A Novel Balancing Algorithm for Lithium Battery Strings Using Bidirectional Charge Circulation

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***Abstract*— In energy storage systems (ESS), numerous battery cells are connected in series to elevate the bus voltage. However, the manufacturing tolerance between the cells often introduces an imbalance in the battery string, which can lead to safety issues. To address this issue, a battery equalizer is employed to harmonize the energy levels among cells. The conventional balancing method utilizes unidirectional converters to redistribute charge among cells with high efficiency and minimal energy loss. However, this approach lacks flexibility in energy transfer direction, which can impede the balancing speed. To overcome this challenge, this paper introduces a bidirectional converter-based cell-to-string equalizer featuring a high-speed balancing algorithm. The performance of the balancing process is confirmed through experiments involving 20 series-connected cells. The results show that the open-circuit voltages of the cells are balanced to within the voltage deviation of 21mV. In addition, the proposed method reduces the balancing time by 50% in comparison to conventional techniques.**

***Keywords*— Balancing, Bidirectional Charging, Lithium battery, SOC**

I. Introduction

With the rapid growth of renewable energy, lithium batteries become essential in energy storage systems. To facilitate the increased power, the battery cells are connected in series to increase the voltage or connected in parallel to obtain a higher capacity. So, the ESS with hundreds of cells in series and parallel becomes more popular. However, due to the different cell characteristics [1], when the string is imbalanced, the over-charge or over-discharge happens to damage the battery cells. Therefore, a battery equalizer is almost always required to balance the cell energy level [2].

There have been several studies on the cell balancing methods [3]. Based on the operating principle, the cell balancing method can be separated into two groups: passive and active methods [4]. In the passive methods, the imbalanced condition of cells is mitigated by the energy dissipation via resistors [5]. The passive cell balancing methods are widely used due to their ultimate low-cost and circuit simplicity. However, their balancing power is especially low, leading to a slow balancing speed, which is a significant disadvantage in the ESS applications. To improve the balancing speed and the performance, active balancing methods are introduced in [6]-[8]. By transferring energy from the higher SOC level cell to the lower SOC level cell, the equalization condition can be achieved with higher efficiency and higher speed than the passive way.

Active cell equalization techniques can be further categorized into four groups as shown in Fig. 1. Among these, the cell-by-adjacent-cell method autonomously facilitates energy exchange between two neighboring cells by employing a switched-energy-tank (SET), such as a switched-capacitors [9], or switched-inductors [10]. Consequently, this approach exhibits high equalization efficiency with a slight increment in the circuit complexity. Based on the advantages of the SET equalizer, a switch matrix is incorporated into the structure to create a governed SET equalizer, directly transferring energy between any pair of cells [11]. Nonetheless, the balancing current becomes small, which prolongs the equalization time, when the voltage deviation becomes small. Therefore, the equalization speed and performance are strongly dependent on the initial voltage distribution of the cells in the series-connected string.

In this case, an isolated converter-based equalizer can be employed to maintain a consistent equalization speed. By combining the advantages of the switch matrix and the isolated converter, the equalizer performs a high degree of equalization and fast equalization speed. Depending on the switch-matrix structure and the converter topology, energy can be transferred either from the battery string to the cell (S2C) or from the cell to the string (C2S) [12], [13].

Various control algorithms can be implemented with the switch-matrix converter structure. The most common is to observe the cell voltages to decide the balancing action of the equalizer. This approach requires a highly accurate battery monitoring circuit and a continuous calculation during every balancing step but the balancing speed is moderate. To reduce the processing time, a unidirectional converter-based equalizer is introduced in [14]. However, this concept only transfers energy from the string to the cell.

