

Energy Research and Development Division  
FINAL PROJECT REPORT

**WIND STORAGE ENHANCED  
TRANSMISSION RESEARCH AND  
DEVELOPMENT**



Prepared for: California Energy Commission  
Prepared by: Southern California Edison and Quanta Technology



MARCH 2012  
CEC-500-2013-044

**PREPARED BY:**

***Primary Author(s):***

Juan Castaneda  
Johan Enslin  
Bhavya Gudimetla  
David Elizondo  
Nagy Abed  
Srijib Mukherjee  
Atousa Yazdani  
Subbaiah Pasupulati

Southern California Edison  
PO Box 800  
Rosemead, CA 91770  
Phone: 800-655-4555  
<http://www.sce.com>

***Contract Number: PIR-07-009***

***Prepared for:***

**California Energy Commission**

Mike Kane  
***Contract Manager***

Linda Spiegel  
***Office Manager***  
***Energy Generation Research Office***

Laurie ten Hope  
***Deputy Director***  
***ENERGY RESEARCH AND DEVELOPMENT DIVISION***

Robert P. Oglesby  
***Executive Director***

**DISCLAIMER**

This report was prepared as the result of work sponsored by the California Energy Commission. It does not necessarily represent the views of the Energy Commission, its employees or the State of California. The Energy Commission, the State of California, its employees, contractors and subcontractors make no warranty, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the uses of this information will not infringe upon privately owned rights. This report has not been approved or disapproved by the California Energy Commission nor has the California Energy Commission passed upon the accuracy or adequacy of the information in this report.

## ACKNOWLEDGEMENTS

Quanta Technology and Southern California Edison are grateful for the support received from the California Energy Commission’s Public Interest Energy Research (PIER) Program.

During the two years of the project, the coordinated effort of the complete team contributed to the successful completion of work products and technology transfer activities.

The Model Development and Management Teams from Southern California Edison and Quanta Technology convened every week throughout the project to develop plans, review progress, develop models, and evaluate results. Together they reported on the project to the Energy Commission. Their dedication to the project objectives, involvement in project design, and attention to detail contributed to completion within the scope of the project.

The Model Development Team listed in the table below includes Southern California Edison (SCE), Quanta Technology, and Oak Creek Energy staff.

Juan Castaneda	Program Manager	Southern California Edison
Johan Enslin	Project Manager	Quanta Technology
Sercan Teleke	Modeling and Analysis	Quanta Technology
Bhavya Gudimetla	Modeling and Analysis	Quanta Technology
Srijib Mukherjee	Subject Matter Expert	Quanta Technology
David Elizondo	Subject Matter Expert	Quanta Technology
Nagy Abed	Modeling and Analysis	Quanta Technology
Atousa Yazdani	Modeling and Analysis	Quanta Technology
Subbaiah Pasupulati	Consultant	Oak Creek Energy

## PREFACE

The California Energy Commission's Energy Research and Development Division 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 Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

Energy Research and Development Division funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

*Wind Storage Enhanced Transmission Research and Development* is the final report for the Commission Agreement number PIR-07-009 conducted by Southern California Edison. The information from this project contributes to the Energy Research and Development Division's Renewable Energy Technologies Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at [www.energy.ca.gov/research/](http://www.energy.ca.gov/research/) or contact the Energy Commission at 916-327-1551.

## ABSTRACT

A project team led by Southern California Edison Company analyzed Southern California Edison's electricity system to identify existing transmission interconnection locations that would benefit from integrating energy storage technologies. The team investigated system contingencies and possible wind storage impacts on the system. Energy storage and converter manufacturers were selected using the Request for Information process. After determining which manufacturers could provide the best technology for implementation, the team selected the energy storage devices that satisfy the criteria for providing promising, commercially viable, economically feasible, and scalable solutions. The team also provided a pathway for commercialization as well as a Technology Transfer Plan. Implementing energy storage devices into the Southern California energy grid will help California meet its Renewable Portfolio Standard goal of obtaining 33 percent of its electricity from renewable sources by 2020, which will reduce greenhouse gas emissions and other air emissions that contribute to air pollution.

The goal of the project was to quantify the benefits and costs of integrating energy storage technologies in the Southern California Edison service area. Three case studies representing three critical power system issues were selected for more detailed analysis and feasibility studies. Two cases in the Tehachapi and Palm Springs wind resource areas were analyzed for wind-related voltage/frequency instability and path congestion, respectively. The third location studied was the South Bay area of Los Angeles County and addressed power quality issues for non-renewable facilities. For each location, major issues were identified that impacted power quality and transmission reliability.

Three promising energy storage technologies were selected, and it was determined that a hybrid combination of these technologies would provide the best solution. The authors recommended that the State of California, Southern California Edison, and other stakeholders pursue an energy storage demonstration project to determine if the expected benefits from these technologies will occur.

**Keywords:** Energy Storage, Wind Energy, Intermittency, Batteries, Compressed Air Energy Storage

Please use the following citation for this report:

Castaneda, Juan. (Southern California Edison). 2012. *Wind Storage Enhanced Research and Development*. California Energy Commission. Publication number: CEC-500-2013-044.

# TABLE OF CONTENTS

ACKNOWLEDGEMENTS .....	i
PREFACE .....	ii
ABSTRACT .....	iii
TABLE OF CONTENTS.....	iv
LIST OF FIGURES AND TABLES.....	v
EXECUTIVE SUMMARY .....	7
<b>1 Introduction .....</b>	<b>13</b>
1.1 Background and Overview.....	13
1.2 Overall Project Goals .....	13
<b>2 Project Approach.....</b>	<b>15</b>
<b>3 Project Outcomes .....</b>	<b>16</b>
3.1 Energy Storage.....	16
3.1.1 Energy Storage Technologies .....	16
3.1.2 Energy Storage Benefits.....	26
3.1.3 Energy Storage Performance Metrics .....	30
3.2 Energy Storage Case Studies .....	34
3.2.1 Grid Quality Issues .....	34
3.2.2 Mitigation Strategies.....	36
3.2.3 Economic Analysis on the Proposed Solutions.....	60
3.3 Energy Storage Commercialization.....	68
3.3.1 Implementation team .....	68
3.3.2 Commercialization Pathway .....	71
3.3.3 Summary of Responses .....	74
3.3.4 Data Monitoring.....	97
3.3.5 Technology Selection.....	107
3.3.6 Technology Transfer Plan.....	108
<b>4 Conclusions and Recommendations .....</b>	<b>109</b>

4.1	Conclusions.....	109
4.2	Recommendations.....	110
4.3	Benefits to California .....	111
<b>REFERENCES .....</b>		<b>112</b>
<b>GLOSSARY .....</b>		<b>117</b>

## **LIST OF FIGURES AND TABLES**

Figure 1: Simple battery model.....	17
Figure 2: Thevenin battery model.....	17
Figure 3: Third order battery model.....	18
Figure 4: Detailed battery model .....	22
Figure 5: Vanadium redox flow model [31] .....	23
Figure 6: BESS integration at a wind farm.....	28
Figure 7: BESS dispatch performance (P <sub>bess</sub> : BESS power, P <sub>wind</sub> : wind power, P <sub>total</sub> : net injected power in MW).....	28
Figure 8: Ramp up and Ramp down requirement with 20% wind penetration to SCE .....	30
Figure 9: Voltage sag occurring at the refinery.....	36
Figure 10: Voltage harmonic spectrum at the refinery .....	36
Figure 11: Voltage profile (a) and the power output for two individual wind farms (b) and (c) during one of the critical contingencies (P and Q shown with dark and light color, respectively) .....	38
Figure 12: Basic Schematic of the BESS – STATCOM .....	39
Figure 13: System Collapse Prevention after the application of 20 MVar STATCOM and 8 MW battery during the contingency (P and Q shown with dark and light color, respectively).....	41
Figure 14: Power output (a) and voltage profile (b) at different wind generation buses before and after the contingency without the energy storage .....	41
Figure 15: The system frequency without the energy storage before and after the contingency .	42
Figure 16: The system frequency with the energy storage during the contingency.....	42
Figure 17: Voltage profile (a) and the wind farms output power (b) before and after the contingency with energy storage.....	43
Figure 18 - Configuration of the BESS including the ESS, PCS and a step-up interconnection transformer to 66 kV voltage level.....	45

Figure 19: Four quadrant operation of the BESS .....	46
Figure 20: Typical charge/discharge profile for the BESS (P <sub>bess</sub> =BESS charge/discharge profile (positive means discharge), P <sub>wind</sub> =Wind power, P <sub>set</sub> =Desired wind profile) .....	47
Figure 21: Another charge/discharge profile for the BESS (P <sub>bess</sub> =BESS charge/discharge profile (positive means discharge), P <sub>wind</sub> =Wind power, P <sub>set</sub> =Desired wind profile) .....	48
Figure 22: U-I characteristics of STATCOM .....	52
Figure 23: STATCOM Overload Capability .....	52
Figure 24: STATCOM control settings for Voltage Regulation .....	53
Figure 25: Loading of the two lines for a summer week .....	54
Figure 26: Expected CAES operation .....	55
Figure 27: Application of STATCOM at the refinery .....	57
Figure 28: Refinery Bus Voltage (pu.) with (blue) and without (orange) STATCOM.....	57
Figure 29: STATCOM Active (MW-blue) and Reactive Power (MVAR-orange).....	58
Figure 30: Induction machine speed (pu.) with (blue) and without (orange) STATCOM .....	58
Figure 31: THD and harmonic contents (%) without STATCOM .....	59
Figure 32: THD and harmonic contents (%) with STATCOM.....	60
Figure 33: Load Current (kA) (Blue) and STATCOM Current (kA) (Red) .....	60
Figure 34: Overall Project Timing.....	71
Figure 35: Proposed Commercialization Pathway for Storage Project.....	74
Figure 36: PCS 100 Inverter Module [49] .....	76
Figure 37: PCS100 rack (16 modules) [49].....	77
Figure 38: BESS Configuration Example [49].....	78
Figure 39: Single line diagram of the system [49].....	80
Figure 40: Altairnano Power Module Container on Shipping Carriage [50].....	81
Figure 41: Inside view of container [50].....	82
Figure 42: Xcel Energy: “Xcel Energy 1MW NAS System” .....	84
Figure 43: Modular Bi-Directional Inverters [52] .....	87
Figure 44: VRB-ESST <sup>TM</sup> : REDOX Flow Battery [53] .....	88
Figure 45: System single line for a 9MW VRB-ESST <sup>TM</sup> [53] .....	89

Figure 46: A typical $\pm 1.25$ MVA SMS Inverter and 2 choppers [54] .....	91
Figure 47: DC Switchgear and DC Filter Bays [54] .....	92
Figure 48: Front cutaway of SMS enclosure with 4 inverters and DC Bays [54].....	93
Figure 49: Rear view of SMS enclosure with 4 inverters and DC Bays [54] .....	93
Figure 50: Single line diagram of the system [54].....	94
Figure 51: Data Concentrator Unit .....	106
Table 1: Study areas and issues .....	34
Table 2: Proposed Solutions at selected locations .....	37
Table 3: ESS (Battery) Functional Specifications.....	48
Table 4: Minimum PCS Functional Specifications.....	49
Table 5: Loading of the lines without energy storage.....	55
Table 6: Loading of the lines with energy storage.....	55
Table 7: Loading of the lines with energy storage and wind.....	56
Table 8: Parameters of the STATCOM.....	57
Table 9: Harmonic current injection at refinery.....	59
Table 10: Summary of economic analysis.....	61
Table 11: Value Stream Calculation for BESS.....	64
Table 12: Value stream calculation with CAES.....	66
Table 13: Value Stream Calculation with STATCOM.....	67
Table 14: Project Tasks and Team members.....	70
Table 15: Summary of the components [49] .....	75
Table 16: PCS Specifications for 1 MW, 1.25 MVA Unit.....	85
Table 17: Summary of the components [52] .....	86
Table 18: Comparison of ESS responses .....	95
Table 19: Comparison of PCS responses.....	96
Table 20: Summary of Costs .....	96
Table 21: Metrics and Measurements Required for Performance Monitoring.....	98

# EXECUTIVE SUMMARY

## Introduction

California's Renewable Portfolio Standard requires that all retail sellers of electricity will have 33 percent of their electric generation comprised of renewable energy by 2020. To comply with this regulation, many companies are adding wind-generated capacity to their generation profiles. In California, there are a large number of wind projects in various stages of development throughout the state. One of the key issues with wind-powered generation is the intermittent and not fully predictable nature of wind resources, which poses challenges to utilities and operators of the electric grid as they make plans for integrating wind power into the electric grid. These operational challenges range from short-term voltage and frequency instability due to minute-to-minute changes in local wind speeds to scheduling and dispatch issues that arise from the uncertainty inherent in hours-ahead to days-ahead forecasts. Additionally, wind plants that generate excessive power at night or other low-load periods sometimes overload transmission assets, making it necessary to curtail wind generation when those conditions prevail. Resolving these issues is necessary to take advantage of the additional capacity that can be provided by wind so that electric generating companies can meet California's Renewable Portfolio Standard requirements.

Energy storage is one option for mitigating the effects of intermittent renewable resources. This report detailed the results of a collaborative effort led by the Southern California Edison Company, with technical support by Quanta Technology, which assessed the technical and economic feasibility of deploying energy storage technologies at strategic substations to mitigate the power and transmission issues discussed above.

## Project Purpose

The goal of this project was to quantify the benefits and costs of integrating energy storage devices or other technologies at three substations in the Southern California Edison Company service area that exhibit significant power, power quality, or transmission issues. For two of the sites, the issues being addressed were directly related to generation from nearby wind plants, whereas the third case concentrated on power disturbances to sensitive loads unrelated to renewable generation. The objectives of the project were to:

- Perform a detailed feasibility analysis of existing wind interconnection locations throughout the Southern California Edison Company system that may benefit from the use of energy storage systems.
- Quantify the critical challenges for the three pre-selected interconnection case studies (sites) that have exhibited power, power quality, or transmission overload issues in the past.
- Identify various system contingencies and possible storage energy impacts on the system for each of the sites.

- Analyze and select the best storage technology for each site based on quantifiable benefits, commercial availability, economic feasibility, scalability, and any other critical selection criteria.
- Identify and propose a commercialization pathway that takes into account sound energy storage technologies and ownership/operation scenarios that are consistent with the electric power industry's business values, existing market structures, and applicable state and Federal policies.
- Identify organizations capable of implementing wind storage technology at selected targeted locations and elsewhere on the California grid.

The sites selected for the analysis were the Cal Cement substation in the Tehachapi wind resource area, the Devers substation near Palm Springs, and the La Fresa substation in the South Bay area of Los Angeles. For each site, at least one year of performance data was collected and analyzed, and system contingencies and possible storage impacts were also identified and analyzed. Based on these analyses, an appropriate energy storage technology was selected that the project team believed would best address the site's power, power quality, or transmission overload issues. Criteria for assessing each energy storage technology included quantifiable benefits, commercial availability, economic feasibility, and scalability. The assessment of quantifiable benefits considered all stakeholders, with a focus on ratepayers and energy providers/wind farms, and also took into account environmental concerns. Once the technology was selected, the project team issued a Request for Information to various energy storage and power conversion vendors, and then identified a team with the necessary competencies to implement a future demonstration project and create a commercialization pathway. They then developed a technology transfer plan to provide key decision makers and the public with information gained from the project.

## Project Results

Energy storage technologies can provide multiple benefits for electric power companies, transmission companies, electricity generators, and electric power end users. These benefits include: improved integration of renewable energy; deferred transmission and distribution upgrades; arbitrage (purchasing inexpensive electricity when demand and cost are low and selling it when demand and price are high); spinning reserve to compensate for generation or transmission outages; improved transmission load capacity; increased stabilization of the transmission and distribution grid; improved load following and frequency regulation; more efficient use of generation assets and reduced dispatch costs; and reduced greenhouse gas emissions.

Six energy storage technologies were considered in the analysis:

- A battery energy storage system (BESS) stores energy electrochemically and consists of a set of low voltage or power battery modules connected in series and/or in parallel to achieve a desired electrical characteristic. Batteries are charged when they undergo an internal chemical reaction and the absorbed energy is delivered when the chemical reaction is reversed. BESS has emerged as one of the most promising near-term storage technologies due to its wide range of power system applications, including area

regulation, spinning reserve, and power factor correction. Battery types include lead acid batteries, lithium ion batteries, nickel cadmium batteries, sodium sulfur batteries, and flow batteries.

- Compressed air energy storage (CAES) relies on compressed air that can be used later as an energy source. When used in a peaking gas turbine, CAES consumes less than 40 percent of the gas used in a conventional gas turbine to produce the same amount of electric output power. Successfully using CAES depends on locating power plants near appropriate underground geological formations such as underground mines, caverns created inside salt rocks, or depleted gas wells.
- Electrochemical capacitors – commonly called supercapacitors – store electrical energy in two series capacitors of the electric double layer that is formed between each of the electrodes and the electrolyte ions. Electrochemical capacitors have lower energy density compared to lead-acid batteries, but can be cycled tens of thousands of times, and also have a faster charge and discharge capability.
- Flywheel energy storage (FES) systems consist of a huge rotating cylinder supported on a stator by magnetically levitated bearings that eliminate bearing wear and increase system life. The flywheel is connected to a motor/generator mounted onto the stator that interacts with the utility grid through power electronics.
- Pumped hydro plants consist of two interconnected reservoirs as well as machinery, valves, a generator-motor, transformers, a transmission switchyard, and connection to a transmission system. The product of the total volume of water and the differential height between the reservoirs is proportional to the amount of stored energy.
- Superconducting magnetic energy storage systems store energy in the field of a large magnetic coil with direct current flowing. It can be converted back to alternative current as needed.

The results of each of the three case studies are discussed below.

The Tehachapi area has approximately 380 megawatts (MWs) and 310 MWs of coincident peak wind power. The primary issue in the Tehachapi wind resource area was voltage instability. Most of the wind turbines are Type 1 turbines, which do not have reactive power capability and absorb large amounts of reactive power from the system. The technology selected to address these issues was a BESS combined with static synchronous compensation to provide contingency support for megawatt-scale real and reactive power. In addition, the battery storage plus static synchronous compensation model would provide voltage profile support and fault-ride through capability. Battery energy storage would also significantly contribute to minimizing the wind power variations and control wind farm power output to within a pre-set value range. For contingency support, the battery absorbed energy (8 MW during four hours maximum) in order to avoid some of the wind farm curtailments. The estimated cost for an 8 MW 4-hour battery energy storage system combined with 20 megavolt-amperes reactive (MVAR) of static synchronous compensation was about 35 million U.S. dollars. The BESS was also a

good alternative for frequency regulation in small/medium scale as it is 170 percent more efficient than hydro, and has two to five times the efficiency of other types of generating units. The applications and economic metric calculations of the battery energy storage system in the Tehachapi study included electric energy time shift, load following, wind curtailment mitigation, hourly wind dispatch, voltage and frequency regulation, power quality, and congestion relief. Several revenue streams were considered for these applications of the BESS, including the avoided cost revenue stream if Southern California Edison can avoid upgrading an existing 66 kV transmission line. The return-on-investment for the battery energy storage system in these applications, based on net present value calculations, was about 10 percent. This was considered a good return on investment as an economic metric to continue and install the battery energy storage system.

The Palm Springs area has an installed wind capacity of approximately 750 MW, most of which are Type 1 turbines. The assumed capacity factor for the area is 30 percent, and like the Techapi area, the turbines absorb large amounts of reactive power from the system. Several lines in the area overload when the wind is lower than 30 percent of the nameplate capacity, and the local peakers that run when wind power is not available have higher operational and maintenance costs. The analysis determined that two critical line overloads can be mitigated by using CAES, which will also reduce the usage of local peakers in the area and reduce the load shedding. The return on investment for a CAES system for this application was around 20 percent.

The South Bay area is comprised of a mostly industrial load, including a few large oil refineries that use large induction machines. The machines stalled if voltage support is not available during voltage sags. Harmonic problems also occurred at this site. The analysis showed that power quality variation is dominated by induction machine load at the area's oil refinery, and that load will collapse after a nearby fault if there is no reactive support. With reactive support, the induction machines can recover their speed and return to their rated value after the fault is cleared. Although BESS was considered for this site, it was found not to be economically feasible. The technology selected for this site was static synchronous compensation, which reduced harmonic current in the area, and yielded a return on investment of around 25 percent.

The proposed commercialization pathway involved four major steps: plan development, design starts, monitoring and verification (M&V), and decommissioning. The plan development step included a project management plan, an M&V plan, ensuring compliance with the National Environmental Protection Act (NEPA), and an energy storage functional specification. The design starts included battery and inverter systems development, manufacture, assembly, and installation; siting, construction, and substation and grid preparations; and baselining. The M&V step included systems operation and data collection; communications, interoperability, and cybersecurity; and study, measurement, validation, and valuation. Once the project is completed, decommissioning will take place by removing the battery storage system and recycling it.

Based on the responses to the Request for Information, three energy storage technologies were selected as being most promising: Li-Ion batteries, a NaS battery system, and flow batteries.

Although each technology had distinct advantages, it was determined that a hybrid combination of these technologies would provide the best solution.

The Technology Transfer plan involved publishing white papers documenting the results of the studies performed at three sites that will be available to the public.

Based on the analyses performed, the authors recommended that the State of California, Southern California Edison, and other stakeholders pursue an energy storage demonstration project to determine if the expected benefits will occur. Although case studies were performed at three different locations, the authors believed the most feasible approach was to undertake one demonstration project. They also stated that a combination of private and public funding will be necessary to conduct such a demonstration.

### **Project Benefits**

Implementing an energy storage demonstration project will help ensure that California can meet the goal of obtaining 33 percent of its electricity from renewable sources by 2020. Increased use of renewable energy in California will result in reduced greenhouse gas emissions, as well as other air emissions that contribute to air pollution that impacts public health.



# 1 Introduction

## 1.1 Background and Overview

As State and Federal government set more requirements that are stringent on utilities to meet vigorous renewable goals, there are a growing number of new participants in the generation business eager to integrate wind energy to the grid. Wind generation is a rapidly growing industry as the wind power capacity grew by 30 percent in 2009 to reach 158 GW worldwide, more than double the 74 GW that existed in 2006. However, the operational, reliability, and economic impacts of integrating wind generation must be addressed before wind integration becomes a viable component of the Western Electricity Coordinating Council (WECC) grid.

Due to the intermittent and unpredictable nature of wind, energy output from wind farms vary greatly and high penetration of wind energy may introduce technical challenges, including grid interconnection, power quality, reliability, protection, generation dispatch, ramping requirements, and regulation services. This study will evaluate currently available energy storage technologies to address some of these issues.

## 1.2 Overall Project Goals

This project has multiple goals as listed below and each is addressed in this report.

- To conduct a detailed feasibility analysis study of existing wind interconnection locations throughout the SCE system that may benefit from the use of storage devices.
- To identify and define three critical challenges for three selected locations. Locations selected are Tehachapi, Palm Springs and South Bay area.
- To quantify the grid power quality and reliability issues and assess the potential improvements on the grid at selected interconnection locations by providing energy storage devices with bidirectional control of real and reactive power.
- To provide access to performance data for a minimum of one year for quantifying and validation project benefits and feasibility. This study is not intended to demonstrate a hardware installation, bench-scale testing, and prototyping of next generation storage technologies.
- Investigate various system contingencies and possible wind storage impacts on the system and select energy storage companies using RFI process and to determine best technology for implementation. Storage device selected should satisfy the criteria for providing promising, commercially viable, economically feasible, and scalable solutions.

- To identify companies capable of implementing wind-storage-enhanced technology at targeted locations. To identify commercialization pathway with sound technologies using ownership and operation scenarios consistent with industry's business values, existing market structures, and applicable California and Federal policies.
- Preparation of Technology Transfer Plan to make the knowledge gained, experimental results, and lessons learned available to key decision makers. The plan will also explain how the information will be made available to the public and its key elements will be included in the project's final report and white paper.
- To deliver final report summarizing all performed work for the study.

## 2 Project Approach

The project approach consists of the following steps:

- Selection of three sites, namely Tehachapi, Palm Springs, and South Bay, for assessing potential improvements on the grid by providing energy storage devices with bidirectional control of active and reactive power.
- Provision of mitigation strategies for power quality, path constraint, and transient stability issues to each of the three selected locations.
- Selection of appropriate energy storage technology after reviewing the existing storage technologies. The size and location of the storage will be based on the solution to contingency problems.
- Issuance of Request for Information to different energy storage and power conversion system vendors. Analysis of the responses based on system needs and benefits and selection of appropriate storage technology.
- Identification of a team with necessary competencies to implement a future demonstration project and identification of commercialization pathway.
- Development of technology transfer plan that will explain how the knowledge gained from the project is made available to the public.

## 3 Project Outcomes

### 3.1 Energy Storage

#### 3.1.1 Energy Storage Technologies

The different battery technologies and other storage types which can be used to perform the above applications are described below:

##### *3.1.1.1 Battery Energy Storage System (BESS)*

Batteries are one of the most cost-effective energy storage options available, which store energy electrochemically [1]. A battery system is made up of a set of low voltage or power battery modules connected in series and/or parallel to achieve a desired electrical characteristic.

Batteries are charged when they undergo an internal chemical reaction under a potential applied to the terminals. They deliver the absorbed energy, or discharge, when they reverse the chemical reaction. Some of the key factors of batteries for storage applications include: high energy density, round trip efficiency, cycling capability, life span, and initial cost [2].

Batteries store DC charge, so power conversion is necessary to interface a battery with an AC power system. Advances in battery technologies offer increased energy storage densities, greater cycling capabilities, higher reliability, and lower cost [3]. Battery energy storage systems have emerged as one of the most promising near-term storage technologies for power applications, offering a wide range of power system applications such as area regulation, spinning reserve, and power factor correction [4]. Common battery types are described below.

##### *3.1.1.1.1 Lead Acid Battery*

Lead acid batteries were invented in 1859 by Gaston Plante and first demonstrated to the French Academy of Sciences in 1860. They are the most mature and oldest of all battery technologies and due to the wide use of lead acid batteries in a wide variety of applications, they have the lowest cost of all battery technologies [5].

Lead acid batteries still remain the technology of choice for automotive starting, lighting, and ignition (SLI) applications because they are robust, tolerant to abuse, tried and tested, and because of their low cost [6]. Their application for energy management, however, has been very limited due to their limited cycling capability. The amount of energy that a lead-acid battery can deliver is not fixed and depends on its rate of discharge.

Lead-acid batteries, nevertheless, have been used in a few commercial and large-scale energy management applications. The largest one was a 40 MWh system in Chino, California, built in

1988. It demonstrated the value of stored energy in the grid but the short cycle life of lead acid batteries made the overall economics of the system unacceptable.

There is still research going on to develop advanced lead acid batteries with improved life cycles. Adding as much as 40 percent of activated carbon to the negative electrode composition increases battery's life up to 2000 cycles which represents a three to four times improvement over the conventional lead acid designs [5].

Limited references exist in the literature that focuses on detailed battery modeling for different technologies. The detailed models are mostly developed for lead acid batteries which are the most mature and oldest of all battery technologies. The currently available dynamic models for batteries are described below:

### Lead Acid Battery Modeling

The simplest and commonly used model of a lead acid battery consists of a constant internal resistance in series with an ideal voltage source [7]-[8] shown in Figure 1. Another commonly used battery model, namely, the Thevenin battery model [9]-[10], consists of an ideal no-load battery voltage, series internal resistance in series with parallel combination of overvoltage resistance and capacitance seen in Figure 2.

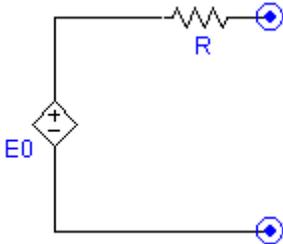


Figure 1: Simple battery model

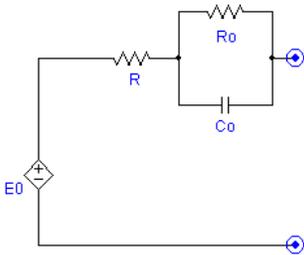
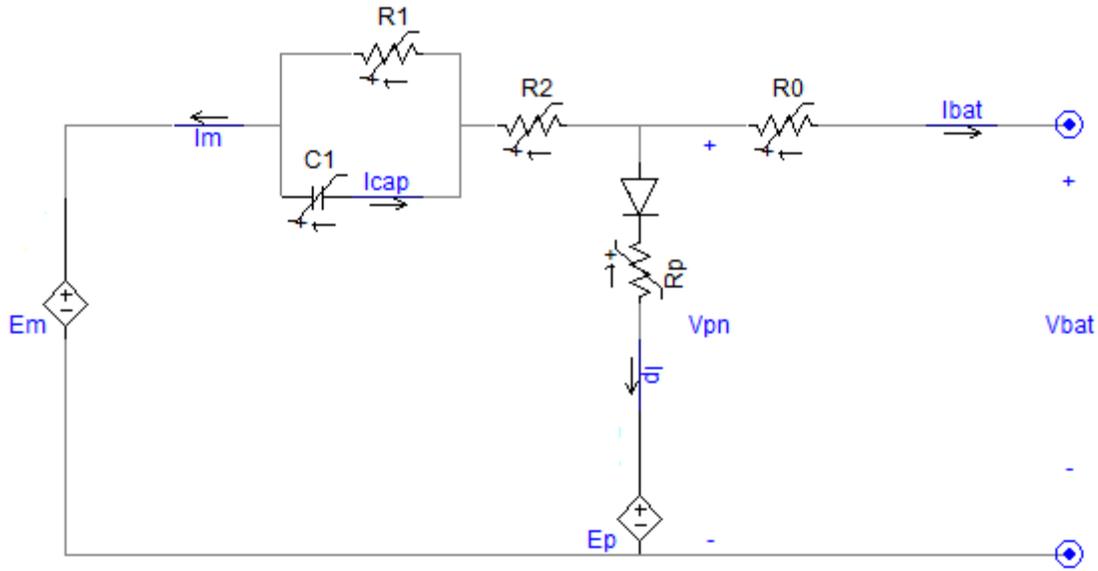


Figure 2: Thevenin battery model

Recently, models that are more realistic have been proposed to take into account of the non-linear parameters of the battery [8]-[9]. These models characterized the battery internal resistance, self-discharge resistance, and overcharge resistance, and separated the charging and discharging process. One of these improved models is a third order model developed by Ceraolo [11]-[12]. Figure 3 shows the model.



**Figure 3: Third order battery model**

In this model, the main branch (containing the elements  $E_m$ ,  $R_1$ ,  $C_1$ , and  $R_2$ ) approximates the battery charge/discharge dynamics, the parasitic branch (containing  $R_p$  and  $E_p$ ) accounts for the self-discharge, and  $R_0$  approximates the overcharge resistance. As the figure indicates, most of the resistive elements are non-linear, current dependent, and are determined empirically [13].

