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Bi-directional Power Control of Grid-tied Battery Energy Storage System Operating in Frequency Regulation

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Abstract—This paper presents a design of an average value PWM voltage source converter (VSC) along with bi-directional active and reactive power flow control in a grid-tied battery energy storage system. A vector control strategy with PI controllers is proposed. In this paper, a grid frequency regulation control design is also implemented in the BESS in order to meet the frequency response requirement by the National Grid Electricity Transmission, the primary distribution network operator in the UK. Simulation results on a 2MW/968kWh lithium-ion BESS are provided to verify the proposed control design based on the control of an experimentally validated battery model.

Keywords—bi-directional power flow control, grid tied battery energy storage system, grid frequency regulation, frequency response, voltage source converter

I. Introduction

Renewable energy sources (RESs) such as solar and wind power provide benefits to the traditional grid, however their generation inherently is intermittent and unpredictable, which will impact the normal grid operation. Energy storage used with renewable energy (RE) can minimise some of these problems and increase the penetration of renewable energy in the grid. Energy storage is also an essential part of smart grid, which can provide grid frequency/voltage support, power quality compensation, peak shaving and spinning reserve [1]-[4]. There are many types of existing energy storage system (ESS) such as pumped hydro, flywheel, compressed air, fuel cells, hydrogen etc [5], [6]. Comparing such ESSs, a battery energy storage system (BESS) has many benefits, including energy efficiency, faster response and flexible storage size [1], [2]. In power distribution networks, the grid frequency is changing continuously due to the imbalance between total generation and demand; if consumption surpasses generation, a decrease in the grid frequency will occur and vice versa. To overcome this issue, the National Grid Electricity Transmission Network (NGET), the primary distribution network operator in the UK, has introduced several types of frequency response services that aims to balance the system frequency closer to nominal frequency (50Hz for the UK) [1],[2]. For delivering such service to the grid, the BESS is an ideal choice. The UK's first grid-tied lithium titanate BESS, called Willenhall Energy Storage System (WESS) [7], was commissioned by the University of Sheffield in 2013 to allow for research on large scale batteries and to create a platform for research into grid ancillary services.

RE systems are commonly interfaced to the grid using power electronic converters. Voltage Source Converters (VSCs) have recently drawn more attention in grid scale applications due to their fast switching response and controllability [4]. This paper presents a lithium-ion based battery energy storage system, which consists of a battery pack with 968kWh capacity and associated battery management system (BMS), a bi-directional ac/dc VSC converter, and a controller [8]. The control of VSC converter manages the bidirectional power flow between the input side converter and the grid, providing high output power quality and maintaining synchronization with the grid. The major functions of the controller are to control the active and reactive power independently, and to maintain the power quality. Several control strategies have been studied in literature [9], [10]. Proper power flow regulation using vector control principle has been presented in [3]. Synchronous PI current control has been proposed in [11] that converts the three-phase grid voltage to a synchronously rotating (d-q) frame for proper decoupling. The currents to the grid become DC variables and hence no steady-state error adjustment is required. For the active and reactive power control, cross coupling is achieved in order to decouple the d-q components and thus causing an effective control of the active and reactive power independently [12].

This paper covers a design of an average value PWM voltage source converter along with bi-directional active and reactive power flow control in grid-tied BESS. A grid frequency regulation control design is also implemented in the BESS to meet the NGET frequency response requirement.

II. A Frequency Response Requirement in the UK Power System

According to NGET requirement of UK dynamic frequency response, the energy storage providers must respond to deviations in nominal grid frequency of 50Hz by increasing or decreasing their power output. The maximum allowable noncritical frequency window (Fig.1), called dead-band (DB), is ±0.1Hz and it has been specified wide to enable flexibility, but it is allowed to be tighter and commonly 15mHz for BESS [15], [15]. When the frequency deviates to values greater than 50.015Hz, the frequency controller absorbs power; when the frequency deviates to values below 49.985Hz, it supplies power (see the left side of the Fig.1). The power versus frequency (P-

F) characteristic of the frequency controller is linear outside the DB to ±0.2Hz (see the right side of Fig.1) [13]. The ESS must provide continuous power at all times with power imported/exported outside the specified envelope reducing the availability payment to the energy storage providers [15].

