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Modeling and Simulation of Battery Energy Storage Systems for Grid Frequency Regulation

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SUMMARY

This paper presents modeling and simulation of battery energy storage systems (BESS) in power system stability studies involving frequency regulation. BESS are applied to serve a variety of functions in the generation, transmission and distribution of electric energy, as well as providing end-energy user benefits. This paper focuses on the application of the BESS for grid frequency regulation. The paper discusses configuration and parameterization of a generic model for the BESS that has recently been approved by the Western Electricity Coordinating Council (WECC). This model has been implemented in widely-used transmission planning software tools such as PSS®E [1]. Dynamic simulations are performed using the Benchmark Test System as well as a real power system example with the parameterized BESS model for over-frequency and under-frequency conditions resulting from imbalance in system generation and load. Simulation results show that the parameterized BESS model responds properly and as expected when regulating grid frequency changes caused by contingency events.

This paper contributes to the areas of energy storage and advanced modeling approaches.

KEYWORDS

Battery energy storage, frequency regulation, over-frequency condition, under-frequency condition, loss of generation.

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I. INTRODUCTION

Energy storage technologies generally include pumped hydro storage, thermal energy storage, compressed air energy storage, battery energy storage, flywheels, etc. As of August 2013, an interactive database [2] from the United States Department of Energy (DOE) reported 202 storage system deployments in the US with a cumulative operational capability of 24.6 GW, using a mix of storage technologies including pumped hydro, compressed air, thermal, various types of batteries, and flywheels (see Figure 1). While pumped hydro, thermal and compressed air storage projects account for over 95% of this total capability, battery storage projects are experiencing significant growth, driven primarily by the advancement of battery technologies.

The 2013 edition of the DOE/EPRI Electricity Storage Handbook [3] describes eighteen services and applications in five umbrella groups, as listed in Table 1. The services and applications identified in this table show that energy storage can be used to support generation, transmission, and distribution, as well as customer-side-of-the-meter needs of the electric grid.

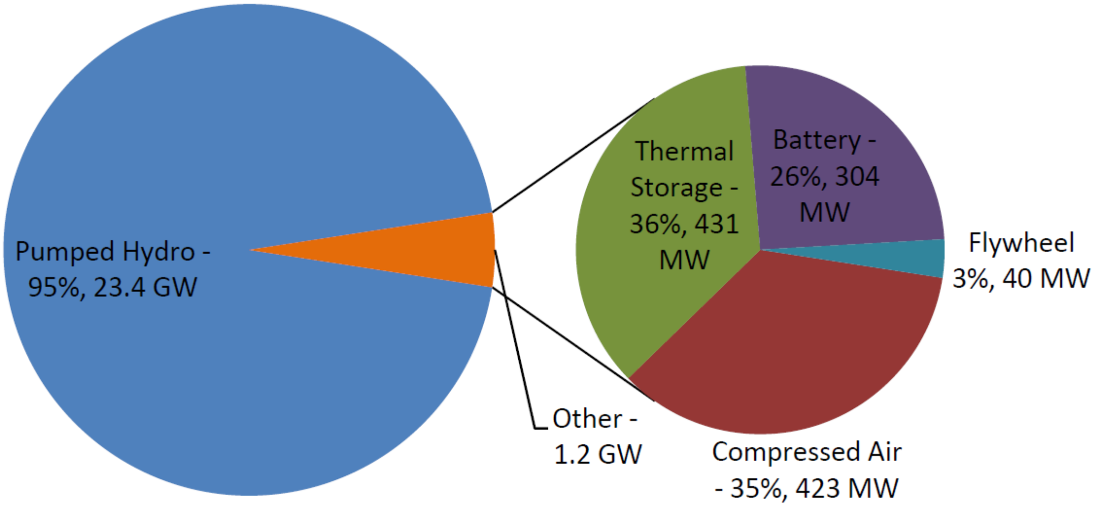
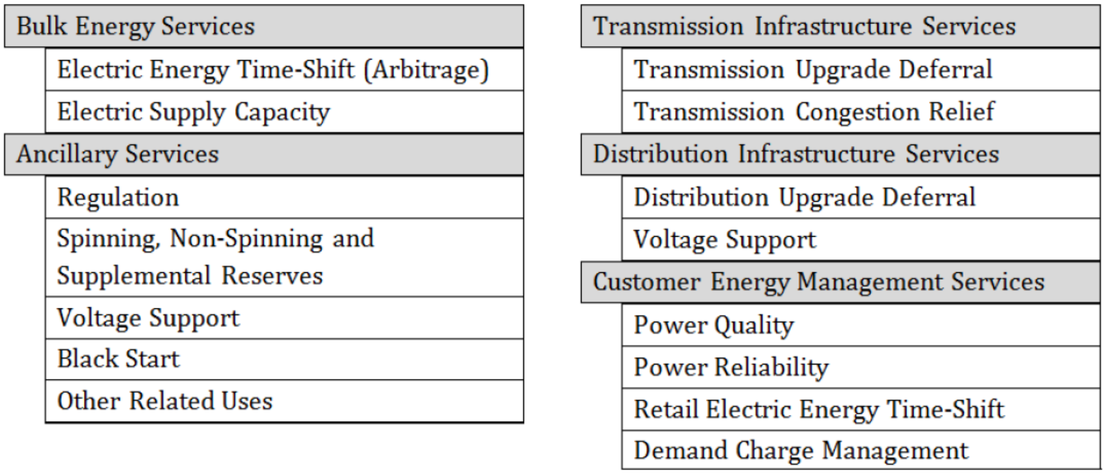