The equations for the circuit components shown in Figure 3 can be written as follows:

$$E_m = E_{m0} - K_E (273 + \theta)(1 - SOC)$$

$$C_1 = \frac{\tau_1}{R_1}$$

$$R_1 = -R_{10} \ln(DOD)$$

$$R_2 = R_{20} \frac{e^{A_{21}(1-SOC)}}{1 + e^{(A_{22} I_m / I^*)}}$$

$$I_p = V_{pn} G_{po} e^{\left(\frac{V_{pn} + A_p (1 - \frac{\theta}{\theta_f})}{V_{po}}\right)}$$

$$R_p = \frac{V_{pn} - E_p}{I_p}$$

$$R_0 = R_{00} [1 + A_0 (1 - SOC)]$$

$$E_p = \text{constant}$$

where  $E_m$  was the open-circuit voltage (EMF) in volts,  $E_{mo}$  was the open-circuit voltage at full charge in volts,  $KE$  was a constant in volts/ $^{\circ}C$ ,  $C_1$  was a main branch capacitance in farads,  $\tau_1$  was a main branch time constant in seconds,  $R_1$  was a main branch resistance in ohms,  $R_{10}$  was a constant in ohms,  $R_2$  was a main branch resistance in ohms,  $R_{20}$  was a constant in ohms,  $A_{21}$  was a constant,  $A_{22}$  was a constant,  $I_m$  was the main branch current in amps,  $I_p$  was the current loss in the parasitic branch,  $V_{pn}$  was the voltage at the parasitic branch,  $G_{po}$  was a constant in seconds,  $V_{po}$  was a constant in volts,  $A_p$  was a constant,  $R_p$  was a parasitic resistance in ohms,  $R_0$  was a resistance in ohms,  $R_{00}$  was the value of  $R_0$  at  $SOC=1$  in ohms, and  $A_0$  was a constant. The SOC and the DOD can be defined as:

$$SOC = 1 - \frac{Q_e}{C(0, \theta)}$$

$$Q_e = Q_{e\_init} + \int_0^{\tau} -I_m(\tau) d\tau$$

$$C(I, \theta) = \frac{K_c C_0^* \left(1 + \frac{\theta}{-\theta_f}\right) \varepsilon}{1 + (K_c - 1) \left(\frac{I}{I^*}\right) \delta}$$

$$DOD = 1 - \frac{Q_e}{C(I_{avg}, \theta)}$$

$$I_{avg} = \frac{I_m}{\tau_1 s + 1}$$

where C is the battery's capacity in Amp-seconds, Qe is the extracted charge in Amp-seconds, Qe\_init is the initial extracted charge in Amp-seconds, Im is the main branch current in Amps, Iavg was the mean discharge current in amps, Kc, δ, and ε are constants, C0\* is the no load capacity at 0°C in Amp-seconds, θ is electrolyte temperature in °C, θf is the electrolyte freezing temperature, I is the discharge current in Amps, and I\* is the nominal battery current in Amps. Typical values for all the constants can be found in [11].

### 3.1.1.1.2 *Lithium Ion Battery*

Pioneer work with the lithium batteries began in 1912 under G.N. Lewis, but it was not until the early 1970s that the first non-rechargeable lithium batteries became commercially available. Attempts to develop rechargeable lithium batteries followed in the 1980s, but failed due to safety problems [14].

The cathode in lithium ion batteries is a lithiated metal oxide (LiCoO<sub>2</sub>, LiMO<sub>2</sub>, etc.) and the anode is made of graphitic carbon with a layer structure. The electrolyte is made up of lithium salts (such as LiPF<sub>6</sub>) dissolved in organic carbonates [15].

When the battery is being charged, the lithium atoms in the cathode become ions and migrate through the electrolyte toward the carbon anode where they combine with external electrons and are deposited between carbon layers as lithium atoms. The reverse of this process occurs during discharge.

The main advantages of Li-ion batteries, compared to other advanced batteries, are their high energy density, high efficiency, and long cycle life. The main difficulty with these batteries is the high cost due to special packaging and internal overcharge protection circuits.

### 3.1.1.1.3 *Nickel Cadmium Battery*

Waldmar Jungner invented the nickel-cadmium battery in 1899. At that time, due to the expense of the materials used in the battery, its use was limited to special applications. In 1932, the active materials were deposited inside a porous nickel-plated electrode, and in 1947, research began on a sealed nickel-cadmium battery [16].

Among rechargeable batteries, nickel-cadmium remains a popular choice for two-way radios, emergency medical equipment, and power tools. There is a shift towards batteries with higher energy densities and less toxic metals but alternative chemistries cannot always match the durability and low cost of nickel-cadmium. The advantages of Nickel-cadmium (Ni-Cd)

batteries are their long lives in stationary applications, and typically being quite resistant to abuse [2].

#### **3.1.1.1.4 Sodium Sulfur Battery**

The sodium sulfur (NaS) battery technology was originally developed in the 1960s for use in early electric cars but was abandoned later for this application [5].

The NaS battery consists of sulfur at positive electrode, sodium at negative electrode as active materials, and beta alumina of sodium ion conductive ceramic which separates both electrodes. This hermetically sealed battery is operated under the condition that the active materials at both electrodes are liquid, and its electrolyte is solid.

During discharge, positive sodium ions flow through the electrolyte and electrons flow in the external circuit of the battery to produce about 2V. This process is reversible since charging causes sodium polysulfides to release the positive sodium ions back through the electrolyte to recombine the sodium element.

This type of battery has a high energy density, a high efficiency of charge/discharge (89–92 percent) [17], long cycle life, and is fabricated from inexpensive materials. However, because of the operating temperatures of 300°C, and the highly corrosive nature of the sodium polysulfides, such cells are primarily suitable for large-scale non-mobile applications such as grid energy storage.

NaS battery technology has been demonstrated over 190 sites in Japan, totaling more than 270 MW of capacity with stored energy suitable for 6 hours of daily peak shaving. The largest NaS installation is a 34 MW, 245 MWh system for wind farm stabilization in Northern Japan [15]. Utilities in the U.S. have deployed 9 MW of NaS batteries for peak shaving, backup power, smoothing wind power, and other applications [5].

#### **Sodium Sulfur Battery Modeling**

In order to model the NaS battery accurately, the following factors need to be taken into account [17]:

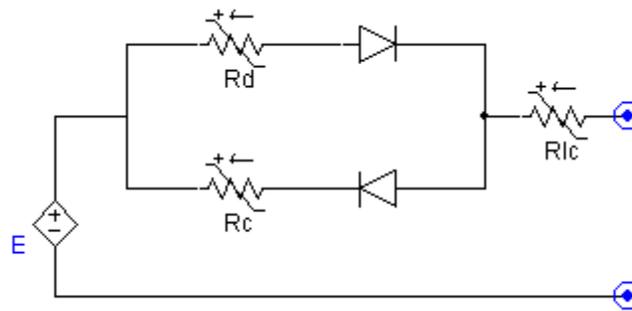
- Internal Resistance
- Temperature Effect
- Battery Electromotive Force
- Depth of Discharge

Since NaS battery's internal resistance is sensitive to and varies with temperature and DOD, the simple battery model shown in Figure 1 is not suitable in modeling the battery, because it does not take into account the varying characteristic of the internal resistance of the battery with

respect to DOD and temperature changes. Such model only applies in some circuit calculation or simulation where the energy from  $E_0$  is assumed unlimited.

The Thevenin battery model shown in Figure 2 has a disadvantage in modeling the NaS battery because the elements are all assumed constant, yet in fact, all the values are a function of battery conditions. In addition, the internal open circuit voltage drops in NaS battery is not taken into account in this model.

In order to take into account the factors addressed above, the modified battery model shown in Figure 4 can be used [17].



**Figure 4: Detailed battery model**

This battery model is relatively simple but meets most requirements for modeling of the NaS battery. It takes into account the non-linear battery element characteristic during charging ( $R_c$ ) and discharging ( $R_d$ ), as well as the internal resistance ( $R_l$ ) which depends on the temperature changes and DOD of the battery as discussed before. Therefore, it can be selected as the most appropriate in modeling the NaS battery.

#### 3.1.1.1.5 *Flow Battery*

Flow batteries allow storage of the active materials external to the battery and these reactants are circulated through the cell stack as required. The first such battery was Zinc Chlorine battery in which the chlorine was stored in a separate cylinder. It was first used in 1884 by Charles Renard to power his airship La France, which contained its own on-board chlorine generator [18].

Flow batteries differ from conventional rechargeable batteries in one significant way which is the ability to scale the power and energy ratings of a flow battery independent of each other [5]. This is made possible by the separation of the electrolyte and the battery stack (or fuel cell stack). More cell stacks allow for an increase in power rating; a greater volume of electrolytes results in more runtime.

Some leading flow battery technologies are Zinc Bromine (ZnBr) and Vanadium Redox batteries (VRB).

The ZnBr battery was developed by Exxon in the early 1970's. Integrated ZnBr energy storage systems are now available on transportable trailers (storage systems including power electronics) with unit capacities of up to 1MW/3MWh for utility-scale applications [15].

VRB was pioneered by the University of New South Wales (UNSW) in Australia in early 1980's. The Australian Pinnacle VRB bought the basic patents in 1998 and licensed them to Sumitomo Electric Industries (SEI) and VRB Power Systems. VRB storages up to 500kW, 10 hrs (5MWh) have been installed in Japan by SEI. VRBs have also been applied for power quality applications (3MW, 1.5 sec., SEI) [15].

### Vanadium Redox Flow Battery Modeling

Since this technology is one of the latest batteries, there is not sufficient published literature which focuses on VRB modeling. A VRB model which consists of the internal voltage, the losses (of both the device itself and the pump system), and electrodes capacitance, is seen in Figure 5.

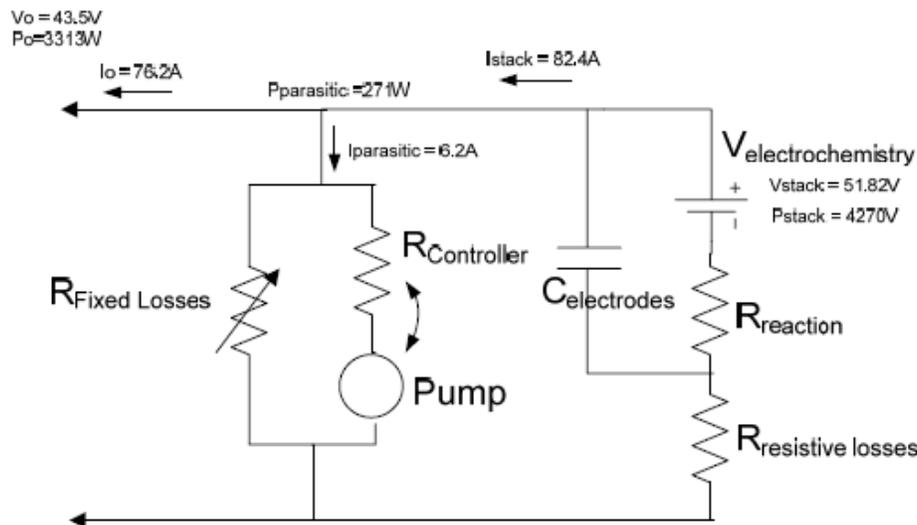


Figure 5: Vanadium redox flow model [31]

#### 3.1.1.2 Compressed Air Energy Storage (CAES)

Compressed Air Energy Storage refers to the compression of air to be used later as the energy source. CAES is a peaking gas turbine power plant that consumes less than 40 percent of the gas used in a conventional gas turbine to produce the same amount of electric output power. This is because, unlike conventional gas turbines that consume about 2/3 of their input fuel to compress air at the time of generation, CAES pre-compresses air using the low cost electricity

from the power grid at off-peak times and utilizes that energy later along with some gas fuel for use during peak periods [15].

To make the CAES concept work depends on locating the plants near appropriate underground geological formations, such as underground mines, caverns created inside salt rocks, or depleted gas wells.

The first commercial CAES plant was a 290 MW unit built in Germany in 1978. The second one was a 110 MW unit built in the U.S.. These units can come on line in 15 minutes when called upon for power. Today, Electric Power Research Institute (EPRI) has a research program to develop advanced CAES designs with a power range varying between 150 MW and 400 MW. In addition to this, an above ground CAES alternative is also studied by EPRI [5].

### *3.1.1.3 Electrochemical Capacitors (Supercapacitors)*

Electrochemical capacitors, commonly called supercapacitors, store electrical energy in two series capacitors of the electric double layer (EDL), which is formed between each of the electrodes and the electrolyte ions. The distance over which the charge separation occurs is just a few angstroms. The extremely large surface area makes the capacitance and energy density of these devices thousands of times larger than conventional electrolytic capacitors [5].

The electrodes of these supercapacitors are often made with porous carbon material. The electrolyte is either aqueous or organic. The aqueous capacitors have a lower energy density due to a lower cell voltage, but are less expensive and work in a wider temperature range. The asymmetrical capacitors that use metal for one of the electrodes have a significantly larger energy density than the symmetric ones do and also have a lower leakage current [15].

Electrochemical capacitors have lower energy density compared to lead-acid batteries, but they can be cycled tens of thousands of times and they have faster charge and discharge capability compared to batteries.

While the small electrochemical capacitors are well developed, the larger units with energy densities over 20 kWh/m<sup>3</sup> are still under development. Rather than operate as a main battery, supercapacitors are more commonly used as memory backup to bridge short power interruptions. Another application is improving the current handling of a battery. The electrochemical capacitor is placed in parallel to the battery terminal and provides current boost on high load demands. The electrochemical capacitors will also find a ready market for portable fuel cells to enhance peak-load performance. Because of their ability to rapidly charge, large supercapacitors are used for regenerative braking on vehicles [20].

### *3.1.1.4 Flywheel Energy Storage (FES)*

Modern flywheel energy storage systems consist of a huge rotating cylinder (comprised of a rim attached to a shaft) that is substantially supported on a stator by magnetically levitated bearings

that eliminate bearing wear and increase system life. To maintain efficiency, the flywheel system is operated in a vacuum environment to reduce drag. The flywheel is connected to a motor/generator mounted onto the stator that interacts with the utility grid through power electronics [15].

The stored energy on a flywheel depends on the moment of inertia of the rotor and the square of the rotational velocity of the flywheel. The moment of inertia depends on the radius, mass, and height (length) of the rotor. Energy is transferred to the flywheel when the machine operates as a motor, i.e., the flywheel accelerates, charging the energy storage device. The flywheel is discharged when the electric machine regenerates through the drive, i.e., the flywheel decelerates [1].

The energy storage capability of flywheels can be improved either by increasing the moment of inertia of the flywheel or by rotating it at higher velocities, or both. Some designs utilize hollow cylinders for the rotor, allowing the mass to be concentrated at the outer radius of the flywheel, improving storage capability with a smaller weight increase [21].

Some of the key features of flywheels are long life (20 years or 10's of thousands of deep cycles), low maintenance, and environmentally inert material. Flywheels can bridge the gap between short-term ride-through and long-term storage with excellent cyclic and load following characteristics [15].

While high-power flywheels are developed and deployed for aerospace and UPS applications, there is an effort going on to optimize low-cost commercial flywheel designs for long duration operation (up to several hours). At present, high speed flywheel systems rated 1000kW (15 min. duration) or larger are being deployed in the U.S. for frequency regulation [5].

#### *3.1.1.5 Pumped Hydro*

A typical pumped hydro plant consists of two interconnected reservoirs, i.e., lakes, tunnels that connect one reservoir to another, hydro machinery, valves, a generator-motor, transformers, a transmission switchyard, and connection to a transmission system. The product of the total volume of water and the differential height between the reservoirs is proportional to the amount of stored energy [5].

Pumped hydro was first used in Italy and Switzerland in the 1890's. Beginning in the early 1900's, several small hydroelectric pumped storage plants were constructed in Europe, primarily in Germany. The first unit in the U.S. was constructed in 1929 in Connecticut. Today, adjustable speed machines are being used to improve efficiency and pumped hydro is available at almost any scale with discharge times ranging from several hours to a few days. Their efficiency is in the 70 percent to 85 percent range [15].

The global capacity of pumped hydro storage plants installed to date totals more than 95 GW with around 20 GW operating in the U.S.. The main function of these plants was to provide off-peak base loading for large coal and nuclear power plants to optimize the overall performance and provide peaking energy each day. Nowadays, their duties have been expanded to include providing ancillary services such as frequency regulation [5].

#### *3.1.1.6 Superconducting Magnetic Energy Storage (SMES)*

Superconducting magnetic energy storage systems store energy in the field of a large magnetic coil with direct current flowing. It can be converted back to alternative current as needed.

Although superconductivity was discovered in 1911, it was not until the 1970's that SMES was first proposed as an energy storage technology for power systems [22].

A magnetic field is created by circulating a DC current in a closed coil of superconducting wire. The path of the coil circulating current can be opened with a solid state switch which is modulated to be either on or off. Due to the high inductance of the coil, when the switch is off, i.e., open, the magnetic coil behaves as a current source and will force current into the capacitor which will charge to some voltage level. Proper modulation of the solid-state switch can hold the voltage across the capacitor within the proper operating range of the inverter. An inverter then converts the DC voltage into AC voltage [23].

SMES systems have attracted the attention of both utilities and the military due to their fast response and high efficiency (charge/discharge efficiency over 95 percent). Possible applications of this technology include load leveling, dynamic stability, transient stability, voltage stability, frequency regulation, transmission capability enhancement, and power quality improvement [1]. Low temperature SMES cooled by liquid helium is commercially available and high temperature SMES cooled by liquid nitrogen is still in the development stage and may become a viable commercial energy storage source in the future [32].

### 3.1.2 Energy Storage Benefits

Energy storage provides several benefits for electric power utilities, transmission companies, electricity generators, and electric power end users. The applications of energy storage can be summarized as follows:

- **Improve integration of renewable energy sources:** Energy storage can be used to dispatch renewable energy sources such as wind and solar [33]. Moreover, electricity generated during off-peak times can be “time-shifted” so that the energy can be sold during peak times.
- **Transmission and distribution deferral:** Defer the need for additional transmission/distribution upgrades by supplementing the existing

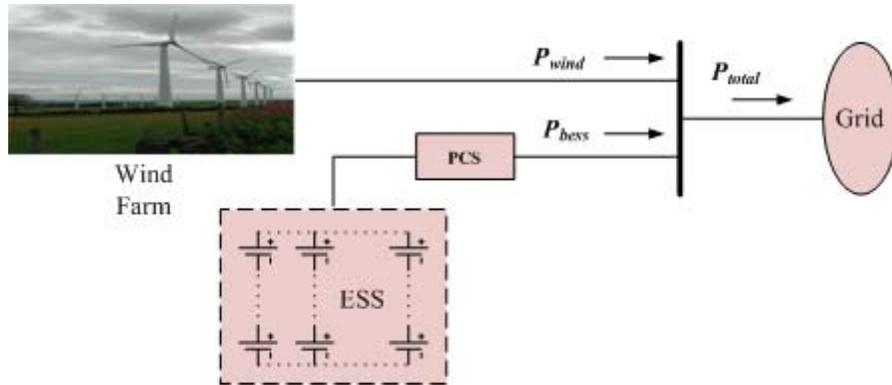
transmission/distribution facilities, i.e., saving capital that otherwise goes underutilized for years.

- **Arbitrage:** Arbitrage involves purchasing inexpensive electricity when its demand and cost are low, and then selling the electricity when demand and price are high. Storage systems that are used for this purpose generally have the capacity to store large amounts of energy, interact with the power grid at the transmission level, and operate on a diurnal cycle of charge and discharge [34].
- **Spinning reserve:** Energy storage systems including batteries, capacitors, and flywheels, interact with the grid via an electronic power controller and respond within minutes to compensate for generation or transmission outages. Therefore, they can accommodate some of the utilities' spinning reserve requirements without any difficulty.
- **Transmission support:** Energy storage improves the performance of the transmission system by increasing the load carrying capacity of it; a benefit accrues if additional load carrying capacity defers the need to add more transmission capacity and/or additional T&D equipment. This provides a benefit to the owner of the transmission system.
- **Stabilize the transmission and distribution grid:** Energy storage facilities designed to support transmission and distribution networks maintain the stability and reliability of the grid by quickly injecting active power into the grid with a short discharge, but a faster reaction time [35].
- **Improve load following and frequency regulation:** Energy storage can act as a buffer that isolates the rest of the power grid from sudden changes in the load and it can also help to maintain frequency regulation during irregular grid conditions, large and rapid changes in the load [36].
- **Enable more efficient use of existing generation assets:** Energy storage can reduce the need for cycling coal-fired plants (i.e., peakers) and creates efficiencies along the grid. Moreover, it also reduces dispatch costs incurred by generation assets.
- **Reduce greenhouse gas emission:** The introduction and use of energy storage technologies can reduce overall greenhouse gas emissions with a clean and reliable energy source as an alternative to fossil fuel generation.

#### 3.1.2.1 Application Examples

**Wind Intermittency Mitigation:** In this strategy, the battery energy storage system (BESS) is utilized to minimize the wind's variability at an individual wind farm of 60 MW capacity through an hourly dispatch [37]. Integration of BESS with a wind farm is shown in

Figure 6.

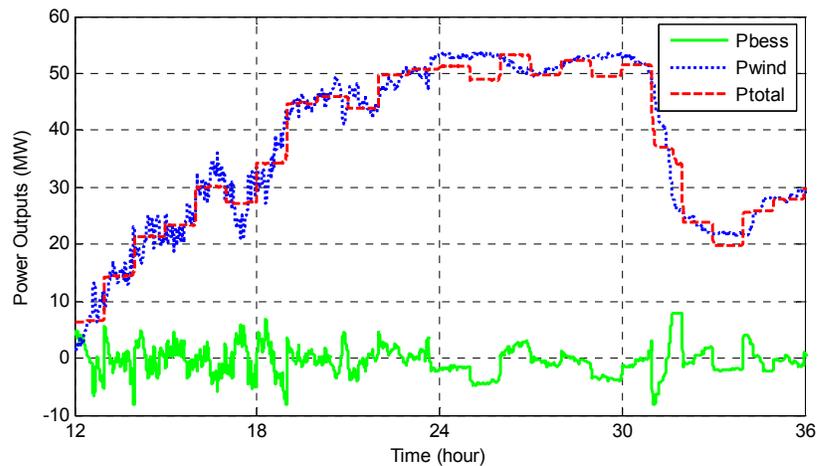


**Figure 6: BESS integration at a wind farm**

For the study, it is assumed that the average wind power output for the next hour ( $P_{set}$ ) can be forecasted with 10 percent mean absolute error of the wind farm power output [38], [39] and the BESS will compensate the differences between the hourly dispatch level,  $P_{set}$ , which comes from the forecast, and the wind farm power output,  $P_{wind}$ . The power at the battery,  $P_{bess}$ , then can be expressed as  $P_{bess} = P_{set} - P_{wind}$  and the total power flowing to the grid becomes  $P_{total} = P_{wind} + P_{bess}$ .

During the study, the basic assumptions regarding the BESS include AC/DC converter losses of 3 percent, the State of Charge (SOC) of the battery is allowed to change between 30 percent and 100 percent, and each battery contributes the same amount of current (uniform SOC among battery cells).

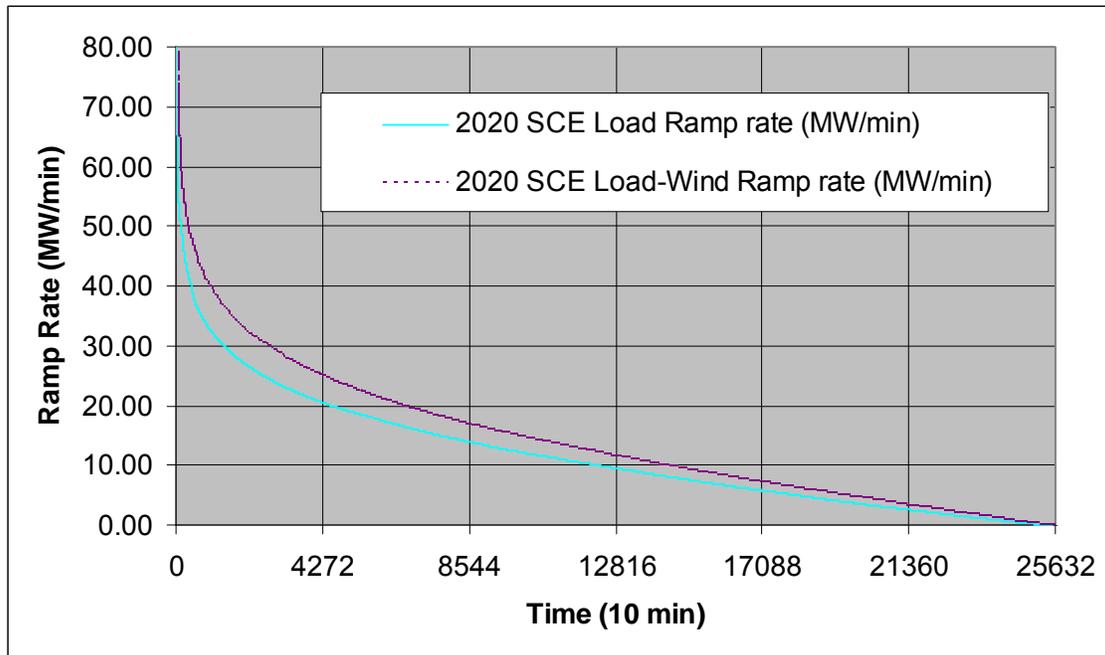
The simulation results obtained with an 8 MW (max 4-hour discharge, i.e., 32 MWh) BESS is shown in Figure 7.

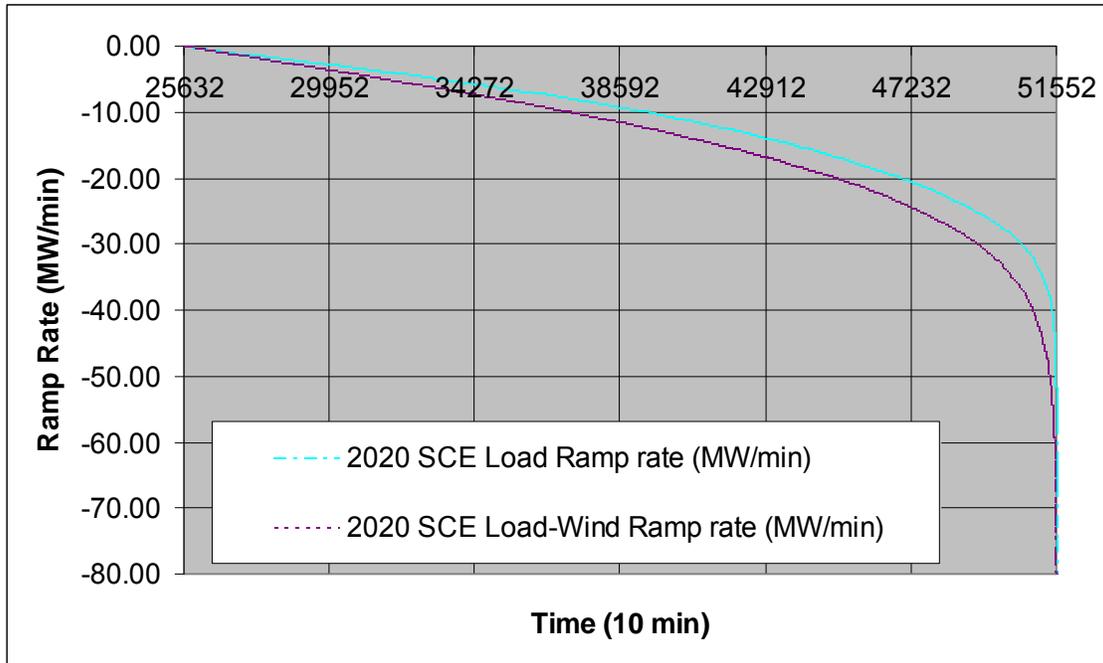


**Figure 7: BESS dispatch performance ( $P_{bess}$ : BESS power,  $P_{wind}$ : wind power,  $P_{total}$ : net injected power in MW)**

It is seen from Figure 7 that the wind power can be dispatched with the help of the BESS and the undesired fluctuations of the wind power are eliminated.

**Wind Ramp Rate Mitigation:** A study to analyze the effects of renewable energy penetration on ramp rate, frequency response, and dynamic power balancing, in SCE system in the year of 2020 is made in [40]. The results showing the effect of 20 percent wind penetration to SCE system on the ramp rates by 2020 is shown below [40].





**Figure 8: Ramp up and Ramp down requirement with 20% wind penetration to SCE**

It is seen from Figure 8 that with the penetration of 20 percent wind to SCE system, the ramp up and ramp down rate requirement increases on average 3MW/min throughout the year. This result shows that the storage management strategy needs to compensate this increase by providing the additional ramping capability required.

### 3.1.3 Energy Storage Performance Metrics

This section contains the results of the literature search aimed at identifying candidate metrics for assessing the performance and value of energy storage.

The main disadvantage of wind energy when compared to other renewable resources is the lack of correlation with demand due to intermittency in wind plant power output. Energy storage can provide backup or supplementary power in times of low wind and can be utilized to improve the electrical quality of wind power output. Storage also provides the benefit of capturing surplus wind power that cannot be utilized by the grid due to low load demand. Energy storage thus has the potential to play a key role in enabling wind energy to match the reliability characteristics of other renewable resources and possibly even conventional electricity generators. This section will identify and define performance metrics that capture and quantify the benefits of energy storage.

**Energy Storage key performance metrics:** Some of the key performance metrics to consider would be:

- **Reliability Performance Gap (RPG) Index**

This metric will help define how the designed energy storage (ES) improves reliability based on events happening on the bulk electric system (the ability to cope with contingencies) concerned with dynamic conditions. This also can be looked at as the effect of ES on the transmission system.

