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Modeling, Simulation, and Applications of Distributed Battery Energy Storage Systems in Power Systems

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SUMMARY

This paper discusses application, modeling and simulation of distributed energy storage (ES) systems in power systems. The focus is on the battery-based ES systems. Such systems have a variety of applications in the areas of generation, transmission and distribution, and end-energy users. This paper first presents a case study that shows an application of a battery energy storage system (BESS) with a renewable energy (e.g., wind) generator serving a load for output smoothing and time shifting. This type of application helps reduce wind energy curtailment, generates additional revenue for the generator and savings for the load. The general characteristics of the BESS are also discussed.

Other typical BESS applications in the power system include performing peak shaving and valley filling tasks, and providing power to the load in an islanded system when the main source of power is lost. The paper then presents a dynamic simulation model for use in power system studies involving these applications. This model has been implemented in the widely-used Power System Simulator PSS®E[1]. Dynamic simulations performed on the model indicate that the model properly responds to a power command from the system control (e.g., SCADA) in peak shaving/valley filling and islanding system operation applications.

This paper contributes to the areas of distributed generation, energy storage and advanced modeling techniques.

KEYWORDS

Energy storage, renewable energy, wind power, solar power, battery, output smoothing, time shifting, peak shaving and valley filling, islanding.

[1] Power System Simulator for Engineering, a software program from Siemens PTI.

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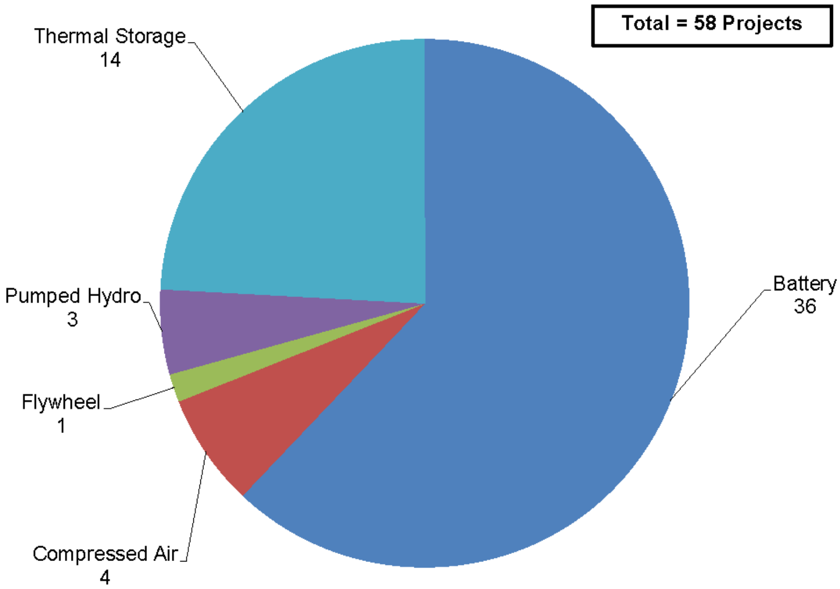
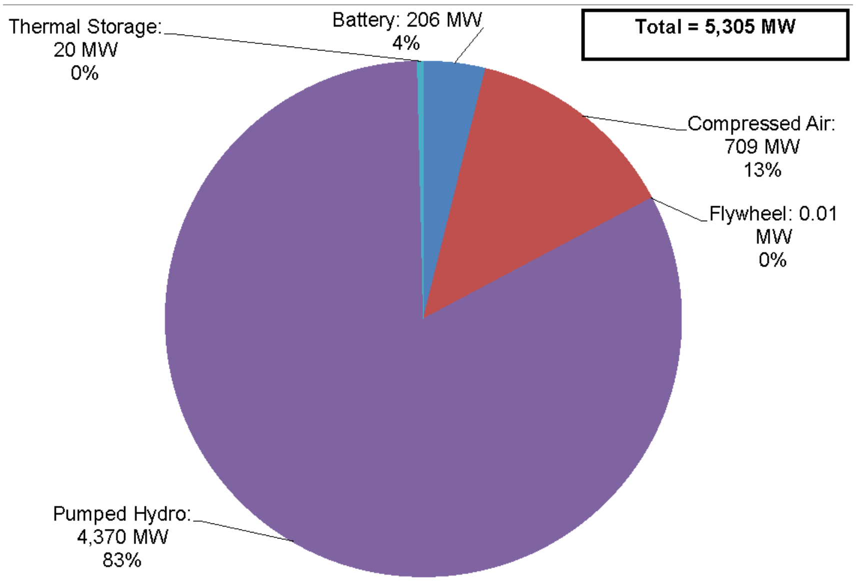
I. INTRODUCTION

