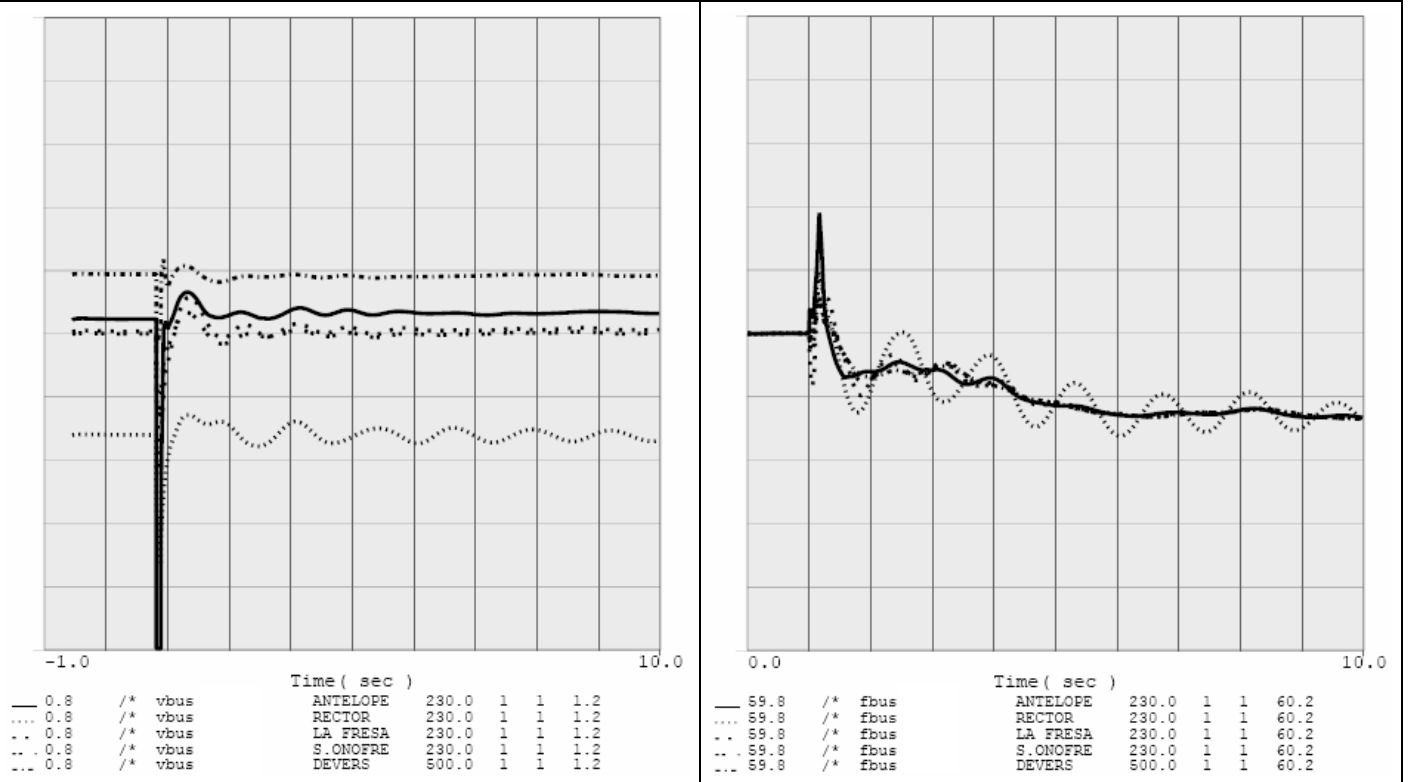


Figure 2a: Scenario 1, bus voltage vs. time

Figure 2b: Scenario 1, bus frequency vs. time

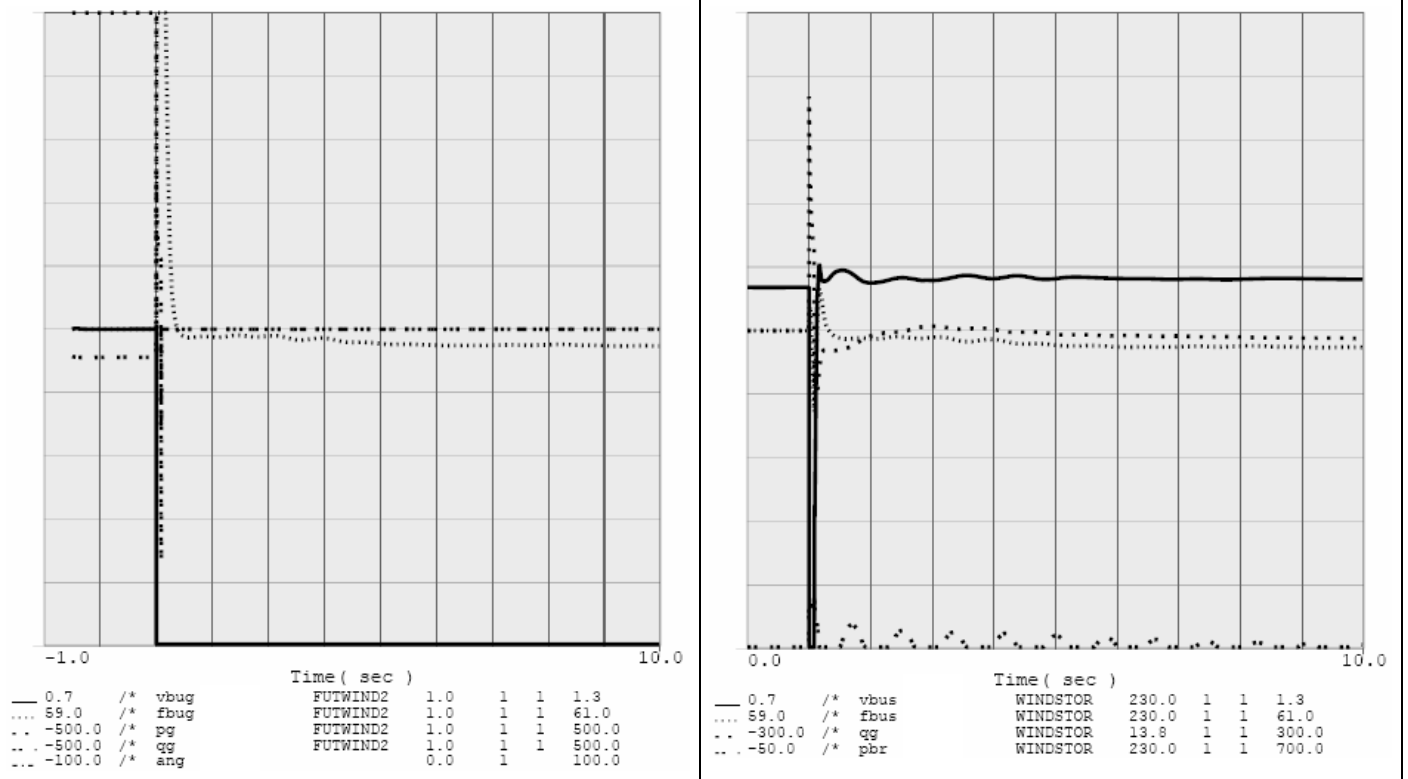


Figure 2c: Scenario 1, loss of wind generation vs. time

Figure 2d: Scenario 1, storage system generation vs. time

Figure 3: Scenario 2: 700 MW wind generation lost, 250 MW fast-acting energy storage responds in 5 cycles.