Events can then be classified into two general classes:

- a. **Disturbance Events**

Disturbance events are the disturbances that significantly affect the integrity of interconnected system operations. These can be categorized as follows:

- i. **Category 1:**

1. The loss of a transmission equipment tied to the ES (single phase line to ground fault with delayed clearing, line tripping due to growing trees, etc.)
2. A frequency below the Low Frequency Trigger Limit more than 5 minutes
3. An inter-area oscillation

- ii. **Category 2:**

1. The loss of multiple bulk transmission components (lines, substations, etc.)
2. The loss of a large amount of generation within the interconnection
3. The loss of entire switching station (all lines, 100 kV or above)
4. The loss of a DC converter station
5. The occurrence of islanding

- iii. **Category 3:**

1. The loss of a large amount of generation (>2,000 MW)
2. The loss of load
3. Under Frequency Load Shed (UFLS) or Under Voltage Load Shed (UVLS)

- iv. **Category 4:**

1. The occurrence of an interconnected system separation or islanding

2. The loss of load
- b. Capacity and Energy Events
- i. Category 1: All resources in use
    1. Required Operating Reserves cannot be sustained
    2. Non-firm wholesale energy sales have been curtailed
  - ii. Category 2: Load management procedures in effect
    1. Public appeals to reduce demand
    2. Voltage reduction
    3. Interruption of non-firm end-use load
    4. Demand-side management
    5. Utility load conservation measures

- **Demand Charge Savings Index (DCS) (peak shaving)**

Demand Charge Savings (DCS) is primarily a measure of component peak shaving. The maximum peak shaved stands for the largest demand reduction per month. The best way to calculate this is sum the demand shaved over a 12-month period multiplied by the on-peak demand charge minus the off-peak demand charge multiplied by the escalation and capacity factors of the ES. The escalation factor is compound growth factor at the demand charge, capacity factor the adjusted saving of a partial year's operation in the first year, and m the index of each month. The formula can be written out as follows:

$$DCS = \sum_{m=1}^{12} \left\{ (Peak\ Shaved)_m \times \left[ (On - peak\ energy\ charge)_m - (Off - peak\ energy\ charge)_m \right] \right\} \\ \times (Escalation\ factor) \times (Capacity\ factor)$$

- **Annual Energy Charge Savings Index (ECS)**

The Energy Charge Savings (ECS) can be computed from tariff and load data where the Energy per discharge each month is multiplied by the cycles per month multiplied by the on-peak energy charge minus the off-peak energy charge divided by the round-trip efficiency of the ES. All of this is multiplied by the escalation and capacity factor. The formula can be written out as follows:

$$ECS = \sum_{m=1}^{12} \left\{ (Energy\ per\ discharge)_m \times (Cycles\ per\ month)_m \times \left[ (On - peak\ energy\ charge)_m - (Off - peak\ energy\ charge)_m \div (Round - trip\ efficiency) \right] \right\} \times (Escalation\ factor) \times (Capacity\ factor)$$

### Performance Metrics for ES Installation

In order to track the performance of the ES device, a variety of performance indicators can be used. Some are included in the sections above but in order to track the performance indicators of ES installation itself, the following should be included as well:

- Round-trip energy efficiency and losses appreciation
- Availability and reliability of the ES solution
- Energy storage cycle life and life time
- Other application specific key performance indicators
  - a. Round-trip energy efficiency and losses appreciation:

This is a measure of the efficiency of the energy charge and discharge cycles:

$$\eta = E_{out}/E_{in}$$

with the round trip efficiency  $\eta$  in %

$E_{out}$  the energy discharge to the grid at the point of interconnection (Wh)

$E_{in}$  the energy charge to the grid at the point of interconnection (Wh)

Most energy storage devices have efficiencies of 75 – 90 percent but are a function of the Depth of Discharge (DOD).

- b. Availability and reliability of the ES solution:

Depending on the application of the energy storage device, availability and reliability needs to be tracked and minimum numbers, need to be prescribed during the specification phase. Several definitions on availability and device reliability are provided and the following definitions are proposed for measuring the ES device availability and reliability. These have to be specified during the specification phase.

## 3.2 Energy Storage Case Studies

### 3.2.1 Grid Quality Issues

Quanta Technology and SCE staff quantified the grid power quality and reliability issues at selected three interconnection locations. Table 1 provides the three study area names and brief explanation of the issues.

**Table 1: Study areas and issues**

<b>AREA</b>	<b>ISSUE</b>
Tehachapi	Renewable: The Tehachapi Area suffers from voltage instability and may benefit from any type of voltage conditioning and regulation.
Palm Springs Area	Renewable: The Palm Springs Area wind generation is limited by thermal constraints on the existing transmission lines.
South Bay Area	Non-renewable: The South Bay Area has loads sensitive to power system disturbances.

The detailed explanation of the issues in the study areas is provided below:

**Tehachapi Area:** Tehachapi is a wind abundant area in SCE. The installed wind capacity in the area is around 380 MWs and around 310 MWs of coincident peak. Most of the wind turbines are Type 1 which does not have reactive power capability and absorb around 100 MVAR reactive power from the system. A summary of the system characteristics and problems in Tehachapi area include:

- 380 MW installed wind capacity (310 MW coincident peak)
- Absorbs around 100 MVAR reactive power from system
- No Low-Voltage-Ride-Through (LVRT) capability
- Non-compliant with FERC – Large Generator Interconnection Procedure (LGIP)
- Routine wind farm curtailments
- N-1 contingency requires > 60 MW wind curtailment
- Voltage collapse concern during line trip
- Operational problems with the installed first generation SVC
- Reactive power support is not well coordinated

**Palm Springs Area:** Palm Springs is also a wind abundant area. The installed wind capacity in the area is around 750 MW and the wind turbines are mostly Type 1. The capacity factor assumed for the wind generation in the area is 30 percent and the wind turbines absorb around 100 MVAR from the system. A summary of the system characteristics and problems in the Palm Springs area are listed below:

- Several lines in this area overload when the wind is lower than 30 percent of the nameplate capacity. Additional generation close to the wind generation adds value to the system.
- The local peakers, which run in lack of wind, have however higher operational and maintenance cost.
- The start/stop cycles of the peakers result in additional maintenance and may impact the generator life-time.
- Load shedding of around 35 MW is required when the temperatures goes above 100°F

**South Bay Area:** This area is composed of mostly industrial load including a few large oil refineries consisting of large induction machines. The machines stall if voltage support is absent during voltage sags. The summary of power quality issues observed at the refinery includes:

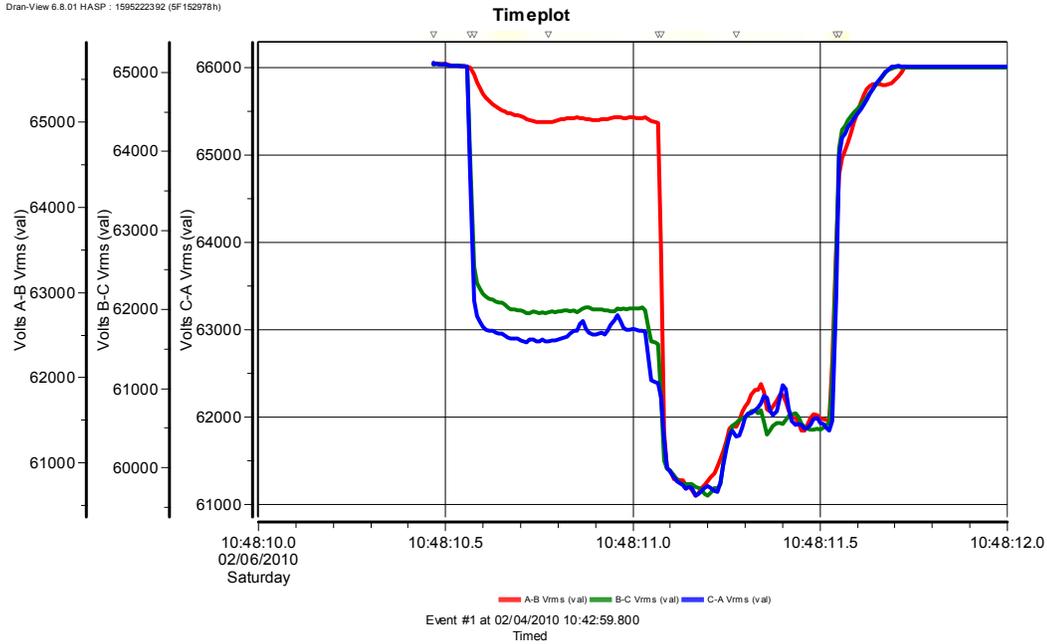
- Voltage sags
- Harmonic problems
- Flickers

SCE personnel provided measurements from one of the refineries for the study. The measurements obtained cover a period from 2/1/2010 to 2/7/2010. This data provided some insight to the power quality issues in the study area.

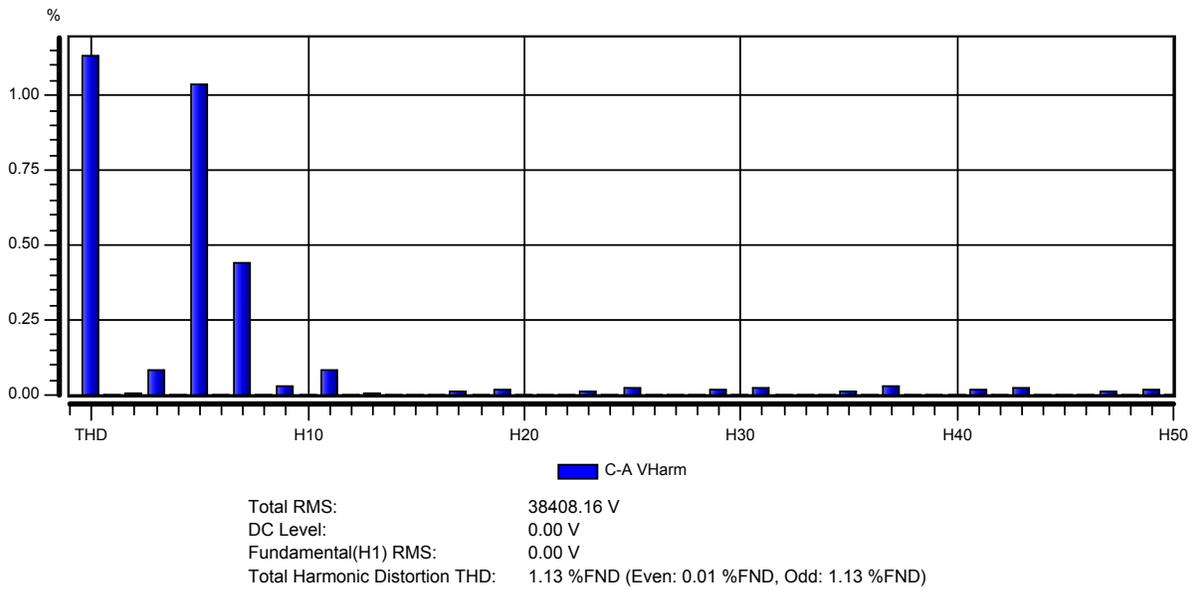
Typical voltage sag occurring at the refinery is shown in Figure 9. It is seen that the voltage drops to 90 percent of the nominal value during the sag which lasts for 1 sec.

The worst case harmonic spectrum of the voltage obtained at the refinery is shown in Figure 10. This figure shows the THD occurring in the measurement period. It is seen that the worst case voltage THD is 1.2 percent during the week long measurements.

During the measurement period mentioned previously, measured data was well within IEEE 510 standard. Previously, some power quality concerns were identified at this location in the SCE system.



**Figure 9: Voltage sag occurring at the refinery**



**Figure 10: Voltage harmonic spectrum at the refinery**

### 3.2.2 Mitigation Strategies

In order to mitigate the power quality, path constraint and transient stability issues addressed in the previous section, Quanta Technology proposed the solutions shown in Table 2 for the selected locations.

**Table 2: Proposed Solutions at selected locations**

AREA	PROPOSED SOLUTION
Tehachapi	Battery Energy Storage System (BESS) and STATCOM
Palm Springs Area	Compressed Air Energy Storage (CAES)
South Bay Area	Static Synchronous Compensator (STATCOM)

The details of the studies for each area are provided below:

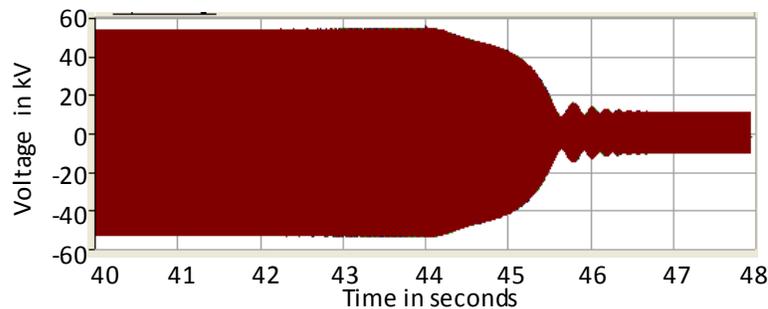
### 3.2.2.1 Tehachapi Area

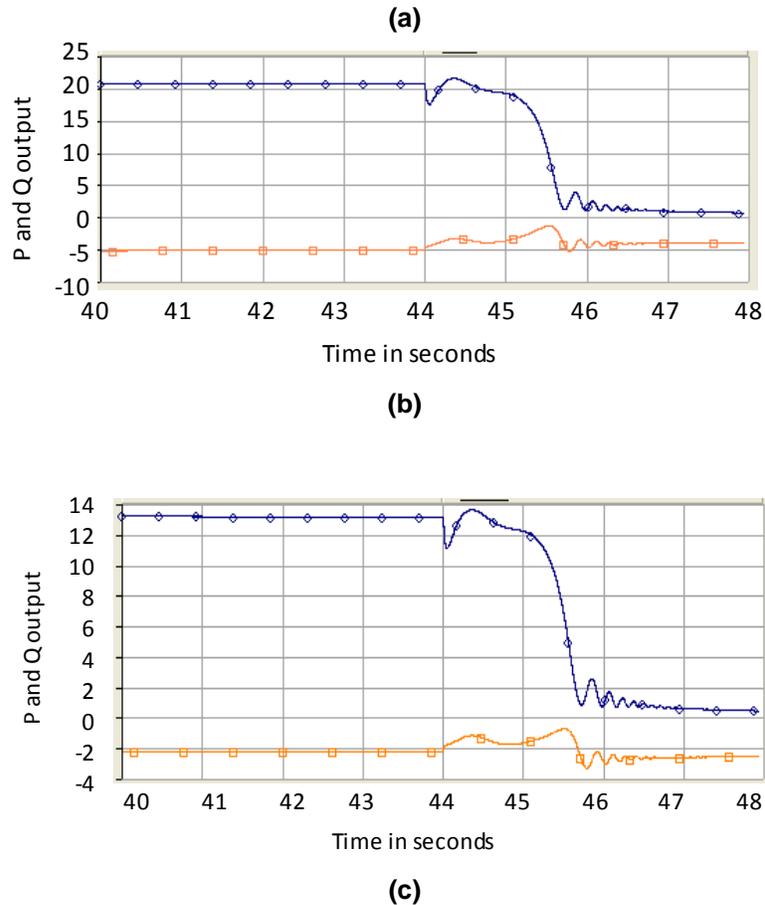
The studies performed in Tehachapi area are based on two software tools: Positive Sequence Load Flow (PSLF) and Power System Computer-Aided Design (PSCAD. The PSLF model is a SCE system wide network database used for bulk power system analysis. The 2009 year SCE base case is used for the steady-state contingency analysis and dynamic simulations. The wind generation static and dynamic characteristics were added to the base case. Wind generation was modeled as Type 1 wind farms, i.e., without any reactive power support [41]. The results obtained from this base case are representative of the operating conditions in the system.

The PSCAD model is essentially a detailed representation of the wind power generation rich area in the SCE system, but the rest of the system is represented by an equivalent. The results obtained from this base case are used to re-confirm the results obtained in PSLF in which the full SCE system is represented.

Contingency analysis on the Tehachapi area was performed and two critical contingencies were identified as unsolved cases/non-converging during steady state load flow simulations. SCE has issued operational instructions that outline the mitigation techniques for these contingencies by wind energy generation curtailment.

Figure 11 shows the voltage profile and the power output for two individual wind farms in the area of study and its performance during one of the two critical contingencies. These results are based on simulations performed in PSCAD software tool. As can be seen in Figure 11 the voltage collapses after the contingency and the power output of the two individual wind farms goes to zero in less than 2 seconds after the contingency.

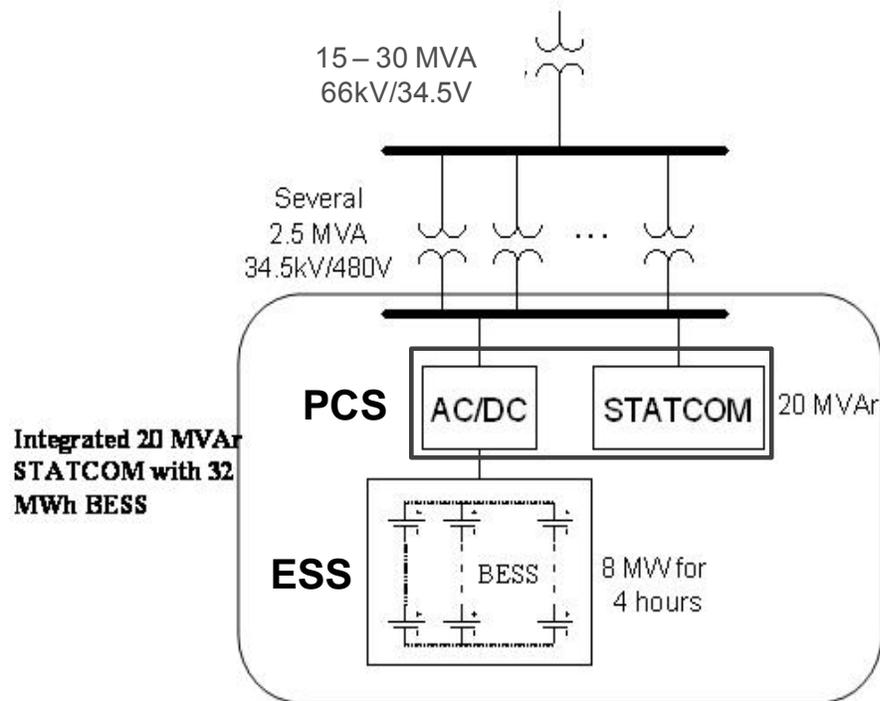




**Figure 11: Voltage profile (a) and the power output for two individual wind farms (b) and (c) during one of the critical contingencies (P and Q shown with dark and light color, respectively)**

After reviewing the existing storage technologies, Quanta Technology and SCE staff selected the energy storage technology as BESS with Static Synchronous Compensator (STATCOM). The size and location of the storage are selected based on the solution to contingency problems mentioned above. The proposed BESS with STATCOM is shown in Figure 12.

The proposed BESS should provide 8 MW up to 4 hours and the STATCOM should be capable of providing 20 MVAR up to 4 seconds in order to mitigate the aforementioned problems.



**Figure 12: Basic Schematic of the BESS – STATCOM**

The substation selection was based on the following criteria:

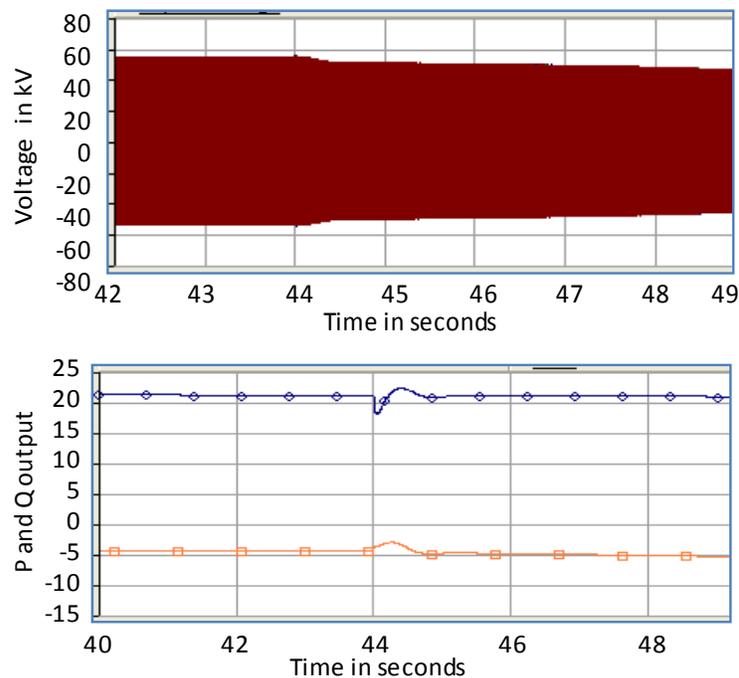
- Close proximity to the high capacity wind farms in the area;
- Existence of at least 10 MW of local loads near the selected substation which can be supplied partially by the storage;
- Mitigation of the voltage and angular stability effects of the critical contingencies;
- Available physical space inside the substation.

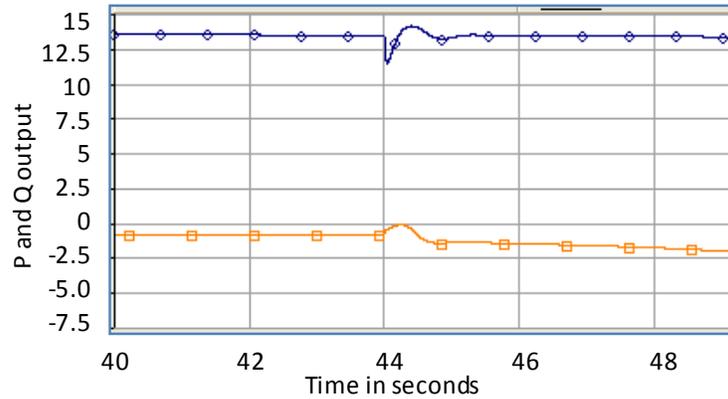
The benefits obtained with the proposed BESS – STATCOM can be summarized as follows:

- Contingency support in terms of MW and MVAR. The BESS – STATCOM prevents the system from collapsing for the critical contingencies.
- Voltage profile support. With the BESS – STATCOM, the voltage recovery is improved by about 10-15 percent.
- Improved fault ride-through support on Type 1 wind farms. The BESS – STATCOM can support the close-by wind farms to ride through low voltage excursions following distant line faults.
- Some portion of the connected wind farms can be dispatched an hour ahead.
- Regulation ancillary services are provided

- Can provide Black-start functionality
- Add additional spinning reserves
- Energy price arbitrage
- Large transmission upgrades to the wind facility can be postponed for several years.
- Curtailments of the wind farm are minimized up to 4 hours

Dynamic simulations in PSLF and PSCAD software tools were performed in order to validate the benefits mentioned above. Figure 13 shows the voltage profile and the power output for two wind farms after one of the two critical contingencies. As it can be seen in the figure, the BESS – STATCOM prevents the voltage collapse up to 5 seconds from the contingency initiation, the voltage profile is fairly maintained and the power output of wind farms remains the same without significant change. In this case, a 20 MVAR STATCOM and 8 MW battery were simulated. The graphs are shown only for 5 seconds in order to show the transitory response. Other controls like governors act after 10 seconds time frame but are not included in the PSCAD model.

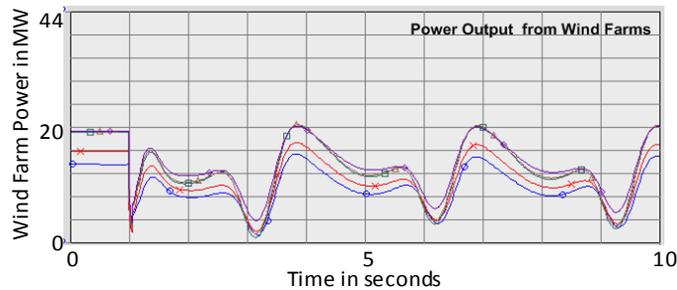




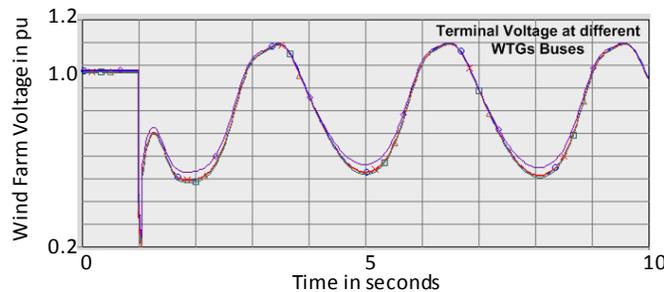
**Figure 13: System Collapse Prevention after the application of 20 MVar STATCOM and 8 MW battery during the contingency (P and Q shown with dark and light color, respectively)**

Two cases are investigated using PSLF: 1) system behavior without energy storage; and 2) system behavior with energy storage with reactive capability of 20MVar.

A three phase fault is simulated at time equal to 1 second and cleared after 4 cycles by disconnecting one of the critical lines. Figure 14 shows the output power and the terminal voltage behavior of different wind farms in the system before and after the critical contingency without the energy storage. It's clear that the system is unstable and within an undamped oscillatory state.



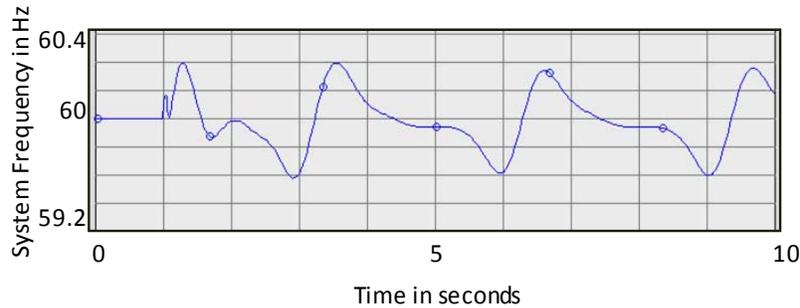
**(a)**



**(b)**

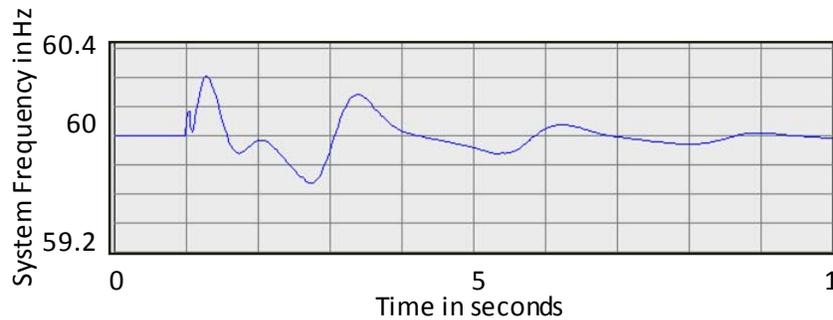
**Figure 14: Power output (a) and voltage profile (b) at different wind generation buses before and after the contingency without the energy storage**

Figure 15 shows the system frequency before and after the critical contingency without the energy storage. The abnormal frequency excursions are the result of system instability.



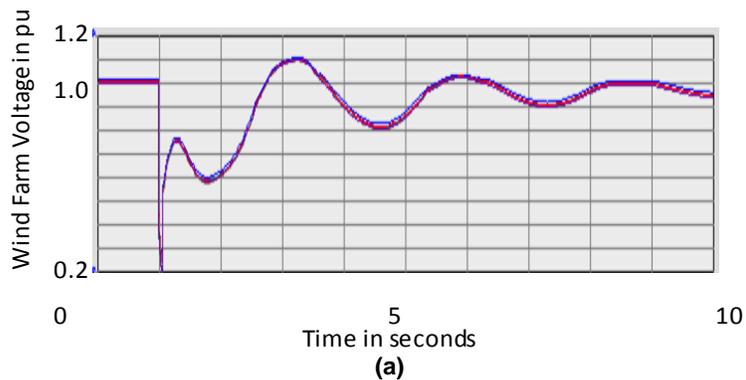
**Figure 15: The system frequency without the energy storage before and after the contingency**

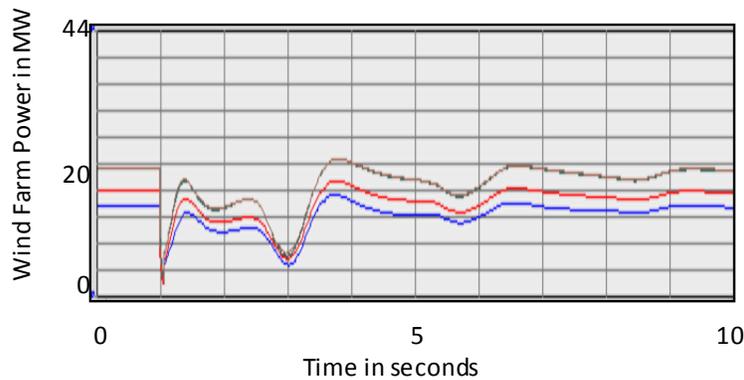
Figure 16 shows the system frequency with the energy storage installed in the system. The figure shows that the system is stable after the contingency and the oscillations are damped.



**Figure 16: The system frequency with the energy storage during the contingency**

Figure 17 shows the voltage profile and the power output of a number of wind farms before and after the critical contingency with energy storage and reactive power support. As can be seen in the figure, the wind farms maintain their pre contingency power output without any oscillatory behavior.





(b)  
**Figure 17: Voltage profile (a) and the wind farms output power (b) before and after the contingency with energy storage**

Besides contingency support, the BESS can be used to dispatch some of the wind farms in the area and minimize the wind's variability at an individual wind farm through an hourly dispatch. The details and results obtained with this application of BESS can be found in the following technical paper, "Application of STATCOM with energy storage for wind farm integration" [42].

### 3.2.2.1.1 Detailed BESS Description

The following paragraphs outline the requirements for the installation and integration of an 8 MW/12 MVar (20 MVar peak) Battery Energy Storage System (BESS) including engineering design, studies, equipment delivery, site development, civil works, installation, commissioning and site acceptance test.