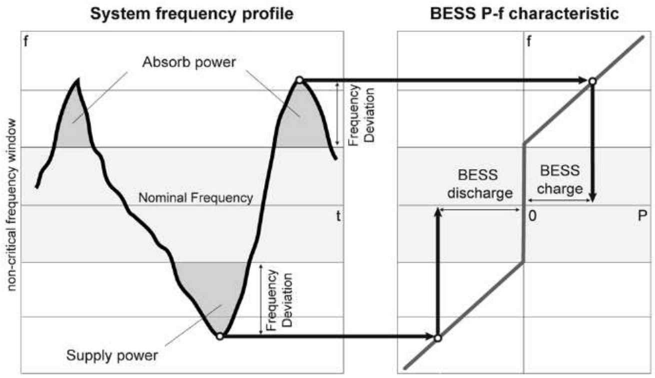

Fig. 1 Power-frequency (P-F) characteristic of the BESS frequency controller in accordance to the NGET requirements [13].

III. VSC CONVERTER DESIGN AND CONTROL OPERATION

The power circuit of a voltage sourced converter (VSC) is shown in Fig. 2, where a vector control method is used with a reference frame oriented along the supply voltage vector position, providing independent control of the active/reactive power flowing (P/Q) between the grid and converter.

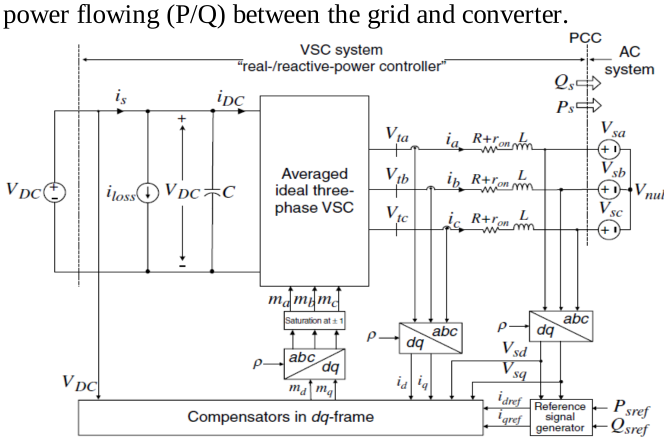

Fig. 2 Active/reactive power control scheme of a voltage source converter [14].

Using the Park transformations [11], the three-phase currents and voltages are converted to dq components. Therefore, in the dq-frame the quantities are DC in nature, hence it is simple to control using simple PI controllers. The currents in the rotating reference frame are proportional to the active power (P) and reactive power (Q) because the point of the common coupling (PCC) side direct axis component voltage (V_d\`) is constant and the quadrative voltage component ($V_q$\`) is equal to zero owing to the reference frame being synchronized with the grid voltage. As a result, by controlling the direct and quadrative axis components of current I_d and I_q, the active and reactive power through an inverter can be controlled. Therefore, the power equations at the grid side can be written as in (1), (2). Using (1) and (2), the reference power of P_{ref} and Q_{ref} can be used to determine the reference currents for a current controlled inverter as given in (3), (4). Using decoupling and feed-forward control loops, the following current dynamics are extracted to achieve the reference dq frame voltages in (5) and (6); where i_d, i_q, V_{sd} and V_{sq} represent the instantaneous values of the rotating reference frame currents and voltages, K_p and K_i are the PI controller coefficients and L is the grid side inductance [14].

