Combined Equalizer Based on Switch-matrix and Bi-directional Converter for Parallel-Connected Battery Packs in Data-Center or Telecommunication

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***Abstract*—In data-center and telecommunication applications, the battery energy storage system is utilized to ensure operational stability. Battery packs are connected in parallel to enlarge the system capacity, and the hot-swap process is adopted to avoid power interruption. However, the battery inconsistency causes an unequal current sharing issue between branches and the hot-swap process makes that issue more serious. This paper proposes a combined equalizer based on the switch-matrix and bi-directional converter to balance the energy between battery packs, and an equalization strategy is presented to improve the limitation of the hot-swap process. The simulation results verify that the SOC of battery packs are equalized within 0.5% in both idle and non-idle modes while the branch currents are confined in the safety level. Besides, the proposed equalization strategy overcomes the inrush current issue in the hot-swap process when the battery pack is replaced and connected to the DC bus.**

***Index Terms*—Battery energy storage system, charge equalizer, parallel-connected battery packs.**

I. Introduction

To prolong the operating time, battery packs are connected in parallel for the data-center and the telecommunication applications. Generally, battery packs connect to the DC bus through a protecting circuit, including one relay S_k for the main connection, and one pre-charge relay (S_{pre_k}) with a resistor (R_{pre_k}) circuit to suppress the current arcing during hot-swap process, where $k = 1, 2, ..., n$. This configuration, which is illustrated in Fig. 1, is popular in commercial applications due to simplicity and cost effectiveness. However, it is too reliant on the self-balancing of the parallel connection, which becomes deteriorated after the aging of battery cells. The experiments in [1]–[3] show that the sharing current of branches are poor when the state-of-charge (SOC) and the battery impedance become mismatching. As a result, one battery pack (or more) is charged/discharged by a far higher current than the others, and over-charging/over-discharging issues happens. The inconsistency affection becomes more serious in Lithium-ion battery applications where a few impedance and SOC differences could make a far difference in the behavior of battery cells.

To equalize the energy between battery packs, a switch-matrix can be used to adjust the number of battery packs that are connected to the DC bus [4]. The switch-matrix is

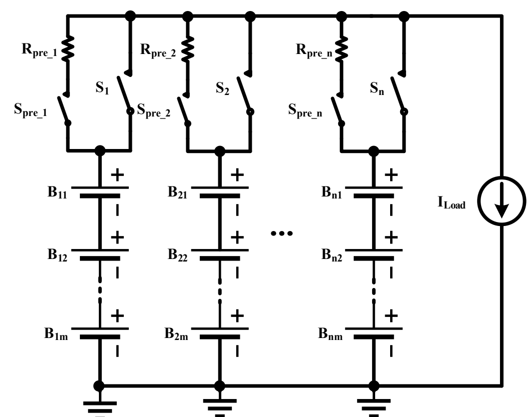

Fig. 1: Commercial protecting circuit of the parallel battery connection.

controlled based on the SOC of the battery packs. In the charging mode, the switches of the higher SOC packs have a priority to turn off to disconnect them from the DC bus. Although it can equalize the energy of the battery packs, the current between branches is still mismatched. To overcome the unequal current sharing issue, the dynamic resistance method is presented in [5], where the current is regulated to equalize the energy between battery packs. Although the equalization performance in view of SOC equalization and current sharing is good, power losses in the resistor reduce its effectiveness.

Besides, inrush current issue in hot-swap applications is a worthy topic to pay attention to. The methods in [4] and [5] cannot avoid the inrush current in the hot-swap process. In [6], the inrush current is estimated to decide when the relay should be turned on. If the estimated inrush current is high, the hot-swap switch is kept disconnecting from the DC bus, and the conventional battery packs have to operate by a higher current for a long time. Besides, in the heavy load condition, the replaced battery pack have to connect to DC bus as soon as possible to share the load burden. As a result, the estimation algorithm is overridden.