Each BESS consist of:

- Energy Storage System (ESS) including its battery management system
- Power Conversion System (PCS) including its control system
- Step Up Power Transformer
- Step Up Transformer High Side disconnect device
- PCS AC and DC side interrupting devices
- Metering Transformers
- Protection Devices
- Fault and Performance Recording Devices
- Backup Power Supply
- Local communications

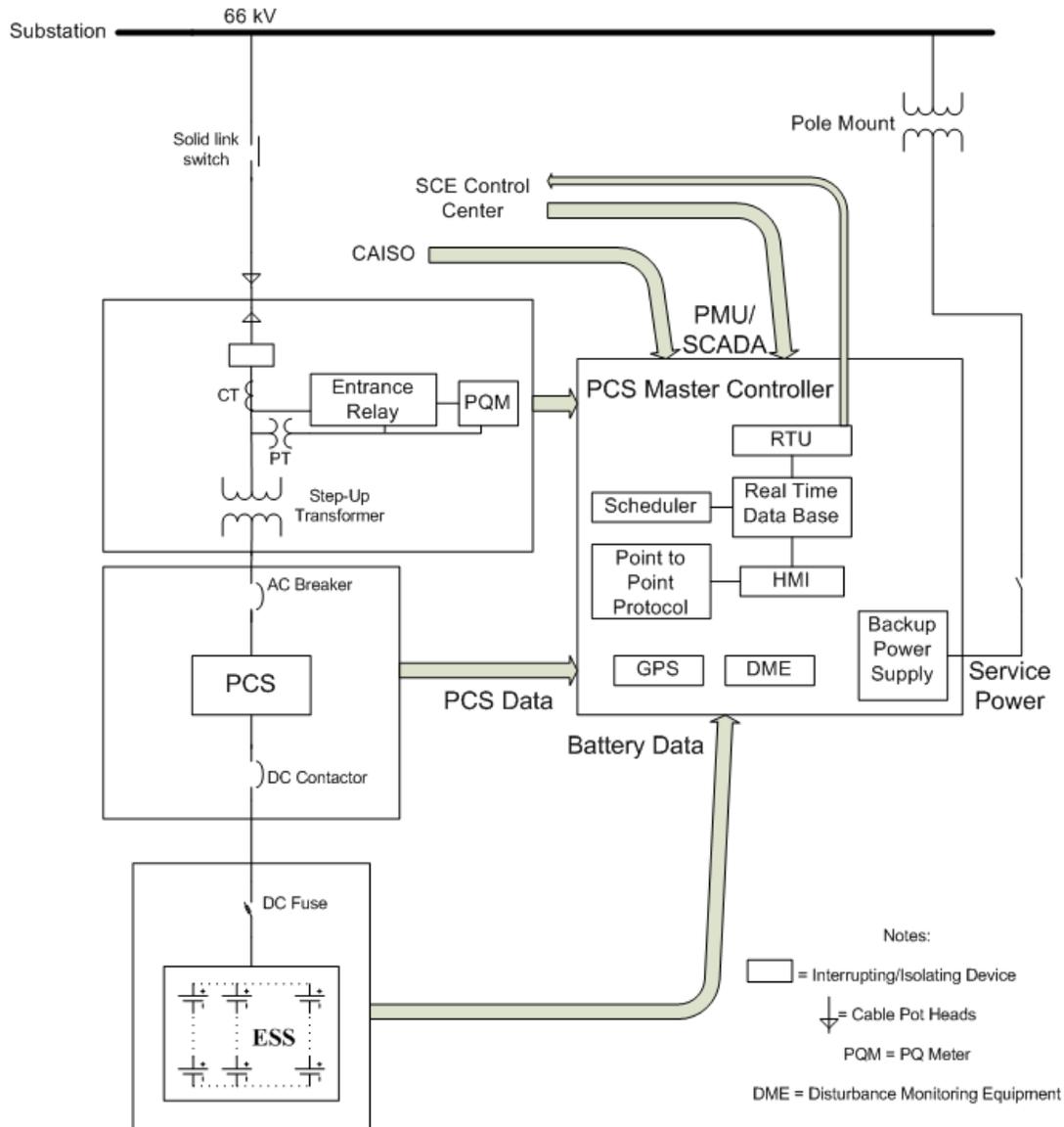
- Software for control functions
- Hardware and software interface to SCE Control Center

The major objectives of the BESS are:

- Contingency support by supplying/absorbing MW
- Minimize wind power curtailment
- Provide low voltage ride through (LVRT) to some of the older wind farms
- Provide dynamic voltage stability on wind farm buses
- Provide support to ageing SVC during contingencies
- Improve wind farm 1-hour ahead dispatchability
- Provide Black-start functionality
- Voltage and frequency regulation
- Decrease system losses
- Add additional spinning reserves
- Energy price arbitrage

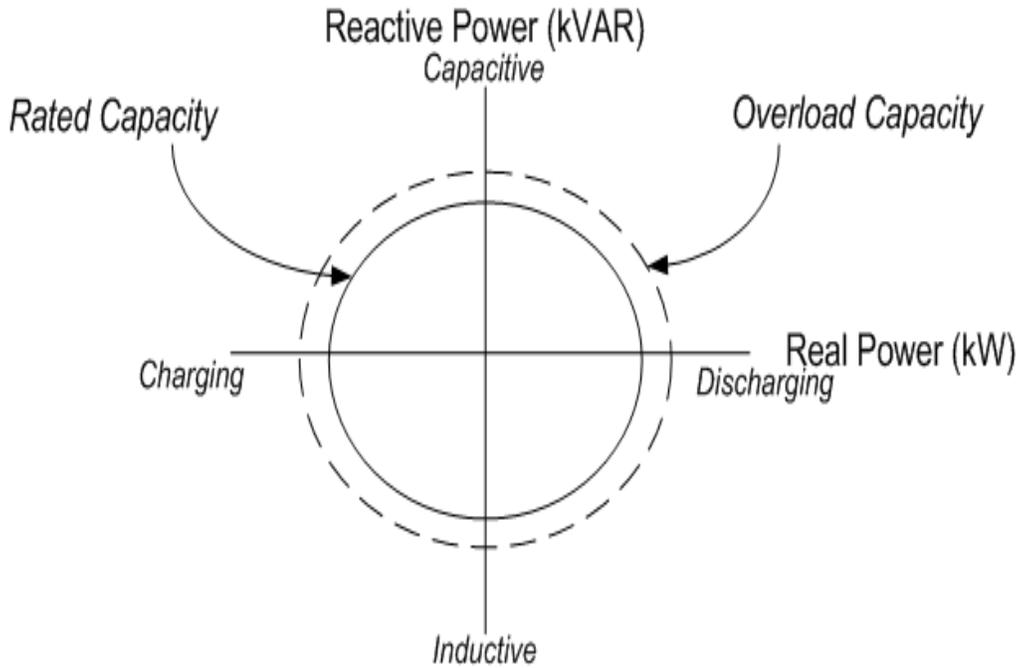
### **System Description**

The BESS configuration is shown in Figure 18.



**Figure 18 - Configuration of the BESS including the ESS, PCS and a step-up interconnection transformer to 66 kV voltage level**

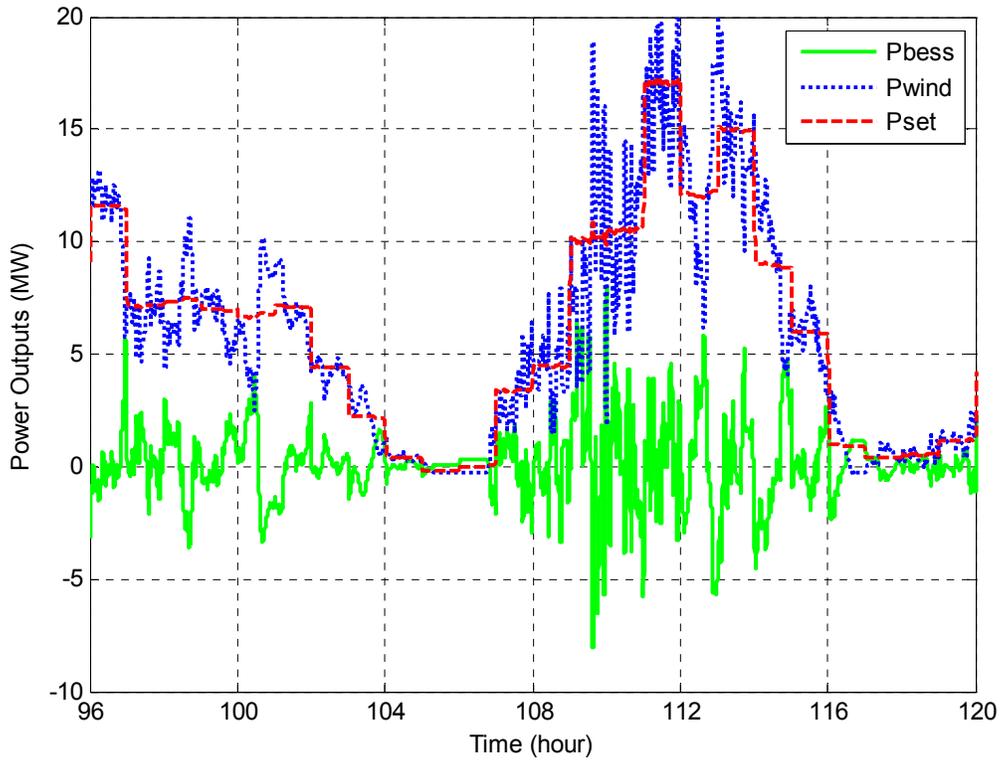
The BESS is configured to operate in full four quadrants in order to achieve bidirectional active/reactive power flow with voltage regulation requirements. The operation of BESS is shown in Figure 19.



**Figure 19: Four quadrant operation of the BESS**

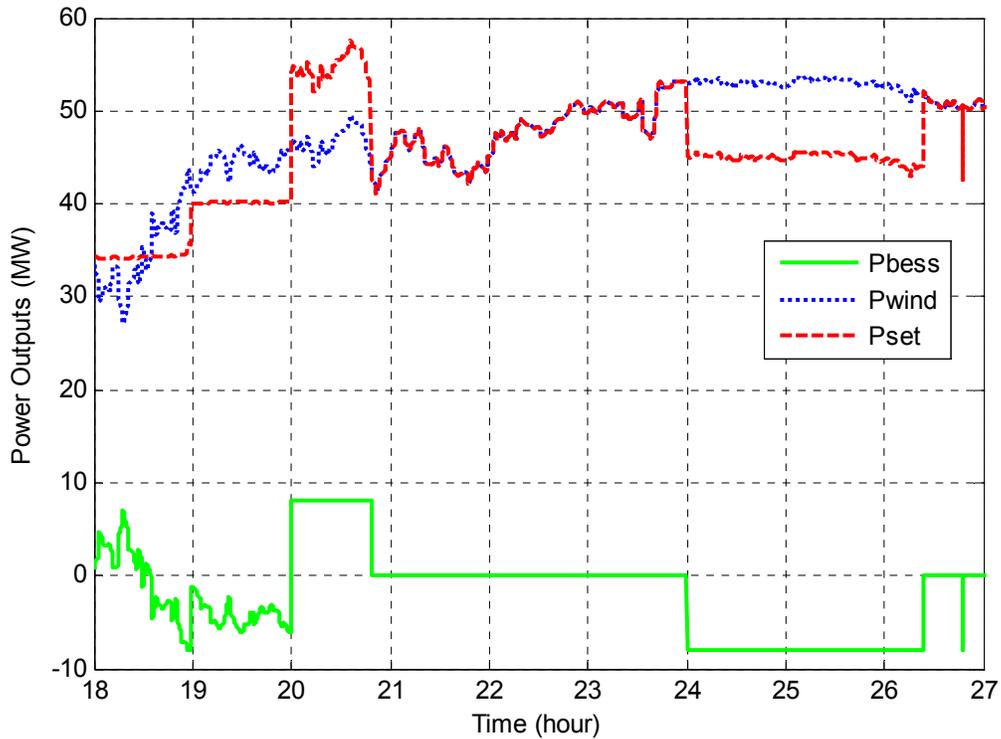
### **Charge/Discharge Profiles for BESS**

A typical charge/discharge profile for the BESS is shown in Figure 20. This profile shows the use of BESS for improving wind farm 1-hour ahead dispatchability. It is seen that the BESS needs to charge/discharge partially many times during the day in order to achieve the desired wind profile.



**Figure 20: Typical charge/discharge profile for the BESS ( $P_{bess}$ =BESS charge/discharge profile (positive means discharge),  $P_{wind}$ =Wind power,  $P_{set}$ =Desired wind profile)**

Another typical charge/discharge profile for the BESS is shown in Figure 21. This profile shows the use of BESS for minimizing wind power curtailment. It is seen that the BESS needs to charge fully in order to minimize the wind power curtailment which is seen at 24th hour and onwards.



**Figure 21: Another charge/discharge profile for the BESS ( $P_{bess}$ =BESS charge/discharge profile (positive means discharge),  $P_{wind}$ =Wind power,  $P_{set}$ =Desired wind profile)**

### 3.2.2.1.2 Functional and Performance Requirements of BESS

The desired functional specifications and performance requirements for the BESS is provided in this section.

### ESS Specifications

Table 3 provides the functional specification for the ESS.

<b>Table 3: ESS (Battery) Functional Specifications</b>	
<b>Description</b>	<b>Value or Range</b>
Nominal Power Rating	8 MW
DC Minimum Energy Rating	> 32 MWh (Based on 90% DOD)
Cycle Life at 80% DOD	> 4500
Cycle Life at 90% DOD	> 2500
Self-discharge rate and tare losses	< 5% per month
Round-trip Efficiency	> 80 % on DC side
Installed Footprint (ESS with Enclosures)	< 500 m <sup>2</sup>
Maximum Height	< 8 m
Peak Power Rating	9 MW (2 hours)

Description	Value or Range
Rated (Fully Charged) DC voltage	> 600 Vdc
Fast Charge Time	< 6 hours
Calendar Life time	≥ 15 years
Energy Density	≥ 30 Wh/kg
Power Density	≥ 30 W/kg
Emission (gas or liquid)	None
Power consumption of peripheral devices (Battery only: ventilation, air conditioning, etc.)	< 80 kW

## PCS Specifications

Table 4 provides the minimum functional specifications for the PCS. The proponent can suggest and justify superior control functionalities as far as the compliance with the minimum requirements for the proposed applications and SCE system design and operation are demonstrated.

**Table 4: Minimum PCS Functional Specifications**

Description	Value and/or Desired Range
Nominal VAR Rating	± 12 MVAR
Peak VAR Rating	± 20 MVAR for 4 seconds (after step-up transformer)
Nominal VA Rating	15 MVA
Interconnection Nominal Voltage	66 kVac via step-up transformer
Battery Interface Voltage (DC input)	> 600 Vdc
Operation	<ul style="list-style-type: none"> <li>• 4 Quadrant Operation (P&amp;Q regulation)</li> <li>• Grid Synchronization</li> <li>• Fast charging &amp; partial discharging capability (threshold control)</li> <li>• Frequency Regulation</li> <li>• Selectable reactive power control modes (voltage regulation, power factor compensation, reactive power compensation)</li> </ul>
Output Voltage Regulation	±5%
Nominal Operating Frequency	60 Hz
System Response Time (output power tracking)	≤ 20 ms
Efficiency at full-load (15 MVA)	≥ 96% (min=96% Including step-up transformer)
Efficiency at half load (7.5 MVA)	≥ 93% (min=93% Including step-up transformer)
Total Voltage Harmonic Distortion	Per IEEE 519 and IEEE 1547
Internal electrical protection	<ul style="list-style-type: none"> <li>• Synch Check</li> <li>• Fast and timed over-current</li> <li>• Over loading (PCS thermal limit)</li> <li>• Under/Over voltage &amp; frequency</li> <li>• Voltage &amp; current unbalance</li> </ul>

Description	Value and/or Desired Range
	<ul style="list-style-type: none"> <li>DC and leakage current prevention (coordinate with interconnection protection)</li> </ul>
Control Monitoring	≤ 1 cycle
System Monitoring	Digital recording of system actions, alarms and warning signals
Control Power Backup	Minimum 15 minute backup of all control and communications needed for the BESS
Time Synchronization	Via GPS

### Control Strategies and Operating Modes

The PCS for the BESS should be designed with similar control and operation functionalities as listed in Table 4 and achieve the objectives previously mentioned. The control strategies of the PCS should comprise several active and reactive power output controls for this purpose. The recommended control strategies and operating modes are detailed below:

P control mode A – Diminish congestion: In this control mode, the BESS will be utilized to reduce the wind farm curtailment by absorbing the excess wind generation up to four hours. The typical charge/discharge profile for the BESS in this mode was shown in Figure 21.

P control mode B – Wind energy firming & shaping: In this control mode, the BESS will smooth the power and voltage fluctuations of the nearby wind farms. Figure 20 shows a typical charge/discharge profile in this mode of operation. The BESS needs to respond between 20 ms to 15 mins in this mode and also needs to provide ride through for the wind farms.

P control mode C – Wind generation output shifting: In this control mode, the BESS is charged up to four hours with low value electric energy generated using wind during off peak hours. The energy stored is used or sold during peak hours afterwards.

P control mode D – Frequency regulation (CAISO AGC): In frequency regulation mode, the BESS will follow the ISO market signal and charge/discharge accordingly. In this mode, the BESS needs to respond as fast as 4 seconds following CAISO AGC specifications.

P control mode E – Spin/Non-spin replacement: Reliable operation of an electric grid includes use of electric supply reserve capacity that can be called upon when some portion of the normal electric supply resources become unavailable unexpectedly. In this control mode, the BESS has to be ready and available to discharge for non Spin in 10 minutes to Pmax for up to 1 hour or longer depending on market bids. For Spin, the

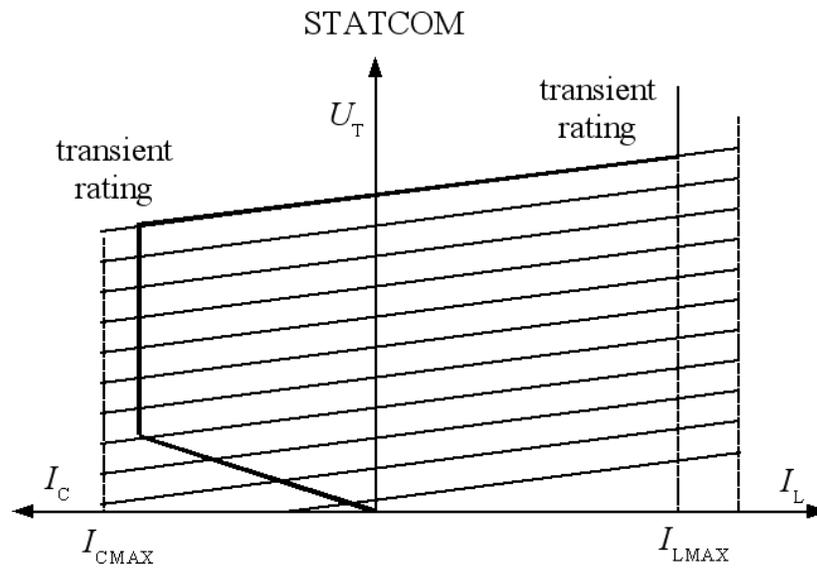
BESS has to be ready and available to discharge from current schedule to Spin award within ramp time following CAISO ADS 5 minute dispatch.

P control mode F – Deliver ramp rate: The BESS will follow the ISO ADS 5 minute market signals and respond with varying ramp rates up to max operational ramp rate.

P control mode G – Arbitrage: In this control mode, the BESS is charged when the electricity prices are low and discharged up to four hours in both schedule follow and INC & DEC ADS dispatches when the prices are high.

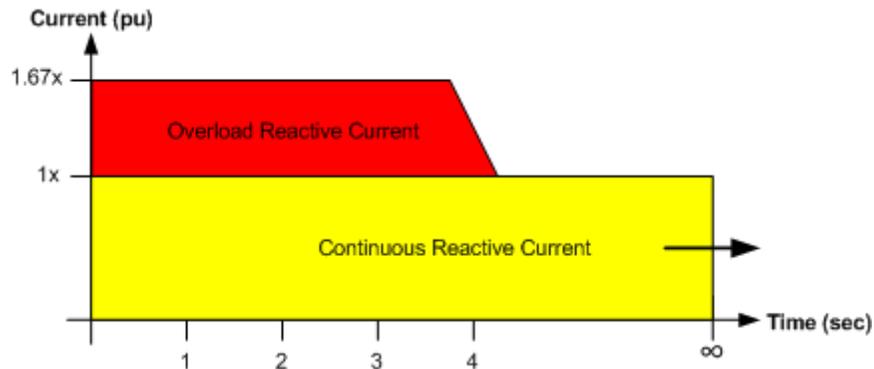
P control mode H – Decrease transmission losses: In this control mode, the BESS is used for limiting the transmission line overloading by charging/discharging up to 4 hours.

In the Q control mode, the PCS is expected to behave like a STATCOM and to respond within 20 ms to changes in the reference signal. The STATCOM is based on a solid-state voltage source, implemented with an inverter and connected in shunt with the power system through a coupling reactor, in analogy with a synchronous machine, generating a balanced set of three sinusoidal voltages at the fundamental frequency, with a controllable amplitude and phase-shift angle. If the line voltage is in phase with the converter output voltage and has the same magnitude, then there can be no current flow into or out of the STATCOM. If the converter voltage is increased, then the voltage difference between the converter output and the line voltage appears on the reactance. As a result, a leading current with respect to the line voltage is drawn and the STATCOM behaves as a capacitor and generates VARs. Conversely, if the converter output voltage becomes less than the line voltage, then the STATCOM draws a lagging current, behaving as an inductor, and absorbs VARs. A STATCOM operates essentially like a synchronous condenser where the excitation may be greater or less than the terminal voltage. The U-I characteristics of a STATCOM is shown in Figure 22.



**Figure 22: U-I characteristics of STATCOM**

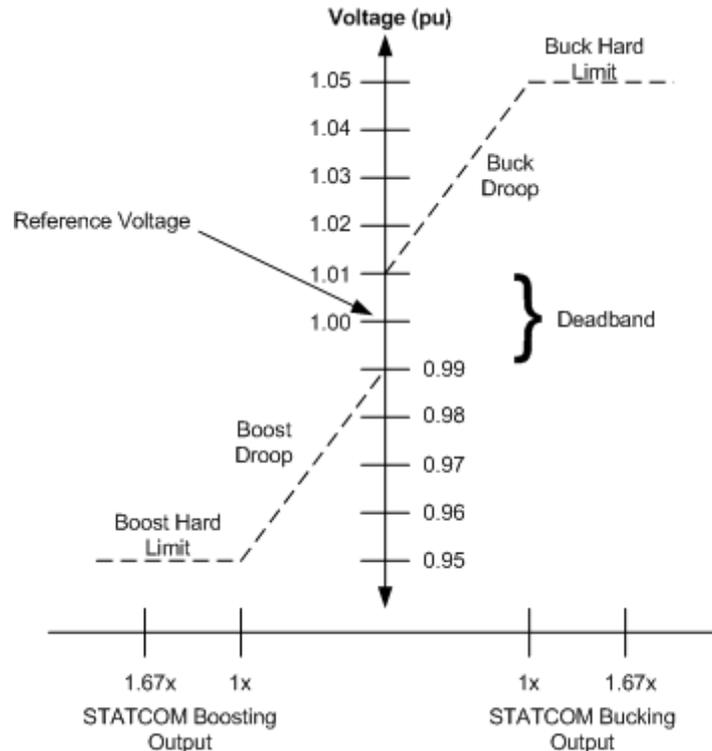
The PCS for this application is expected to provide 1.67 times rated current for up to 4 seconds. Illustration of this overload capability is shown in Figure 23.



**Figure 23: STATCOM Overload Capability**

The reactive power control modes that PCS is expected to operate are as follows:

Q control mode A – Voltage regulation: This control mode utilizes a voltage set point identified by the SCE control center to regulate voltage at the PCC. Although limited by the PCS size, the BESS generally should have the voltage regulation capability within  $\pm 5$  percent of the nominal feeder voltage. A typical STATCOM control characteristics for voltage regulation is shown in Figure 24. It is expected that the PCS should have similar control settings.



**Figure 24: STATCOM control settings for Voltage Regulation**

Q control mode B – Power factor correction: This control mode is utilized to provide reactive power supply capabilities for BESS to locally compensate feeder power factor (pf), measured at the PCC, to a pre-specified set point. The pf correction set point is remotely determined by the SCE control center and communicated to the BESS.

Q control mode C – Reactive power compensation: This control mode is principally similar to the previous mode with the exception of not requiring a power factor measurement. A pre-specified set point for the reactive power output of the BESS - positive (lagging) or negative (leading) - is determined and communicated to the BESS by the SCE control center.

In addition to the remote control from SCE control center, all the control modes and set points shall be able to be specified locally through the HMI at the BESS.

### 3.2.2.2 Palm Springs Area

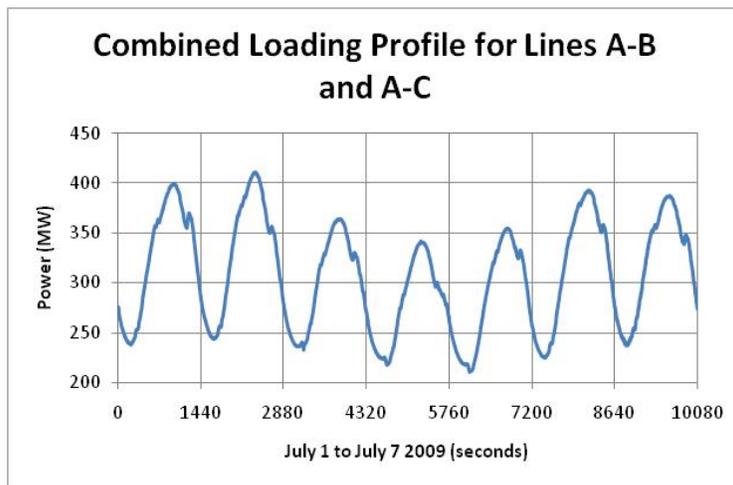
The studies performed in this area are based on PSLF version 17 and the 2009 year SCE Heavy Summer PSLF base case is used. For study preparation, the following tasks were performed:

- Identified the wind location and size in the study area using the data provided by SCE.
- Added the wind generation to the case and adjusted the reactive power requirement for each unit.

- Redispatched the system to accommodate for the installed wind generation.
- Represented CAES as a generator with no reactive capability.

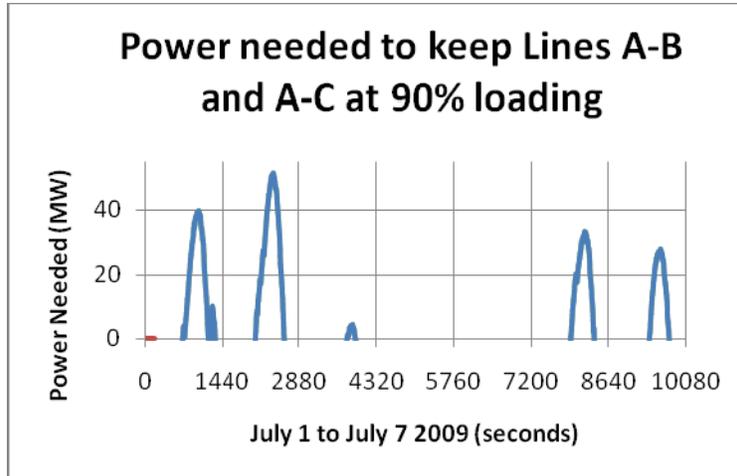
In order to address the concerns mentioned in the previous section, CAES is modeled in one of the buses that is close to wind generation in the area. The inspection of the power flow case shows that the two 115 kV lines A-B and A-C are overloaded in the base case by 21.1 percent and 6.35 percent respectively. The CAES is modeled at bus B during the study to mitigate the overload issue.

In order to determine the size of the CAES, the power profile shown in Figure 25, which is obtained using the data from SCE, is assumed for the lines A-B and A-C.



**Figure 25: Loading of the two lines for a summer week**

To determine the size and duration of the CAES, it is assumed that the line loadings are desired to be kept at 90 percent of their nominal rating. The lines A-B and A-C have a total rating of 400 MW. With this assumption, the CAES will begin supplying power when the load profile goes over 360 MW. The expected operation of CAES for a weekly period is shown in Figure 26.



**Figure 26: Expected CAES operation**

It is seen from Figure 26 that the CAES needs to operate 5 days of the week. Moreover, from the day one profile, it is seen that the CAES need to supply energy up to 8 hours. Therefore, it can be concluded that the CAES rating will be atleast 50 MW for 8 hours i.e. 400 MWh.

To show the effectiveness of CAES in thermal overload mitigation, several cases are tested in PSLF. Table 5 shows the results of the base case in which there is no CAES.

**Table 5: Loading of the lines without energy storage**

	Percentage loading (%) without wind generation	Percentage loading (%) with wind generation
<b>A-B</b>	$(121.10\%)^1 / (92.70\%)^2$	$(112.44\%)^1 / (86.10\%)^2$
<b>A-C</b>	$(106.35\%)^1 / (78.77\%)^2$	$(94.80\%)^1 / (70.22\%)^2$

- 1- As a percentage of the nominal line rating
- 2- As a percentage of the emergency line rating

It is seen from Table 5 that the two 115 kV lines A-B and A-C are overloaded in the base case by 21.1 percent and 6.35 percent, respectively. However, when the 250 MW wind is modeled in the case, the line overloads decrease around 10 percent.

Table 6 shows the results with CAES placed at Bus B.

**Table 6: Loading of the lines with energy storage**

	Percentage loading (%) without wind generation	Percentage loading (%) with wind generation
<b>A-B</b>	$(105.10\%)^1 / (80.47\%)^2$	$(96.30\%)^1 / (73.77\%)^2$
<b>A-C</b>	$(105.80\%)^1 / (77.80\%)^2$	$(94.80\%)^1 / (70.20\%)^2$

- 1- As a percentage of the nominal line rating
- 2- As a percentage of the emergency line rating

The impact of CAES on line A-B loading is observed from Table 6. The loading of this line decreases around 15 percent, whereas the line A-C loading doesn't change much. It is also seen that with the energy storage, the overloading of the two lines are eliminated for the case with wind generation included.

Since the line overloads are eliminated with energy storage and wind in the case, a final scenario is simulated in which two of the local peaker units with a total rating of 90 MW are turned off. It is seen from Table 7 that the two lines are still within their nominal ratings in this scenario. Hence, the CAES can help to reduce the start/stop cycles of local peakers, too.

**Table 7: Loading of the lines with energy storage and wind**

	<b>Percentage loading (%) with wind generation</b>
<b>A-B</b>	$(99.90\%)^1 / (76.70\%)^2$
<b>A-C</b>	$(97.70\%)^1 / (72.30\%)^2$

- 1- As a percentage of the nominal line rating
- 2- As a percentage of the emergency line rating

### 3.2.2.3 South Bay Area

The 2010 year SCE PSLF base case is used for developing the PSCAD case in which the simulations are performed for this area.

The PSCAD case obtained from SCE didn't contain any loads and it was essentially a representation of the key buses around the refinery, and the rest of the SCE system is represented by an equivalent. Using the PSLF 2010 base case, the inductive and resistive loads were added to the PSCAD case accordingly. The total load added to the system was about 800 MW and 90 MVAR. After that, the transformer tap settings were changed in order to make the voltage levels as close as possible to the PSLF case. After the modifications, the power flows in PSCAD were compared with the PSLF case and the difference in the power flows were within 10% for each line.

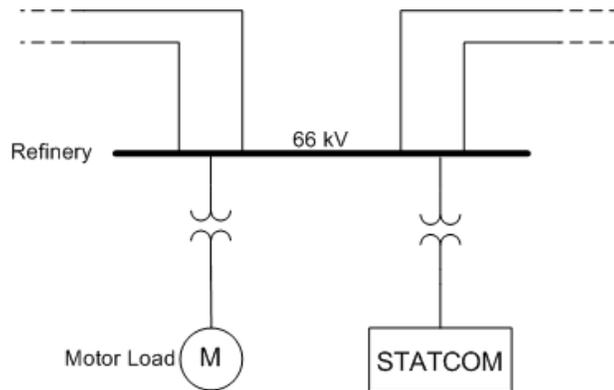
Since the refinery bus load consists of motor loads in reality, the next step in the PSCAD modeling part was to replace the resistive and inductive load at the refinery bus with induction motors in order to represent various compressor/fan/pump loads existing at that bus.

An average model for the STATCOM with the parameters tabulated in Table 8 is used.