Figure 1: Rated Power of US Grid Storage Projects from DOE Database

Table 1: Electric Grid Energy Storage Services



Bulk Energy Services	
	Electric Energy Time-Shift (Arbitrage)
	Electric Supply Capacity
Ancillary Services	
	Regulation
	Spinning, Non-Spinning and Supplemental Reserves
	Voltage Support
	Black Start
	Other Related Uses

Transmission Infrastructure Services	
	Transmission Upgrade Deferral
	Transmission Congestion Relief
Distribution Infrastructure Services	
	Distribution Upgrade Deferral
	Voltage Support
Customer Energy Management Services	
	Power Quality
	Power Reliability
	Retail Electric Energy Time-Shift
	Demand Charge Management

Reference [4] discusses modeling, simulation and application of battery energy storage systems (BESS) for peak shaving and off peak storage, renewable source integration and islanding operations support. This paper focuses on modeling and simulation of the BESS applied for grid frequency regulation. Figure 2 shows a single line diagram of a typical BESS which uses an IGBT[1]-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. The subsequent sections discuss modeling, simulation and case study of the BESS for grid frequency regulation.

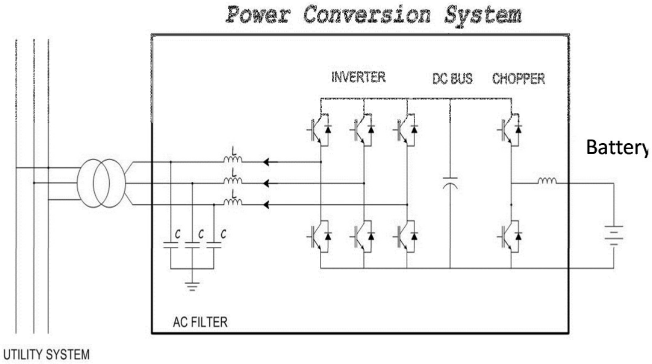


Figure 2: Single Line Diagram of a Typical BESS

II. MODELING AND SIMULATION OF THE BESS FOR GRID FREQUENCY REGULATION

Figure 3 shows the overall structure of the WECC generic model for the BESS (that has recently been approved) that is comprised of three major modules:

1. Generator/converter module (regc_a) – This module processes the real and reactive current commands from the electrical control module, and outputs real and reactive current injection into the grid model.
2. Electrical control module (reec_c) – This module acts on the active and reactive power reference from the plant controller module, with feedback of terminal voltage and generator power output. This module provides real and reactive current commands to the generator/converter module. This module also includes selection of real or reactive power control priority and models the state of charge (SOC) of the battery.
3. Plant controller module (repc_a) – this module processes voltage and reactive power output to emulate volt/var control at the plant level. It also processes frequency and active power output to emulate active power control. This module provides active and reactive power commands to the electrical control module.