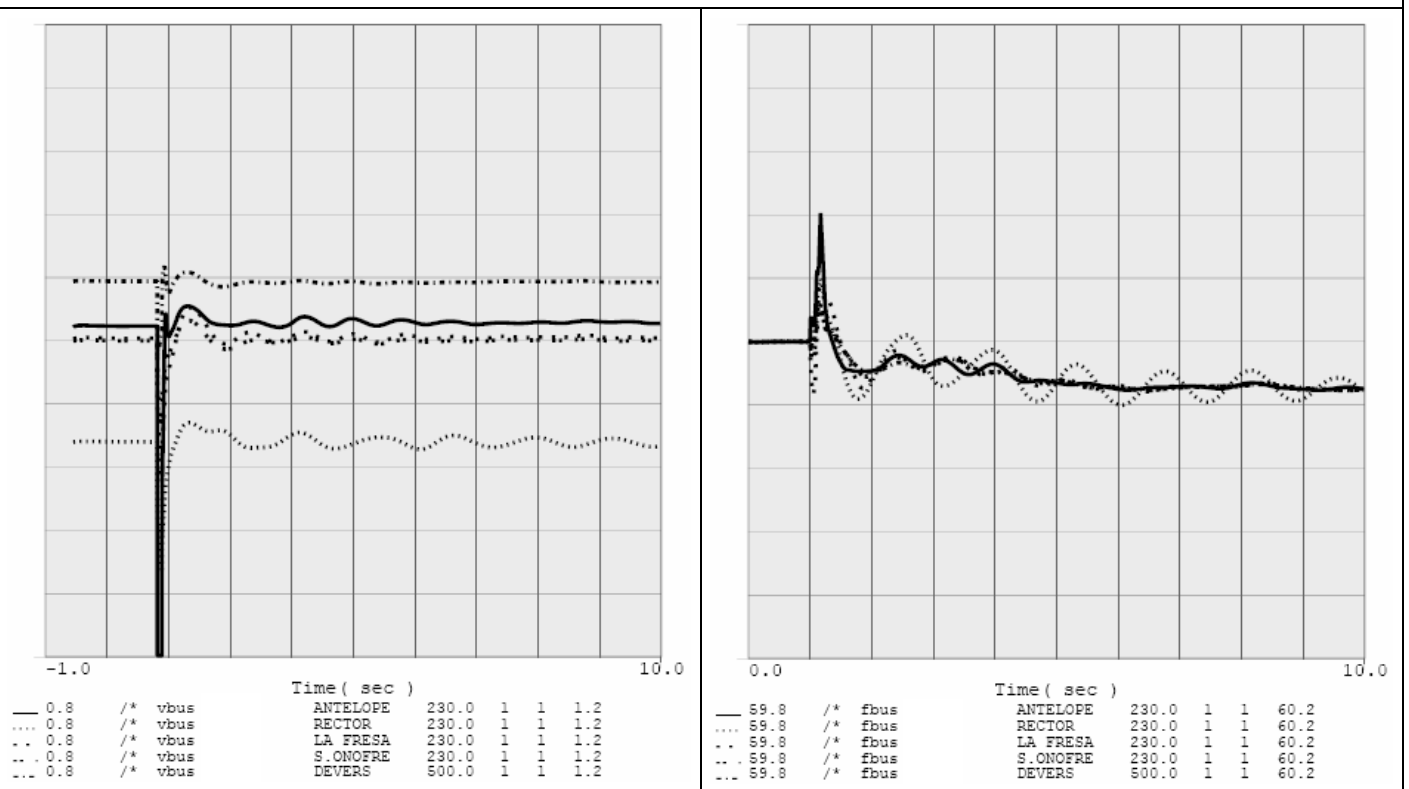


Figure 3a: Scenario 2, bus voltage vs. time

Figure 3b: Scenario 2, bus frequency vs. time

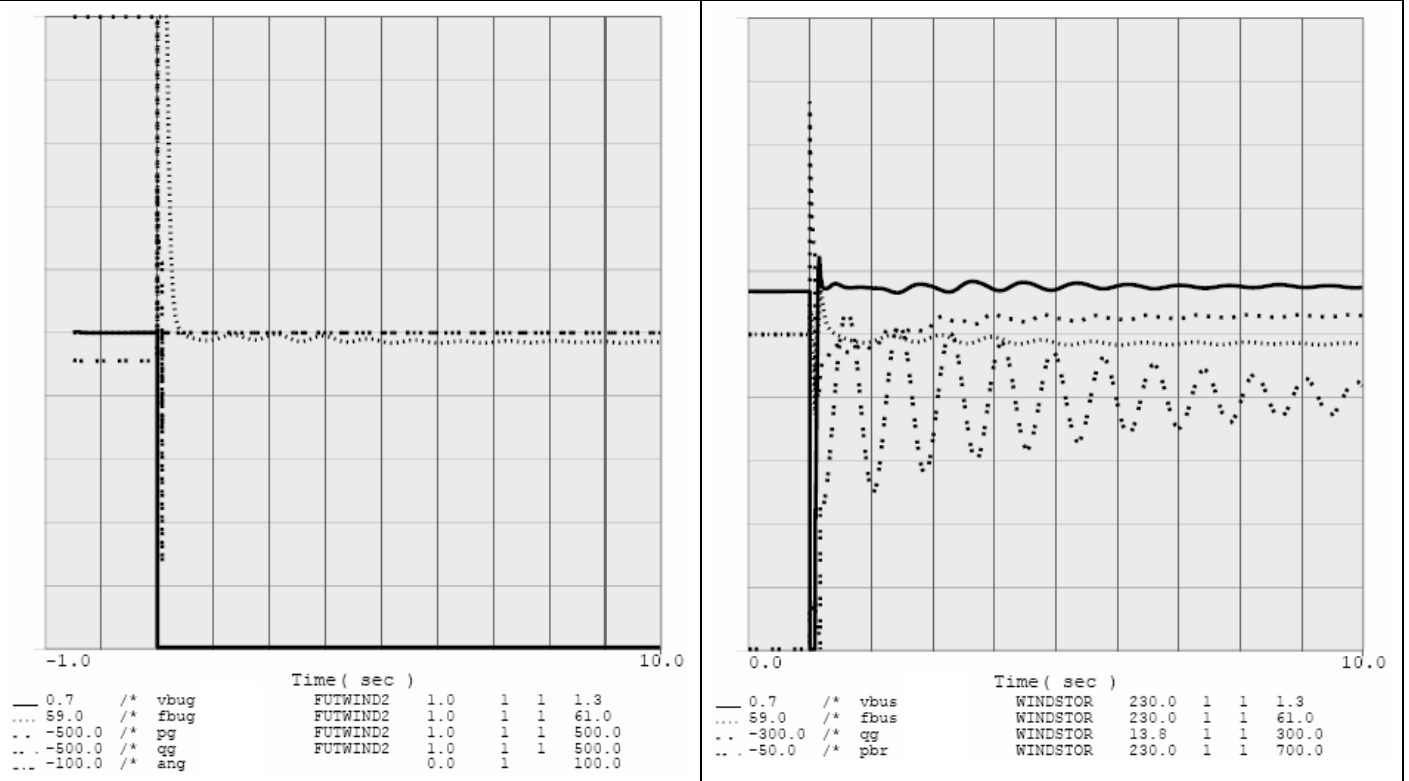


Figure 3c: Scenario 2, loss of wind generation vs. time

Figure 3d: Scenario 2, storage system generation vs. time

Figure 4: Scenario 3: 700 MW wind generation lost, 500 MW fast-acting energy storage responds in 5 cycles.

