Partial Power Dual Active Bridge Converter Control for Grid Connected Battery Hub Systems

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***Abstract*—Energy storage systems are vital in ensuring the reliability of renewable dominant power grids. A battery hub system (BHS) is one such solution that aids the grid to provide a continuous power supply. Conventionally, grid-connected battery storage systems are built using identical battery packs whose performance is predictable. As batteries age, their capacity and characteristics vary unevenly which deteriorates the system's performance. BHS must be controlled through power electronics converters, which ensure balanced operation and take care of mismatches. Usually, partial power converter configurations are more efficient than full power converters but need a complex control strategy. Partial-rated converter topology is suggested in this paper, which ensures online charge balancing and uninterrupted power supply to load. In this paper, the control strategy required for proper control and coordination of the modular DC-DC converters based on the state of charge of the individual battery pack is presented. The proposed architecture reduces the switch ratings, converter costs, and system losses and increases system efficiency.**

***Index Terms*—Active balancing, Battery energy storage system, Battery hub system, DC-DC converters, Dual active bridge converter (DAB), State of charge (SoC), Partial power converter.**

I. INTRODUCTION

In stationary storage applications, battery hub systems (BHS) provide electricity during utility disruptions. Battery hub systems in both automotive and stationary applications require series and parallel connections of battery packs to meet voltage and power requirements. BHS consists of battery packs of different make, chemistry, and age. This makes BHS have a mismatch in capacity and series resistance from 1% to 10% in new batteries and can increase drastically with aging [1]. In a series of connected strings, the net capacity of the string is decided by the pack having the worst capacity. This impacts the power handling capacity and effective lifetime of BHS significantly. [2] Proposes that periodic charge balancing of packs maximizes available pack energy, which determines its voltage limits. This mandates the need for battery pack balancing in BHS. Modular DC-DC converters need to be connected across each battery pack to control battery power flow. The concept of modular DC-DC converters in input parallel output series, input parallel output parallel, input series output series, and input series output parallel configurations for sharing of input-output currents and voltages has been explained in [3]. Control strategy for modular cell balancing architecture using bypass DC-DC converters that perform real-time active cell balancing has been discussed in [4]. A voltage balancing strategy through a DAB-based input-series-output-parallel (ISOP) configuration for an energy storage system in a Bipolar DC microgrid is discussed in [5].

An input voltage balancing control strategy for DAB-based ISOP DC-DC converters is proposed in [6], where the coupling effect between input voltage sharing regulators (IVSR) and output voltage regulators (OVR) is eliminated. [7] Proposes independent input parallel output configuration of converter where diverse battery packs can be integrated together for power transfer. But this configuration uses converters of full ratings, and packs will need separate charge balancing circuitry, increasing the cost and complexity of the system. With full-rated DC-DC converters, heat loss is more so the need for a heating, ventilation and air conditioning system is more as presented in [8]. A detailed review of different partial power bidirectional dual active bridge(DAB) converters is provided in [8]. Different topology of series-connected partial power converters for reducing the power processed by the converters has been discussed in [9]. Comparison in the topology of modular DC-DC converters of full ratings and partial power ratings is shown in Fig. 1
Based on the study of existing typologies, this paper proposes DAB-based ISOP topology as shown in Fig. 1(b).

In this architecture, DAB operates in partial power mode, which reduces the required switch rating, cost, and losses and increases the efficiency of the system. A control strategy for the partial power converters is also developed to achieve the following functionalities:

1) Controlled power flow between the DC Grid and BHS based on load demand.
2) Operation of DAB in bypass mode.
3) Active charge balancing of battery packs.

II. GRID CONNECTED BATTERY HUB SYSTEM

ISOP configuration of BHS has a string of battery packs connected in series. Across each battery pack a DAB is connected. Bidirectional power flow between the battery pack, DC grid, and load is controlled by the DAB. The system is grid-connected and BHS acts as power backup which ensures uninterrupted power supply to load during grid intermittence. The topology description is given in this section.