Energy storage (ES) technologies generally include pumped hydro storage, compressed air energy storage, flywheels, batteries, super capacitors, superconducting magnetic energy storage, thermal energy storage, etc. [1] Some of the ES technologies (e.g., pumped storage hydro power plants) have been widely applied in power systems. Pumped hydro and compressed air storage technologies are considered bulk or "large centralized" power energy storage systems. Other ES technologies such as batteries or flywheels are presently receiving more attention for use in transmission and distribution systems. The battery-based ES technology is usually referred to as "distributed" energy storage systems since these devices are normally deployed close to load centers, transmission system points of reinforcement, or renewable generation sources. The installation site for distributed ES may be in or near utility substations, in convenient locations on distribution feeder circuits, or even at consumer premises behind the energy measuring meter. As of August 2012, the Energy Storage Database [2] from the United States Department of Energy (DOE) contained 58 energy storage projects with a total capacity of 5.3 GW in the U.S. as shown in Figure 1.



(a) U.S. Energy Storage Projects



(b) U.S. Energy Storage Capacity

Figure 1: U.S. Energy Storage Projects and Capacity by Technology Type, DOE Database

While the pumped hydro and compressed air storage projects account for about 96% of this total capacity, battery storage projects are experiencing significant development, driven primarily by the growth of Sodium-Sulfur (NaS) battery technologies. There are various power system applications that drive the need for energy storage technologies. Table 1 summarizes and classifies major ES applications into three categories, Generation, T&D, and End User [3].

Table 1: Classification of Major Energy Storage Applications

Generation Applications	Transmission and Distribution Applications	End-User Applications
• Provide renewable sources governor response and system frequency regulation. (Renewable generation typically lacks governor response and frequency regulation capability.) • Balance energy needs such as peaking shaving/valley filling. (Renewable generation non-controllable variability increases balance energy needs.) • Provide short-term and quick start reserves. • Provide renewable energy production shifting, smoothing and leveling.	• Increase transmission capacity factor for renewable sources. • Relieve transmission congestion and relax transmission reliability limits. • Defer transmission, distribution or transformer upgrades, capital expenditure due to congestion, or peak load growth. • Provide voltage and VAR support and reliability enhancement to manage the fluctuations of renewable energy production. • Support islanding system operation and/or serve loads in isolated areas.	• Store renewable generation production. • Provide time-shifting, load-following and load-leveling of demand to avoid peak prices. • Provide reliability enhancement to avoid power interruptions. • Allow utility control for targeted reliability enhancement. • Provide renewable generation and load demand response management. • Provide load specific voltage support. • Provide emergency power.

This paper focuses on applications, modeling and simulation of the BESS in power systems. Figure 2 shows a single line diagram of a typical BESS which uses IGBT-based dc-to-ac power conversion system. The 4 quadrant power electronic system converts utility ac voltage to dc voltage for energy storage in batteries or vice versa to release battery energy back to the utility system. The L-C filter is intended to reduce high frequency harmonics from the Pulse Width Modulation conversion technique used in the BESS. This system can be used with renewable generation (wind or solar) applications as well as grid applications such as peak shaving and valley filling, system reliability enhancement, and islanding system operations. The subsequent sections discuss these applications and modeling and simulation of the BESS in power system studies involving these applications.