$$P_s = V_{sd} i_d \tag{1}$$

$$Q_s = -V_{sd} i_d \tag{2}$$

$$i_{dref} = P_{sref}/V_{sd} \tag{3}$$

$$i_{qref} = -Q_{sref}/V_{sd} \tag{4}$$

$$V_{dref} = K_p(i_{dref} - i_d) + K_i \int (i_{dref} - i_d)dt - \omega_n L i_q + V_{sd} \tag{5}$$

$$V_{qref} = K_p(i_{qref} - i_q) + K_i \int (i_{qref} - i_q)dt - \omega_n L i_d + V_{sq} \tag{6}$$

By using the dq-frame reference voltages of V_{dref}, V_{qref} and dividing them with $V_{dc}/2$, the modulation signals of M_d and M_q are extracted and converted to three-phase signals by utilizing Clarke's transformation [11]. By using a PWM (pulse with modulation), the three-phase modulation signals are compared to a unity triangular wave signal to attain the switching pulses for the inverter switches [14].

IV. SIMULATION RESULTS

The proposed bi-directional active and reactive power control design of the VSC converter in the BESS is simulated in MATLAB/Simulink as shown in Fig. 4; and the simulation results provided in this paper are all based on a 968kWh BESS model, which has been experimentally validated on the WESS plant in the UK [7], with a maximum power of ±2MW. It is noted that the VSC of BESS in Fig. 4 (orange block) has been designed by using the average value voltage source converter design method described in Section III. The parameters used in the model are given in TABLE I.

TABLE I
THE PARAMETERS USED IN THE BESS MODEL [15]

Parameter	Value
Nominal frequency	50 Hz
Low/high DB set in the model	±0.05 Hz
Max/min EFR power limit	±2 MW
Battery rated power/capacity	2 MW/0.968 MWh
Battery initial SOC	40%
Battery SOC operational limit	30-100%

A. Simulation Results of the BESS model with constant active power control

The developed BESS model is operated in bi-directional constant active and reactive power (P/Q) control mode based on its power set points in the VSC converter as shown in Fig. 4. The active power control setting in the converter is given in TABLE II. The simulation results in Fig. 3 show that based on the constant P/Q settings in the VSC control (TABLE II), the BESS discharges from its maximum SOC (100%) to a lower SOC (30%), releasing maximum power of 2MW to the grid in 1219 seconds; the battery then rests for 1 second and starts to charge from its lower SOC to its maximum, absorbing 2MW power from the grid at 1220 to 2439 second. After that, the battery is rested for 3000 seconds, delivering no charge/discharge power to/from the grid. The simulation results verify that the BESS can successfully work in both charging and discharging mode based on the power control settings in the VSC converter.

TABLE II
CONSTANT ACTIVE POWER CONTROL PARAMETERS SET IN THE VSC CONVERTER

Time (sec)	Active power setting in VSC converter
0-1219	-2 MW (discharging mode)
1219-1220	-2MW to +2MW (switching discharging to charging mode)
1220-2439	+2MW (charging mode)
2439-2440	+2MW to 0MW (switching charging to resting mode)
2440-3000	0MW (resting mode)

The BESS total discharge time can be calculated as the following: First, the battery energy is calculated by multiplying battery power and it's discharging time, $E(Wh) = P \cdot T$, hence total battery discharge time is obtained as $968kWh/2MW = 1742.4\ sec$. Therefore the battery discharge from 100% SOC to 30% SOC should equal to 1219 sec. Simulation results verify that, the BESS can discharge from its maximum to its minimum SOC in around 1219 second as seen in Fig. 3. The battery power can also be calculated by multiplying the battery voltage and current, $P(W) = V \cdot I$. Therefore, the minimum battery current at 100% SOC is calculated using its maximum battery voltage (712V) as $I_{min} = 2MW/712V = 2808A$; and the maximum battery current at 30% SOC is calculated using it's a minimum battery voltage (550V) as $I_{max} = 2MW/550V = 3636A$. As seen from Fig. 3, in discharging mode, the battery current increases from its minimum value (2808A) to maximum value (3636A), releasing 2MW power to the grid; and vice versa. These crosschecks verify that the proposed constant power control of the VSC converter in the grid-tied BESS shows a good performance.