A. DC-DC bidirectional dual active bridge converter

The DAB converter is a bidirectional DC-DC converter with galvanic isolation between two active bridges through a high-

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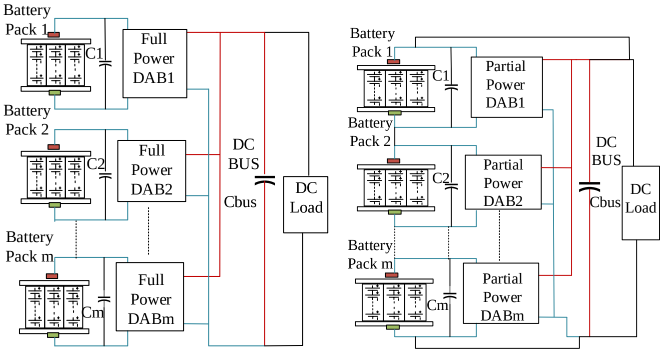
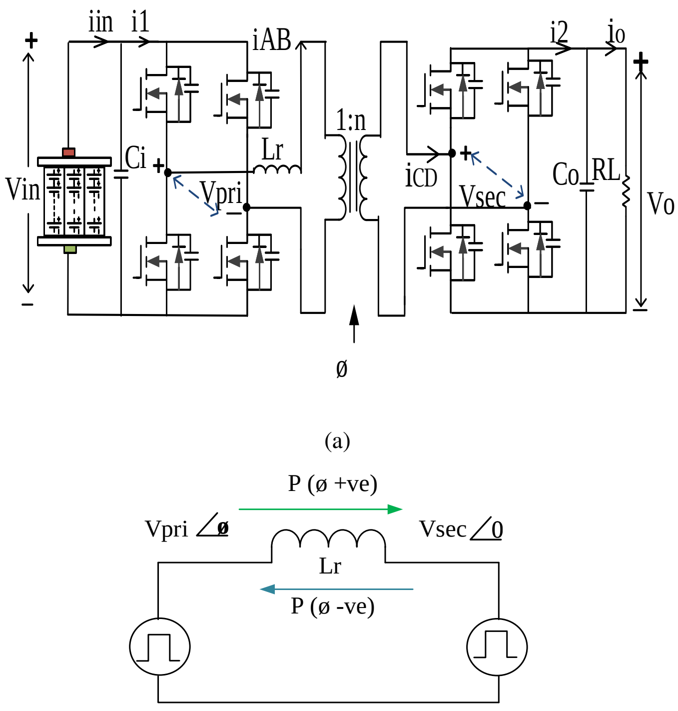


(a) (b)

Fig. 1: (a) Full Power converter (b) Partial Power converter

frequency transformer [10], as shown in Fig. 2(a). The transformer provides galvanic isolation and a high conversion ratio. DAB has several advantages, including zero-voltage switching (ZVS) operation, high voltage gain, and high efficiency.



(a)

(b)

Fig. 2: (a) DAB converter circuit (b) Power transfer in DAB

The power transmission in DAB module [11] is given by (1):

$$P = \frac{\phi(1-\phi)V_{pri}V_{sec}}{2f_sL_rn}, \tag{1}$$

where, ϕ is the phase-shift between V_{pri} and V_{sec} and f_s is the switching frequency. V_{pri} and V_{sec} are voltages of primary and secondary H-bridge of the DAB as shown in Fig. 2. Assuming lossless switches and transformer, the power transmission (P) by the DAB is expressed as:

$$P = V_{in}i_{in} = V_oi_o. \tag{2}$$

where, V_{in}, V_o are input, output voltages of DAB and i_{in} and i_o are input, output currents of DAB. Considering average model of DAB, the module currents i_1 and i_2 (Fig. 2(a)) can be expressed as:

$$\begin{cases} i_1 = \dfrac{\phi(1-\phi)V_o}{2f_sL_rn} \\ i_2 = \dfrac{\phi(1-\phi)V_{in}}{2f_sL_rn} \end{cases} \tag{3}$$

$$C_i\frac{dV_{in}}{dt} = i_{in} - i_1 \tag{4}$$

$$C_o\frac{dV_o}{dt} = i_2 - \frac{V_o}{R_L}. \tag{5}$$

where, C_i, C_o are input, output capacitors. L_r is leakage reactance, n is turns ratio of transformer and R_L is the load resistance.