**Table 8: Parameters of the STATCOM**

Parameter	Value
Continuous Rating	15 MVAR
Transient Overload Rating	2.5 x continuous rating for 2 seconds
Voltage reference	1 pu.
Drop	4%
Voltage control proportional gain	0.5
Voltage control integral time constant	0.004065 sec

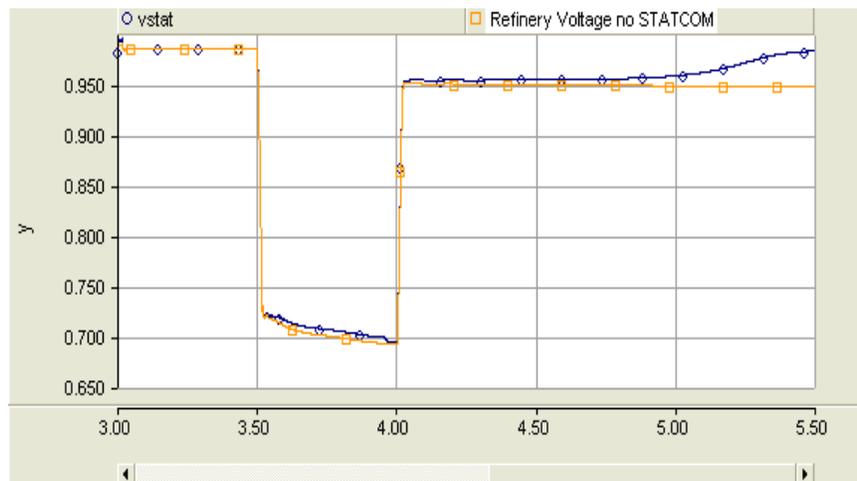
Figure 27 shows the application of STATCOM at the refinery.



**Figure 27: Application of STATCOM at the refinery**

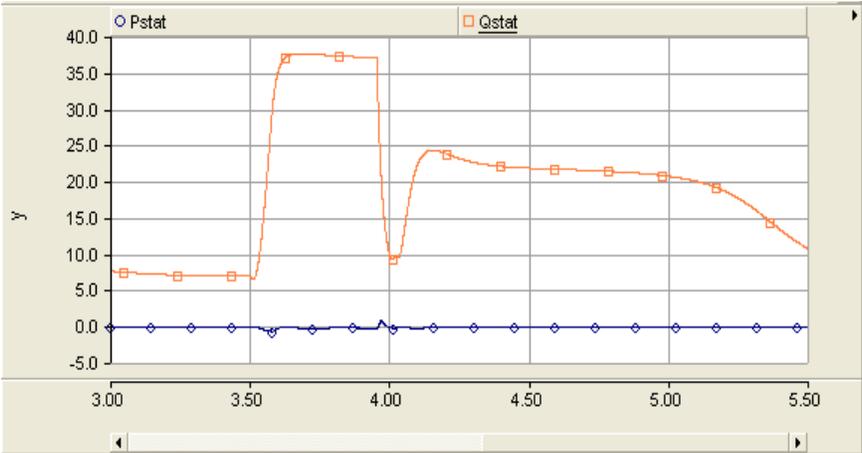
In order to show the effectiveness of STATCOM in voltage regulation and contingency support, a three phase to ground fault is created in one of the lines that is close to the refinery. The fault is set to occur at  $t=3.5$  sec and cleared after 0.5 sec.

Figure 28 shows the refinery bus voltage during the fault with and without STATCOM. It is seen that the STATCOM helps to bring the voltage back to its nominal value within 1.5 sec whereas the voltage doesn't reach the nominal value back without the STATCOM.



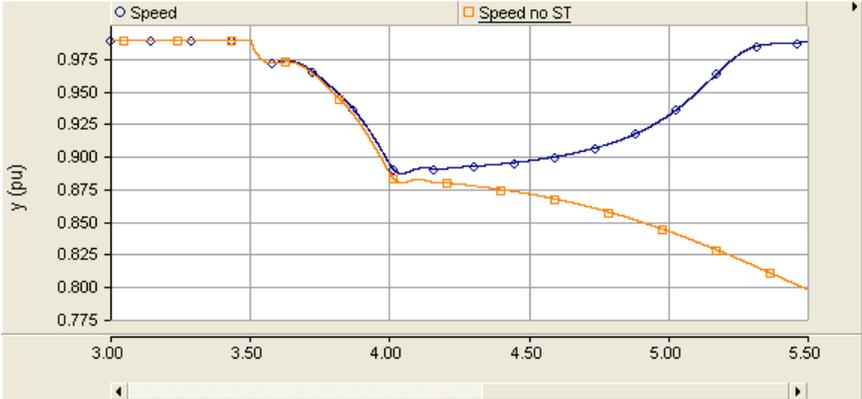
**Figure 28: Refinery Bus Voltage (pu.) with (blue) and without (orange) STATCOM**

Figure 29 shows the active and reactive power of the STATCOM. It can be observed that the STATCOM injects around 37 MVAR during the fault and around 22 MVAR after the fault to bring the voltage back to nominal value. It is also seen that no active power is injected since there is no energy storage device connected.



**Figure 29: STATCOM Active (MW-blue) and Reactive Power (MVAR-orange)**

Figure 30 shows the speed of the induction machine with and without STATCOM. As can be seen, the induction machine collapses for the case without STATCOM whereas it survives with the help of STATCOM.



**Figure 30: Induction machine speed (pu.) with (blue) and without (orange) STATCOM**

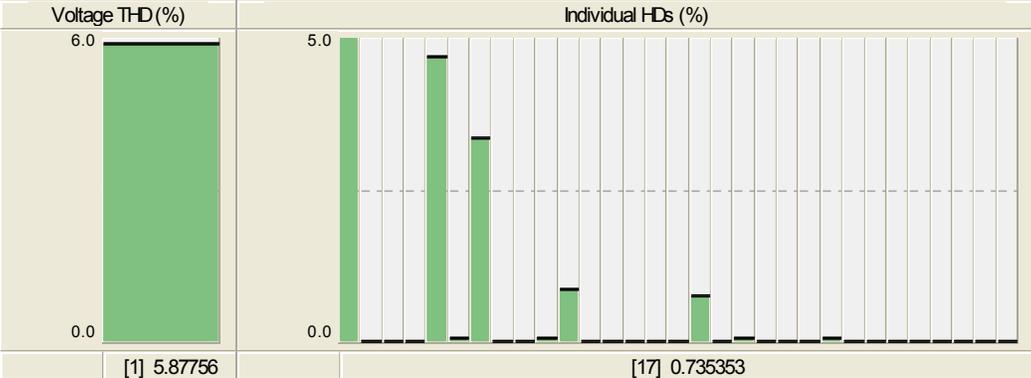
By looking at Figure 29 and Figure 30, it can be concluded that the reactive power injected by STATCOM during and after the fault helps the induction machine to recover its speed and reach to rated value within 1 sec after the fault is cleared.

The STATCOM can also be used for harmonic compensation and for this purpose; a harmonic current source is connected to the refinery bus. The harmonic content of this source is given in Table 9.

**Table 9: Harmonic current injection at refinery**

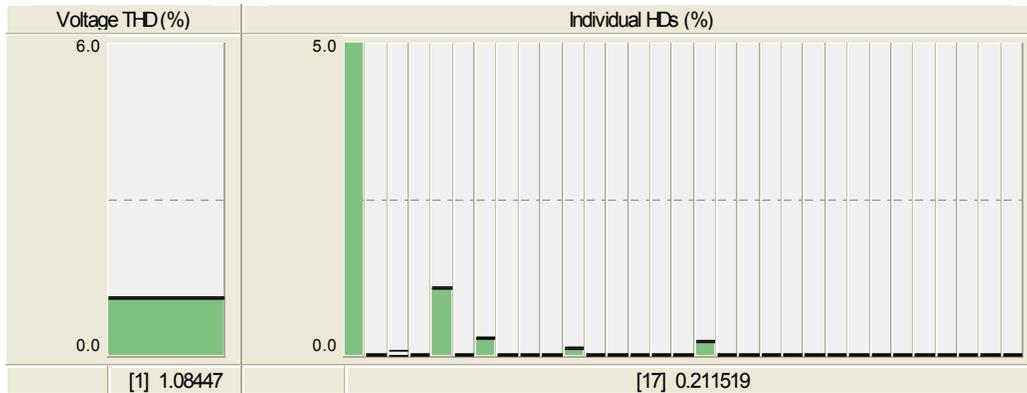
Harmonic Content	Percentage of the fundamental Current (%)
2	0.057143
3	0.125714
4	0.137143
5	64.61714
6	0.411429
7	29.08571
8	0.034286
10	0.331429
11	3.314286
17	16.72
19	0.754286

Figure 31 shows the THD and harmonic content of the voltage at Refinery without STATCOM. It is seen that the THD is about 6 percent.



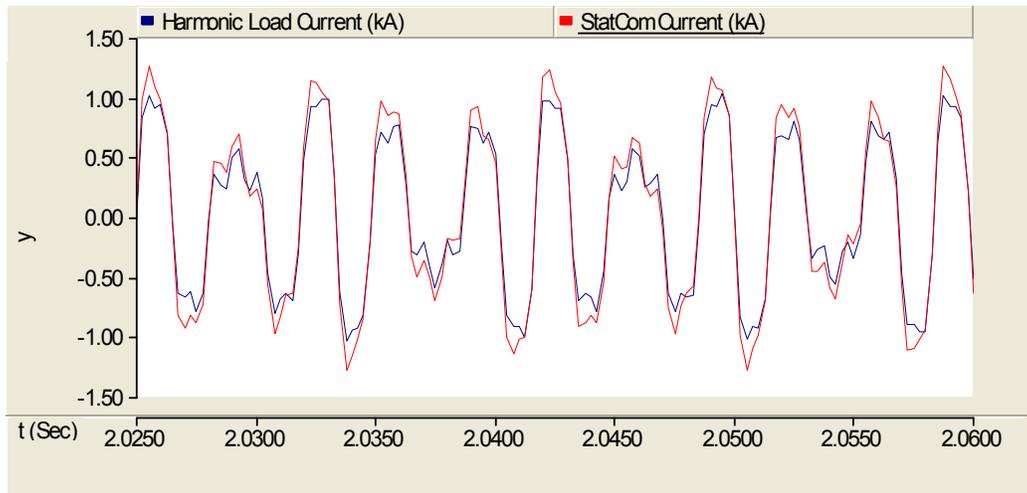
**Figure 31: THD and harmonic contents (%) without STATCOM**

Figure 32 shows the THD and harmonic content with STATCOM. The THD decreases to 1 percent with STATCOM which corresponds to an 82 percent reduction in THD.



**Figure 32: THD and harmonic contents (%) with STATCOM**

The STATCOM in harmonic compensation mode acts as an Active Power Filter (APF) and compensate the harmonic currents injected by the harmonic current source shown in Table 9. Figure 33 shows the harmonic load current and the current injected by STATCOM. It is seen that the STATCOM can inject currents similar to the harmonic current source with opposite polarity easily and eliminate most of the harmonic content.



**Figure 33: Load Current (kA) (Blue) and STATCOM Current (kA) (Red)**

### 3.2.3 Economic Analysis on the Proposed Solutions

Having shown the benefits obtained with energy storage and/or FACTS devices in the previous section; in this section, the focus will be to perform an economic analysis and to calculate the

value streams associated with energy storage and/or FACTS devices at the selected three locations. The summary of the economic analysis is shown in Table 10.

**Table 10: Summary of economic analysis**

AREA	Energy Storage and/or FACTS device	Return on Investment (ROI) in one year (%)
Tehachapi	Battery Energy Storage System (BESS) – STATCOM	10.08
Palm Springs Area	Compressed Air Energy Storage (CAES)	20.12
South Bay Area	Static Synchronous Compensator (STATCOM)	25.39

The details of the calculations for each area are provided below:

**Tehachapi Area:** The proposed BESS – STATCOM in Tehachapi area is expected to perform many tasks other than contingency support which was shown in the simulations. These tasks can be summarized as:

- Electric energy time shift
- Load following
- Frequency regulation
- Reserve capacity
- Congestion relief
- Delay in line upgrade
- Electric service reliability
- Wind capacity firming
- Wind generation grid integration
- Voltage Support
- Decreased Transmission Losses
- Power Quality

A brief description of each application is provided below:

**Electric energy time shift (Arbitrage):** In this application, the BESS is charged with low price energy during off peak times and discharged during peak times when the electricity price is high.

**Load following:** Load following is the use of on-line generation, storage or load equipment to track inter and intra hour changes in customer load [43]. Load following is one of the

ancillary services required to operate the electricity grid. Storage is well-suited to load following for several reasons. First, most types of storage can operate at partial output levels with relatively modest performance penalties. Second, most types of storage can respond very quickly when more or less output is needed for load following. Finally, storage can be used effectively for both load following up (i.e. during load increase) and for load following down (i.e. during load decrease), either by discharging or by charging [44].

**Frequency regulation:** Frequency regulation is the use of online generation that is equipped with Automatic Generation Control (AGC) that can change output quickly (MW/min) to track moment to moment fluctuations in customer loads and to correct for unintended fluctuations in generation. The objective of regulation is to maintain the interconnection frequency by managing the difference between actual and scheduled power between balancing areas and to match supply to load in a balancing area [43]. Energy storage can be an attractive alternative for this application with its rapid response.

**Reserve Capacity:** Reliable operation of an electric grid includes use of electric supply reserve capacity that can be called upon when some portion of the normal electric supply resources become unavailable all of a sudden. In the electric utility realm, this reserve capacity is classified as an ancillary service [44]. Energy storage used for this service does not discharge at all; it just has to be ready to discharge if needed.

**Congestion Relief:** In many areas, transmission capacity additions are not keeping pace with the growth in peak electric demand. As a result, transmission systems are becoming congested during periods of peak demand, driving the need and cost for more transmission capacity and increased transmission access charges [44]. In this application, energy storage can be installed at locations that are electrically downstream from the congested portion of the transmission system. Energy can be stored when there is no transmission congestion, and can be discharged (during peak demand periods) to reduce transmission capacity requirements.

**Delay in line upgrade:** Similar to transmission congestion relief, energy storage that is placed electrically downstream from the congested portion of the transmission system can help to prevent the overloads in the lines and delay potential line upgrades.

**Electric service reliability:** The electric service reliability application makes use of energy storage to provide highly reliable electric service. In the event of a power outage lasting more than a couple seconds, the energy storage can provide enough energy to ride through outages of extended duration; to complete an orderly shutdown of processes; and/or to transfer to on-site generation resources [44].

**Wind capacity firming:** Capacity firming allows use of an intermittent electric supply resource as a nearly constant power source. Such use may reduce power-related charges (e.g., capacity payments or demand charges) [44]. Energy storage used for this application can help to increase the capacity factor of the wind generation in the area (i.e. increase it from 30 percent to 40 percent).

**Wind generation grid integration:** In this application, the energy storage can be used to reduce the wind output variability, to prevent congestion in case of high wind. It can also be used as a backup for unexpected wind generation shortfall.

**Voltage Support:** An important technical challenge for electric grid system operators is to maintain acceptable voltage levels in the system. Energy storage with reactive power capability can provide voltage support and respond quickly to voltage control signals (i.e. on the order of ms for STATCOM).

**Decreased Transmission Losses:** Similar to any process involving conversion or transfer of energy, energy losses occur during transmission [44]. If energy storage is charged during night time when losses are low and discharged during day time (on-peak), it will help to reduce I<sup>2</sup>R losses.

**Power Quality:** Power quality application involves using energy storage to protect the loads downstream (from storage) against short-duration events that affect the quality of power delivered to the load. These short duration events include voltage variations, low power factor, harmonics and interruptions in service [44]. Energy storage used for this application needs to provide high quality power and respond quickly.

For ROI calculations, the cost of 8MW/32 MWh battery is assumed to be \$30M. Using this assumption, the ROI calculation is shown in Table 11.

**Table 11: Value Stream Calculation for BESS**

<b>Value Stream</b>	<b>Avoided Cost/Revenue</b>	<b>Unit</b>	<b>Explanation of Calculation</b>	<b>Yearly Avoided Cost/Revenue (\$)</b>
Electric Energy Time Shift	40.00	\$/kW-year	8 MW, 2 hours of storage	\$320,000.00
Load Following	20.00	\$/MW-service hour	8 MW, 365 hours/year (1 hours/day)	\$58,400.00
Frequency Regulation	38.55	\$/MW-service hour	8 MW, 2190 hours/year (6 hours/day)	\$675,396.00
Reserve Capacity	3.00	\$/MW-service hour	8 MW, 365 hours/year (1 hours/day)	\$8,760.00
Congestion Relief	5.00	\$/MW-service hour	8 MW, 1095 hours/year (3 hours/day)	\$43,800.00
Delay in line upgrade	55000.00	\$/mile	33 miles with 0.11 fixed charge rate	\$199,650.00
Electric Service Reliability	50.00	\$/kW-year	8 MW, 1 hour of storage	\$400,000.00
Wind Capacity Firming	12.00	\$/kW-year	8 MW, 2 hours of storage	\$96,000.00
Wind Grid Integration	50.00	\$/MW-service hour	8 MW, 1095 hours/year (3 hours/day)	\$438,000.00
Voltage Support	40.00	\$/kW-year	8 MW, 1 hour of storage	\$320,000.00
Decreased Transmission Losses	8.00	\$/kW-year	8 MW, 1 hour of storage	\$64,000.00
Power Quality	50.00	\$/kW-year	8 MW, 1 hour of storage	\$400,000.00
			<b>Total Avoided Cost/Revenue per year</b>	<b>\$3,024,006.00</b>
			<b>ROI</b>	<b>10.08%</b>

From the analysis, it is seen that the ROI with BESS in one year is around 10 percent. This result shows that in order to make BESS economically feasible, it should be used for multiple functions especially for frequency regulation and improving wind grid integration.

**Palm Springs Area:** Having shown in the previous section that the CAES can help to mitigate the thermal line overloads and to reduce the start/stop cycles of some local peakers in the area, other benefits of the CAES still need to be addressed in order to make it economically feasible.

The CAES at the selected location can also be used for:

- Electric energy time shift
- Load following
- Frequency regulation
- Electric supply reserve capacity
- Transmission congestion relief
- Delay in line upgrade
- Electric service reliability
- Wind capacity firming
- Wind generation grid integration

The assumptions for CAES are:

- Power Rating = 50 MW
- Energy Rating = 400 MWh
- Cost = \$ 50 M

Using these assumptions and the applications for CAES described above, the value streams considered with CAES and the ROI with CAES for one year is calculated and shown in Table 12. The explanation of calculation and avoided cost/revenue values are mostly based on [44].

**Table 12: Value stream calculation with CAES**

Value Stream	Avoided Cost/Revenue	Unit	Explanation of Calculation	Yearly Avoided Cost/Revenue (\$)
Electric Energy Time Shift	40.00	\$/kW-year	50 MW, 2 hours of storage	\$2,000,000.00
Load Following	20.00	\$/MW-service hour	50 MW, 2000 hours/year (5.48 hours/day)	\$2,000,000.00
Frequency Regulation	38.55	\$/MW-service hour	10 MW, 2190 hours/year (6 hours/day)	\$844,245.00
Reserve Capacity	3.00	\$/MW-service hour	10 MW, 2190 hours/year (6 hours/day)	\$65,700.00
Congestion Relief	5.00	\$/MW-service hour	50 MW, 1460 hours/year (4 hours/day)	\$365,000.00
Delay in line upgrade	59600.00	\$/mile	13.4 miles with 0.11 fixed charge rate	\$87,850.40
Electric Service Reliability	50.00	\$/kW-year	10 MW, 1 hour of storage	\$500,000.00
Wind Capacity Firming	24.00	\$/kW-year	50 MW, 2 hours of storage	\$1,200,000.00
Wind Grid Integration	50.00	\$/MW-service hour	50 MW, 730 hours/year (2 hours/day)	\$1,825,000.00
Fuel Savings of peakers	5.00	\$/MBTU	90 MW, 365 hours/year (1 hour/day), 1055 Btu/kWh fuel reduction	\$173,283.75
O&M Cost reduction of peakers	1000000.00	\$	Reducing 200 Start/Stops for two units (90 MW total) per year	\$1,000,000.00
			<b>Total Avoided Cost/Revenue per year</b>	<b>\$10,061,079.15</b>
			<b>ROI</b>	<b>20.12%</b>

From the analysis, it is seen that the ROI with CAES in one year is around 20 percent. This result shows that in order to make CAES economically feasible, it should be used for multiple functions besides overload mitigation.

**South Bay Area:** A similar analysis that was done with the other two areas is performed for the proposed STATCOM in the South Bay Area. The assumptions for the STATCOM are:

- VA Rating = 15 MVA
- Overload VA Rating (2 sec) = 40 MVA
- Cost = \$5M

Using these assumptions, the value streams considered with STATCOM and the ROI with STATCOM for one year is calculated and shown in Table 13.

**Table 13: Value Stream Calculation with STATCOM**

Value Stream	Avoided Cost/Revenue	Unit	Explanation of Calculation	Yearly Avoided Cost/Revenue (\$)
Voltage Regulation [45]	30.00	\$/hp	20% reduction in maintenance cost for IM	\$865,416.00
Delay in Line Upgrade	0.89	miles	\$55K/mile with 10 year delay to build	\$48,950.00
Local Voltage Support (Cost per Voltage Sag) [46]	25512.00	\$/voltage sag	6 Sags/year	\$153,072.00
Power Quality (Harmonics) [47]	1889.67	\$/MW	107 MW load	\$202,194.33
			<b>Total Avoided Cost/Revenue per year</b>	<b>\$1,269,632.33</b>
			<b>ROI</b>	<b>25.39%</b>

From the analysis, it is seen that the ROI with STATCOM in one year is around 25 percent.

## 3.3 Energy Storage Commercialization

### 3.3.1 Implementation team

The Tehachapi Storage Project (TSP), co-funded by DOE, SCE and A123 and studied by SCE and Quanta Technology, documents the requirements for a turn-key installation and integration of a large scale energy storage including engineering design, studies, equipment delivery, site development, civil works, installation, training, commissioning and site acceptance testing [48]. The TSP project definition is based on one of the identified applications of this project. The scope of the work is divided between utility and battery manufacturer for the complete development of the project.

This system will be installed in the utility substation facility near Tehachapi, California. The Utility will provide the facility and utilities. This system will be used in a demonstration installation to test different storage control applications to integrate wind energy, including providing N-1 dynamic reactive power support, following key contingencies in the power grid in the Tehachapi region. This battery system can also support the potential usage of several ISO ancillary applications like frequency regulation and spinning reserves.

Key project components may include:

- Energy Storage System (ESS) including its battery management system
- Power Conversion System (PCS) including its control, monitoring and energy management systems
- Step Up Power Transformer to 66 kV
- Step Up Transformer High Side disconnect device
- PCS AC and DC side interrupting devices
- Metering Transformers
- Protection Devices
- Fault and Performance Recording Devices
- Backup Power Supply
- Local communications
- Software for control and monitoring functions
- Hardware and software interface to SCE Control Center
- Hardware and Software interface to ES&M GMS system

- Hardware and Software interface to CAISO
- Hardware and software interface to SCE for logging and tracking performance measures

Normally Key Performance Indicators are identified for such a project and may be based on the following performance measures:

- Support with voltage/grid stabilization
- Decrease transmission losses
- Diminish congestion
- Increase system reliability by load shed deferral
- Defer transmission investment
- Optimize size and cost of renewable energy-related transmission
- Provide system capacity/resource adequacy
- Integrate renewable energy (smoothing)
- Shift wind generation output
- Frequency regulation
- Spin/non-spin replacement reserves
- Capacity for ramping, reductions in ramping needs
- Energy price arbitrage

Key performance indicators for this project include effectiveness of the Battery Energy Storage System (BESS) to perform voltage and frequency regulation, energy efficiency and loss appreciation for complete installation, effectiveness of the BESS for power quality improvements including: BESS availability, power quality improvements including energy (MWh) delivered and absorbed, voltage support/grid stabilization, decreasing transmission system losses, diminishing congestion, increasing system reliability, deferring transmission investment, optimizing size and cost of renewable energy related transmission, providing system capacity/resource adequacy/system availability, integrating renewable energy, shifting wind generation output, replacing & participating in spin/non-spin reserves, following ISO AGC/ADS market signals, energy price arbitrage.

In order to achieve a successful design, procurement, deployment, testing and operation of a demonstration-scale or larger energy storage facility; a team consisting of national leaders in energy storage technology, renewable energy integration and power systems operations are required. An example team may contain a utility, an ISO, a battery manufacturer, a converter

manufacturer, a consulting company and a university. The role of each team member for such a project is summarized in Table 14.

**Table 14: Project Tasks and Team members**

<b>Project Task Category</b>	<b>Team Members</b>
Project Management and Oversight Committee	Utility
Regulatory and Reporting	Utility
Budget, Accountability and Contract Management	Utility
Battery and Inverter System design and supply	Battery Manufacturer, Converter Manufacturer
Siting, Construction, and Substation and Grid Preparations	Utility,
Baselining	Utility, Consulting Company, University, ISO
Grid Operations	Utility
Communications and Cyber security	Utility
Study, Measurement and Validation	Utility, Consulting Company, University, ISO
Decommissioning	Utility, Battery Manufacturer, Converter Manufacturer

The utility should be the project leader and serves as the electric transmission and distribution operating entity on the project team. The utility should have primary responsibility for all project tasks and should direct the activities of other team members.

The ISO will help develop performance measurement methodologies for the project and will be involved in the analysis of all data collected during operation. Moreover, the ISO will co-publish all system benefits and performance reports produced by the project team.

The battery manufacturer and converter manufacturer will design and manufacture the energy storage system and the converter that will connect the storage unit to the grid. They will also provide storage system and converter maintenance services during the project.

The consulting company will be responsible for developing specifications for the energy storage system and the converter to be used by the battery manufacturer and converter manufacturer. Moreover, the consulting company will support the project on system impact analysis, as-built modeling, ROI calculations and provide measurement and validation function of the project by analyzing data collected from the system and battery system.

The university will provide students and resources to the project and will assist consulting company in data analysis.

To summarize, the implementation team should possess the following qualifications:

- Construction, engineering, contract management and project management experience
- Creative and effective planning and problem solving experience
- Large contract pricing/estimation experience
- Knowledge and understanding of the technology and industry best practices related to the applied technologies (energy storage, wind generation, transmission construction)

- Hands-on experience with the technology and applications related to the applied technology
- Previous experience with various utility construction standards and practices (transmission, substation, energy storage, etc.)
- Effective contract negotiation capabilities

Overall schedule for a typical large scale energy storage project of this nature assumed to begin in early 2010 can be seen from the Figure 34 given below.

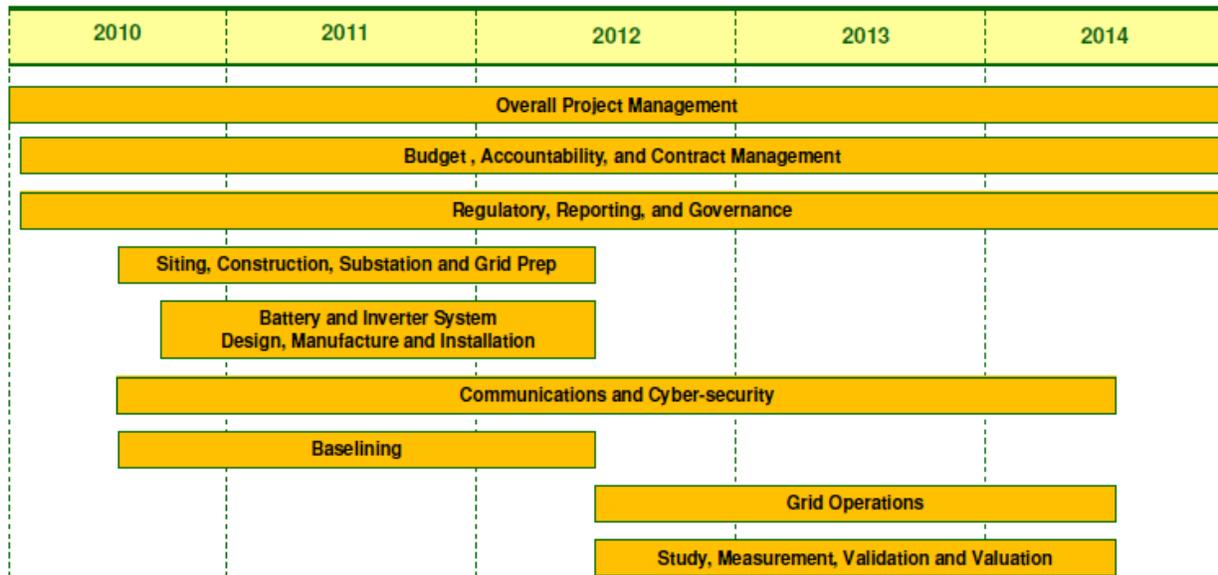


Figure 34: Overall Project Timing

### 3.3.2 Commercialization Pathway

The expected steps required for commercialization are as follows [48]:

#### **Project Definition and National Environmental Protection Act (NEPA) Compliance**

- Develop Project Management Plan
- NEPA Compliance
- Finalize Energy Storage Manufacturing Plan
- Develop Functional Specifications for ESS and PCS systems
- Develop and finalize Measurement and Verification (M&V) Plan
- Plan for Baseline Measurements

- Conceptual design of BESS system

### **Final Design, Construction, and Baselineing**

- Battery and Inverter Systems Development, Manufacture, Assembly and Installation
  - Detailed Design & Engineering
  - Procurement Process
  - Lab Bench Testing
  - Pre-Construction
  - Construction (Site)
  - Acceptance Testing in Collaboration with Grid Operations
  - Complete System Validation
- Siting, Construction, and Substation and Grid Preparations
  - Project Process Clarification
  - Site Preparation and Final Operational Models
  - Complete Design
  - Construction
  - Test
- Baselineing
  - Install PMU and Data Measurement Devices
  - Begin Baseline Data Collection
  - Install Cyber security and Communications Equipment
  - Ongoing Baseline Data Collection
  - Validate Data Capture, Transfer, Communications, and Cyber security

### **Operations, Measurement, and Testing**

- System Operations and Data Collection
  - Conduct Grid Operations
  - Substation Training and Maintenance
- Communications, Interoperability and Cyber security
- Study, Measurement, Validation and Valuation

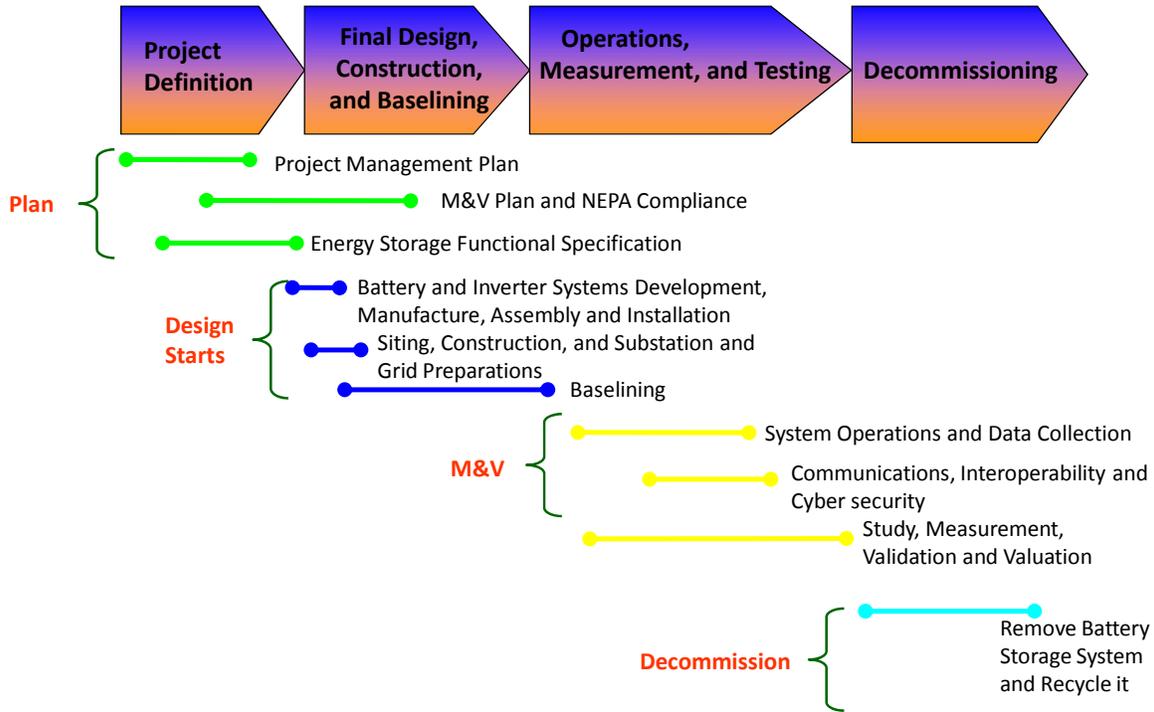
- Data Gathering
- Report Preparation
- Computer Simulation Analysis
- Complete testing of stacking scenarios

### **Decommissioning**

- Contract Closure
- Remove Battery and Recycle It
- Remove Interconnections and Devices
- Disconnect From Grid Communications
- Remove Control Systems
- Remove Project Assets
- Reassign / Demo Building Completed
- Issue Updated Standard Operating Bulletins and updated Substation / SAS Drawings
- Remove Battery Storage System from EMS

Figure 35 shows the commercialization steps.