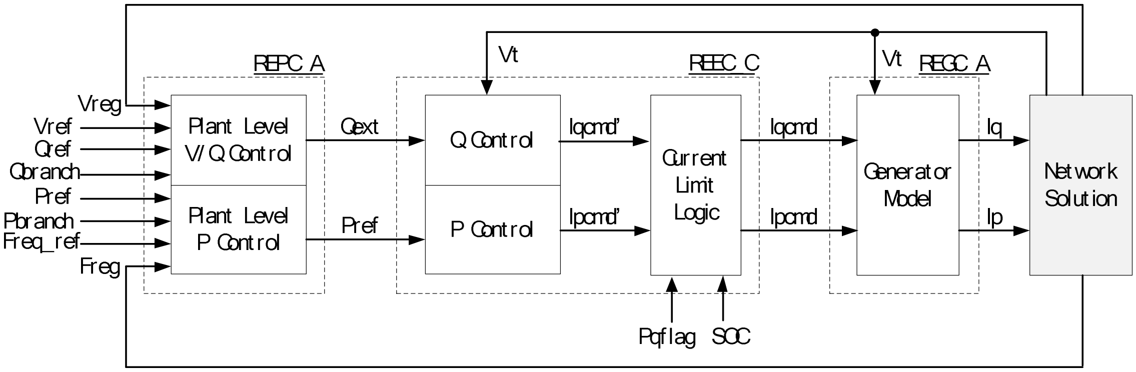


Figure 3: WECC Generic Battery Energy Storage Model Structure

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[1] Insulated-Gate Bipolar Transistor

Details of the three module block diagrams are described in [5-6]. These model modules have been parameterized to represent the dynamic performance of the BESS for power system stability analysis including frequency regulation in PSS$^{®}$E.

Figure 4 shows a PSS$^{®}$E one-line diagram of the WECC Benchmark Test System [7] with the parameterized BESS model.