B. Grid connected BHS in input series output parallel Configuration

The BHS consists of a string of series-connected battery packs with a capacitor in series. The parallel connection of the string capacitor with the output side of the converter serves to manage power flow for any battery pack mismatch. The battery pack module (BPM) consists of a battery pack and a DAB connected across it. The output power of each battery pack can be controlled independently by the bidirectional DAB sub-module, which acts as a bypass converter. The bypass converters will operate only when there is an SoC mismatch between any battery packs. BPM are connected in series on the input side and in parallel at the output side, forming ISOP configuration as shown in Fig. 3. The output of BPM is connected across the capacitor c, whose voltage v_c is the fraction of the total DC bus voltage and hence reduces the power rating of DAB. Additionally, charge balancing of series battery packs can be accomplished by adjusting the voltage of the capacitor in the string v_c.
The capacitor voltage v_c and current flowing from the DC bus I_{DC} are mathematically given as:

$$v_C(t) = V_{DC}(t) - \sum_{j=1}^{m} V_{in,j}(t) \tag{6}$$

$$I_{DC}(t) = I_{Load}(t) - \sum_{j=1}^{m} I_{o,j}(t) \tag{7}$$

where, m is the number of BPM in the string, v_C is the capacitor voltage in the string, V_{DC} is the DC grid voltage, I_{DC} is the current of the DC bus. $I_{o,j}$ is the output current of j^{th} BPM, I_{Load} is the load current and I_{string} is the string current as shown in Fig. 3 given in (8). The individual battery currents for discharging ($I^d_{bat,j}$) and charging ($I^c_{bat,j}$) case can be expressed as:

$$I^d_{bat,j}(t) = I_{in,j}(t) + I_{string}(t) \tag{8}$$

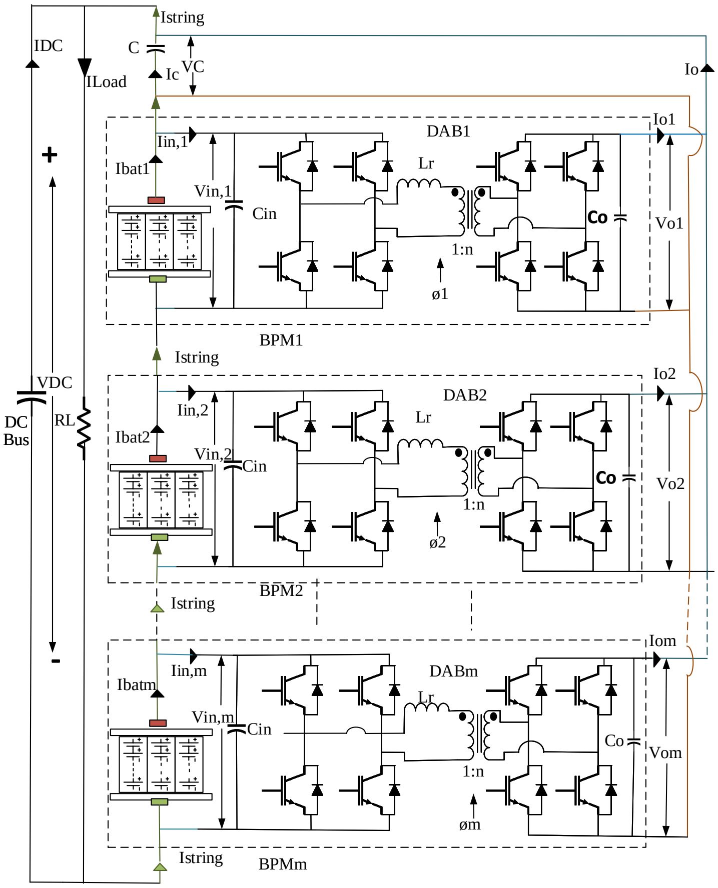


Fig. 3: DC grid connected BHS-ISOP-DAB configuration

$$I^{c}_{bat,j}(t) = -\big(I_{in,j}(t) + I_{string}(t)\big) \tag{9}$$

The partial power converters adjust their respective output voltage V_{oj} $\forall$ $(j = 1, 2, ...m)$ for active charge equalization of individual battery packs connected in the string.