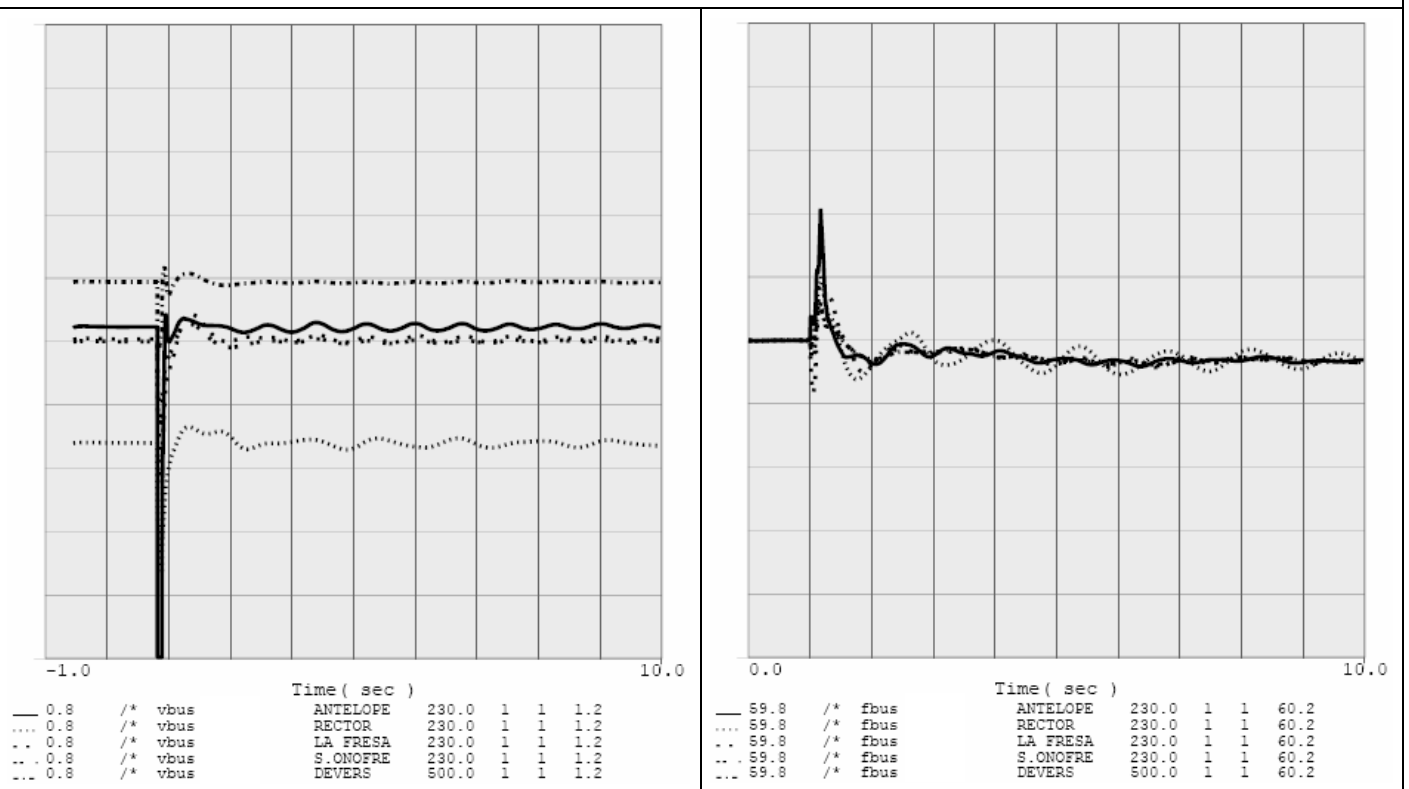


Figure 4a: Scenario 3, bus voltage vs. time

Figure 4b: Scenario 3, bus frequency vs. time

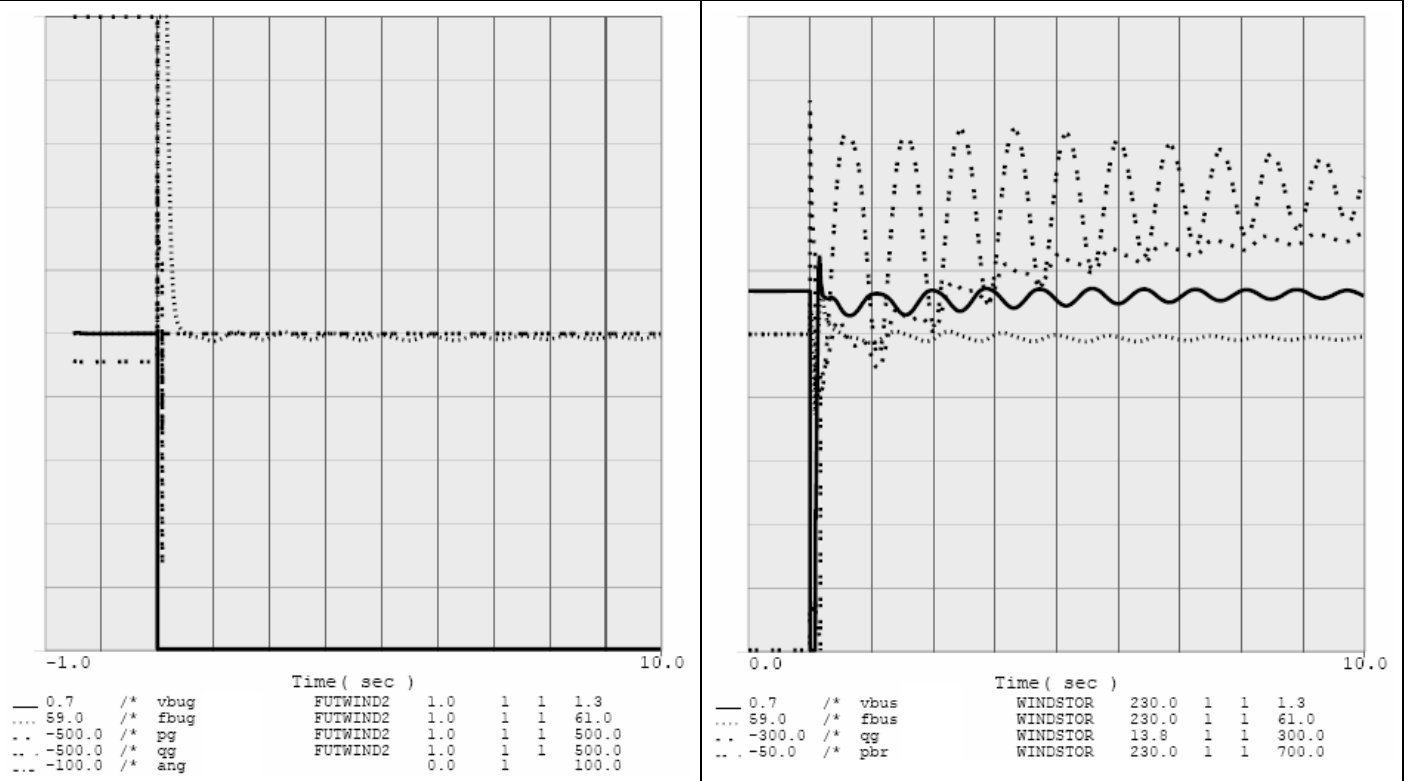


Figure 4c: Scenario 3, loss of wind generation vs. time

Figure 4d: Scenario 3, storage system generation vs. time

Figure 5: Scenario 4: 700 MW wind generation lost, 750 MW fast-acting energy storage responds in 5 cycles.