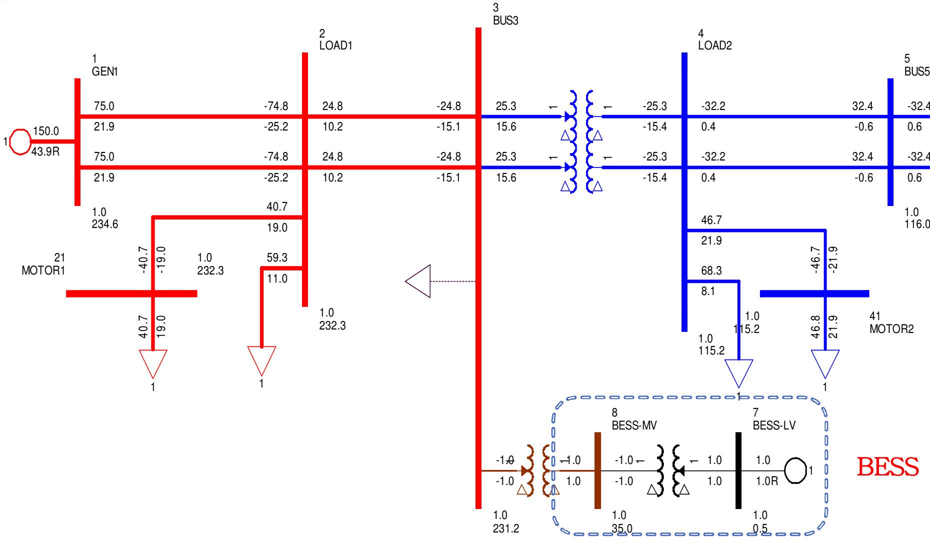

Figure 4: WECC Benchmark Test System with BESS Model

Figures 5 and 6 show simulations using the BESS model for frequency regulation in over- and under-frequency conditions caused by load changes in the system. The disturbance is a 2.5 MW load drop or rise at Bus #3 (see Figure 4). When the load increases, the system frequency (red line) drops and the BESS discharges to produce MW (green line). When the load decreases, the system frequency (red line) rises and the BESS charges, absorbing MW (green line).

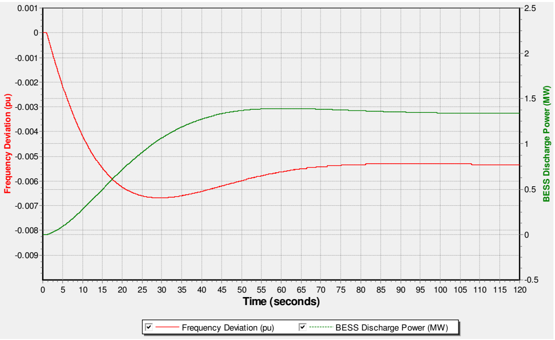

Figure 5: BESS Discharge in Under-Frequency Condition (Red=Frequency Deviation (p.u.); Green=BESS Discharge (Producing MW)

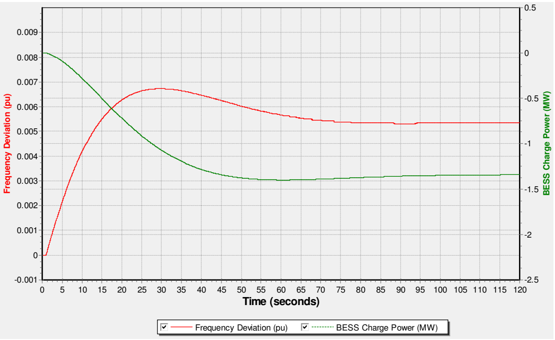

Figure 6: BESS Charge in Over-Frequency Condition (Red=Frequency Deviation (p.u.); Green=BESS Charge (Absorbing MW)

III. CASE STUDY

The parameterized BESS model was applied in the study of frequency regulation for an isolated power system shown in Figure 7. The power system mainly consists of 132 kV and 66 kV networks with a total load approaching 100 MW. This is an island system with generation that is mainly hydro and diesel as prime movers. Contingencies frequently cause loss of generation or separation of the system and hence frequency issues are common on the system. For simulation purposes, four distributed

BESS systems were applied on the system, three rated ±4MW/5MVA each and one rated ±8MW/10MVA, to mitigate the frequency issues caused by loss of generation or fault events. These BESS system parameters in the models represent the S&C PureWave® Storage Management System (SMS). These BESS systems are located close to loads and can supply or absorb up to 4 MW or 8 MW power when imbalance in generation and load in the system occurs, thus mitigating frequency excursions caused by such an imbalance.

While the BESS can regulate power and frequency, it may also provide voltage and reactive support within its MVA rating. In the study, priority is real power control as it is the primary purpose of the BESS.