In order to accelerate the balancing process, this paper proposes a bidirectional equalizer with a novel balancing algorithm. In Section II, the topological configuration of the

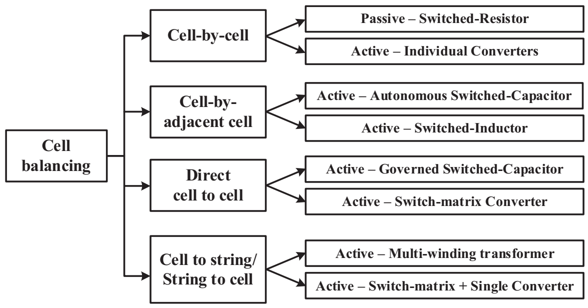

Fig. 1. Classification of the cell balancing methods.

equalizer and the operation principle are introduced. Then, the processing time is theoretically analyzed in Section III. The experimental results and comparison are provided in Section IV and the conclusion is presented in Section V.

II. System Configuration and Operation

The proposed balancing method requires a bi-directional converter, which can charge or discharge a cell. In addition, the converter should be able to connect to every cell by turns to process the equalization. Thus, the topological configuration of the proposed structure is illustrated in Fig. 2(a). The switch-matrix is used to dock any cell in the string to the low-voltage side of the bidirectional converter. The high-voltage side of the converter is connected to the string, and thus, energy can be transferred as C2S or S2C.

To minimize the number of switches within the matrix, an even-odd configuration in Fig. 2(b) is adopted. For a system consisting of N cells, this structure requires only $N+5$ switches in total, including $N+1$ switches (S_{M1} to $S_{M(N+1)}$) for managing the equalization bus and four switches (S_{R1}, S_{R2}, S_{R3}, S_{R4}) for changing the polarity of cells. Specifically, when selecting an odd cell, S_{R1} and S_{R4} are activated, while S_{R2} and S_{R3} are engaged for an even cell. In this study, relays are employed for these switches, as they naturally provide isolation and obviate the need for a floating gating circuit required in MOSFET/IGBT-based circuits.

To decide the switching action of the switch-matrix, the battery monitoring integrated circuits (BMICs) are used. In this paper, a commercial BMICs chip (Analog Device, LTC6811) is used, which can transfer cell data between BMICs by daisy chain iso-SPI communication. Besides, an MCU is required to collect all data from the BMICs, decide the switching actions of the switch-matrix, and control the balancing current of the bi-directional equalizer.

In the equalizing process, the operations of the equalizer are divided into two stages: forward circulation and reverse circulation. In the forward charge circulation, the equalizer is used to charge the targeted cell from the battery string. In the reverse charge circulation, the cell is discharged by the

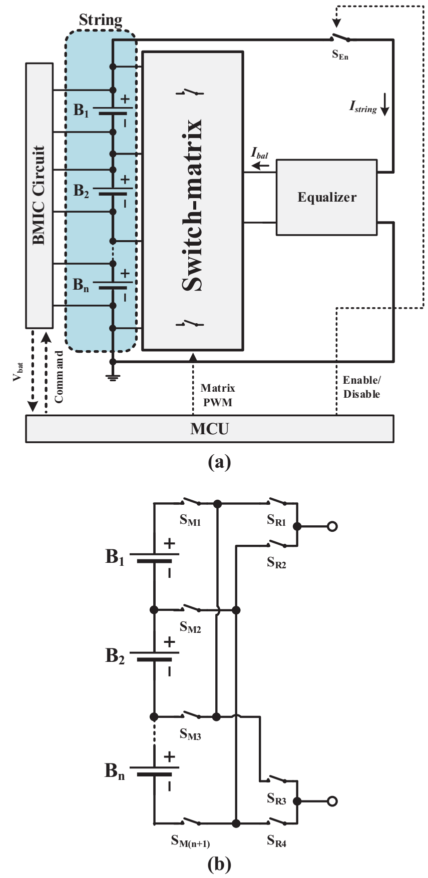

Fig. 2. Topological configuration of the cell equalizer: (a) overall structure; (b) N+5 switch-matrix structure.

equalizer and the energy is transferred from the individual cell to the string.

III. Proposed Balancing Algorithm

In this section, a concise overview of the conventional method is provided, and the proposed method is introduced along with its processing time estimation. Subsequently, the simulation to compare the processing times of both methods is implemented, aiming to highlight their respective advantages and strengths.