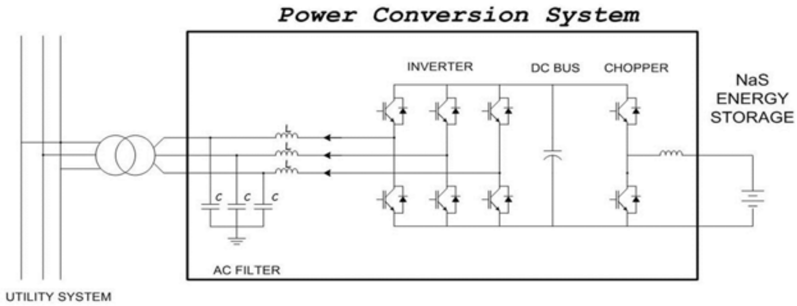


Figure 2: Single Line Diagram of a Typical BESS

II. APPLICATION OF THE BESS WITH A RENEWABLE GENERATION SOURCE

Wind and solar energy are considered intermittent power sources that the grid must accept whenever available or energy curtailment would be needed. During absence of wind or sun times when these sources are not generating, a replacement of this energy must be provided. The BESS can store the power when it is produced and then use that power for renewable production smoothing or time shifting. Figure 3 shows a simplified one-line diagram for a utility grid serving a load on an island where energy costs are relatively high. There is a possibility of installing a wind turbine generator (WTG) on the island to serve the load with a lower energy production cost. But there are some system operation constraints for the WTG. Since the WTG is a renewable energy source with non-controllable variability, partial unpredictability and locational dependency, the utility power is required to make up for the balance of the load when there is no wind, or the WTG production cannot meet the load. In addition, often the utility system does not allow for reverse power when the WTG production is higher than the load. Hence, excess energy production from the WTG will have to be dissipated via a load bank, curtailed or stored. The BESS can be used to store as much excess energy as possible so that energy curtailment can be minimized. This is a typical application for renewable output smoothing and time shifting by the BESS. In this application, the curtailed energy from the WTG represents an opportunity cost that can be captured with storage, since it is otherwise energy that is lost if it cannot be used or stored in the hourly interval when it is produced. The meters in Figure 3 monitor energy flows into the load from the utility system and/or WTG.

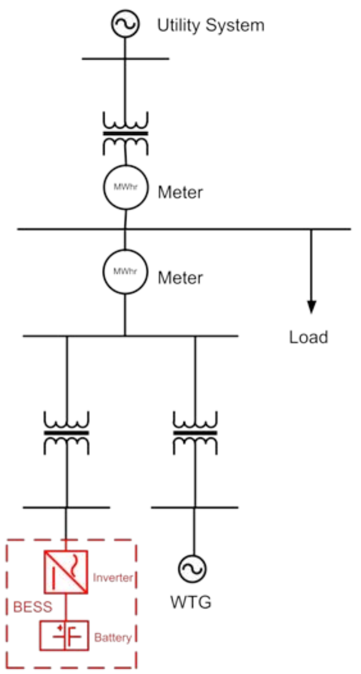


Figure 3: Simplified System

Scenarios with or without the WTG and/or the BESS in the system in Figure 3 were analyzed. In the analysis, a sample hourly production profile of a 1.5 MW WTG (red curve in Figure 4) was assumed. The load was assumed to be 1 MW and constant over time. The BESS was assumed to be rated at 1 MW / 6 MWh. For analysis purposes, the utility power retail rate and the WTG power billing rate were assumed to be \$400 and \$300 respectively.

For illustrative purpose, Table 2 summarizes some of the analysis results, which show that the WTG lowers the total cost of energy for the customer (load) significantly due to the lower WTG billing rate and generates a large saving for that customer given the load assumed. The BESS further reduces total energy cost and increases the saving for the customer. In this case, the BESS reduces energy curtailment from the WTG by about 650 MWh, which is stored in the battery and then discharged into the load (blue curve in Figure 4) when there is no wind or the WTG production cannot meet the load. This is considered to be annual revenue of approximately \$195,000 generated by the BESS.

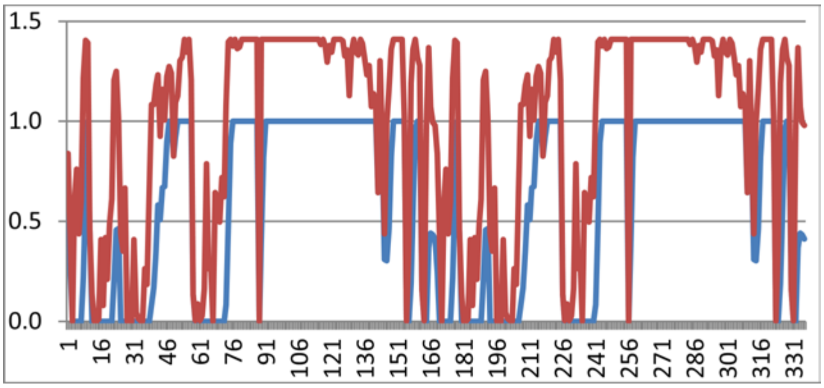


Figure 4: Sample WTG Production Hourly Profile (Red Curve) and BESS Charging and Discharging Operation (Blue Curve)