# Commercialization Pathway



**Figure 35: Proposed Commercialization Pathway for Storage Project**

### 3.3.3 Summary of Responses

Based on the detailed BESS description given in section 3.2.2.1.1, and functional and performance requirements of BESS given in section 3.2.2.1.2, Quanta Technology issued an RFI and sent it to many ESS and PCS vendors. The following sections will summarize the responses.

#### 3.3.3.1 List of Equipment Providers

The companies that responded to the RFI are shown in alphabetical order by company name:

- ABB
- Altairnano
- NGK
- Parker SSD
- Prudent
- S&C

Quanta Technology and SCE reviewed the responses, summarized the relevant information from each response and sent the summaries to each equipment provider to assure no sensitive

information is released. Quanta Technology and SCE then summarized the responses and prepared this report which addresses the previously described objectives.

### 3.3.3.2 ABB Technical Description

This section is based on the ABB response to the RFI [49].

#### 3.3.3.2.1 Description of Battery System

Battery solution proposed by ABB is hybrid solution with a combination of 6 MW of Li-Ion energy storage batteries and 2 MW of Li-Ion power source batteries.

#### 3.3.3.2.2 Description of Power Converter System

The ABB Energy Storage System will consist of three 4 MW/4 MVA<sub>r</sub> Power Conversion Systems (PCS). PCS has reactive power support capability. PCS is provided in three outdoor 40 ft ISO containers with four 1 MW inverter lineups and a step-up transformer (480V/13.8 kV) in each container. Advantages of this integrated system with transformer in the PCS container are minimization in the site installation effort, site interconnections, construction of numbers of foundations, testing of the complete unit before delivery to site. Table 15 provides the summary of all components included in the package.

**Table 15: Summary of the components [49]**

Quantity	Components
1	69 kV SF6 Circuit Breaker with CT's, protection relay and a PQM meter
3	69 kV oil filled transformer
1	12/15 MVA, oil-filled, 66 kV/13.8 kV power transformer with surge arrestors and no load taps
3	Outdoor ISO 40 ft container with four 1 MW inverters and a step up transformer
1	Site dispatch controller including an ABB AC800 M PLC in a control box with a PC based HMI, DNP3 SCADA interface and local controls
6	1 MW / 6 MWh Zinc-Air, battery system
2	1 MW / 250 kWh Lithium-Ion, battery system

DC battery connections are connected inside the enclosure at four incoming DC circuit breakers – one for each 1 MW inverter lineup. DC power is then connected to inverter modules where it is converted to AC voltage. AC output is connected to common AC bus system and then to circuit breaker with output 480 VAC.

Output of the transformer is then fed to a fused disconnect / grounding switch assembly. Auxiliary power circuits are also included with UPS. DC power to AC power conversion in the PCS is performed using IGBT-based inverter modules. PCS 100 inverter is used in this process and presented in the Figure 36 given below. Module is a four-quadrant switching-mode converter. For control, purposes two AC line currents and the DC link voltages are measured.



**Figure 36: PCS 100 Inverter Module [49]**

Main features of the PCS 100 inverter module:

- Compact design
- Module size from 125 to 2800 kVA
- Small in size providing high output
- High ratings with units connected in parallel
- Provision of built in sine filter
- Advanced self-diagnostic with redundancy in parallel connected units
- Auto disconnection of faulty unit in case of module failure, remaining system online

Typically, 1 MW system requires 12-13 inverter modules and is mounted in a rack configuration with common AC and DC bus as shown in Figure 37.

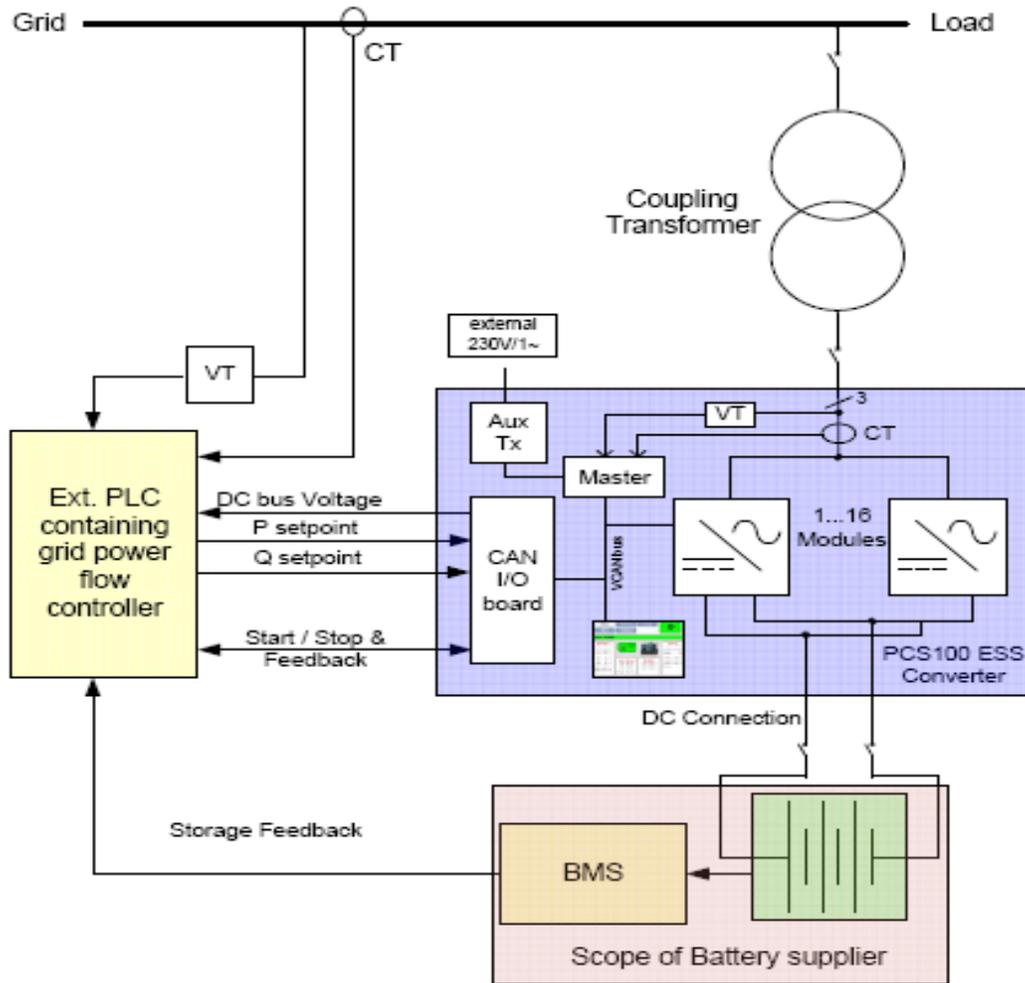
### **PCS Control**

The PCS system controls both real power (P) and reactive power (Q) based on the system requirements. System features are given below [49]:

- Dynamic Active Power Control
- Dynamic Reactive Power Control
- Generator Emulation Control Mode (voltage sourcing with Voltage and Frequency droop)
- High and Low Voltage Ride Through
- Auto Island Functionality with Synchronization Back to Grid (Optional)
- Black Start Capability (Optional)



**Figure 37: PCS100 rack (16 modules) [49]**



**Figure 38: BESS Configuration Example [49]**

**PCS System for BESS Configuration:**

Figure 38 shows PCS system for BESS configuration. PLC main control has a graphical panel display and inverter control. Each inverter lineup communicates directly with a common PCS Master Control PLC located in the container. The PLC communicates to and from the Site Dispatch Control (SDC) and the Battery Management System (BMS). The Master Controller monitors and manages the enclosure cooling / heating and other sensors such as smoke alarms, humidity sensors etc. System is equipped with an HMI (Human Machine Interface) for local control such as monitoring of actual operating values and alarm / fault status and is capable of displaying and logging data from the individual PCS and BMS and from the grid protection unit as well.

Site Dispatch Control (SDC) interface provides remote control. SDC acts as an interface between the utility side SCADA control and the PCS units with freely programmable ABB AC800 M control PLC with software. The SDC coordinates required power demand from the customer and optimizes the individual PCS output and battery state of

charge. Only one SDC is provided regardless of number of PCS units. Including with the PCS ABB also supplies compact HMI 800 Workplace which includes PC-based work station and a 21" flat screen panel. A GPS signal is supplied via Ethernet for SDC to work as time synch master for the PCS system. Available communication protocol with SCADA is Modbus. Other protocols like DNP 3 or IEC 61850 are also available. The overall single line diagram of the system is shown in Figure 39 [49].

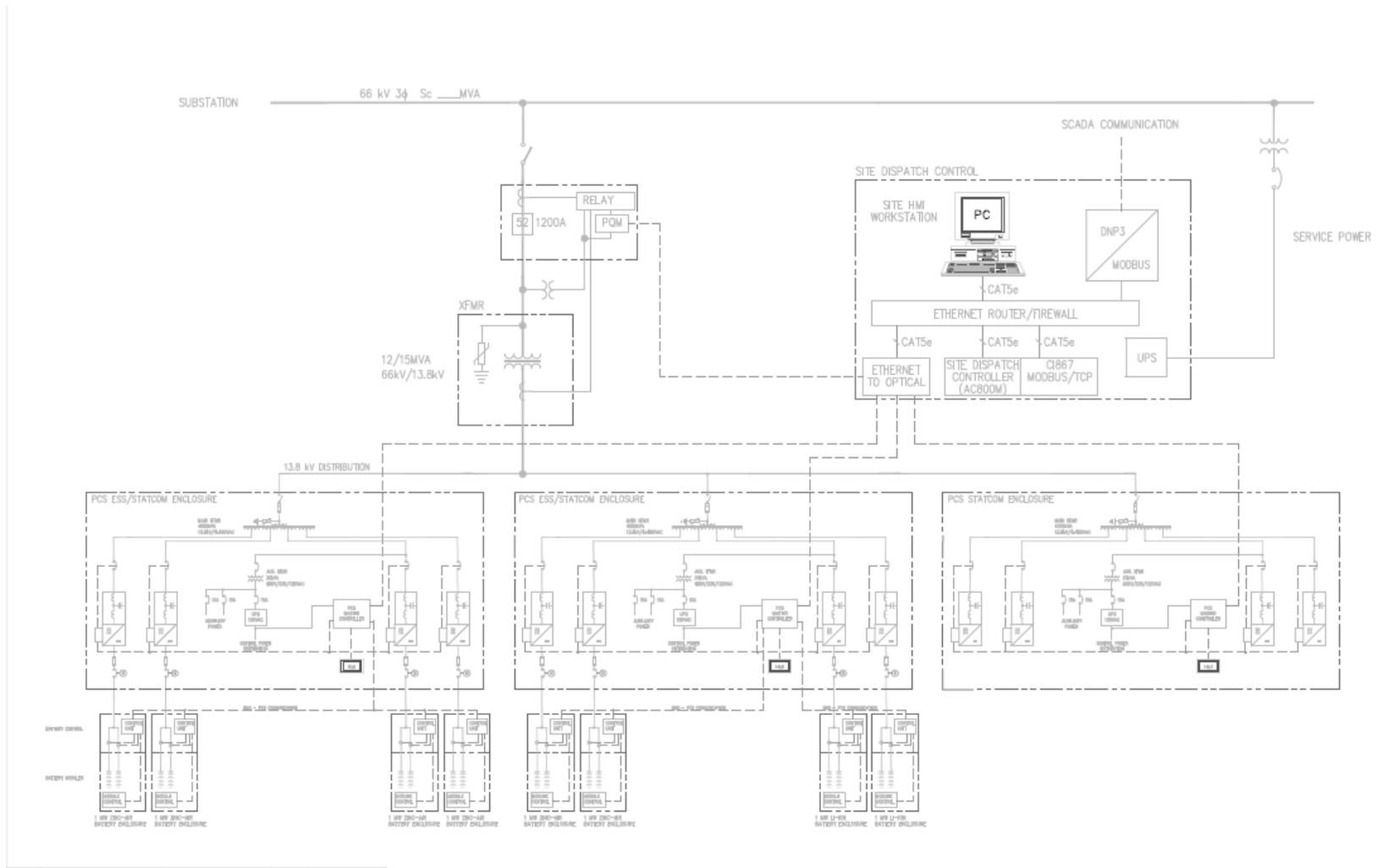


Figure 39: Single line diagram of the system [49]

### 3.3.3.2.3 *Budgetary Estimate*

ABB package includes three 69kV PT's and a breaker, protection relay, PQ meter, 66/13.6kV step down transformer, 12 MW PCS, 6 MW Energy Battery Container and 2 MW Power Battery Container and site dispatch controller. Pricing for the equipment is \$33-34M, site installation charges are \$410k and site commissioning charges are \$180k [49].

### 3.3.3.3 *Altairnano Technical Description*

This section is based on the Altairnano response to the RFI [50].

#### 3.3.3.3.1 *Description of Battery System*

Altairnano recommends a hybrid battery system based on the project requirements. This hybrid battery will consist of an Altairnano battery for the high power transients, and coupled with an energy battery (such as a flow or NaS battery) for the long duration energy needs. The Altairnano battery is suitable for contingency support, voltage profile, and improved fault ride through support, wind ramp rate smoothing, and frequency regulation. An energy battery is suitable for the hour ahead dispatch functionality and energy arbitrage [50].

While Altairnano recommends using a hybrid battery system, their technology is also capable of meeting the system requirements outlined in the RFI. Based upon their analysis of the expected duty cycle, a 32 MWh Altairnano battery would have an expected life in excess of 20 years.

While they would meet or exceed the technical requirements of the RFI, the 32 MWh system would exceed the desired installed footprint. The overall system would require 8,000 sq ft of space and would be approximately 30 feet high [50].

The Altairnano power module container and inside of the container is shown in Figure 40 and Figure 41, respectively.



**Figure 40: Altairnano Power Module Container on Shipping Carriage [50]**



**Figure 41: Inside view of container [50]**

Altairnano's technology is based on its nano lithium titanate (nLTO) battery electrode material. As a substitute for graphite, the standard anode material employed in common lithium ion rechargeable batteries, nLTO enables a battery with better performance characteristics [50].

Principal features used to compare rechargeable batteries include efficiency, power density, energy density, charge/discharge rates, temperature range, cycle life, and safety. Substituting nLTO for the graphite anode creates a battery that is capable, according to [50]:

- Possessing a greater full DOD cycle life (exceeds 12,000 cycles)
- Very high (rapid) recharge rates. (90 percent in 6 minutes, 95 percent in 10 minutes)
- Extremely high power densities.
- The capability to charge and discharge rapidly at very high and very low temperatures. (-40°C to 55°C)
- Giving rise to a battery technology that eliminates the preponderance of safety failure modes present in common lithium ion and other battery technologies

#### 3.3.3.3.2 *Description of Power Converter System*

The Altairnano energy storage system (ESS) design provides for use of inverters from multiple vendors. Altairnano has worked with several vendors on grid integration that can meet the Project's functional specifications.

#### 3.3.3.3.3 *Budgetary Estimate*

Altairnano package includes the batteries, inverters, and all other ancillary components with budgetary estimate of \$49,510,400 [51].

#### 3.3.3.4 *NGK Technical Description*

This section is based on the NGK response to the RFI [51].

##### 3.3.3.4.1 *Description of Battery System*

The NaS battery system proposed by NGK will consist of NaS battery modules rated 8 MW, battery enclosures for outdoor installation and battery management system. The NaS battery system may be used for various applications such as an operation in conjunction with a large PV farm and/or wind farm, frequency regulation control, time-shifting wind generation, and reliability enhancement [51].

As of mid-2010, over 300 MW of NAS Battery Installations have been deployed globally, and orders have been received for another 300+ MW. In response to this demand, NGK has recently increased manufacturing capacity to 150 MW per year. A 1MW NaS Battery installation is shown in Figure 42.



**Figure 42: Xcel Energy: “Xcel Energy 1MW NaS System”**

The energy storage capacity of the 1MW NaS Battery System is 6.32 MWh-dc (in other words, 6.0 MWh-ac with proper PCS).

The NaS Battery System is designed for the following range of site conditions [51]:

- Ambient Temperature: -20 to +40 degrees C (outdoor)
- Relative Humidity: 10 percent to 95 percent (Non condensation)
- Installation Condition: Outdoor Installation
- Altitude: 2,000 m or less
- Seismic load level (horizontal): 1.0 G
- Other Environmental Condition: No salty air, no corrosive gases

The DC input and output specifications for a 1 MW battery subsystem are as follows [51]:

- Rated Discharge Power: DC 1.05MW
- Charge Power: DC 0.95MW
- Nominal DC Voltage: 640V
- Stored Electric Energy: DC 6.32 MWh
- Mean Temperature at Start of Operation: 300 Degrees C

### 3.3.3.4.2 Description of Power Converter System

In majority of the cases, the PCS vendor for NaS Batteries manufactured by NGK and deployed in the U.S. is S&C Electric Company, who has been selected as the PCS supplier and EPC contractor in six of the seven NaS systems deployed in the U.S. Their design is described below for a 1 MW unit.

The primary function of the PCS is to provide bi-directional (AC to DC and DC to AC) power conversion between the utility grid at 480 Vac and the battery trains during charging and discharging. Power conversion is accomplished by a pulse-width modulated (PWM) power converter consisting of one DC converter (referred to as a “chopper”) for each of two battery trains and a single inverter rated at 1.25 MVA. PCS specifications are summarized in Table 16.

In addition to its power conversion function, the PCS provides the primary control interface for programmed and/or remote networked control of the installation, as well as the DC power and control interface between the PCS and NaS Battery. The battery system controller is connected to the PCS via an Ethernet/IP connection.

**Table 16: PCS Specifications for 1 MW, 1.25 MVA Unit**

<b>Grid Interface</b>	<b>Specification</b>
PCS Enclosure Standard/Dimensions	Packaged in 4MW, 5MVA containers (or 13.7W×2.4D×3.1H per container) (or 3.4W×2.4D×3.1H per MW)
3-Phase AC PWM Inverter (Current source or voltage source with current limit)	120kVA / 480Vac / 1500Amps (Can be paralleled)
Output current THD	< 5% (IEEE 519-1992)
Standard	IEEE 1547
Control / Communications	Master Control with local HMI or System-oriented Modbus RTU SCADA
Control Algorithms	>Pre-programmed profiles >Load follow to set-point control >ISO AGC signals
Standby Heat Loss (parasitic loss during standby)	10 to 20 kW per MW
Projected Life	20 years
<b>Battery Interface</b>	<b>Specification</b>
2 parallel battery trains (battery requirement)	1 DC/DC chopper per battery train
Nominal Voltage (OCV, charged)	640 VDC
Minimum Voltage (end of discharge)	465 VDC
Maximum Discharge Current (end of discharge)	1400 Amps
Maximum Voltage (end of charge)	780 VDC
Maximum Charge Current (beginning of charge)	900 Amps

### 3.3.3.4.3 Budgetary Estimate

The total plant cost for NGK including everything changes between \$24M-\$32M depending on application, location, environment and other factors.

### 3.3.3.5 Parker SSD Technical Description

This section is based on the Parker SSD response to the RFI [52].

### 3.3.3.5.1 Description of Battery System

Not provided.

### 3.3.3.5.2 Description of Power Conversion System

Parker SSD PCS consists of 4 containers adding up of 15 MW and each container includes the following components and can be seen in Table 17.

**Table 17: Summary of the components [52]**

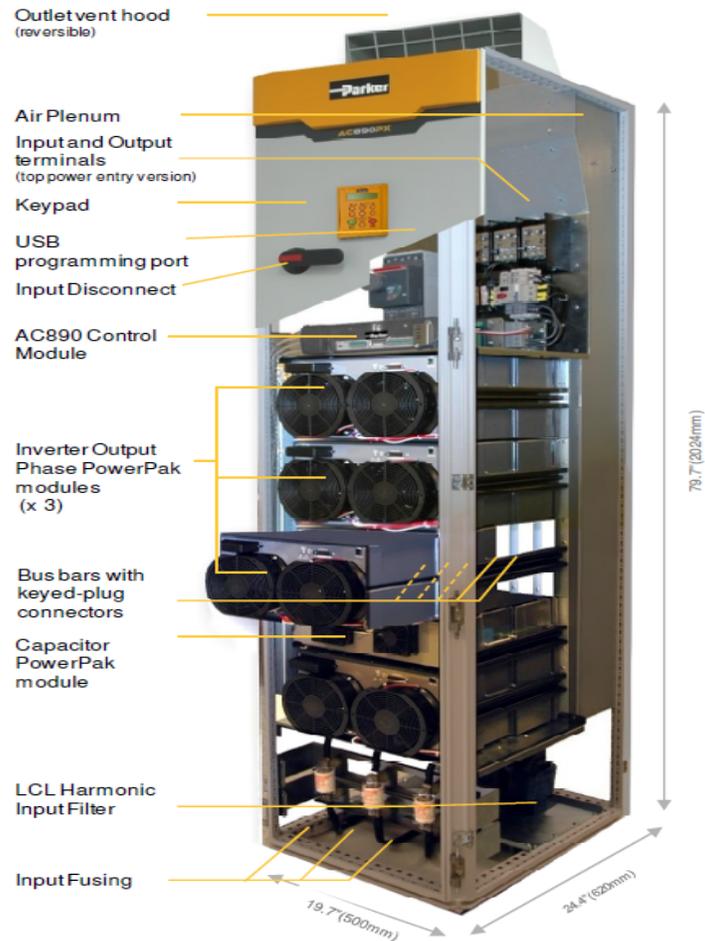
Quantity	Components
1	20' Painted, Insulated Container housing the 890PX inverters
4	1 Mw Converters w/ 2 Phase Cooling, Externally Vented
1	Large 2x Door Opening on one side of the container
1	Man Door on opposite size of container
1	Power Distribution Panel for 110VAC supply
4	LC Filter
1	Air Conditioner
2	UPS for Backup Power
1	PLC for ISO communication
1	PC interface w. Microsoft Windows and configuration tools
1	Ground fault detection

### System Description

Out of 4 containers as discussed above, 3 containers will accommodate 4x1 MW inverters and 1 container will accommodate 3x1 MW inverters. Inverter system is capable of 4 Quadrant Operation, Grid Synchronization, Charging and Discharging capability, Frequency Regulation, Selectable reactive power control modes like voltage regulation, power factor compensation, and reactive power compensation. PCS is compliant with FERC 661, UL 1741 and IEEE 1547 requirements; also, system meets IEEE 519 at the point of common coupling. Each of the individual units has anti-islanding capability.

Parker inverters are tested thoroughly to give protection for surge suppression. In the case of momentary loss of power, parker inverter will prevent phenomenon of out of phase when power is restored, protects itself from many common issues like over voltage, over frequency and loss of phase, and houses many different communication protocols (Ethernet/IP, Modbus TCP, DeviceNet, Profibus, ControlNet, CanOpen, Firewire).

Parker inverter system is built with the AC890PX series. The inverter is cooled with Vaporizable Dielectric Fluid (VDF) and the Parker Patent high density cold plate technology. Inverter is tested using Highly Accelerated Life Testing, which combines thermal and vibration technologies to stress a product beyond its specifications (HALT) [52]. Figure 43 shows an overview of AC890PX modular bi-directional inverters.



**Figure 43: Modular Bi-Directional Inverters [52]**

### 3.3.3.5.3 *Budgetary Estimate*

Parker SSD package includes 15MW Power Converter system in containers. Parker has indicated their preference of not releasing budgetary price information for the system described. However, Parker staff is available for further discussions on the topic based on a particular customer need.

### 3.3.3.5.4 *Prudent Energy Technical Description*

This section is based on the Prudent Energy response to the RFI [53].

### 3.3.3.5.5 *Description of Battery System*

Prudent energy proposed vanadium-based redox regenerative fuel cell (VRB) that converts chemical energy into electrical energy and VRB Energy Storage System with rating 8 MW for 4 hours (32 MWh). System contains forty eight 175 kW modules. VRB-ESS™ meets duty cycle requirements like contingency support by supplying/absorbing MW, minimizes wind power curtailment, provides low-voltage-ride-through (LVRT) to the older wind farms, provides dynamic voltage stability on wind farm buses, provides support to ageing SVC during contingencies, helps to improve wind farm 1-hour ahead dispatchability, provides black-start

functionality, voltage and frequency regulation, helps in reducing system losses and provides additional spinning reserve and energy price arbitrage.

### VRB-ESS™: REDOX Flow Battery Components

Vanadium-based redox regenerative fuel cell (VRB) is an electrical energy storage system that converts chemical energy into electrical energy. Energy is stored chemically in different ionic forms of vanadium in a dilute sulfuric acid electrolyte [53]. This type of battery uses an electrolyte where energy is stored and a cell stack where energy conversion occurs. The REDOX flow battery has two reservoirs to house the two different electrolyte solutions and a cell stack. Each cell has two half cells separated by a proton exchange membrane (PEM) and two electrodes. Positive half-cell contains Vanadium (II/III) REDOX and negative half-cell contains Vanadium (IV/V) REDOX [53]. As can be seen in Figure 44, VRB-ESS™ has 4 cell stacks. Figure 45 shows the single line diagram for 9 MW system.

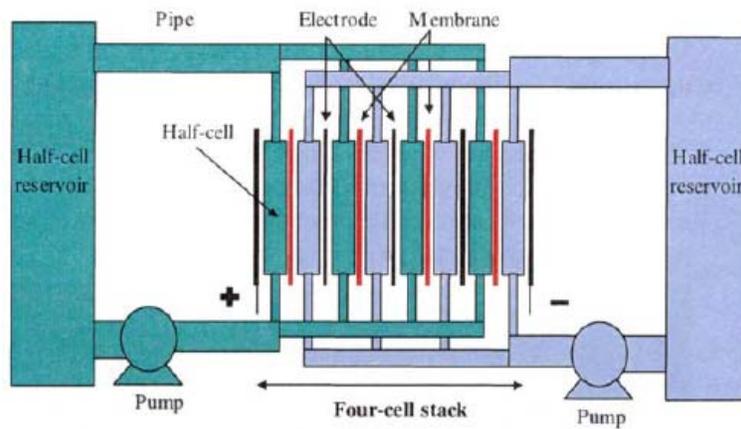


Figure 44: VRB-ESS™: REDOX Flow Battery [53]

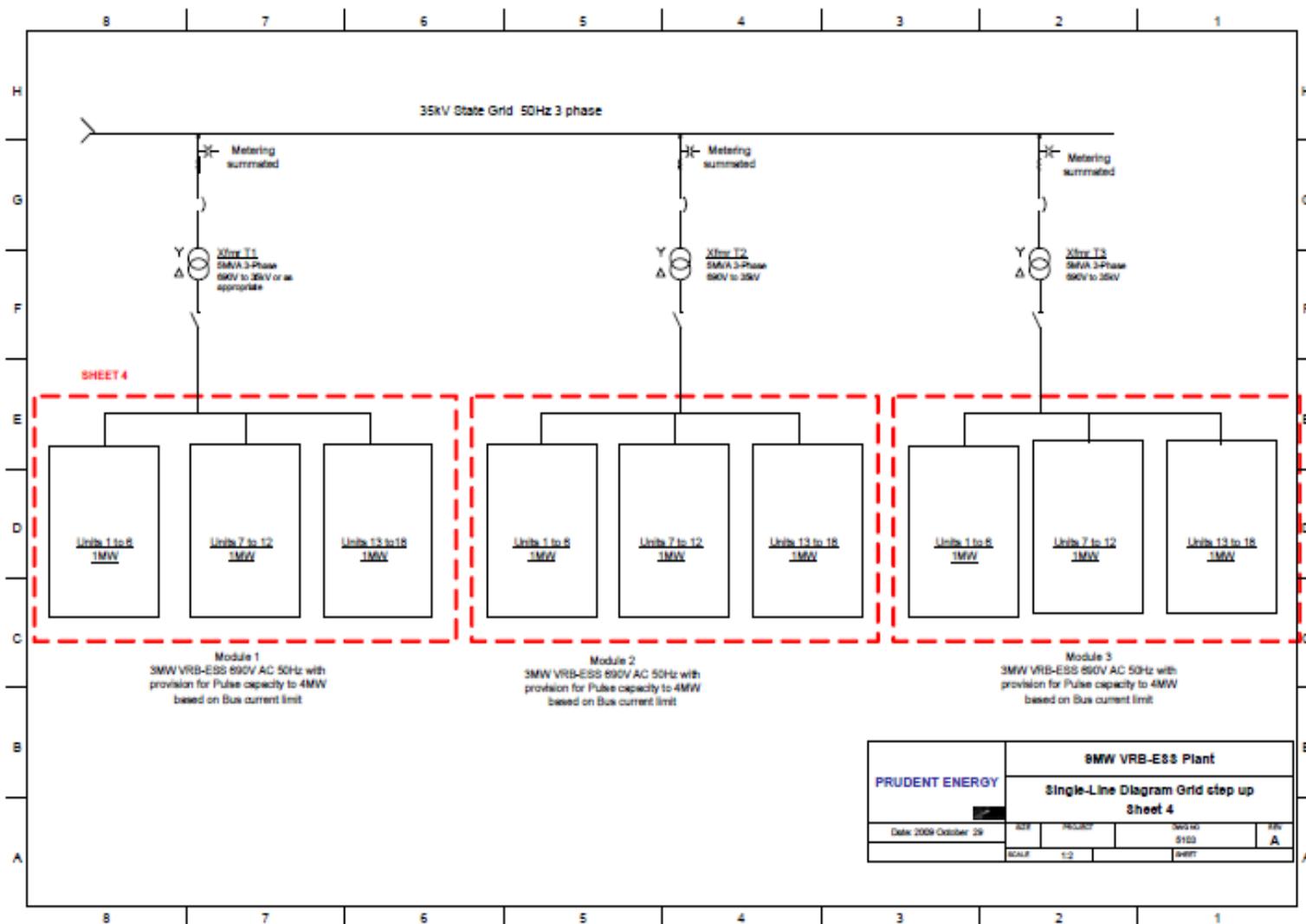


Figure 45: System single line for a 9MW VRB-ESS™ [53]

#### 3.3.3.5.6 *Description of PCS*

Prudent Energy controls bi-directional power flow into and out of battery system. PCS is an integrated unit with the battery and cannot be separated. It is a 2 stage device i.e., conversion from DC-DC using a buck boost chopper feeding 1000V dc bus and conversion from DC-AC for charge and discharge control. PCS lineup consists of one unit per 150/175 KW module for high reliability, since in case of event failure, the effected unit can be taken out. PCS has the capability of 4-quadrant operation and supports rapid change of voltage or power. Isolation transformer and local protection is also included in the package. The VRB-ESS™ operates with three levels of controls [53]. Level 1 is unit control which provides unit control of pumps, flows, temperatures and pressures within each unit. Level 2 controls each PCS unit operation in terms of IGBT phase angle firing, DC bus management, THD and harmonics and safety. Level 3 controls and communicates with level 1 & 2.