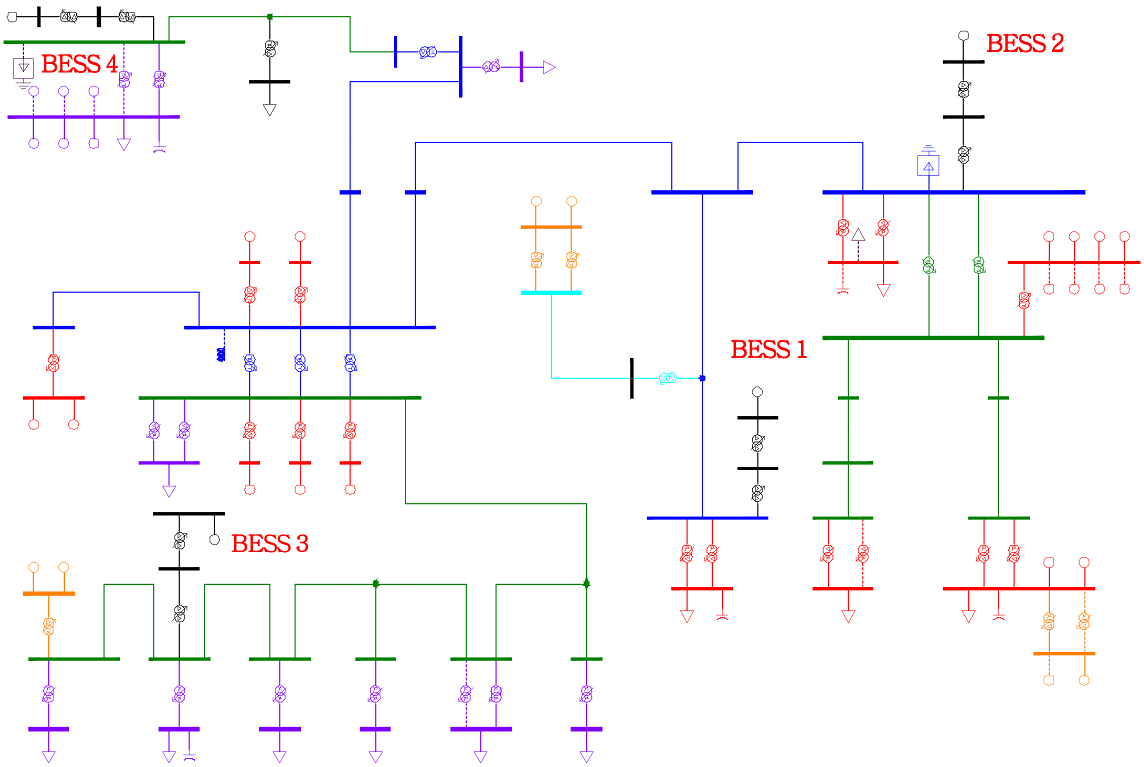

Figure 7: Isolated Power System with BESSs

Several contingencies involving loss of generation or separation of the system were simulated. These contingencies cause under-frequency and/or over-frequency conditions in the system. When loss of generation occurs, the BESS starts regulating system frequency along with other remaining online generators. For illustrative purpose, two such contingency cases are discussed here.

The first contingency case was a 5-cycle, 3-phase fault at the high side of a generator step-up transformer resulting in the tripping of two generators (about 10% of total generation lost). Figure 8 shows the system frequency response with and without the BESS. During the fault, the system frequency increases and the BESS reduces or absorbs power (charging). After the fault event is cleared, the system frequency starts dropping and the BESS discharges to produce power. Without the BESS, the system frequency drops as much as 1.5% (red line). With the BESS, it drops by about 0.65% (red line). As shown in the figure, in the steady state the final system frequency settles at a higher value with the BESS (green line) than without the BESS (red line). The final steady state frequency value and the allocation of the lost generation are determined by the frequency control droop function of the BESS and the governor droop characteristics of the remaining online generators.

Figure 9 shows the MW output of the BESS in response to the under-frequency condition following the contingency. The BESS makes up for the lost generation (discharging) to supply the loads and reduces the frequency deviation in both steady state and dynamic conditions, as compared to the case without the BESS.