In other conditions, when the WTG production is such that the BESS operates with 100% Depth of Discharge (DOD) per day, that is, the BESS has one cycle of full charging from the WTG in excess of the 1 MW required and full discharging when the WTG generation does not have sufficient output each day, the revenue and saving can be further increased. For example, the revenue from the BESS when operating with 100% DOD per day would be:

- Revenue from BESS = 6 MWh × \$300 × 365 (days) = \$657,000/year

When operating with 90% DOD per day, the revenue from the BESS would be:

- Revenue from BESS = 90% × 6 MWh × \$300 × 365 (days) = \$591,300/year

Table 2: Analysis of the Cases without or with the WTG and/or BESS

Case	Cost of Energy from Utility	Cost of Energy from WTG and/or BESS	Total Payment from Load	Savings for Load due to WTG and/or BESS	WTG Energy Curtailment (MWHr)	Cost of WTG Energy Curtailment	Discharging MWHr from BESS	Revenue from BESS
Energy from Utility only	$3,504,000	$0	$3,504,000	$0	0	$0	0	$0
Energy from Utility and WTG	$1,555,824	$1,461,132	$3,016,956	$487,044	1,315	$394,359	0	$0
Energy from Utility and WTG plus BESS	$1,297,149	$1,655,138	$2,952,287	$551,713	674	$202,153	647	$194,006

Typically the designed life of a typical 1 MW / 6 MWh battery ranges from 2500 cycles (100% DOD) to 4500 cycles (90% DOD) [4]. Table 3 shows an analysis of the revenue from the BESS operating in 100% DOD or 90% DOD for its life cycle. In the 100% DOD case, the battery appears to need to be replaced in 7 years. However, engineering experience indicates that when the capacity of battery starts degrading after the designed life cycle, it still provides a good DOD capability for a number of years. Hence, replacement of the battery may not be needed for 10 years. In the 90% DOD case, no replacement of the battery is needed for 13 years.

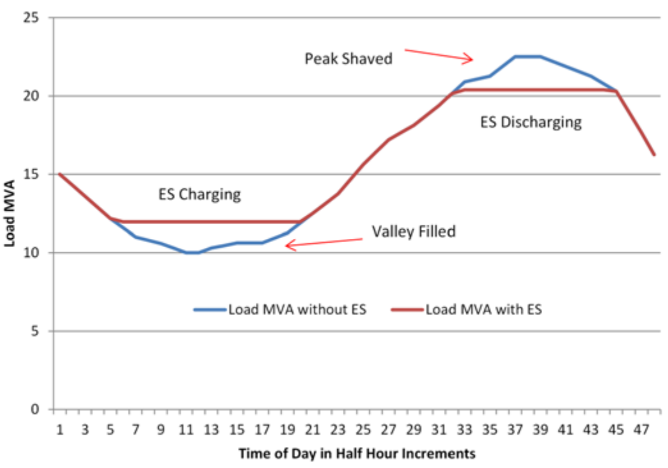


Figure 5: Peak Shaving and Valley Filling by BESS

In general, the designed life cycle of a wind power plant is about 20 years. Therefore, in either 100% or 90% DOD case, the cost of the BESS could be recovered within the first 10 years of the plant operation. After that, the BESS could generate net revenue for the rest of the life cycle.

Table 3: Analysis of the Revenue from the BESS

Depth of Discharge (DOD)	Battery Designed Life (Cycles)	Battery Designed Life (Equivalent Years)	Revenue from BESS	Total Revenue from BESS for Life Cycle
100%	2,500	7	$657,000	$4,613,764
90%	4,500	13	$591,300	$7,474,298

III. MODELING AND SIMULATION OF THE BESS FOR PEAK SHAVING/VALLEY FILLING OR ISLANDING SYSTEM OPERATION

In the system shown in Figure 3, when the BESS is interfaced with SCADA or an Automatic Restoration System (ARS), it can perform other functions such as peak shaving and valley filling as shown in Figure 5. The system can also provide voltage and reactive support and other reliability enchancement, such as support for isolated areas as an energy source during power outages. For instance, upon loss of utility power, the ARS can reconfigure the system and use the stored energy to serve local loads which have become isolated from the utility grid (e.g, islanding mode). In all these applications, a dynamic simulation model of the BESS would be necessary for power system studies.