A. *Balancing Algorithm*

In virtue of the switch-matrix and the bidirectional equalizer, the forward and reverse energy flow controls are possible. The energy direction of the balancing processes is shown in Fig. 4. The energy can be delivered in two strategies: string-to-cell and cell-to-string.

1) Conventional Method

In the conventional method [14], the equalizer is a unidirectional converter; hence, only either the string-to-cell strategy illustrated in Fig. 3(a) or the cell-to-string strategy shown in Fig. 3(b) can be considered. The charging process is

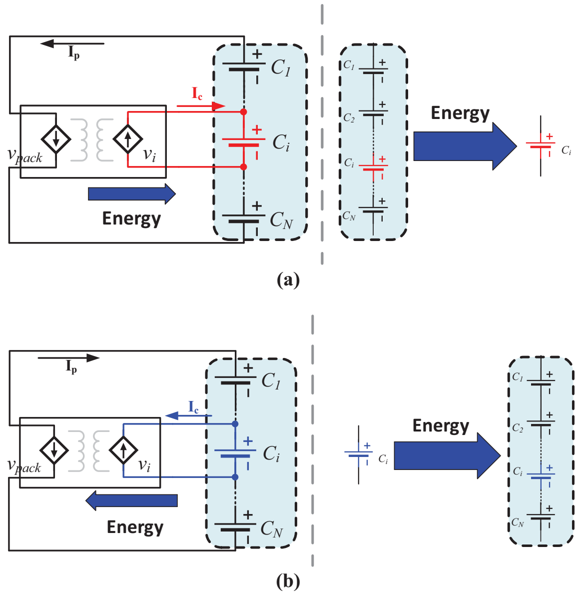

Fig. 3 Energy flow strategies: (a) forward charge circulation (S2C), (b) reverse charge circulation (C2S).

divided into N steps, where N is the number of battery cells. The time of each step, T_i, is calculated as

$$T_i = \frac{C_0}{I_{Bal}}\left[SOC_i(t_0) - SOC_{\min}(t_0)\right] \quad (1)$$

where C_0 is the nominal capacity of a battery, $SOC_i(t_0)$ is the initial SOC of the i^{th} cell and $SOC_{min}(t_0)$ is the minimum of the initial SOC levels for all cells.

2) Proposed Method

The main concept of the proposed method revolves around the ability of the equalizer to circulate both from high-SOC cells to the string and from the string to low-SOC cells. Under ideal conditions neglecting loss, the final SOC of the battery string, SOC_{end}, aligns with the average SOC level of the individual cells. To attain this final goal, cells with a SOC higher than SOC_{end} are categorized as high-SOC cells, while those with a SOC lower than SOC_{end} are considered low-SOC cells. The proposed procedure consists of four sequential steps, as depicted in Fig. 4:

- Step 1: Identify the cell with the maximum SOC, SOC_{max}, and minimum SOC, SOC_{min}.
- Step 2: If the difference between SOC_{max} and SOC_{min} is larger than the SOC threshold, SOC_{th}, activate the equalizer and move on to the next step. Otherwise, go to Step 1.
- Step 3: The equalizer is activated in one of two modes: forward circulation and reverse circulation. The mode will be toggled whenever Step 3 is recalled. Moreover, the equalizer operates in the forward circulation mode if the difference between SOC_{min} and SOC_{end} is greater than $SOC_{th}/2$. Otherwise, it operates in the reverse circulation mode when the deviation of SOC_{max} and SOC_{end} is greater than $SOC_{th}/2$.
- Step 4: The equalizer is turned off every 15 seconds and go to Step 1.

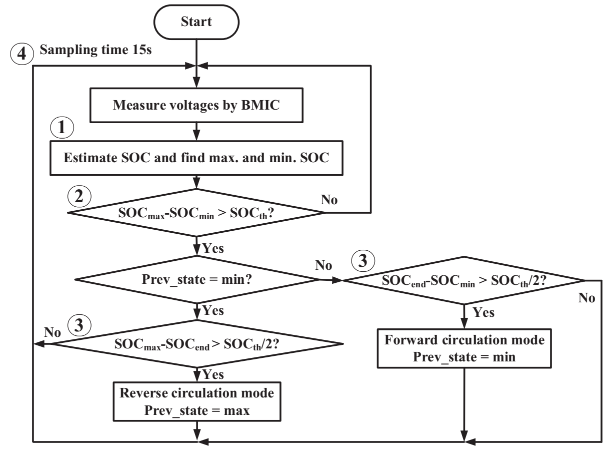

Fig. 4. Control flowchart of the proposed method.