This paper proposes a combination of a switch-matrix and a bi-directional converter to equalize the energy of parallel-connected battery packs and suppress the inrush current during the hot-swap process. The battery inconsistency is analyzed

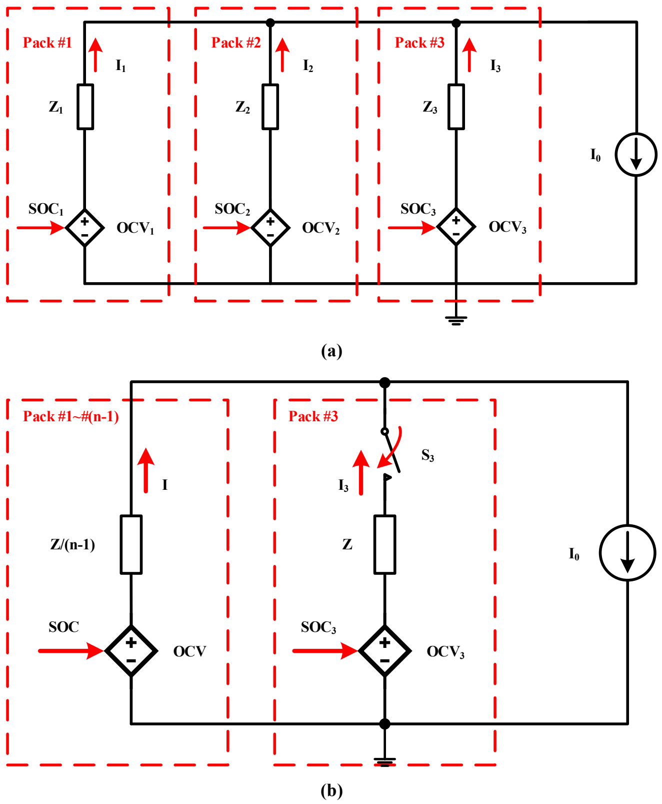

Fig. 2: Equivalent circuit of the parallel battery connection: (a) in normal operation; (b) in hot-swap operation

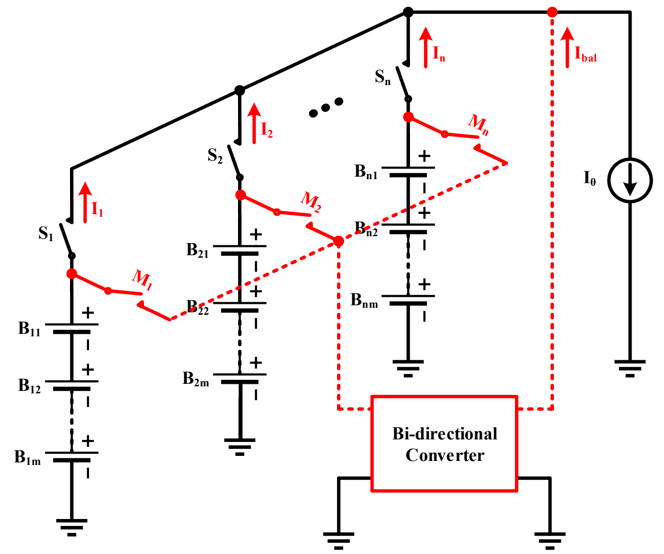

Fig. 3: Topology of proposed equalizer.

and the proposed method is introduced in section II. The performance is verified in section III, and the conclusion is made in section IV.

II. Research Motivation and The Proposed Method

A. Battery Inconsistency and Limitation of conventional Hot-swap Techniques

In parallel battery connection, the currents flow through the branches by nature sharing based on the battery voltage and the internal impedance to make the branch voltage equal in the steady state. This transient behavior is called the self-balancing effect. During the idle mode when there is no load current, the energy is transferred from the high voltage battery to the low voltage battery. However, due to the mismatch of battery impedance, the state-of-charge (SOC) are different from each other although the terminal voltage is the same. During the non-idle mode when the battery cells are charged or discharged by the load current, I_0, the battery packs are charged or discharged by the different current levels. The operation of three parallel-connected battery packs is represented as the equivalent circuit in Fig. 2(a), where a battery pack is modeled by one voltage source, OCV_k, and one impedance, Z_k, $(k = 1, 2, 3)$. According to Kirchhoff's law, the branch current, I_k, are determined by satisfying the following conditions

$$\begin{aligned} Z_1I_1 - Z_2I_2 &= OCV_1 - OCV_2 \\ Z_1I_1 - Z_3I_3 &= OCV_1 - OCV_3 \\ I_1 + I_2 + I_3 &= I_0 \end{aligned} \tag{1}$$

When the SOCs and impedance of the battery packs are mismatched, the load-sharing of branches become different. As a result, one battery pack is charged or discharged by a higher current level than the others, and the battery pack faces with the over-charging or over-discharging issue. Because the over-charged or over-discharged pack is short-circuited inside the battery [7], all packs are shorted by a chain reaction.