III. CONTROL METHOD FOR GRID CONNECTED BATTERY HUB SYSTEM

A control strategy for individual bypass converters to achieve uninterrupted and independent balancing of all packs is detailed here. Each bypass converter employs a voltage control loop with a standard PI controller for controlling the string capacitor voltage as per the mismatch in the different pack capacities. Mismatch in SoC is mapped into voltage, and each DAB is operated in a closed loop to achieve reference voltage. j^{th} BPM is controlled through the phase shift angle of DAB ϕ_j, Consequently, m number of control variables $(\phi_1, \phi_2, ..., \phi_m)$ are regulated to control power flow in each BPM. The phase shift angle decides the direction of power flow between the primary and secondary voltage of both H bridges of the DAB. The control structure is designed to achieve the following modes of operation of BHS:

(i) Floating mode

During this mode of operation, when there is no mismatch in the battery pack capacity, the DABs will disable power transfer in BPM. The currents in the BHS and DC grid are given by:

$$i_{DC}(t) + i_{string}(t) = i_{Load}(t) \tag{10}$$

$$i_{bat,1}(t) = i_{bat,2}(t) = ... = i_{bat,j}(t) = i_{string}(t) \tag{11}$$

$$i_{in,1}(t) = i_{in,2}(t) = ... = i_{in,j}(t) = 0 \tag{12}$$

and capacitor voltage v_c is given by:

$$v_c = V_{DC} - (V_{in,1} + V_{in,2} + ... + V_{in,m}) \tag{13}$$

(ii) Operational mode

This mode of operation is active when there is an SoC mismatch between battery packs in the series connected string. The net contribution of the string is decided by its average SoC. The battery pack whose SoC is greater than the average SoC will deliver the extra current into the corresponding DAB connected across the battery pack. The pack with a lower SoC than the average SoC will take current from the corresponding DAB to meet the string current requirement. In this mode, DAB will operate in a bidirectional mode of operation, which can either receive power from the DC grid or deliver power to the grid as per the state of charge of the individual battery pack of the string and load requirements. Hence, active balancing of individual battery packs is done while supplying uninterrupted load demand. The different operating conditions of the battery pack module are:

Case I - ALL battery packs discharging:
When the SoC of the BHS is high i.e. greater than 60 %, then BHS discharges and the DC grid supplies load demand. In this case, charge balancing is achieved while discharging.

$$I_{DC}(t) + I_{string}(t) = I_{Load}(t) \tag{14}$$

$$I^{d}_{bat,j}(t) = I_{string}(t) \pm I_{in,j}(t) \tag{15}$$

$$i_{in,1}(t) \neq i_{in,2}(t) \neq ... \neq i_{in,m}(t) \tag{16}$$

Case II - ALL battery pack charging:
When the overall SoC of the BHS is less than 60 %, then BHS gets charged by the grid, and load demand is met by the DC grid. In this case, charge balancing is achieved while charging.

$$I_{DC}(t) = I_{string}(t) + I_{Load}(t) \tag{17}$$

$$I^{c}_{bat,j}(t) = I_{string}(t) \mp I_{in,j}(t) \tag{18}$$

$$I_{in,1}(t) \neq I_{in,2}(t) \neq ... \neq I_{in,j}(t) \tag{19}$$

Case III - k number of battery packs charging and l number of battery packs discharging, where $m = k + l$:
When the SoC of the k no. of packs in BHS is less than 60 % and the SoC of the l no. of packs in BHS is more than 60 %then packs with higher SoC will aid the DC grid to meet the load demand and provide charging current to k no. of packs in BHS.

$$I_{string}(t) = I_{DC}(t) \pm I_{Load}(t) \tag{20}$$

$$I^{c}_{bat,k}(t) = I_{string}(t) \mp I_{in,k}(t) \tag{21}$$

$$I^{d}_{bat,l}(t) = I_{string}(t) \pm I_{in,l}(t) \tag{22}$$

A. *Control Strategy for grid-connected BHS*

Each battery pack is charged or discharged to meet the reference SoC by the controller.

$$SoC_{ref} = \frac{SoC_1 + SoC_2 + ... + SoC_m}{m} \tag{23}$$

The net output voltage of DAB is maintained at:

$$v_{cref} = V_{DCref} - (V_{b1} + V_{b2} + ... + V_{bm}) \tag{24}$$

$V_{b1}, V_{b2}...V_{bm}$ are the voltages across individual battery packs in the BHS.