Figures 6 and 7 show the block diagrams of the BESS for active power control, and voltage and reactive power control. Figure 8 shows the block diagram of the BESS for voltage control when operating in islanding mode. These controls have been implemented in a dynamic simulation model with PSS®E [5].

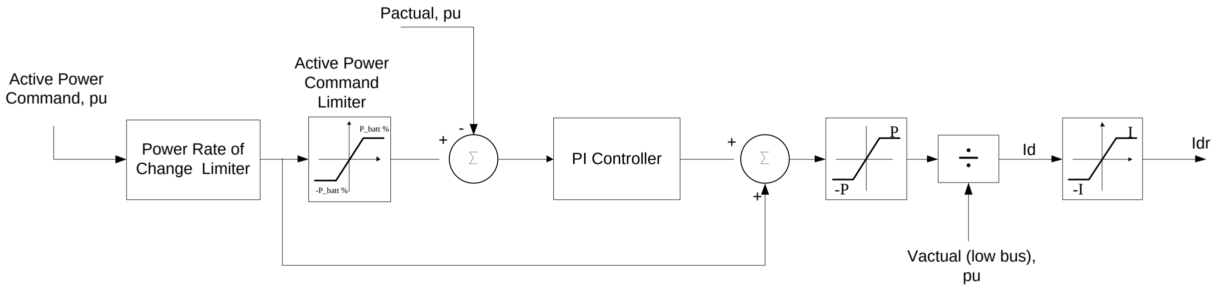


Figure 6: BESS Active Power Control Block Diagram

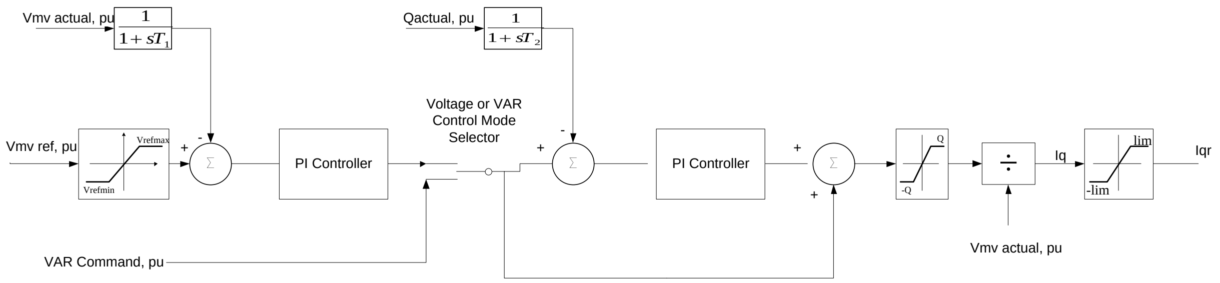


Figure 7: BESS Voltage and Reactive Power Control Block Diagram

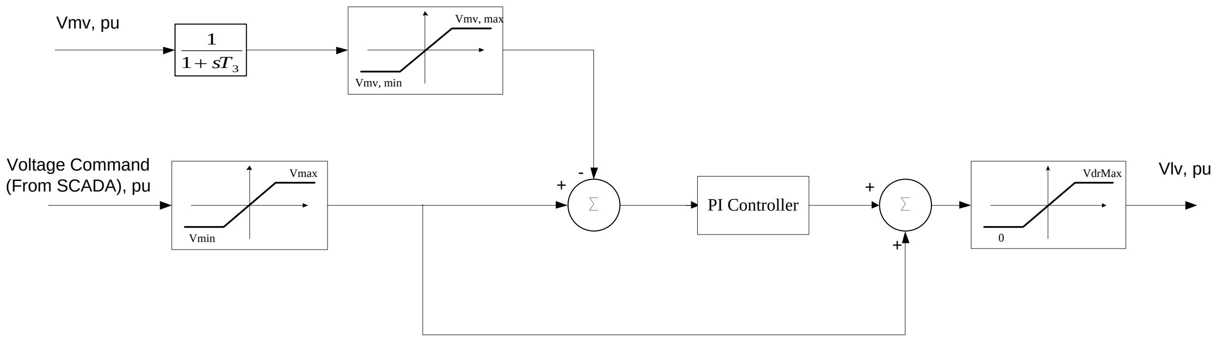


Figure 8: BESS Voltage Control Block Diagram for Islanding Operation Mode

A. *Peak Shaving and Valley Filling Simulation*

Figure 9 shows a simplified system model set up in PSS®E, in which the BESS is modeled as a Flexible AC Transmission Systems (FACTS) or Unified Power Flow Controller (UPFC) device that can operate in peak shaving mode (active power, voltage and/or reactive power control) and in islanding mode (i.e., voltage source mode). In this setup, the load is about 3.0 MW and 1.0 MVAr. The utility grid is supplying the load as well as charging the BESS (about 1.0 MW), which the grid sees as a valley filling action in this case. The BESS is also absorbing 1.0 MVAr reactive power from the grid. When the utility sends an active power increase command to the BESS via SCADA and reduces its active power to the load by the same amount at the same time, the BESS will start discharging energy into the load. Figure 10 shows the BESS response to that command generated from its dynamic simulation model

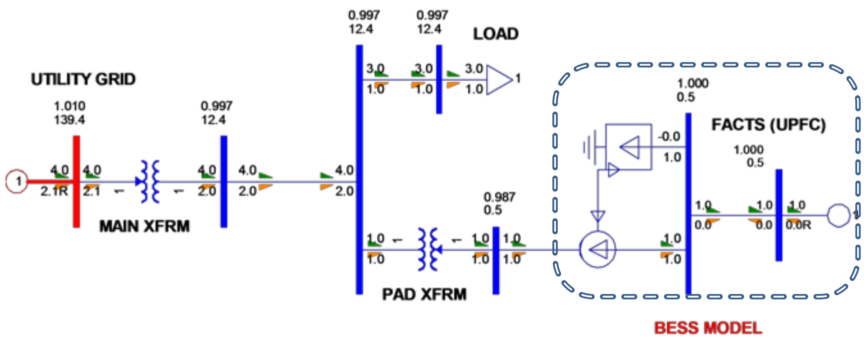


Figure 9: Simplified System with the BESS Modeled as a FACTS (UPFC) Device

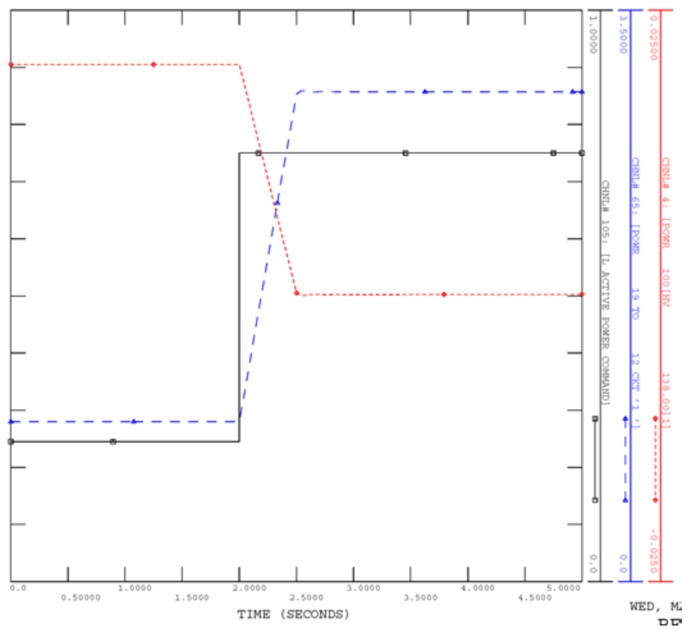


Figure 10: BESS Model Responses (Black=Power Raise Command, Blue=MW Output from BESS, Red=Power Reduction from the Grid)