In hot-swap process, the replaced battery pack is connected to the DC bus when its SOC is far different from the others. For an illustration, the equivalent circuit of the hot-swap process for battery pack #3 is presented in Fig. 2(b). Assume that the SOCs of the battery pack #1 and #2 are equal while the impedance of the branches is the same such that $Z_1 = Z_2 = Z_3 = Z$, the branch currents are represented by

$$\frac{Z}{2}I - ZI_3 = OCV - OCV_3 \tag{2}$$

$$I + I_3 = I_0 \tag{3}$$

where I is the total current in the branch $\#1 \sim \#(n-1)$.

By solving (2) and (3), the individual current of the branches are calculated by

$$I_3 = \frac{1}{3}\left(I_0 - \frac{2(OCV - OCV_3)}{Z}\right) \tag{4}$$

$$I = I_0 - I_3 \tag{5}$$

For example, the battery packs #1 and #2 are discharged by a 4A constant current (I_0) and the open circuit voltages of packs #1 and #2 (OCV) are identical as 16.35V. When the voltage of the replaced battery pack (#3) is 15.45V and

TABLE I: Battery parameter and test conditions

Battery parameters			
Capacity of battery pack	$2500mAh$		
Voltage of battery pack	$11V \sim 16.8V$		
Maximum charge/discharge rate	$1C - rate$		
Test conditions			
	Idle mode	**Charging mode**	**Discharging mode**
Initial $SOC_{1,2,3}$	$90\%, 90\%, 60\%$	$20\%, 20\%, 60\%$	$90\%, 90\%, 60\%$
Charging/Load current	0	$4A$	$-4A$

the impedance of all packs, Z, is 0.052Ω, the current flowing through pack $\#3$ is $-10.2A$ and the total current of the other branches is $14.2A$. It means that the pack $\#3$ is charged and the packs $\#1$ and $\#2$ have to discharge by a higher current to equalize the SOC of packs when the hot-swap process is executed. After that, the currents are gradually balanced, but it takes a long time to reach the steady state. Sometimes, it may lead the battery packs to over-load condition to make a safety problem.

B. Proposed Equalizer and equalization strategy

The proposed equalizer is illustrated in Fig. 3, where one bi-directional converter and one switch/relay matrix are utilized to regulate the current of the battery packs. The equalization strategy is different in the hot-swap process during idle mode, charging mode, and discharging mode. Besides, the hot-swap process is divided into two intervals which consists of multiple cycles. During interval A, the SOC of battery packs are equalized by transferring energy between branches or regulating the branch currents. Next, the replaced battery pack is direct connected to the DC bus by the switch, S_3, and the converter is turned off to reduce the power losses during interval B.

- **Hot-swap process during the idle mode**: After identifying the SOCs of the highest voltage pack and the lowest voltage pack, the switch M_i of the highest voltage pack is turned on to dock it to the input of the converter. Besides, the switch S_j of the lowest voltage pack is turned on to connect to the output of the converter, where i and j denote the switch index number of the highest and the lowest pack voltage, respectively. The converter is controlled to transfer energy from the highest voltage pack to the lowest voltage pack by a constant current. After a holding time, T_{hold}, another equalization cycle is repeated. Observed that, the indices of the highest voltage pack and the lowest voltage pack are re-assigned during the equalization process due to the voltage comparison algorithm. When the SOCs of all packs are equalized, the switches and the converter are turned off and the replaced battery pack docks to the DC bus by switch S_k.
- **Hot-swap process during the charging mode**: Differently from the idle mode, the SOCs are equalized by an intentionally unbalanced current between branches. Only one switch S_i is turned off while the other S_j $(j = 1, 2, .., n; j \neq i)$ switches are kept on, where i denote the index of the highest pack voltage. Hence, the highest voltage pack is charged by the converter (through the switch M_i) with a constant current, I_B. The value of I_B is calculated by

$$I_B = \frac{1}{2}\frac{SOC_{min}}{SOC_{max}}\frac{I_0}{n} \tag{6}$$

where SOC_{min} and SOC_{max} are the SOC of the highest voltage pack and the lowest voltage pack; n is the total number of the parallel battery packs. As a result, the highest voltage battery pack is charged by a smaller current than the others. When the SOC of all packs are equal, the converter and the switch M_k are turned off while all the switches S_k are turned on. After that, the charging process repeats until the battery packs become fully charged.