#### 3.3.3.5.7 *Budgetary Estimate*

Prudent Energy package includes flow batteries with Step up transformers and high voltage connections. Due to the nonlinear behavior of price with respect to kW and kWh ratings, Prudent Energy prefers not to release budgetary price information for the system described. However, Prudent Energy would be happy to talk with potential customers on specific opportunities.

#### 3.3.3.6 *S&C Technical Description*

This section is based on the S&C response to the RFI [54].

##### 3.3.3.6.1 *Description of Battery System*

S&C has teamed with NGK Isolator Company of Japan for the battery part of the proposal. The NGK provides sodium sulfur (NaS) batteries. See NGK response for battery description.

##### 3.3.3.6.2 *Description of Power Converter System*

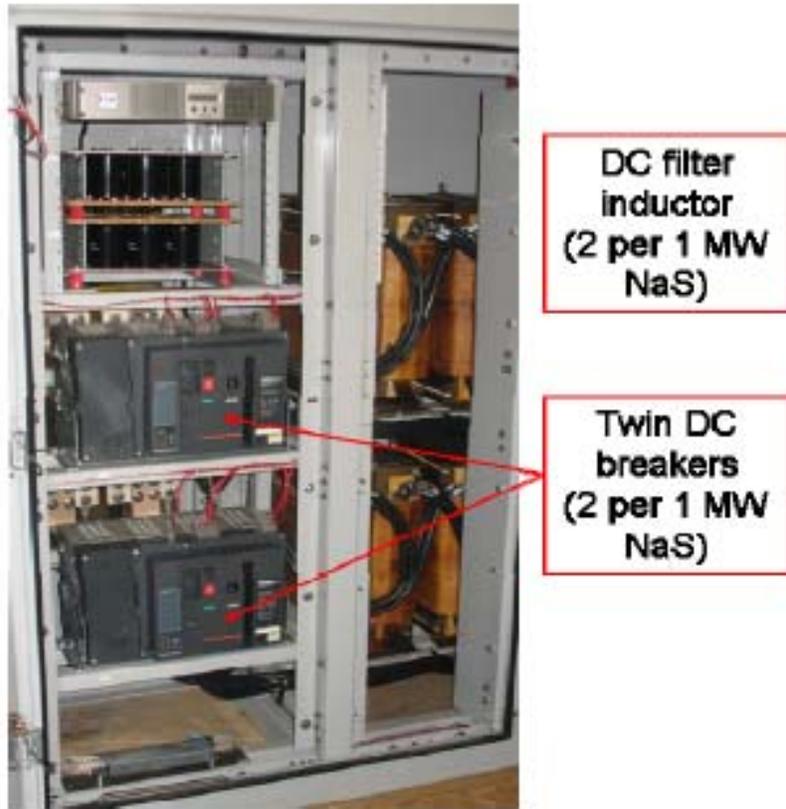
The S&C power conversion system (PCS) will consist of two 4 MW Storage Management System (SMS) each in a 45 ft ISO container which will be used to charge/discharge the batteries; and a 7.5 MVA DSTATCOM in a 45 ft ISO container which will be used for reactive power compensation. The details of the SMS are provided below.

One of the most important subsystems of the SMS is the two (2)  $\pm 1.25$  MVA inverter blocks. Figure 46 below shows two (2)  $\pm 1.25$  MVA inverter block. The panel between the two (2)  $\pm 1.25$  MVA blocks contains an individual 480 volt breaker for each inverter. The IGBT (Insulated Gate Bipolar Transistor) is the main power electronics component for the  $\pm 1.25$  MVA inverter block. Each  $\pm 1.25$  MVA inverter block consist of 12 IGBTs and has its own local control, breaker, AC filter components [54].



**Figure 46: A typical  $\pm 1.25$  MVA SMS Inverter and 2 choppers [54]**

The other important operational subsystem of the SMS is the two (2)  $\pm 1$  MW DC to DC converter “chopper” blocks. The use of this subsystem is to take the variable DC voltage from the battery and create a fixed DC voltage which forms the DC link of the inverter system. The control of the chopper by the SMS controls allows charging, or discharging within the requirements which have been provided by battery suppliers. Each chopper connects to 1 MW of NaS batteries and can be independently controlled. Moreover, filtering is also provided with the chopper section so that the NaS batteries see only DC. The choppers are controlled to determine the direction of power flow and are current limited by the controls in accordance with the battery controller’s commands [54]. Figure 47 below shows the DC switchgear and filter bays.



**Figure 47: DC Switchgear and DC Filter Bays [54]**

Each S&C inverter block consists of its own controls, circuit breaker and a small AC filter used to eliminate any high-frequency harmonic voltages in the output of the PWM waveform coming from the inverter. The individual DC breakers are used to protect each individual battery string. Moreover, the inverters and choppers blocks are air-cooled [54].

Figure 48 and Figure 49 show details of the SMS layout and the various interface points that are a part of the 45 foot (13.7m) enclosure. In a 45 foot enclosure up to four (4)  $\pm 1.25$  MVA blocks along with the associated DC switchgear for connection to each of the four (4) 1 MW of batteries can be accommodated. A single-line diagram for a 5.0 MVA/4.0 MW SMS is shown in Figure 50 [54].

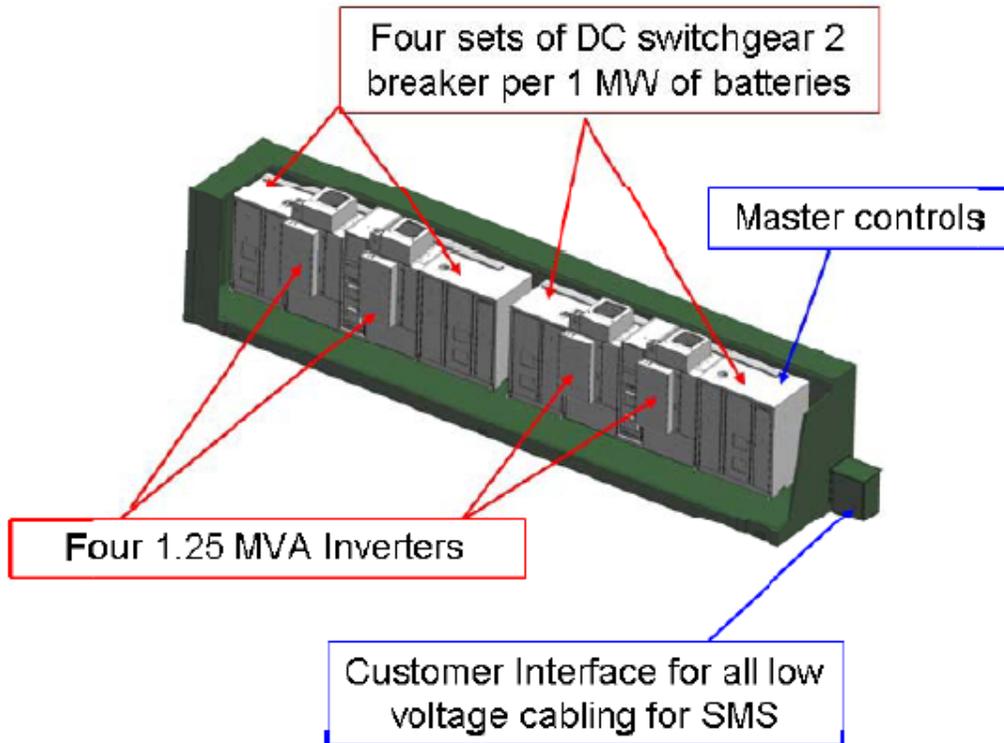


Figure 48: Front cutaway of SMS enclosure with 4 inverters and DC Bays [54]

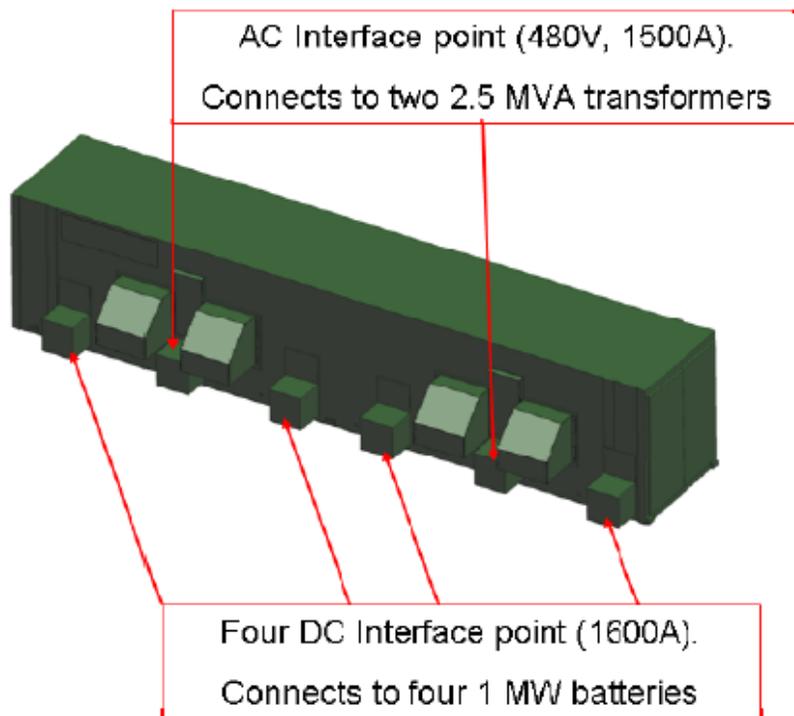
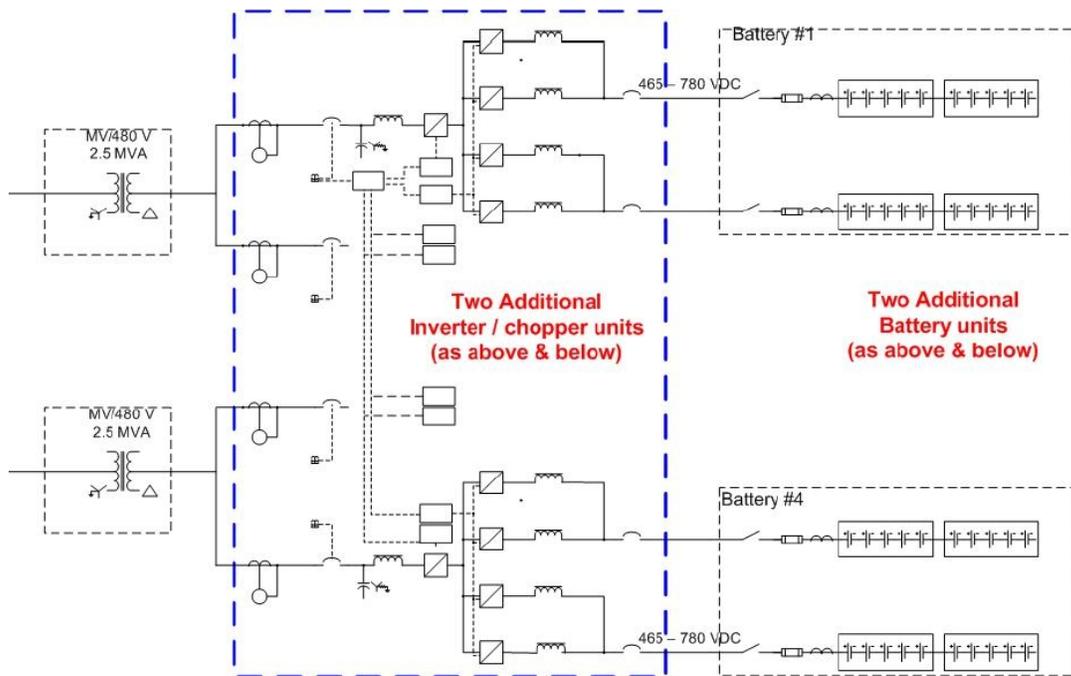


Figure 49: Rear view of SMS enclosure with 4 inverters and DC Bays [54]



**Figure 50: Single line diagram of the system [54]**

### 3.3.3.6.3 Compliance/Deviation to RFI requirements

S&C addresses the following comments and clarifications in their proposal:

- The NaS solution offered by S&C is six (6) hours or 48 MWh total which is better than the 32 MWh required in the RFI.
- The S&C and NGK joint proposal will meet the general requirements of the RFP.
- The installation assumptions are:
  - SCE / Quanta Technology supplies all step-up transformers and performs high-voltage connection to transformers.
  - SCE / Quanta Technology supplies all high-voltage connections and equipment to tie in the complete energy storage system to the grid.

### 3.3.3.6.4 Budgetary Estimate

S&C, 8 MW NaS Battery System consists of eight (8) 1.0 MW, 6-hour battery modules including battery enclosures, control boxes and support services, 2\*4 MW SMS in 45ft ISO, 7.5 MVA DSTATCOM in 45 ft ISO, 7 x 2.5 MVA 480/35 kV transformers including installation. S&C proposed estimate for three different types of battery systems. Price for the whole package listed above with NaS battery system is \$30M. Pricing for Li-ion batteries is \$54M [54].

### 3.3.3.7 Comparison of All responses

The summary and comparison of ESS responses are shown in Table 18.

**Table 18: Comparison of ESS responses**

Description	Desired Value or Range	NGK	ABB (Li-Ion)	Prudent	Altairnano	S&C (NaS Batteries)
Nominal Power Rating	8 MW	8 MW	8 MW	8 MW	8 MW	8MW
DC Minimum Energy Rating	> 32 MWh (Based on 90% DOD)	48 MWh	39.5 MWh	32 MWh	32 MWh	50.56 MWh
Cycle Life at 80% DOD	> 4500	4500	5000	> 10000	20000	Comply
Cycle Life at 90% DOD	> 2500	4500	5000	> 10000	15000	Comply
Self-discharge rate and tare losses	< 5% per month	0%	2.5% per month	< 5% per month	<5% per year	0% self-discharge, 460 kW tare losses
Round-trip Efficiency	> 80 % on DC side	85%	>90%	84%	>91%	78% on AC side
Installed Footprint (ESS with Enclosures)	< 500 m <sup>2</sup>	190 m <sup>2</sup>	252 m <sup>2</sup>	2400 m <sup>2</sup> (single story)	743 m <sup>2</sup>	2388 m <sup>2</sup> (including PCS)
Maximum Height	< 8 m	5.3 m	<4 m	≤ 8 m	9.14 m	Comply
Peak Power Rating	9 MW (2 hours)	8 MW	9 MW for 2 hours	12 MW for 10 mins every hour	9.5 MW	8 MW
Rated (Fully Charged) DC voltage	> 600 Vdc	640 Vdc	> 600 Vdc	400 Vdc	1050 Vdc	640 Vdc
Fast Charge Time	< 6 hours	6 hours	< 6 hours	6 hours	15 min	8 hours
Calendar Life time	≥ 15 years	15 years	15 years	10 -15 years	20 years	15 years
Energy Density	≥ 30 Wh/kg	69 Wh/kg	> 200 Wh/kg	11 Wh/kg	72 Wh/kg	97.8 Wh/kg
Power Density	≥ 30 W/kg	11.5 W/kg	> 200 W/kg	25 W/kg	1250 W/kg	15.5 W/kg
Emission (gas or liquid)	None	None	None	None	None	None
Power consumption of peripheral devices (Battery only: ventilation, air conditioning, etc.)	< 80 kW	400 kW	<60 kW	160 kW	48 kW	460 kW

The summary and comparison of PCS responses are shown in Table 19.

Table 19: Comparison of PCS responses

Description	Desired Value or Range	S&C	ABB	Parker SSD	Prudent
Nominal VAR Rating	± 12 MVar	13.5 MVar	12 MVar	12 MVar	12 MVar
Peak VAR Rating	± 20 MVar for 4 seconds (after step-up transformer)	>20 MVar for 4 sec	18 MVar	20 MVar	13.2 MVar
Nominal VA Rating	15 MVA	17.5 MVA	15 MVA	15 MVA	16.8 MVA
Battery Interface Voltage (DC input)	> 600 Vdc	470-745 VDC	NF	600-1050 VDC	750-1000 VDC
Output Voltage Regulation	±5%	480VAC±3%	±10%	NF	< 1.5%
Nominal Operating Frequency	60 Hz	60 Hz ±0.1 Hz	60 Hz	60 Hz	50/60 Hz
System Response Time (output power tracking)	≤ 20 ms	2-4 ms	<20 msec	10 ms	1-8 ms
Efficiency at full-load (15 MVA)	≥ 96% (min=96% Including step-up transformer)	96.1%	97%	98%	97%
Efficiency at half load (7.5 MVA)	≥ 93% (min=93% Including step-up transformer)	95.8%	NF	>93%	94%
Total Voltage Harmonic Distortion	Per IEEE 519 and IEEE 1547	Comply	< 3.0%	Comply	Comply

NF = Not Found in Response

The summary of costs is shown in Table 20.

Table 20: Summary of Costs

Bidder	Exclusion	Cost
S&C (NaS Option)	Step up transformers and high voltage connections (They provide 480/35 kV transformers)	\$30M
S&C (Li-Ion Option)	Step up transformers and high voltage connections (They provide 480/35 kV transformers)	\$54M
Parker SSD (No battery)	Step up transformers and high voltage connections	Confidential
ABB (Hybrid Solution)	None	\$33-34M
Prudent (Flow Battery)	Step up transformers and high voltage connections (They provide 690/35 kV transformers)	Confidential
NGK (Battery)	(Includes battery with BMS and enclosures)	\$16M-\$20M
NGK (Power Electronics)	(Includes balance of plant, power electronics, all costs for installation, step up transformers)	\$8M-\$12M
NGK (Total)	None	\$24M-\$32M
Altairnano (Li-Ion)	(Includes inverters and other ancillary components)	\$49.5M

### 3.3.4 Data Monitoring

Typical data sets to monitor improvements for obtaining, archiving, and assessing sub-hourly system data necessary to track the performance of an energy storage system including transients and power quality events can be obtained by using technologies such as Digital Fault Recorders (DFRs) and Phasor Measurement Units (PMUs). The required performance data is then made available through Phasor Data Concentrators (PDC), the DFR records from a DFR/PMU, grid data through the EMS/SCADA system, as well as output data from other application modules used in systems operations. Monitoring local sub-station and output data through CTs and PTs, measuring quantities, such as voltage/current magnitude, active and reactive power, and so on, can be accomplished typically by visualization software and integrated Human Machine Interface (HMI) equipment.

The results of these different data streams and applications modules are normally stored in the operational and historian databases as real-time streaming data for use by the Key Performance Indicator monitoring units through specified visualization software.

These application modules are divided into two main categories: real-time applications, and non-real-time applications. The real-time applications are executed continuously in real-time and must meet certain real-time performance requirements once instantiated, while non-real-time applications are executed only when they are called and typically have less stringent requirements on their performance.

For real-time wide-area monitoring applications, the ability to generate real-time warnings, alarms, and to enable real-time trending are required.

Typical real-time applications are:

- Voltage Magnitude Monitoring
- Current Magnitude Monitoring
- Frequency Magnitude Monitoring
- Power Magnitude Monitoring
- Reactive Power Magnitude Monitoring
- Voltage Phase Angle Difference Monitoring
- Low Frequency Oscillation Monitoring
- Voltage Stability Monitoring

The non-real-time applications included in this specification are:

- Fault Location
- Post Event Analysis

In order to track the performance of the battery energy storage system (BESS), several metrics have been determined and some of these metrics require specific measurements. Others are generally available in systems operation and does not require additional measurement capabilities. A table summarizing these metrics and required measurements is shown in Table 21. Depending on the storage application additional monitoring equipment may be required e.g., ISO frequency regulation control signal, special protection schemes, load following, etc.

**Table 21: Metrics and Measurements Required for Performance Monitoring**

<b>Metrics</b>
Reliability Performance Gap (RPG) Index
Demand Charge Savings Index (DCS) (peak shaving)
Annual Energy Charge Savings Index (ECS)
CAIDI: Customer Average Interruption Duration Index
ASAI: Average System Availability Index
Availability and reliability of the storage device
Round-trip energy efficiency of storage device
Energy storage life time
<b>Measurements Required</b>
Frequency Magnitude Monitoring
Disturbance Events Monitoring
Load Monitoring for load following
Charge/Discharge Energy Monitoring
Voltage Magnitude Monitoring
Current Magnitude Monitoring
Active Power Magnitude Monitoring
Reactive Power Magnitude Monitoring
State of Charge (SOC) of the BESS

### 3.3.4.1 Monitoring Requirements

#### **Voltage Magnitude Monitoring**

Voltage magnitude in a power system is one of the basic indicators of system health. An unexpected, unusual voltage drop can be an indicator of system overload or worse. This application allows the user to monitor the voltage magnitude at multiple buses where PMUs are installed. The application will generate warnings / alarms for the monitored voltages, when preset limits are exceeded.

#### Data Input Requirements for Voltage Magnitude Monitoring:

Should be specified to receive the real-time streaming digital phasor data in IEEE C37.118 format from the Phasor Data Concentrator (PDC) output.

Should be specified to retrieve the archived data as data files for playback in IEEE C37.118 format and/or binary files from the operational database, historical data archive and/or file folder.

#### Data Output Requirements for Voltage Magnitude Monitoring:

Should be specified to generate at minimum a real-time output data stream in IEEE C37.118-2005 format for all monitored targets.

Should be specified to monitor all monitored outputs (data, alarms and warnings) included in the above IEEE C37.118 data stream.

Should be specified to generate additional real-time output data streams in IEEE C37.118-2005 or other protocols for all monitored targets or a partial list of monitored targets.

The output data rate should be selectable, from the following (but not limited to) – a) every N<sup>th</sup> sample of the available data, b) an average of N samples, c) Same as input data rate etc.

It should be able to save / archive its output data (including alarms and warnings) in the database as a historical record.

#### **Current Magnitude Monitoring**

Current magnitude in a power system is one of the basic indicators of system status. An unexpected, unusual current draw can be an indicator of system overload or worse. This application should allow the user to monitor the total current flow over a specified group of transmission lines where PMUs are installed. It allows the user to define a closed area by including all the transmission lines entering / leaving that area. The application will monitor the net current flow in or out of that area. It will generate warnings / alarms for the monitored current flow, when preset limits are exceeded. Current flow along a single line can be monitored by including only a single line in the application.

#### Data input requirements for Current Magnitude Monitoring

Should be specified to receive the real-time streaming digital phasor data in IEEE C37.118 format from GCC-PDC output.

Should be specified to retrieve the archived data as data files for playback in IEEE C37.118 format and/or binary files from the operational database, historical data archive and/or file folder.

#### Data output requirements for Current Magnitude Monitoring

Should be specified to generate at minimum a real-time output data stream in IEEE C37.118-2005 format for all monitored targets.

Should be specified to monitor all monitored outputs (data, alarms and warnings) included in the above IEEE C37.118 data stream.

Should be specified to generate additional real-time output data streams in IEEE C37.118-2005 or other protocols for all monitored targets or a partial list of monitored targets.

The output data rate should be selectable, from the following (but not limited to) – a) every N<sup>th</sup> sample of the available data, b) an average of N samples, c) Same as input data rate etc.

It should be able to save / archive its output data (including alarms and warnings) in the database as a historical record.

### **Frequency Magnitude Monitoring**

Frequency magnitude in a power system is one of the basic indicators of system health. An unexpected, unusual frequency drop can be an indicator of system overload or worse. This application allows the user to monitor the frequency magnitude at multiple buses where PMUs are installed. The application will generate warnings / alarms for the monitored frequency, when preset limits are exceeded. Data Input and Output requirements are similar to both Voltage and Current Magnitude Monitoring.

### **Active Power Magnitude Monitoring**

This application allows the user to monitor the total power flow over a specified group of buses where PMUs are installed. It allows the user to define a closed area by including all the transmission lines entering / leaving that area and the buses inside the area that the lines connect to. The application typically monitors the net power flow in or out of that area. It will generate warnings / alarms for the monitored power flow, when preset limits are exceeded. Power flow along a single line can be monitored by including only a single line (and the associated bus) in the application.

### **Reactive Power Magnitude Monitoring**

This application allows the user to monitor the total reactive power flow over a specified group of buses where PMUs are installed. It allows the user to define a closed area by including all the transmission lines entering / leaving that area and the buses inside the area that the lines connect to. The application typically monitors the net reactive power flow in or out of that area. It will generate warnings / alarms for the monitored reactive power flow, when preset limits are exceeded. Reactive power flow along a single line can be monitored by including only a single line (and the associated bus) in the application.

### **Voltage Phase Angle Difference Monitoring**

The voltage phase angle differences between different buses are important system parameters. They are accurate indicators of power flow and system stability. Real time monitoring of these parameters will be a significant contributor towards corrective actions. This application allows the user to monitor the phase angle differences between multiple buses and a selectable reference bus in the system where PMUs are installed. The application will generate warnings / alarms for the monitored voltage phase angle differences, when preset limits are exceeded.

### **Low Frequency Oscillation Monitoring**

Each system has some natural oscillation frequencies. When the system is excited with a disturbance such as a fault, it works as an impulse to the system and the oscillating modes reflect in the measured quantities. Depending on the observability of the modes of oscillation in the measurement, the modes can be detected by spectral analysis or other means. The corresponding frequency and damping of each mode can be calculated using different algorithms. If the damping ratio is lower than 5 percent it is considered as poorly damped system where the oscillation may continue for a prolonged duration causing other undesirable events to happen. The low frequency oscillation monitoring application will provide the information in real time so that corrective actions can be taken. The low frequency oscillation detection application normally identifies the low frequency oscillation present in an event if it falls under the range of interest (typically the low frequency range should be user selectable and lies within 0.1 Hz to 2 Hz). This helps to identify the critical poorly damped modes so that the operator can make decisions on re-dispatch or some other means to alleviate the small signal stability problem.

### **Voltage Stability Monitoring**

Voltage Stability is the ability of an interconnected power system to maintain acceptable voltages at all applicable load buses under normal conditions and abnormal conditions. Interconnected systems on the Western Interconnection comply by meeting NERC and WECC voltage and reactive control reliability standards and system performance planning standards under both normal and contingency conditions. NERC balancing areas balance generation to load while ensuring voltage levels, reactive flows and reactive resources are monitored, maintained, controlled and maintained within limits to protect equipment and maintain the reliable operation of the interconnection. The goal of the interconnection is to deliver energy to fluctuating loads at applicable buses without allowing the voltage to drop below nominal operating levels. If a bus is loaded beyond its limit, the system becomes voltage unstable causing circuit breakers to trip. This loading limit depends on the system conditions and varies from situation to situation. The objective of the voltage stability monitoring application is to

provide a real-time online tool for assessing the power system reliability margin with respect to voltage stability from phasor measurement data. The outcome will assist bulk power operators to take pre-emptive remedial measures thereby preventing voltage instability and furthermore voltage collapse linked cascading failures of the system.

### **State of Charge Monitoring**

The State of Charge of a battery is its available capacity expressed as a percentage of its rated capacity. Knowing the amount of energy left in a battery, compared with the energy it had when it was new, gives the user an indication of how much longer a battery will continue to discharge before it needs recharging. Using the analogy of a fuel tank in a car, SOC estimation is often called the “Fuel Gauge” function [55].

As it is not desired to deplete or overcharge the battery, the SOC of the battery should be kept within proper limits (i.e. between 30-100 percent) and need to be determined accurately for the controller operation [56], [57].

Several methods exist in literature which can be used in SOC estimation [58]-[63]. Some of these methods are discharge test, Ah counting, artificial neural network and Kalman filter. A summary and a brief explanation of these methods can be found in [64].

It should be noted that the SOC reference is normally the rated capacity of a cell which is a new cell. It is not the fully charged capacity of the cell when it was last charged (i.e. the current charge-discharge cycle). This is because the cell capacity gradually reduces as the cell ages and it is also affected by temperature and discharge rate. For example, towards the end of the cell's life its actual capacity will be approaching only 80 percent of its rated capacity and in this case, even if the cell were fully charged, its SOC would only be 80 percent. This difference is important if the user is depending on the SOC estimation as he would in a real gas gauge application in a car. Therefore, these ageing and environmental factors must be taken into account if an accurate estimate is required.

### **Charge/Discharge Energy Monitoring**

In order to calculate the round trip efficiency of the BESS, the energy going in and out of the BESS need to be measured. For this purpose, the energy discharge to the grid at the point of interconnection (Wh) and the energy charge to the grid at the point of interconnection (Wh) needs to be monitored.

### **Disturbance Events Monitoring**

In order to assess the availability and the reliability of the BESS, the disturbance events such as the loss of a transmission equipment tied to the BESS (single phase line to ground fault with delayed clearing, line tripping due to growing trees, etc.) needs to be monitored.