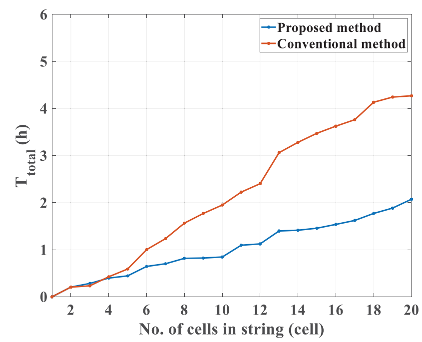

Fig. 5. Processing time comparison between the conventional and the proposed method.

B. Processing Time Estimation

To estimate the time of the balancing process, the balancing algorithm is analyzed. The balancing current I_{Bal} should be decided by considering the maximum allowable current of the battery. The balancing current is expressed as

$$I_{Bal} = \eta_c \frac{v_{string}}{v_{cell}} I_{string} \quad (2)$$

where η_c is the efficiency of the converter, I_{string} is the input current of the converter, v_{cell} and v_{string} are the cell voltage and string voltage of the lithium battery, respectively. The SOC of one battery cell is defined as

$$SOC(t) = SOC(t_0) + \frac{1}{C_0}\int_{t_0}^{t} i(\tau)d\tau \quad (3)$$

where $i(\tau)$ is the charging current of the cell. If the system is loss-less, which means the Coulombic efficiency of the battery is unity and there is no loss in the converter, and the charging current, I_i, is constant, the SOC of the i^{th} cell after $T_i = t-t_0$ is calculated as

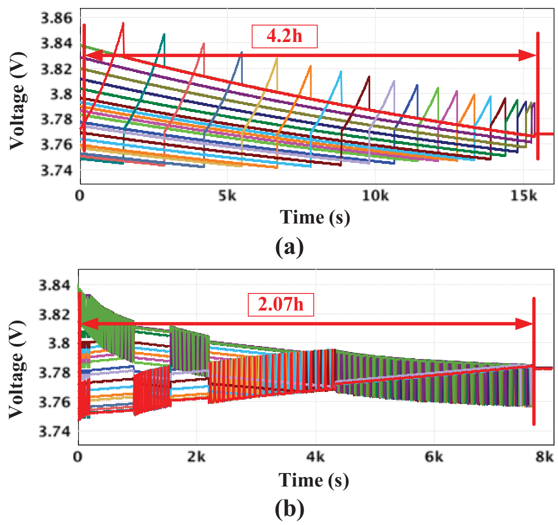

Fig. 6. Simulated voltage profiles: (a) conventional method, (b) proposed method.

$$SOC_i(t) = SOC(t_0) + \frac{1}{C_0} I_i T_i \,. \tag{4}$$

Then the required period of one battery to reach the SOC level is expressed as

$$T_i = \frac{C_0}{I_i}\left[SOC_i(t) - SOC(t_0)\right]. \tag{5}$$

If the converter operates in the constant current charging mode with I_{Bal}, the total time for the balancing process with N cells, $T_{process}$, is expressed as

$$T_{process} = \sum_{i=1}^{N} T_i \tag{6}$$

and thus

$$T_{process} = \frac{C_0}{I_{Bal}} \sum_{i=1}^{N} \left| SOC_i(t) - SOC_i(t_0) \right|. \tag{7}$$

In the final balanced condition, the SOC of the battery string, SOC_{end}, can be regarded as

$$SOC_{end} = \frac{1}{N} \sum_{i=1}^{N} SOC_i(t_0)\,. \tag{8}$$

Therefore, the $T_{process}$ is re-expressed as

$$T_{process} = \frac{C_0}{I_{Bal}} \sum_{i=1}^{N} \left| SOC_{end} - SOC_i(t_0) \right|. \tag{9}$$

Fig. 5 demonstrates the comparison of the calculated processing time between the conventional method and the proposed method with the different numbers of cells in the battery string. In this figure, the processing time increases when the number of cells increases. It is remarkable that the processing time of the proposed method is always faster than the conventional method and the difference in the processing time between them becomes dramatically larger when the number of cells is increased.