- **Hot-swap process during the discharging mode**: The equalization strategy of the discharging mode is similar to the charging mode. However, the branch current of the lowest voltage pack is utilized instead of the highest voltage pack. The lowest voltage pack is disconnected from the DC bus and discharged by a constant current, I_B. By operating with a different current sharing ratio, the SOCs of the packs are equalized gradually. When the equalization is achieved, all switches S_k are turned on to connect all battery packs to the DC bus. The discharging process keeps going until all battery packs are fully discharged.

III. Verification

To verify the performance of the proposed equalizer, simulations of three parallel-connected battery packs, which consist of 4 series-connected Lithium-ion battery cells in each (4S3P configuration), are implemented on PSIM. The proposed equalizer is applied to the battery system in the hot-swap process during the idle, the charging, and the discharging modes, where the battery inconsistency and the inrush current issue in the hot-swap process are mitigated. The battery parameters and the initial conditions of the tests are shown in Table I. Because the battery system usually requires a long

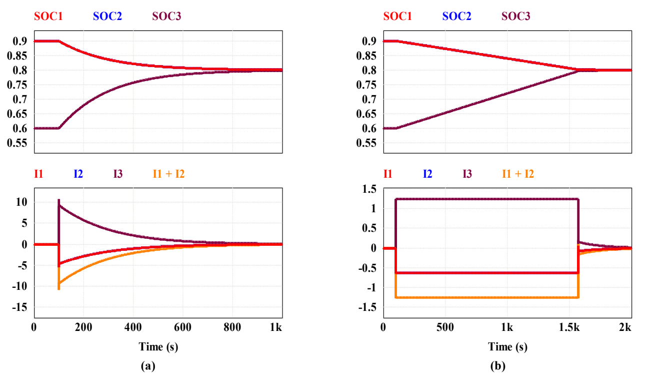

Fig. 4: SOC and Current profiles of battery packs in idle mode: (a) conventional method; (b) proposed method.

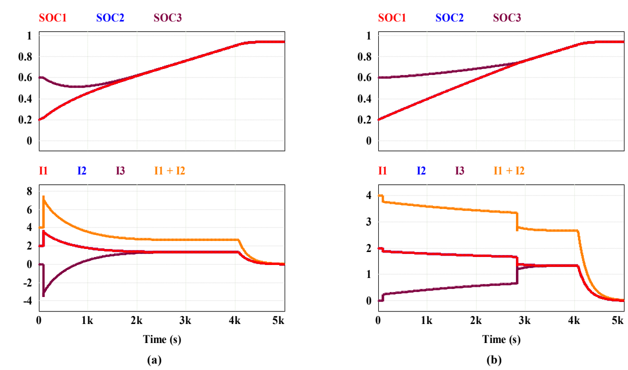

Fig. 5: SOC and Current profiles of battery packs in charging mode: (a) conventional method; (b) proposed method.

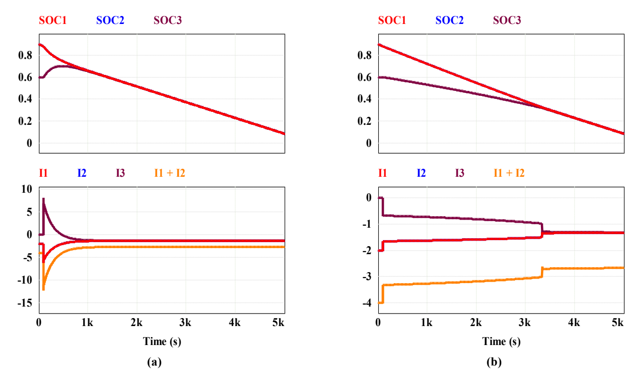

Fig. 6: SOC and Current profiles of battery packs in discharging mode: (a) conventional method; (b) proposed method.

time to achieve the equalization, the average model of the bi-directional converter is used in the simulations. In all tests, the proposed method is compared with the conventional method, where the battery packs are connected to the DC bus directly through the relays. When the tests begin, only battery packs #1 and #2 are connected to the DC bus and the hot-swap process is executed after 100 seconds.