## **Load Data Monitoring**

To see the performance of BESS in Demand Charge Savings, Annual Energy Charge Savings and Load Following applications, the load data and the demand of the system need to be monitored.

## **Locational Marginal Price data requirements**

Locational Marginal Price (LMP) is the price of supplying the next MW of load at a specific location, considering generation marginal cost, cost transmission congestion and losses. LMP's generally consist of three components:

- Energy
- Congestion
- Losses

LMP's determines transparent prices at all price locations on the grid. In California generators are paid the LMP. The load pays the averaged LMP in an area. LMP's manage all congestion in the day-ahead markets to create physically feasible schedules prior to real-time operations. Location price patterns can often help determine where generation and transmission upgrades are needed.

Transmission system congestion occurs when available, low cost supply cannot be delivered to the demand location due to transmission limitations. As market participants compete to utilize the transmission system, RTO provide a non-discriminant mechanism to address the transmission congestion problem. LMP's can be compared at on-peak, off-peak, an average with a maximum and a minimum. They can be reported in monthly, weekly, hourly location marginal price outputs and also as hub LMP outputs. Hubs can be defined to match common market trading points, or measure LMO or congestion exposure of a portfolio of generation assets or load obligations. A hub is usually defined a list of buses with weighting options, describing how the bus LMP's are accumulated to form a hub LMP. Typical system data that would be inputted to calculated nodal or zonal LMP prices can include:

- Adjusted Market Price
- An organizations average billing rate
- Any pooled billing rates
- Regional Marginal Energy cost
- Emergency Energy prices

When calculating LMP's the following needs to be considered:

- A DC Power Flow Model (DC Power flows are proportional to the admittance of each path)
- Generation Shift Factors on monitored branches
- Computation of applicable that is set as a typical linear optimization commonly called a Security Constrained Economic Dispatch (SCED) with an objective function to minimize cost and applicable constraints.

LMP values are calculated based on generation offer data and the power flow characteristics of the transmission system.

#### *3.3.4.2 Disturbance Monitoring Equipment*

The power system is routinely subjected to faults or disturbances which can range from transient faults on transmission/distribution lines to system-wide disturbances involving many states or countries. Investigation of each incident is critical in optimizing the performance of protection systems with the goal of preventing future incidents from becoming wide-area disturbances [65]. The tools required to perform post-incident analyses include Disturbance Recording Equipment (DRE) which can capture pre-event, event, and post-event conditions with a high degree of accuracy.

Disturbance Monitoring Equipment (DME) are the devices capable of monitoring and recording system data pertaining to a disturbance [66]. Such devices include the following categories of recorders [70]:

#### **SER – Sequence of Event Recorder**

The Sequence of Events Recorder (SER) provides a permanent record of events which occur within milliseconds of each other, such as the operation of circuit breakers or the shutdown sequences of compressors and other high speed devices. The SER will provide the time of the event, the state of the point, and the point identification [71].

A SER captures the sequence of events for monitored changes of state occurring in substations or power plants. It is used in conjunction with records from DFRs or DSRs to complete post-event analyses [65]. For non-fault conditions, the SER record may be the only recorded data available.

SERs enable rapid root-cause analysis after multiple events have occurred due to the secure recording of events in their sequence of occurrence. SERs are therefore utilized a diagnostic tool to minimize plant downtime. SERs are often interfaced with a SCADA system, Distributed control system (DCS), or Programmable logic controller (PLC) [72].

SER reports are used by electrical engineers to analyze large and small electrical system blackouts. After the Northeast Blackout of 2003, the North American Electric Reliability Corporation (NERC) specified that electrical system data should be time-tagged to the nearest millisecond [72].

### **DFR – Digital Fault Recorder**

A DFR is generally used to record faults on the power system. The sampling rate is high (many samples per cycle) to provide the resolution required, but the length of the record is short (a few seconds at most), limited to immediate pre-fault, fault, and post-fault conditions [65].

- Includes Digital Relays (as reported by some regions)
- Differential Relay: It is applied for transformer and bus protection. Application includes protection for over-current, overvoltage, under-voltage, ground fault, under-frequency, etc.
- Feeder Relay: Used for the protection of radial branches of the electrical network. It has the entire features differential relay except the differential function.
- Motor and Generator Protection Relay: These relays are used to protect large motors. Besides all the protecting and measuring features, it also has some extra characteristics such as vibration protection, temperature protection.

### **DRD – Dynamic Recording Device**

- DDR – Dynamic Disturbance Recorder

Dynamic Disturbance Recorders (DDR), which record incidents, that portray power system behavior during dynamic events such as low frequency (0.1 Hz – 3 Hz) oscillations and abnormal frequency or voltage excursions [67].

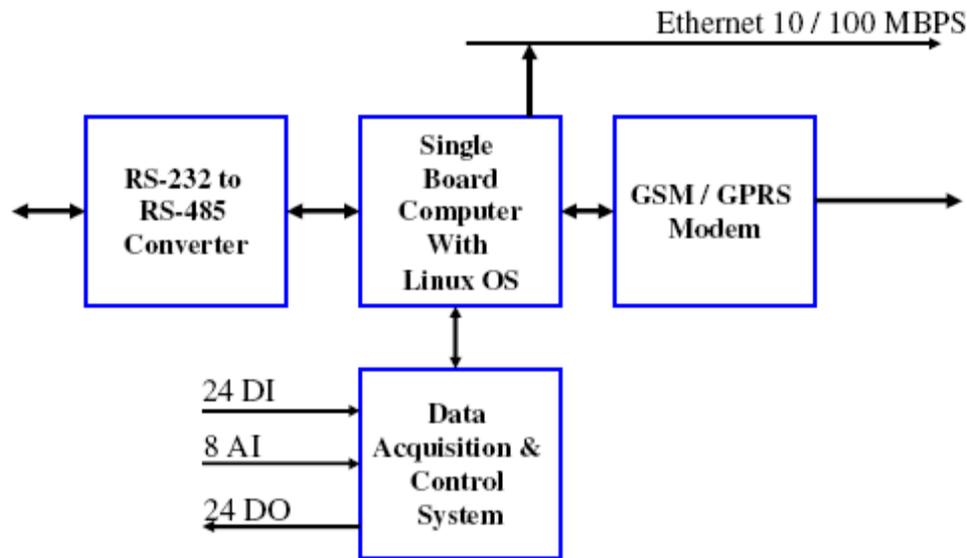
- PSDR – Power System Data Recorder
- PMU – Phasor Measurement Unit

The phasor measurement unit (PMU) is a power system device capable of measuring the synchronized voltage and current phasor in a power system. Synchronicity among phasor measurement units (PMUs) is achieved by same-time sampling of voltage and current waveforms using a common synchronizing signal from the global positioning satellite (GPS) [68]. The ability to calculate synchronized phasors makes the PMU one of the most important measuring devices in the future of power system monitoring and control.

- DSR (Dynamic Swing Recorder)

A DSR is used to record power swings on the system. The sampling rate is lower (one sample every 1-10 cycles) but the length of the record is longer to capture a long, low frequency power swing. Some DSRs are capable of continuous recording.

**Substation Data Concentrator:** The main objective of the Substation Data Concentrator Unit (DCU) is to acquire feeder meter data and breaker status from all such entities within a substation, without any human intervention [69]. The data thus collected is transmitted out to a data centre located at sub-division office using communication technologies like GSM/ GPRS/ EDGE.



**Figure 51: Data Concentrator Unit**

At the sub-division office, the data collected from all the DCUs (each DCU representing one substation) is collated and organized as per electrical hierarchical structure. The compiled data is used to generate localized reports. Also, the data is further transmitted to a data centre, for use at a higher level of distribution system management.

**Phasor Data Concentrators (PDC)**

The IEEE C37.118 protocol was developed to standardize the streaming synchrophasor data traffic, and phasor data concentrators were developed to provide time alignment between the various signals. These concentrators also provided a framework for interfacing to the application(s), providing data archiving and access to historical data, and other functions such as managing specific data flows between organizations. Because synchrophasor applications are undergoing a transformation from research-grade to production-grade operations and

planning applications, there exists a need to develop a new paradigm with which the synchrophasor data can be disseminated and shared between organizations [74].

Within an organizational entity, traffic to and from PDCs must conform to IEEE standard C37.118. This is not considered a requirement for all traffic beyond the PGW because it is expected that additional control and administrative traffic is required that is not supported by C37.118.

PDCs verify the integrity and completeness of the data stream from the PMUs and ensure delivery of the data to local data consumers, including Phasor Gateways. The Phasor Gateways verify the access rights and control the flow of traffic out to NASPInet clients and in from NASPInet servers [75].

The PDC will capture data on a continuous basis and archive long term data to the server. Each organization will have primary responsibility for the historical record of data from its PMUs and the PDCs are expected to either be the main system on which the historical archive is kept, or from which the historical archive is managed.

The PDC software will reside on the server connected to user Network. The software that operates the PDC is completely contained within the organizational unit's network. No part of the PDC is directly exposed to NASPInet.

The PDC handles the temporary capture of data of unspecified time duration. The PDC acts as the principal buffer between data sources (PMUs) and data sink (applications).

One would at least have one PDC between any given PMU and application, and if the data is transmitted over the NASPInet data bus, most likely two PDCs would be involved one in each organizational unit.

The PDC must be capable of handling data from a large number of PMUs (75 or higher based on Eastern and / or Western North America's present installed based phasors). This is in contrast to the Phasor gateway (PGW), which does not buffer data, but may be required to handle large number of pub/sub connections [75].

### **High-speed Transducers**

Transducers are the mechanical, electrical, electronic, and electromechanical devices that convert one form of the energy into the other form of energy. In the indirect method of measuring physical quantity transducer is used which is coupled to a chain of the connecting apparatus that forms the part of the measuring system. In this system, the quantity which is to be measured (input) is converted into measurable quantity (output) by the transducer [76].

### **3.3.5 Technology Selection**

Based on the responses to RFI, the promising energy storage technologies are Li-Ion, NaS and flow batteries. Each technology has its own advantages and disadvantages such as NaS has high energy rating, Li-Ion has high power density, Flow batteries' power and energy ratings can be independently scaled. However, based on our application requirements, a single technology is not enough to satisfy each criteria, and hence a hybrid combination of different technologies would be the ideal solution. For example, a combination of NaS and Li-Ion batteries can be used such that the NaS provide the required long term energy (i.e. 8 MW for 4 hour) and Li-Ion can provide the required power (i.e. 9 MW for a short time).

### 3.3.6 Technology Transfer Plan

Technology transfer plan is to publish white papers on the studies performed at the selected locations. Once the papers are published, they will be available to public and hence knowledge gained from this project will be transferred to public.

## 4 Conclusions and Recommendations

### 4.1 Conclusions

The project was successfully completed according to the project objectives by Quanta Technology and SCE.

Below is the summary for three selected locations in which energy storage and/or FACTS devices have been modeled.

#### **Antelope Bailey Area**

Antelope Bailey area study demonstrated the benefits of the application of 8 MW/4 hours Battery Energy Storage System (BESS) / 20 MVar STATCOM to address the problems at the wind farms.

Benefits include:

- Contingency support in terms of MW and MVar. The STATCOM-BESS system prevents the system from collapsing for the critical contingencies.
- Applying the BESS/STATCOM system results in faster voltage recovery, about 10-15 percent.
- Improved fault ride-through support on Type 1 wind farms. The STATCOM-BESS system can support the close-by wind farms to ride through low voltage excursions following distant line faults.
- Some portion of the connected wind farms can be dispatched an hour ahead.
- The ROI with BESS/STATCOM system is 10 percent.

#### **Palm Springs Area**

The Palm Springs area study demonstrated the application of CAES in order to mitigate critical line overloads in the area. The results of the study showed that:

- The two critical line overloads can be mitigated.
- The start/stop cycles of the local peaker units can be reduced.
- The load shedding can be reduced.
- The CAES can be used for multiple functions besides transmission line overload mitigation.
- The ROI with CAES in one year is around 20 percent.

#### **South Bay Area**

The focus of the South Bay Area study was to evaluate the application of STATCOM or STATCOM with BESS in order to avoid transmission upgrades on the two lines carrying power from La-Fresa to Refinery substation. For this purpose, two different cases are studied: one with

15 MVAR STATCOM and the other with 15 MVAR STATCOM and 10 MW BESS. From the simulation results, it is seen that:

- The aggregated motor load (mainly induction machines) at the refinery bus will collapse after a nearby fault if there is no reactive support.
- The application of STATCOM/STATCOM+BESS will help the aggregated motor load to recover without stalling and reach to rated speed back, after the fault is cleared by supplying reactive power during and after the fault.
- As motor loads require mostly reactive power to recover their speed, the application of a BESS is not economically feasible. Therefore, only a 15 MVAR STATCOM is recommended for regulating the voltage and provides contingency support.
- STATCOM can also be used to reduce the harmonic current and it can decrease the THD by 80 percent as shown by the 15 MVA STATCOM in an APF operating mode.
- The applications and economic metric calculations of the STATCOM and STATCOM + ES in the La-Fresa system include power quality issues mitigation, voltage regulation and line upgrade delay.
- Return-on-Investment (ROI) for the STATCOM in these applications, based on NPV calculation is about 25.39 percent.

## 4.2 Recommendations

Based on the conclusions in this report, it is reasonable to recommend that the State of California, Southern California Edison and other stakeholders pursue an energy storage demonstration project to prove the expected benefits. Energy storage in general promises several benefits that can address RPS requirements while improving transmission operational performance. It is recommended that the merits of energy storage should be explored sooner than later given the pace of renewable energy implementation in southern California.

Although three scenarios are presented in this report, it would be feasible to commence a battery energy storage project in a timely manner, especially in light of the growing challenges with expanding wind farms putting pressure on transmission capacity in their respective regions. Ultimately, the location of the demonstration project would depend on the host utility and local conditions.

Without the support of combined private and public funding the economic feasibility of conducting an energy storage demonstration project would be slim. The technical feasibility risk is mitigated by the successful performance of STATCOM technology, battery storage and CAES in other parts of the world. However, there are some features of the combining a STATCOM with a battery energy storage system that have never been demonstrated on a utility scale. In theory, the value and productivity of wind farms could be improved by the addition of energy storage, but this can only be verified by an actual installation under “live” operating conditions with real-time data acquisition systems to capture actual performance over an extended period and under different operating conditions.

### **4.3 Benefits to California**

Installation of storage in multi MW's helps dealing with wind's intermittency, integrate renewables more smoothly into the grid, and store renewable energy for sale at peak times. The California assembly passed the legislation which states that a percentage of electricity generated in the state be stored. Thus, studies conducted on three different locations for determining size of energy storage technology to install plays a key role in obtaining 33 percent of its electricity from renewable sources by 2020.

## REFERENCES

- [1] P. F. Ribeiro, B. K. Johnson, M. L. Crow, A. Arsoy, and Y. L. Liu, "Energy storage systems for advanced power application," in Proc. IEEE, vol. 89, no. 12, pp. 1744–1756, Dec. 2001.
- [2] J. McDowall, "Conventional battery technologies—Present and future," in Proc. IEEE Power Engineering Society Summer Meeting, vol. 3, July 2000, pp. 1538–1540.
- [3] M. A. Casacca, M. R. Capobianco, and Z. M. Salameh, "Lead-acid battery storage configurations for improved available capacity," IEEE Trans. Energy Conversion, vol. 11, pp. 139–145, Mar. 1996.
- [4] N.W. Miller, R. S. Zrebiec, R.W. Delmerico, and G. Hunt, "Design and commissioning of a 5 MVA, 2.5 MWh battery energy storage," in Proc. IEEE Power Engineering Society Transmission and Distribution Conf., 1996, pp. 339–345.
- [5] B. Roberts, "Capturing grid power," IEEE Power and Energy Mag., vol. 7, no. 4, pp. 32 – 41, July-Aug. 2009.
- [6] The Electropaedia, "Lead Acid Batteries," Battery and Energy Technologies, 2005 [Online]. Available: <http://www.mpoweruk.com/leadacid.htm>
- [7] M. Dürr, A. Cruden, S. Gair, J.R. McDonald, "Dynamic model of a lead acid battery for use in a domestic fuel cell system," Journal of Power Sources, vol. 161, no. 2, pp. 1400-1411, 27 October 2006.
- [8] H.L. Chan, "A new battery model for use with battery energy storage systems and electric vehicles power systems," IEEE PES Winter Meeting, vol. 1, pp. 470 – 475, 23-27 Jan. 2000.
- [9] Z.M. Salameh, M.A. Casacca, W.A. Lynch, "A mathematical model for lead-acid batteries," IEEE Trans. Energy Convers., vol. 7, no. 1, pp. 93 – 98, March 1992.
- [10] Battery Application Manual, Gates Energy Products, Inc., Gainesville, FL, 1989.
- [11] M. Ceraolo, "New Dynamical Models of Lead-Acid Batteries," IEEE Trans. Power Syst., vol. 15, no. 4, pp.1184-1190, November 2000.
- [12] S. Barsali, M. Ceraolo, "Dynamical Models of Lead-Acid Batteries: Implementation Issues," IEEE Trans. Energy Convers., vol. 17, no. 1, pp.16-23, March 2002.
- [13] R. A. Jackey, "A Simple, Effective Lead-Acid Battery Modeling Process for Electrical System Component Selection," 2007, <http://www.mathworks.com/products/simparameter/technicalliterature.html>
- [14] I. Buchmann, "The Lithium Ion Battery," Batteries in a Portable World, 2001 [Online]. Available: <http://www.buchmann.ca/chap2-page6.asp>
- [15] Electricity Storage Association, "Technologies," 2009 [Online]. Available: <http://www.electricitystorage.org/site/technologies/>
- [16] I. Buchmann, "The nickel-based battery, its dominance and the future," Battery University, 2003 [Online]. Available: <http://www.batteryuniversity.com/partone-4.htm>
- [17] L. Chung, M.F.M. Siam, A.B. Ismail, Z.F. Hussien, "Modeling and simulation of sodium sulfur battery for battery-energy storage system and custom power devices," National Power and Energy Conference Proceedings, pp. 205-210, 29-30 Nov. 2004.
- [18] The Electropaedia, "Flow Batteries," Battery and Energy Technologies, 2005. [Online]. Available: <http://www.mpoweruk.com/flow.htm>

- [19] C. Abbey, J. Chahwan, M Gattrell, G. Joos, "Transient Modeling and Simulation of Wind Turbine Generator and Storage Systems," Cigre, Conference on Power Systems, Montreal, Oct. 1-4 2006.
- [20] I. Buchmann, "What's the role of the Supercapacitor?," Battery University, 2003 [Online]. Available: <http://www.batteryuniversity.com/partone-8.htm>
- [21] P. Taylor, L. Johnson, K. Reichart, P. DiPietro, J. Philip, and P. Butler, "A summary of the state of the art of superconducting magnetic energy storage systems, flywheel energy storage systems, and compressed air energy storage systems," Sandia National Labs, SAND99-1854, 1999.
- [22] R. B. Boom and H. A. Peterson, "Superconductive energy storage for power systems," IEEE Trans. Magn., vol. MAG-8, pp. 701-704, Sept. 1972.
- [23] California Energy Commission, "DER Equipment- Energy Storage/UPS Systems," Distributed Energy Resource Guide, 2002 [Online]. Available: [http://www.energy.ca.gov/distgen/equipment/energy\\_storage/energy\\_storage.html](http://www.energy.ca.gov/distgen/equipment/energy_storage/energy_storage.html)
- [24] M. Dürr, A. Cruden, S. Gair, J.R. McDonald, "Dynamic model of a lead acid battery for use in a domestic fuel cell system," Journal of Power Sources, vol. 161, no. 2, pp. 1400-1411, 27 October 2006.
- [25] H.L. Chan, "A new battery model for use with battery energy storage systems and electric vehicles power systems," IEEE PES Winter Meeting, vol. 1, pp. 470 - 475, 23-27 Jan. 2000.
- [26] Z.M. Salameh, M.A. Casacca, W.A. Lynch, "A mathematical model for lead-acid batteries," IEEE Trans. Energy Convers., vol. 7, no. 1, pp. 93 - 98, March 1992.
- [27] Battery Application Manual, Gates Energy Products, Inc., Gainesville, FL, 1989.
- [28] M. Ceraolo, "New Dynamical Models of Lead-Acid Batteries," IEEE Trans. Power Syst., vol. 15, no. 4, pp.1184-1190, November 2000.
- [29] S. Barsali, M. Ceraolo, "Dynamical Models of Lead-Acid Batteries: Implementation Issues," IEEE Trans. Energy Convers., vol. 17, no. 1, pp.16-23, March 2002.
- [30] R. A. Jackey, "A Simple, Effective Lead-Acid Battery Modeling Process for Electrical System Component Selection," 2007, <http://www.mathworks.com/products/simparameter/technicalliterature.html>
- [31] C. Abbey, J. Chahwan, M Gattrell, G. Joos, "Transient Modeling and Simulation of Wind Turbine Generator and Storage Systems," Cigre, Conference on Power Systems, Montreal, Oct. 1-4 2006.
- [32] S. Teleke, "Control Methods for Energy Storage for Dispatching Intermittent Renewable Energy Sources". PhD Thesis, North Carolina State University, Raleigh, NC, 2009 [Online]. Available: <http://www.lib.ncsu.edu/theses/available/etd-11022009-151719/>
- [33] S. Teleke, M. E. Baran, A. Q. Huang, S. Bhattacharya and L. Anderson, "Control Strategies for Battery Energy Storage for Wind Farm Dispatching," IEEE Trans. Energy Conversion, vol. 24, no. 3, pp. 725-732, Sep. 2009.
- [34] Electricity Storage Association, "Applications," 2009 [Online]. Available: <http://www.electricitystorage.org/site/applications/>
- [35] Energy Storage Council, "Energy Storage The Missing Link in the Electricity Value Chain," an ESC white paper, May 2002.

- [36] Energy Storage Council, "About Energy Storage," 2007 [Online]. Available: <http://www.energystoragecouncil.org/aboutenergystorage.htm>
- [37] J. Castenada, J. Enslin, D. Elizondo, N. Abed, S. Teleke, "Application of STATCOM with energy storage for wind farm integration," IEEE T&D Conf, pp. 1-6, 2010.
- [38] M. Ahlstrom, L. Jones, R. Zavadil, W.S Grant, "The future of wind forecasting and utility operations," IEEE Power and Energy Magazine, pp. 57-64, no.6, Nov.-Dec. 2005.
- [39] B. Ernst, "Wind Power Forecast for the German and Danish Networks," Wind Power in Power Systems, T. Ackermann, Ed. John Wiley & Sons, 2005, pp. 365-381.
- [40] Srijib Mukherjee, Sercan Teleke, Veera Bandaru "Frequency Response and Dynamic Power Balancing in Wind & Solar Generation," Project Report prepared for SCE, November 30 2009.
- [41] CIGRE TF38.01.10, "Modeling New Forms of Generation and storage" 2001.
- [42] J. Castenada, J. Enslin, D. Elizondo, N. Abed, S. Teleke, "Application of STATCOM with energy storage for wind farm integration," IEEE T&D Conf, pp. 1-6, 2010.
- [43] B. Kirby, "Frequency Regulation Basics and Trends," Oak Ridge National Laboratory, ORNL/TM-2004/291, December 2004.
- [44] J. Eyer and G. Corey, "Energy Storage for the Electricity Grid: Benefits and Market Potentials Assessment Guide" Sandia National Labs, SAND2010-0815, February 2010.
- [45] PREDICTIVE MAINTENANCE INSPECTION, INC, "How can condition monitoring help a maintenance program?", <http://home.hiwaay.net/~pmi/>
- [46] V. Jovica, C. P. Gupta, "Probabilistic Assessment of Financial Losses due to Interruptions and Voltage Sags – Part II: Practical Implementation", IEEE Transactions on Power Delivery, Vol. 21, no. 2, pp 918-924, April 2006.
- [47] K. Thomas, L. Jin-Sheng, "Costs and Benefits of Harmonic Current Reduction for Switch-Mode Power Supplies in a Commercial Office Building", <http://www.activeharmonicfilters.com/Contractors/pcs-costsandbenefitsofharmoniccurrentreduction.pdf>
- [48] Southern California Edison Company, "Tehachapi Wind Energy Storage Project," submitted to US Department of Energy, August 26 2009.
- [49] ABB, "PCS Units for 8 MW / 12 MVar BESS Project", October 2010.
- [50] Altairnano, "Altairnano Energy Storage System Overview", July 2010.
- [51] NGK, "Reference Specifications for 1 MW NAS Battery System", June 2010.
- [52] Parker SSD, "Quanta Technology Power Converter System Budgetary", July 2010.
- [53] Prudent Energy Corporation, "Response to Southern California Edison Request for Information - BESS", July 2010.
- [54] S&C, "Wind-Storage-Enhanced Transmission Research and Development Project RFI for BESS", June 2010.
- [55] The Electropaedia, "State of Charge (SOC) Determination," Battery and Energy Technologies, 2005 [Online]. Available: <http://www.mpoweruk.com/soc.htm>
- [56] R. Hara, H. Kita, T. Tanabe, H. Sugihara, A. Kuwayama, S. Miwa, "Testing the technologies," IEEE Power and Energy Mag., vol. 7, no. 3, pp. 77 – 85, May-June 2009.

- [57] K.Yoshimoto, T.Nanahara, G.Koshimizu, "New Control Method for Regulating State-of-Charge of a Battery in Hybrid Wind Power/Battery Energy Storage System," IEEE PES, pp. 1244 – 1251, Oct. 29-Nov. 1 2006.
- [58] S. Pang, J. Farrell, J. Du, M. Barth, "Battery State-of-Charge Estimation," American Control Conference, vol. 2, pp. 1644 – 1649 25-27 June 2001.
- [59] J. Chiasson, B. Vairamohan, "Estimating the state of charge of a battery," IEEE Trans. Control Systems Tech., vol. 13, no. 3, pp. 465 – 470 May 2005.
- [60] Il-Song Kim, "Nonlinear State of Charge Estimator for Hybrid Electric Vehicle Battery," IEEE Trans. Power Elec., vol. 23, no. 4, pp. 2027 – 2034 July 2008.
- [61] O. Caumont, P. Le Moigne, C. Rombaut, X. Muneret, and P. Lenain, "Energy Gauge for Lead-Acid Batteries in Electric Vehicles," IEEE Trans. Energy Convers., vol. 15, no. 3, pp. 354 – 360 Sept. 2000.
- [62] A. J. Salkind, C. Fennie, P. Singh, T. Atwater, D. E. Reisner, "Determination of state-of-charge and state-of-health of batteries by fuzzy logic methodology," Journal of Power Sources, vol. 80, pp. 293 – 300, 1999.
- [63] C.C. Chan, E.W.C. Lo, S. Weixiang, "The available capacity computation model based on artificial neural network for lead-acid batteries in electric vehicles," Journal of Power Sources, vol. 87, pp. 201 – 204, 2000.
- [64] S. Piller, M. Perrin, A. Jossen, "Methods for state-of-charge determination and their applications," Journal of Power Sources, vol. 96, pp. 113 – 120, 2001.
- [65] Northeast Power Coordinating Council, "Guide for Application of Disturbance Recording Equipment," Document B-26, September 6, 2006.
- [66] NERC "Glossary of Terms Used in Reliability Standards," November 1, 2006, available at [www.nerc.com](http://www.nerc.com)
- [67] Northeast Power Coordinating Council, "Disturbance Monitoring Equipment Criteria," Document A-15, August 23, 2007.
- [68] Reynaldo Francisco Nuqui, "State Estimation and Voltage Security Monitoring Using Synchronized Phasor Measurements," Dissertation submitted to the Faculty of the Virginia Polytechnic Institute and State University, July 2, 2001.
- [69] SANDS, "Substation Data Concentrator Unit Technical Specifications," 2009 [Online]. Available: [http://www.sandsindia.com/data\\_concentrator\\_unit.php](http://www.sandsindia.com/data_concentrator_unit.php)
- [70] North American Electric Reliability Council, "Interconnection Dynamics Working Group", <http://www.nerc.com/docs/docs/pubs/DMERreport5-3-05.pdf>
- [71] Monaghan Engineering, Inc, "Quantum Sequence of Events Recorder", <http://www.monaghan-engineering.com/Office/Adobe/Ser%20x53%20Users%20Guide%20V300.pdf>
- [72] Wikipedia, "Sequence of Events Recorder", 2010 [online], Available: [http://en.wikipedia.org/wiki/Sequence\\_of\\_events\\_recorder](http://en.wikipedia.org/wiki/Sequence_of_events_recorder)
- [73] Neto, F.R.; Teixeira, E.P.; Basso, M.A, "Digital Relays and Reliability Improvement in the Power Supply for a Critical Process plant", IAS Annual Meeting, pp 1298-1300 vol.2, 2003.
- [74] Protection Automation and Control World, "The North American Synchro-Phasor Initiative", 2009 [online], Available:

[http://www.pacw.org/issue/autumn 2009 issue/industry reports/ieee guide for distribution protection/complete article/1.html](http://www.pacw.org/issue/autumn%202009%20issue/industry%20reports/ieee%20guide%20for%20distribution%20protection/complete%20article/1.html)

- [75] D. Chassin, R. Carroll, D. Bakken, "NASPI Phasor Gateways and Their Relationship to Phasor Data Concentrators".
- [76] Bright hub, "What are Transducers? Working of the Thermometer", 2010 [online], Available: <http://www.brighthub.com/engineering/mechanical/articles/41926.aspx>

## GLOSSARY

AGC	Automatic Generation Control
APF	Active Power Filter
BESS	Battery Energy Storage System
CAES	Compressed Air Energy Storage
CPUC	California Public Utilities Commission
DCS	Demand Charge Savings Index
DFRs	Digital Fault Recorders
DOD	Depth of Discharge
ECS	Energy Charge Savings
EDL	Electric Double Layer
EPRI	Electric Power Research Institute
ES	Energy Storage
ESS	Energy Storage System
FACTS	Flexible AC Transmission Systems
FES	Flywheel Energy Storage
LGIP	Large Generator Interconnection Procedure
LVRT	Low Voltage Ride Through
LVRT	No Low-Voltage-Ride-Through
NEPA	National Environmental Protection Act
PCS	Power Conversion System
PCS	Power Conversion System
PDC	Phasor Data Concentrators
PIER	Public Interest Energy Research
PMUs	Phasor Measurement Units
PSCAD	Power System Computer Aided Design
PSLF	Positive Sequence Load Flow Software
RD&D	Research Development and Demonstration
RFI	Request for Information
RPG	Reliability Performance Gap
SCE	Southern California Edison
SMES	Superconducting Magnetic Energy Storage
SOC	State of Charge
STATCOM	Static Synchronous Compensator
UFLS	Under Frequency Load Shed
WECC	Western Electricity Coordinating Council
UVLS	Under Voltage Load Shed
WECC	Western Electricity Coordinating Council