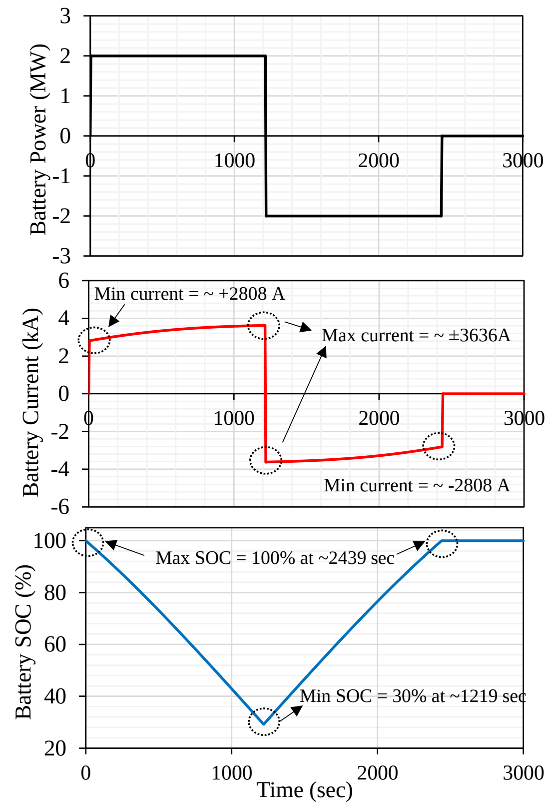

Fig. 3 Simulation results of the BESS model with constant power control.

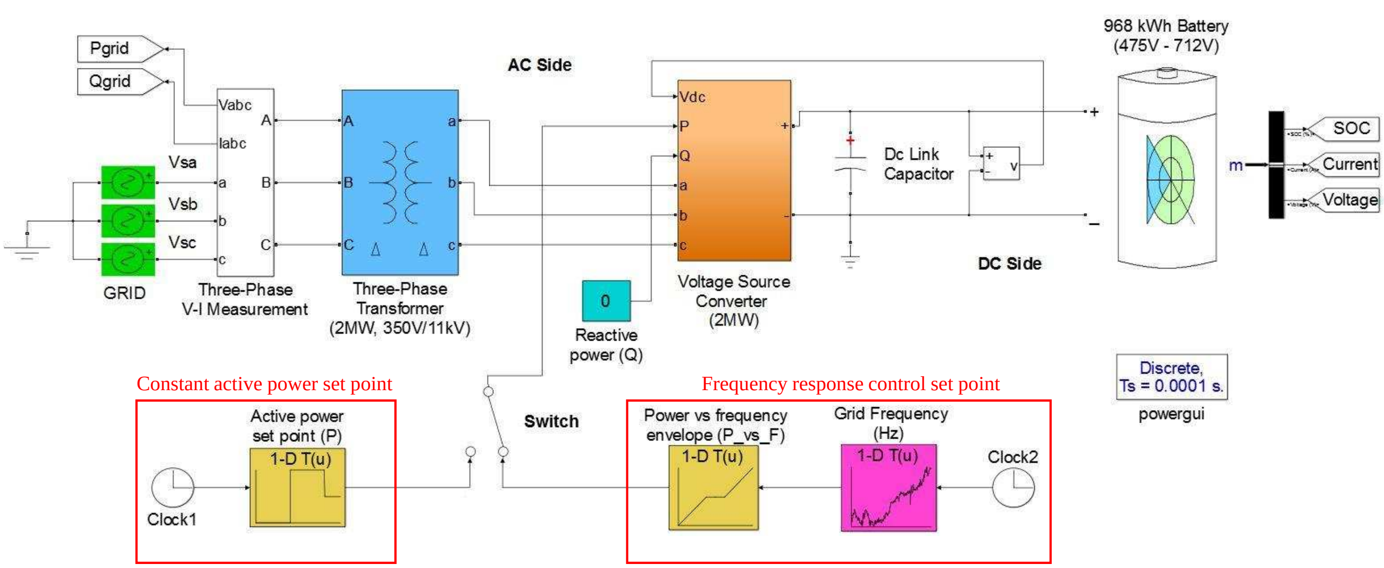

Fig. 4 The grid-tied BESS (2MW/968kWh) with both constant power control and frequency response control designed in MATLAB/Simulink.