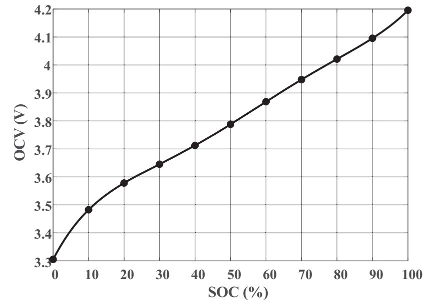

Fig. 7. OCV-SOC curve of the LiB sample used in this paper.

C. *Simulation results*

To verify the processing time analysis of both the conventional and proposed methods, the simulations are implemented in PSIM. Significant initial SOC deviations were intentionally introduced. The initial SOC values were randomly scattered within the range of 30% to 60%, as detailed in Table I.

Fig. 6 illustrates the simulation results for both the conventional and proposed methods. Notably, the conventional method achieves balance within 4.2 hours, as depicted in Fig. 6(a), whereas the proposed method remarkably accomplishes the same battery string balance in just 2.07 hours, as shown in Fig. 6(b). As a result, the proposed method significantly improves the balancing speed, being twice as fast as the conventional approach. Besides, this implementation is achieved without any complex computational burden. The next section will present an experimental setup and results to corroborate the findings from the theoretical analysis and simulation results.

IV. Experimental Results

A. *LiB Cell Characterization*

In order to estimate the SOC of the cells, the SOC-OCV look-up table (LUT) is obtained according to [15]. Several experiments according to IEC standard [16] are conducted to collect the data of the LiB sample (cylindrical NMC, 18650, 3.6V/2.7Ah) for the SOC-OCV LUT. The experiment procedure is described as follows:

- Step 1: The chamber temperature is carefully set to 25°C, and the lithium-ion battery (LiB) sample is fully charged within the chamber. The sample is allowed to rest for a minimum of 1 hour before proceeding to the next step.
- Step 2: The cell is discharged by a constant current, reducing the SOC of the cell by 10%. The sample is then given a 1-hour resting period prior to going to the next stage.
- Step 3: The OCV of the LiB is measured at the adjusted SOC level.

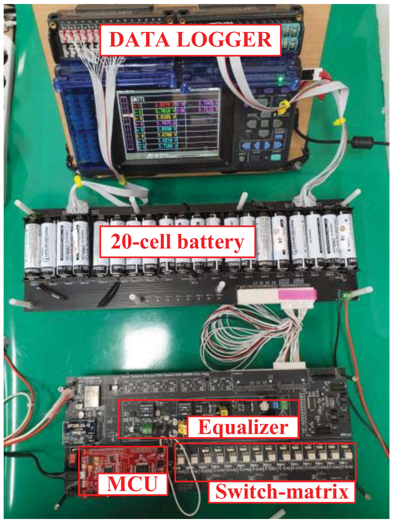

Fig. 8. Experimental setup.

- Step 4: Steps 2 and 3 are repeated until OCV readings for each SOC level are comprehensively collected.

Fig. 7 presents the SOC-OCV curve of the lithium battery sample. Subsequently, the SOC-OCV LUT is created. As a result, the SOC of each cell is estimated by the OCV measurement.

B. Experimental Setup

To verify the performance of the proposed method as well as the theoretical analysis result, the hardware experiment is implemented with the lithium battery string consisting of a 20-series. The initial SOC distribution is set similarly to the simulation setup. The equalizing system includes a bi-directional forward converter as the equalizer, a switch-matrix, and a BMIC as shown in Fig. 8. TABLE I shows the experimental parameters.