Each DAB output voltage, V_{oj} is regulated to common V_{ojref} by controlling ϕ_j in close loop. V_{oj} is equal to v_c as shown in Fig 3. Each battery pack SoC and voltage are related as in equation (25)

$$V_{map,j} = K_{map}(SoC_{ref} - SoC_j) \tag{25}$$

$$V_{ojref} = (v_{cref} - V_{mapj}) \tag{26}$$

where, $V_{map,j}$ and SoC_j are mapped voltage and state-of-charge for the j^{th} battery pack, K_{map} is the constant of proportionality. Each converter regulates its output voltage V_{oj} to V_{ojref} as shown in Fig. 4. Hence, the converter modules share output voltages according to their pack SoC. The control variable that controls the power flow in each BPM is the phase shift angle (ϕ_j) of DAB. The PI regulator generates the corresponding phase shift angle ϕ_j for each j^{th} DAB.

The detailed control is given in Fig 4. In balanced state all battery packs have the same SoC, leading to $\Delta SOC_j = 0$, $V_{map,j} = 0$ and V_{ojref} equal to $V_{c,ref}$, V_{ojref} equal to V_{oj}, $\Delta V_{oj} = 0$, $\phi_j = 0$. Therefore, there is no power transfer between the individual module DAB H-bridges.

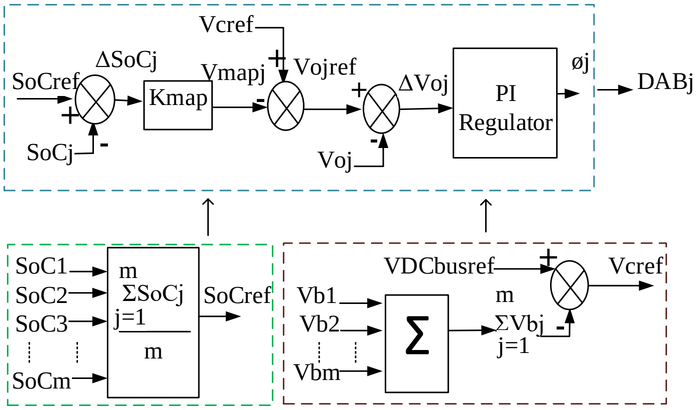


Fig. 4: Operational control strategy of DC grid connected BHS-ISOP-DAB System

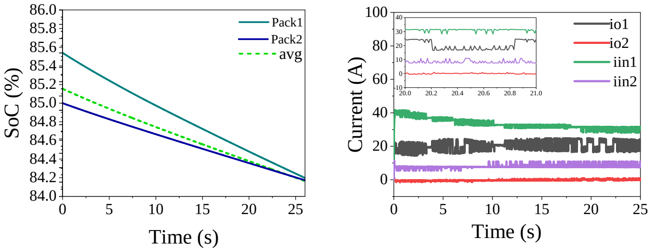
In the case of pack SoC mismatch $\Delta SOC_j \neq 0, V_{map,j} \neq 0$ and $V_{ojref} = (V_{c,ref} - V_{map,j})$ which implies $\Delta V_{oj} = (V_{ojref} - V_{oj})$ and $\phi_j = \Delta V_{oj}(k_p + \frac{k_i}{s})$.
This causes power flow between the H-bridges of the DAB of individual battery pack modules till charge equalization is achieved.