implemented in PSS®E. In the simulation plot, the black curve is the power increase command, the blue curve is the MW output to the load from the BESS, and the red curve is the power reduction from the utility grid. In this condition, the utility grid sees a load shaving action by the BESS. The simulation indicates that the BESS dynamic model properly responds to a change in system condition.

B. Islanding Operation Simulation

The BESS dynamic simulation model previously described can also be used to study islanding system operations when the utility power is lost due to a contingency. A simulation was performed for this application. In this case, the BESS model is configured such that a SCADA command is received by the BESS at about 2 seconds into the simulation to switch into islanding mode. This is when the grid power is lost due to a contingency, the load and the BESS are isolated from the grid, and the BESS replaces the lost grid power by providing the needed MW and MVAr balances. Figures 11 and 12 show the BESS model and grid responses generated from PSS®E, which illustrate how the BESS switches into an islanding operation mode (e.g. isolated from the grid) from peak shaving mode, therefore supplying the active and reactive power demanded by the load at a constant voltage. The figures also show that how both the active and reactive power from the utility decrease to zero as the main power from the grid gets disconnected from the islanded load. The BESS adjusts its initial active and reactive power outputs from -1 MW (charging) and -1 MVAR (absorbing) to 3 MW (discharging) and 1 MVAr (producing), respectively, to meet the load. The responses indicate that the BESS dynamic model responds to an islanding system condition properly and correctly.