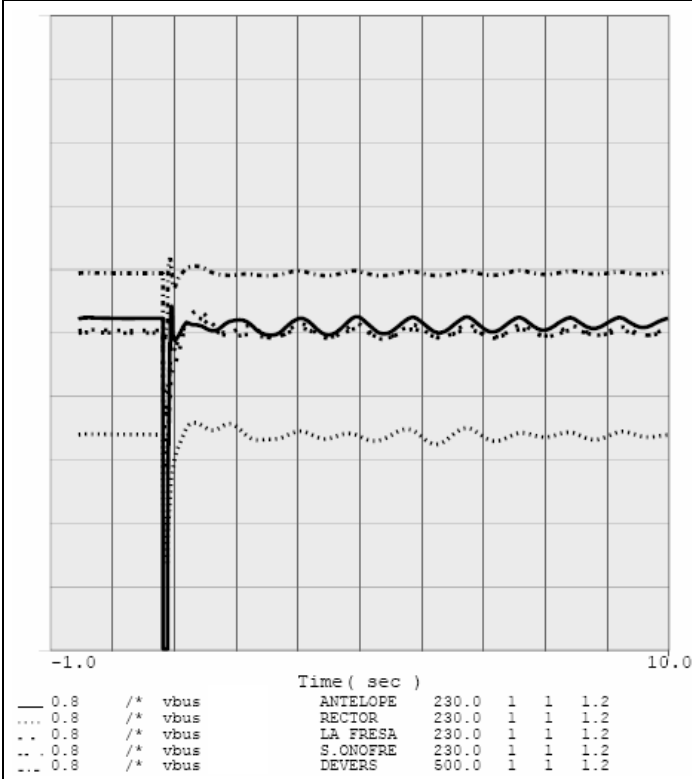


Figure 5a: Scenario 4, bus voltage vs. time

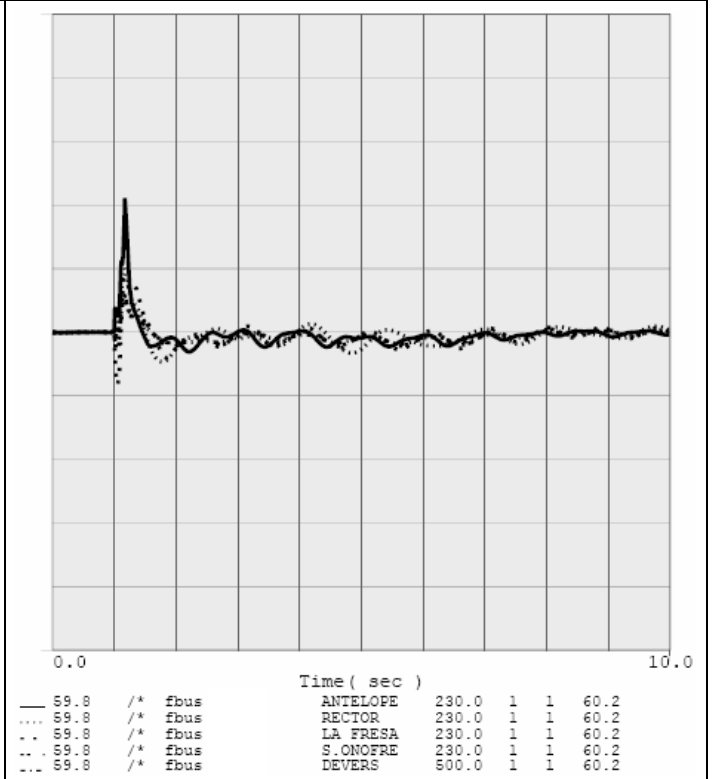


Figure 5b: Scenario 4, bus frequency vs. time

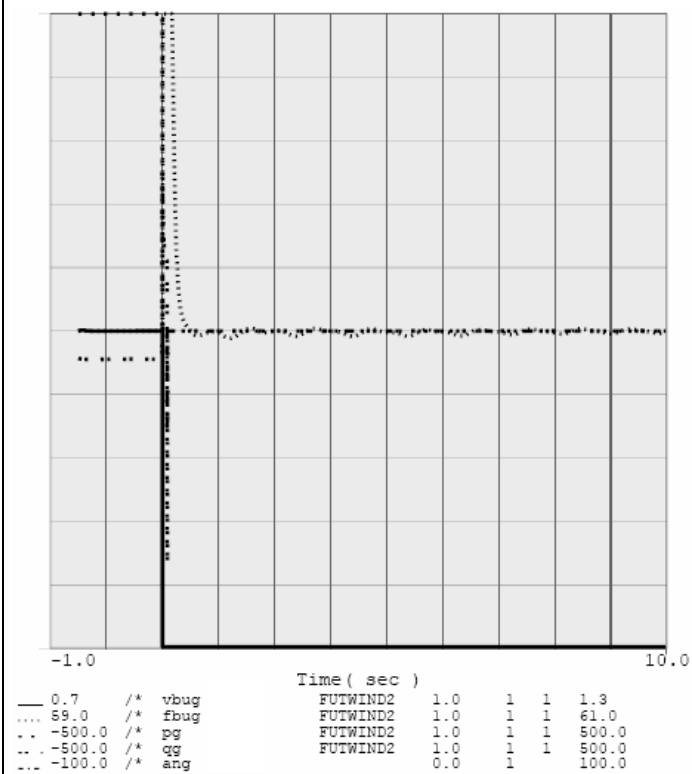


Figure 5c: Scenario 4, loss of wind generation vs. time

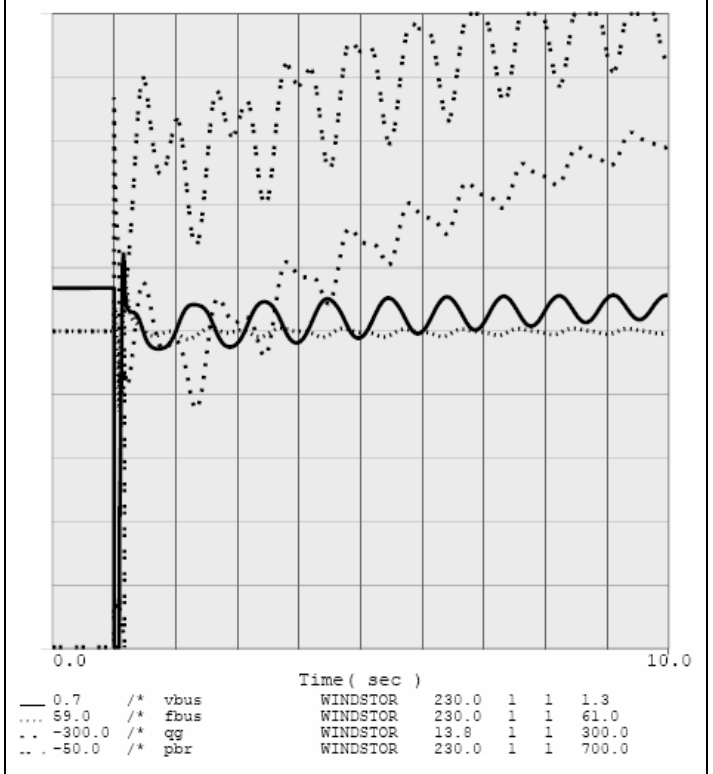


Figure 5d: Scenario 4, storage system generation vs. time

IV. CONCLUSIONS

We provide an early conceptual roadmap outlining incentives and mechanisms needed to facilitate the introduction of energy storage into the California wholesale market. Dynamic simulations performed for this study also demonstrate one of several potential system benefits that drive our interest in:

- 1) Promoting better understanding of the potential significant system benefits available via this technology.
- 2) Promoting development of market and regulatory mechanisms to incent its utilization where beneficial to California's electrical market participants.