IV. SIMULATION RESULTS AND DISCUSSION

The grid-connected BHS shown in Fig. 3 is simulated in MATLAB/SIMULINK@2022b for two series-connected battery packs in the string. The DC grid voltage is regulated at 200V. Two lithium-ion battery packs, each of 50V and 20Ah, are considered. Each module level DAB is designed to handle 2kW bidirectional power and operated at 20kHz switching frequency. For larger gains, a 1 : 2 high-frequency linear transformer is used for DAB. The control strategy detailed in section III is evaluated for three different operating conditions.

A. *Case I- Both battery pack discharging*

In this case, a total load of 2kW is connected across the DC Bus. During this case, both the battery packs are discharging and contributing to load along with pack balancing, as shown in Fig. 5(b). The initial SoC of battery pack 1 and 2 are 86 % and 85 %, respectively. Due to the mismatch, the rate of discharge of the battery pack is adjusted to reach an average SoC, SoC_{ref}. As the SoC of battery pack 1 is higher, it supplied more load current than pack 2. Fig. 5(b) input-output current shared by each DAB is shown. Here, by adjusting the phase shift angle, output currents are regulated based on the available state of charge of individual battery packs.



(a) SOC of pack1& 2 (b) input, output DAB currents

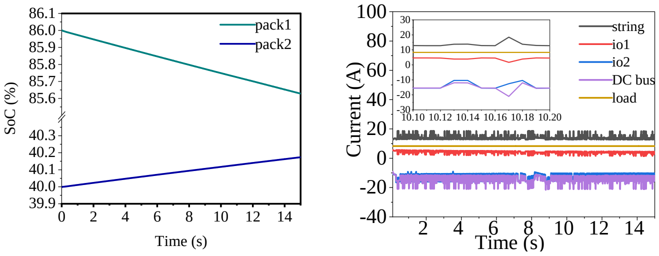
Fig. 5: Case I- both battery pack are discharging

B. *Case II- One battery pack discharging and other charging*

For load demand of 2 kW and the initial SoC of battery pack 1 is 86 % and for battery pack 2 is 40 %, the control action enables pack 1 to discharge and pack 2 to charge for balancing the BHS. Fig. 6(a) shows the SoC of battery 1 and battery 2, here battery pack 1 assists the DC bus to meet load demand. Pack 2 is charged till BHS is balanced. The rate of discharge of pack 1 is more than that of pack 2. Output currents of each DAB, string current, DC grid current, and load current profile is shown in 6(b).

C. *Case III- Both battery packs are Charging*

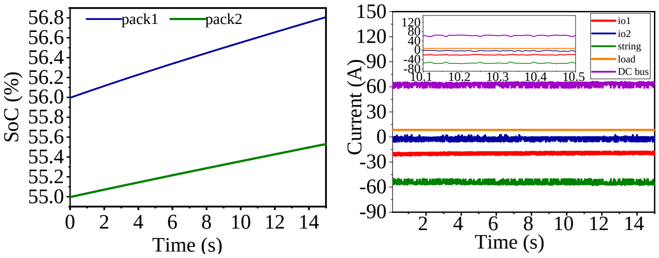
For a constant load demand of 2kW, with pack 1 and pack 2 having less capacity, the controller enables pack charging if a grid is available. The DC bus meets load demand and provides charge balancing of BHS. In this case, an initial SOC of 56 % is set for battery pack 1 and 55 % for battery pack 2, and by the control action pack 1 and pack 2 are charged till BHS is balanced. SoC profile of battery 1 and battery 2 is shown



(a) SOC of battery pack 1& 2 (b) current waveforms

Fig. 6: Case II- pack 1 discharging pack 2 charging

in Fig. 7(a) simulated for 15 seconds. Output currents of each DAB, string current, DC grid current, and load current profiles are shown in 7(b).



(a) SOC of battery pack 1& 2 (b) current waveforms

Fig. 7: Case III- pack 1 & pack 2 charging

V. CONCLUSION

A novel control strategy is proposed for a modular grid-connected BHS which combines the functions of active battery pack balancing and providing backup support to the DC grid for uninterrupted load demand. The role of the series capacitor in the string is to compensate for the mismatch in the battery capacity. The operational control strategy here is presented for the three different modes of operation of the grid-connected BHS. Future studies can implement the control technique to consider GCBHS mismatch in chemistry and make.

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