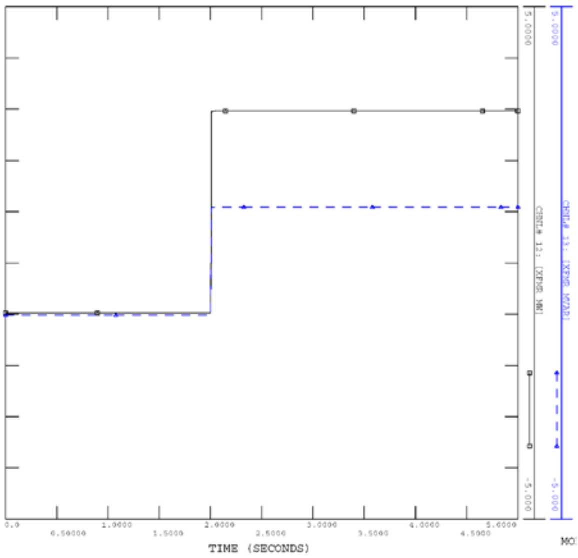


Figure 11: BESS Model Responses in Islanding System Operation (Solid=MW Output, Dashed=MVAr Output)

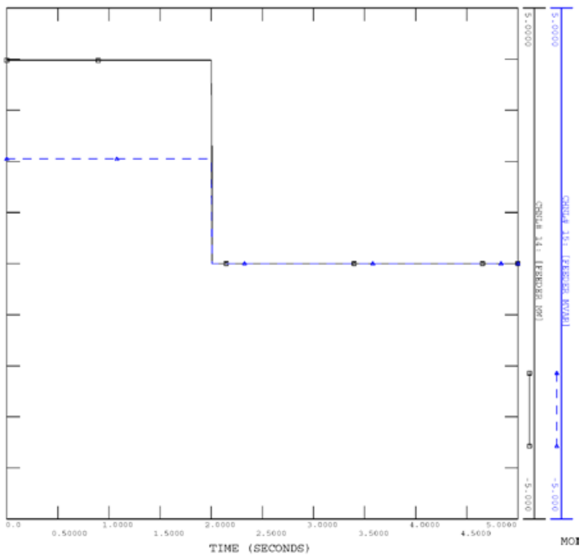


Figure 12: Grid Power Responses in Islanding System Operations (Solid=MW Power, Dashed=MVAr Power)

IV. CONCLUSIONS

Some typical applications of the BESS include output smoothing and time shifting for intermittent renewable (wind and solar) energy sources, and peak shaving and valley filling for the power grid, and islanding system operations. This paper presented case studies to discuss these types of applications. The paper also included modeling and simulation of the BESS with the widely-used Power System Simulator PSS®E. Simulation results show that the BESS dynamic model responds properly and correctly as expected when operating in peak shaving/valley filling mode and in islanding operation mode in a simplified system. This model can be used for power system studies involving those typical BESS applications.

V. ACKNOWLEDGEMENT

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VI. BIBLIOGRAPHY

[1] International Electrotechnical Commission Market Strategy Board: “Electrical Energy Storage,” White Paper, December 2011.
[2] US DOE Electricity Advisory Committee Report, “Progress and Prospects, Recommendations for the U.S. Department of Energy,” October 2012.
[3] US DOE Electricity Advisory Committee Report, “Bottling Electricity: Storage as a Strategic Tool for Managing Variability and Capacity Concerns in the Modern Grid,” December 2008.
[4] K. Mattern, A. Ellis, S.E. Williams, C. Edwards, A. Nourai, D. Porter, “Application of Inverter-Based Systems for Peak Shaving and Reactive Power Management,” Presented at the IEEE PES Transmission and Distribution Conference and Exposition, April 21-24, 2008, Chicago, IL, USA.
[5] Siemens PTI Software Program Manual, “PSS®E Rev 32.0.5, Program Operation,” October 2010.