B. Simulation Results of the BESS model with frequency response control

In order to demonstrate the performance of the BESS model with frequency response control in Section III, the real frequency data for the 1st April of 2015 (first 900 seconds) [15] is used herein, as example data. Fig. 5 shows the BESS model simulation results for the UK frequency response service described in Section II. On the frequency plot, the DB is shown by the dotted green lines. Fig. 5 shows the simulation results of the BESS model operating in frequency regulation. As seen from the simulation findings in Fig. 5, the BESS responds to changes in nominal grid frequency (50Hz), by increasing or decreasing their power output. Specifically, the BESS delivers power to the grid to respond to changes in grid frequency outside of the DB of ±0.05Hz set in the model (see TABLE I). Within the DB, there is not a requirement to provide power to the grid, hence the BESS does not respond to the system frequency. The simulation results verify that the BESS with its frequency response control can successfully perform a mandatory response to a frequency event, which can offer source of revenue to a battery asset owner.

TABLE III
FREQUENCY RESPONSE CONTROL PARAMETERS (P VS F) SET IN THE VSC CONVERTER [15].

Frequency (Hz)	49.8	49.95	50	50.05	50.2
Power (MW)	-2	0	0	0	2

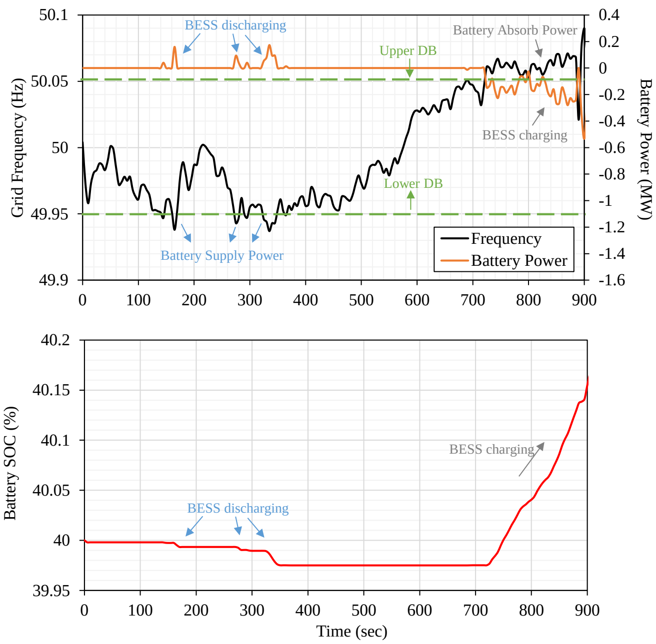

Fig. 5 Simulation results of the BESS model with frequency response control for 1st April 2015

V. CONCLUSION

This paper develops a design of an average source voltage source converter along with bi-directional active/reactive power control for a 2MW/968kWh grid-linked BESS. A vector control strategy with PI controllers is proposed. Furthermore, a grid frequency response control design is implemented in the BESS model in order to meet the NGET published requirement. When there is a deviation of frequency on the grid, the BESS supplies a power response according to a specified frequency response envelope. Simulations of the BESS model operating in frequency regulation were carried out using NGET real frequency data for 1st April 2015 (first 900 seconds). The simulation findings show that the grid-tied BESS can successfully provide/absorb power to/from the grid thanks to the bi-directional power flow control design implemented in the VSC converter in the BESS; therefore, the BESS meets the UK's NGET frequency specification and successfully delivers continuous frequency response service to the grid.

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