The authors' advocacy of furthering the industry's understanding and application of energy storage to facilitate integration of wind generation is consistent with national policy. The Energy and Security Independence Act of 2007 is recent legislation that makes it national policy to support the modernization of the transmission and distribution system in the US while maintaining a reliable and secure infrastructure that meets demand growth and provides characteristics that make the grid "Smart." The Act envisions and encourages the "Smart Grid." The Smart Grid, as prescribed by the Act, will anticipate and be prepared to accept and make use of new renewable and intermittent resources while maintaining a robust grid infrastructure. New technologies incorporated in the Smart Grid are expected to make it more reliable and more modern. For example, of the 10 designated Smart Grid characteristics, #7 includes storage capability and characteristic #10 recognizes that certain barriers will need to be identified and lowered to achieve the Smart Grid⁴.

V. DISCLAIMER

This report was prepared by a principal executive of MegaWatt Storage Farms and staff of Southern California Edison Companies. Neither Company nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by either company or any agency thereof. The views and opinions of the authors expressed herein do not necessarily state or reflect those of either Company or any agency thereof.

VI. REFERENCES

- [1] "Integration of Renewable Resources", CAISO, Nov-2007, p. 93-94.
- [2] "SCE Comments on Integration of Renewables Report", Garry Chinn, 12-Oct-2007, <<http://www.caiso.com/1c7a/1c7ab03d3a70.pdf>>, p.8.
- [3] "Reliability Criteria", Part I: NERC/WECC Planning Standards, WECC, Apr-2005, <<http://www.wecc.biz/documents/library/procedures/CriteriaMaster.pdf>>
- [4] "Energy Independence and Security Act of 2007", Title XIII: Smart Grid, Section 1301, 12-Jan-2007, <<http://thomas.loc.gov/cgi-bin/query/D?c110:8:/temp/~c110IXTey5:>>.

VIII. BIOGRAPHIES

Edward Cazalet is Vice President and Cofounder of MegaWatt Storage Farms, Inc. (MegaWatt). MegaWatt manages and deploys electricity storage on the grid for renewables integration and reliability. Previously, Dr. Cazalet was a Governor of the California Independent System Operator and CEO and founder of both Automated Power Exchange (APX) and Decision Focus, Inc. Dr. Cazalet has been a consultant to numerous electric utilities and has developed numerous utility system computer models. Dr. Cazalet's web site is www.cazalet.com. He has a PhD in engineering-economics from Stanford University and is an IEEE member.

Charles Vartanian is Project Manager for DER Development at SCE's Distributed Energy Resources group (DER). Charlie is the primary technical liaison for the group supporting joint technical research studies with external entities. These studies are actively evaluating how to best integrate and leverage DER assets for future utility grid benefit. Before this assignment, Charlie worked for SCE's Transmission & Interconnection Planning group. Charlie received his MSEE from USC, and his BSEE from Cal Poly Pomona. Charlie is a licensed Professional Engineer in California, and is a member of IEEE.

Stephanie Hamilton is in charge of Distributed Energy Resources for SCE. At SCE, Ms. Hamilton oversees a diverse portfolio R&D of new and emerging DER technologies, such as concentrating solar, fuel cells, microturbines and balance of plant components such as inverters. Previously Ms. Hamilton held energy positions at some of the largest utilities in the US in both natural gas and power in both their regulated and unregulated subsidiaries, including Southern California Gas, Public Service New Mexico, and Grant County PUD. Ms. Hamilton holds an MBA and a BS in Mechanical Engineering and is widely published on energy and energy-related issues. Her latest book is *The Handbook of Microturbine Generators*. Meanwhile, she is an original member of DOE's 13-member GridWise Architecture Council which is focused on increasing interoperability in the North American power industry.

Benjamin Coalson is a Research and Development Intern at SCE's Distributed Energy Resources group. He is currently pursuing a Bachelor of Science degree at California State University, Los Angeles (CSULA), with a specialization in power systems, and looks forward to continuing his engineering career at SCE following graduation in spring of 2008. Ben provides a wide range of technical and logistical support to his colleagues at SCE DER. Prior to coming to SCE, he participated in various aerospace research projects at CSULA, as well as the summer internship program at Jet Propulsion Laboratory, where he researched laser heterodyne metrology for the SIM PlanetQuest mission. Ben is a student member of the IEEE, and a member of the Tau Beta Pi and Eta Kappa Nu engineering honor societies.

⁴ Title XIII, Smart Grid: Section 1301