The hot-swap process during idle mode is illustrated in Fig. 4, where there is no load flow through the battery packs. The SOC and current profiles of the conventional method in Fig. 4(a) show that battery packs #1 and #2 discharge to pack #3 by a high current (about $10A = 4C - rate$) for a long duration (over 200 seconds). Considering that the maximum current of one battery pack is 2.5A ($1C - rate$), such a high current may puts the battery packs in a over-load situation. On the contrary, the proposed method utilizes the bi-directional converter to charge the battery pack #3 through the battery packs #1 and #2. The balancing current is constant as 1.25A ($0.5C - rate$) to prevent the overload condition as Fig. 4(b). Although the equalization time is twice than the conventional method, battery packs are protected from the overload condition. When the SOC of battery packs are equalized within 0.5% at 1600 seconds, the converter is turned off, and the battery pack #3 directly connects to the DC bus through the switch S_3. Because the SOC difference is small, the inrush currents are greatly reduced to $0.25A$.

During the charging mode, battery packs are charged by a 4A-16.8V CC-CV charging method. In the beginning, only packs #1 and #2 are charged while pack #3 is waiting to be connected to the DC bus. By the conventional method, battery pack #3 is docked to the DC bus while the SOCs of battery packs are still mismatched. As a result, battery pack #3 have to be discharged by a $4A$ current (and gradually decreasing) to charge the other packs as in Fig. 5(a). The SOC profile in Fig. 5(a) explains the equalization process, where the SOC of battery pack #3 is decreased to the equalization state. After that, battery packs are charged by the CC-CV method until they are fully charged. On the other hand, the proposed method solves the issues by a different way. Before the battery pack #3 is docked to the DC bus, it is charged by a smaller current (which is calculated by (6)) through the bi-directional converter and the other battery packs share the remaining charging current to increase the SOC levels as in Fig. 5(b). When the SOC levels of the battery packs are matched after 2800 seconds, the converter is turned off while the switch S_3 is turned on to dock the battery pack #3 to the DC bus. Because the SOC levels are uniform, the battery packs are charged by an equal current to the end of the charging process.

Similarly to the charging mode, the proposed method discharges the battery pack #3 by a smaller current until the SOC levels are matched during the discharging mode. After 3400 seconds, all battery packs are connected to the DC bus and deliver the energy to the load by an identical current as in Fig. 6(b). Obviously, the proposed method mitigate the inrush current issue existing in the conventional method as in Fig. 6(a).

IV. Conclusion

This paper proposes an equalizer and a control strategy for parallel-connected battery packs. By utilizing single bi-directional converter and one switch-matrix, the SOC levels of the battery packs can be equalized. Besides, the inrush current issue during the hot-swap process is eliminated. The test results of the proposed method in the idle, charging, and discharging mode show a good performance where the SOC levels of the battery packs are equalized within 0.5% without any overload condition. In the second-life battery application, the aged battery cell/pack is recommended to operate under a light load only because they are sensitive of over-charging, over-discharging, and over-load issues. Thus, the proposed method can be applied to the ESS for the data-center and telecommunication applications, especially in the BESS using the seconds-life battery. The hardware experiments will be made as a future work to further verify the performance of the proposed method.

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REFERENCES

[1] Castano-Solis, Sandra, et al. "The influence of BMSs on the characterization and modeling of series and parallel Li-ion packs." Energies 10.3 (2017): 273.

[2] Gogoana, Radu, et al. "Internal resistance matching for parallel-connected lithium-ion cells and impacts on battery pack cycle life." Journal of Power Sources 252 (2014): 8-13.

[3] Gong, Xianzhi, Rui Xiong, and Chunting Chris Mi. "Study of the characteristics of battery packs in electric vehicles with parallel-connected lithium-ion battery cells." IEEE Transactions on Industry Applications 51.2 (2014): 1872-1879.

[4] T. Kim, W. Qiao and L. Qu, "Power Electronics-Enabled Self-X Multicell Batteries: A Design Toward Smart Batteries," in IEEE Transactions on Power Electronics, vol. 27, no. 11, pp. 4723-4733, Nov. 2012, doi: 10.1109/TPEL.2012.2183618.

[5] Phuong-Ha La, and Sung-Jin Choi. "Novel Dynamic Resistance Equalizer for Parallel-Connected Battery Configurations." Energies 13.13 (2020): 3315.

[6] Seongjun Lee and Jonghoon Kim, "Inrush Current Estimation and Hot-swapping for Safe Parallel Battery Pack," International Journal of Electronics Volume 107, 2020 - Issue 10. doi: 10.1080/00207217.2020.1727031.

[7] Guo, Rui, et al. "Mechanism of the entire overdischarge process and overdischarge-induced internal short circuit in lithium-ion batteries." Scientific reports 6 (2016): 30248.