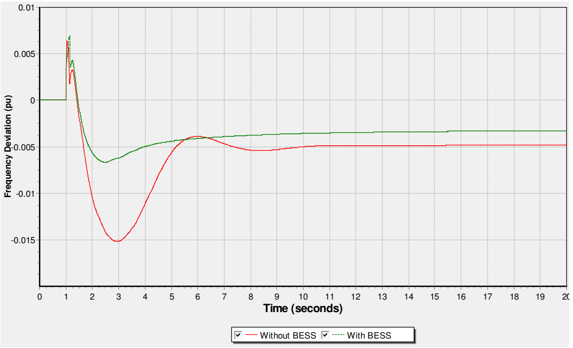

Figure 8: BESS Regulating Under-Frequency Condition

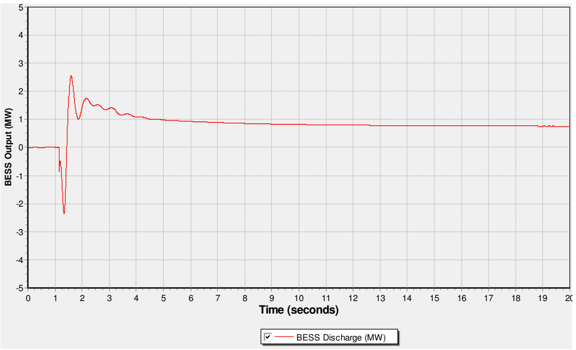

Figure 9: BESS in Charging/Discharging

The second contingency case was a 5-cycle, 3-phase fault at a 138 kV bus with the tripping of a line splitting the system into two parts: One part has a generation shortage causing the system frequency to drop and the other part has a generation surplus causing the system frequency to rise.

Figure 10 shows the system frequency response in the part with generation surplus, with and without the BESS. During the fault, without the BESS, the system frequency rises as much as 3.7% (green line); with the BESS, the system frequency rises by about 2%. As shown in the figure, in the steady state condition, the final system frequency settles at a lower value with the BESS (red line) than without the BESS (green line). The BESS reduces the frequency deviation in both steady state and dynamic conditions, as compared to the case without the BESS.

Figure 11 shows the MW output of the BESS in response to the over-frequency condition following the contingency. The BESS absorbs the surplus generation (charging) and reduces the frequency deviation in both steady state and dynamic conditions, as compared to the case without the BESS.

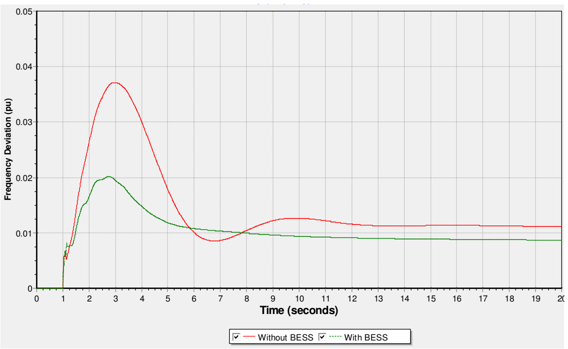

Figure 10: BESS Regulating Over-Frequency Condition

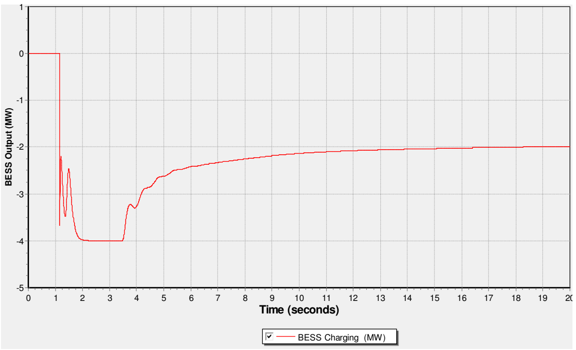

Figure 11: BESS in Charging (Absorbing MW)

IV. CONCLUSIONS

This paper presented a case study to discuss the application of distributed Battery Energy Storage Systems (BESS) for frequency regulation in an isolated power system area. The paper also included modeling of the BESS using the WECC generic battery energy storage model that has recently been approved. This model has been parameterized to represent the dynamic performance of the BESS in dynamic simulations. Simulation results show that the BESS dynamic model responds properly and as expected when regulating system frequency changes caused by contingency events. The distributed approach applied energy storage systems closer to the loads for maximum effectiveness and also provides stored energy to different system areas when the system separates following contingency events.

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