C. Processing Time

The theoretical processing time, as calculated by (9), is 2.07 hours. Fig. 9 provides a visual illustration of the experimental voltage results during the balancing process. Both methods effectively reach a balanced state with a final voltage deviation of no more than 21 mV. Fig. 9(a) shows that the conventional method requires 4.2 hours to balance the battery string, whereas the proposed method, illustrated in Fig. 9(b), achieves almost the same balancing status in only 2.1 hours. Additionally, the proposed method places no significant computational burden, making it readily adaptable to various embedded-control systems.

TABLE I: EXPERIMENTAL PARAMETERS

Configuration	20S (18650-3.6V/2.7Ah)
I_{Bal} [A]	2
I_{string} [A]	0.1
Initial SOC of the cells [%] (according to physical layout)	47, 32, 48, 34, 36, 54, 37, 30, 39, 41, 56, 43, 60, 44, 46, 49, 50, 33, 52, 58

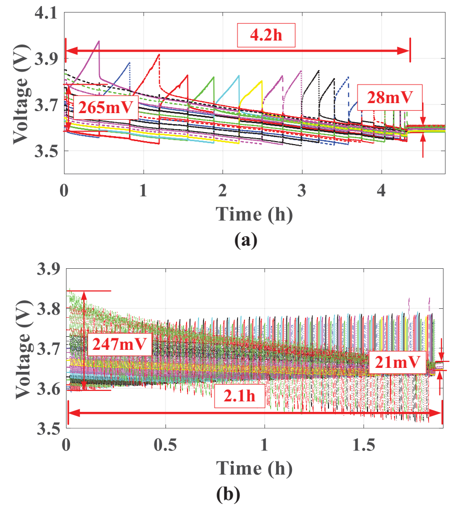

Fig. 9. Experimental voltage profiles: (a) conventional method, (b) proposed method.

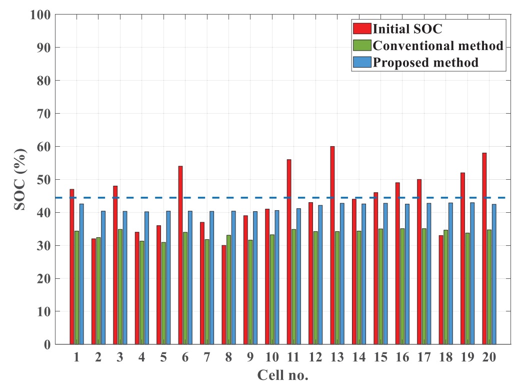

Fig. 10. Balancing performamce comparision between thr conventional and the proposed method.

D. SOC Loss

Fig. 10 presents the final SOC profile of the 20-cell battery string in a comparative analysis between the conventional and proposed methods, contrasted with the initial SOC configuration. Overall, Fig. 10 provides an overview of the SOC profiles of battery cells at the end of the process, demonstrating that SOC is balanced within a 3% SOC difference, but there is some SOC loss during the balancing process. Theoretically, according to (8), the SOC of the battery string after the balancing process denoted as SOC_{end}, is expected to be 44.45%. However, in practice, the actual balanced SOC level of the battery string falls slightly below SOC_{end}, which indicates the existence of SOC loss. Specifically, in the proposed method, the battery string attains the final SOC of 41.5%, while in the conventional method, the final SOC is 33.6%. In conclusion, the proposed method reduces SOC loss by 7.9% compared to the conventional approach. This demonstrates a clear correlation between balancing time and energy loss in the process: the longer processing time results in increased energy loss.

V. Conclusions

This paper proposes a bidirectional charge circulation algorithm for battery cell balancing. The experimental results show that the OCVs of batteries are equalized within 21mV of cell voltage difference and 3% of SOC difference. The balancing time of the proposed method is twice as fast as the conventional method. The processing time is theoretically determined based on the initial SOC levels, which matches well with the experimental results. Since the proposed method is simple to implement and requires a low computation burden, the proposed method is adaptable to any embedded-control system.

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