High-speed Target SOC Alignment Algorithm for Second-life Battery Pack Maintenance

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***Abstract*—Since the retired battery pack from EV piles up, reusing the battery pack for the battery energy storage system (SL-BESS) is a promising solution. Due to the different aging characteristics, the performance of the cells inside the battery pack becomes mismatched, which raises a safety issue for the cells. For the maintenance, the battery pack requires a full diagnosis to scan the characteristics and to equalize the state of charge level. Although the cell equalizer exists in the battery pack, it requires a long time of operation to align the SOC of cells and does not provide a target SOC balancing. This paper proposes a high-speed SOC alignment algorithm for such a seconds-life battery application. The performance of the alignment algorithm is verified by the real-time simulations for the 20-series battery string. The SOC levels of the cells are adjusted to the target level and the SOC deviation is within 3%. The proposed method only requires 50% operation time of the conventional method.**

I. Introduction

The electric vehicle (EV) fleet on the road is expanded fast since the fossil fuel crisis becomes serious. It also raises another environmental concern when the battery pack of the EV has to be replaced when their state-of-health (SOH) becomes lower than 80% [1]. According to the international energy agency (IEA), the forecast retired battery capacity can reach 120GAh by 2030 [2]. Although some parts of the battery pack can be recycled such as plastic and metal, the Lithium and other rare elements require a lot of labor to recover [3], [4]. On the other hand, because the 80% of the battery capacity is still remaining, re-utilizing the retired battery pack for the energy storage system is a more promising way [5].

However, such a re-purposing of battery packs makes another challenge. First, the used cells are prone to different aging characteristics. When the characteristic of the cells inside the battery pack become mismatched, it requires a high performance and high-speed equalization system to ensure safety. Besides, before the retired battery pack is shipped to other sites, a full diagnosis of the cells and a state-of-charge (SOC) alignment process should be executed. In fact, the SOC levels of the cells have to be reduced under 30% if it is transported by air [6]. Thus, a high-speed SOC alignment process with set point freedom is required. This process also can be applied to the car repair shop, where the battery pack of the EV is routinely maintained.

In the SOC alignment process, the cooperation of the charger and the cell equalizer is essential. But, this topic has not been explored very much. In terms of fast charging strategy, the characteristics of the cells inside the battery pack are assumed to be similar [7]. Various charging strategies are introduced in [8]. Among them, the most common methods are the constant current (CC) charging and the constant current - constant voltage (CC-CV) charging due to their simplicity. However, the charging time is long due to safety considerations. Otherwise, the higher performance charging methods such as the multistage charging (MC), the constant temperature - constant voltage (CT-CV) charging, etc, are also introduced, which reduce the charging time but can maintain the battery life-time [9], [10]. However, in the second-life battery case, the impact of the battery aging on the cell inconsistency to the charging process should be investigated.

On the other hand, the cell balancing research only focuses on the equalization without consideration of arbitrary SOC set point. The equalization techniques are classified into passive and active balancing methods catalogs [11], [12]. The passive methods use resistors or MOSFET to dissipate the redundant energy from the high-SOC-level-cell to achieve the equalization. Due to the simple circuitry, the passive balancing methods are widely adopted in the EV industry. However, the energy dissipation scheme reduces the efficiency of the equalizer. On the contrary, the active balancing methods, such as switched capacitor and switched inductor-based methods, transfer energy from the higher-SOC-level cell to the lower-SOC-level-cell [13]–[15]. Thus, the equalization efficiency is significantly increased. However, the equalization speed becomes low when the voltage deviation between the cells decreases or the impedance of the battery increase. Considering the large capacity of the battery pack, a high-speed battery cell balancing method combined with the SOC adjustment is required.

To achieve the high-speed equalization with a programmable target SOC adjustment at the same time, a coordinated operation algorithm of the pack-charger and the uni-directional converter is introduced in [16]. However, the uni-directional converter limits the flexibility of the balancing strategy and prolongs the operation time. This paper proposes a high-speed SOC alignment algorithm based on the bi-directional energy exchange to reduce the energy loss and operation time. The system configuration is described in Section II. The theoretical operation, optimal analysis, and simulation results are shown in Sections III, and IV, and the conclusion is made in Section V.

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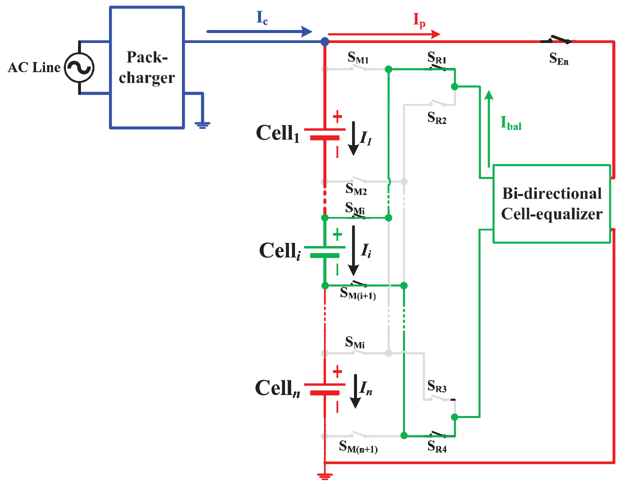

Fig. 1: Configuration of the system

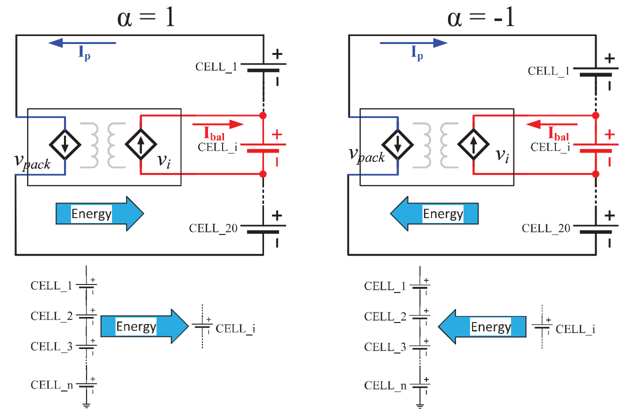

Fig. 2: Principles of operation of bidirectional cell-equalizer: a) pack-to-cell, b) cell-to-pack.

II. System Configuration

A. Circuit Configuration

The SOC alignment algorithm is implemented on a calibrator that includes a bi-directional pack-charger to charge/discharge the battery pack and a bi-directional converter with a switch-matrix to equalize the energy of the cells. The configuration of the calibrator is illustrated as Fig. 1. The switch-matrix only requires N+5 solid state relay (SSR) to choose the cell that is docked to the low voltage side of the equalizer while the high voltage side of the equalizer is docked to the battery pack terminal. It is also possible to use MosFET instead of SSR in the switch-matrix.

B. Operation Principle

By controlling the switch-matrix, the target cell is connected to the low voltage side of the cell-equalizer. Then, the cell-equalizer is controlled by a PI controller to charge/discharge the chosen cell by a constant current. Because the high voltage side of the cell-equalizer is connected to the whole pack terminal, the pack current flows into or out of the battery pack during the equalization process. With a conversion efficiency η of the cell-equalizer, the pack current is calculated by

$$I_p = \frac{v_i.I_{bal}}{\eta.v_{pack}} \tag{1}$$

where I_p is the pack current of the cell-equalizer, I_{bal} is the balancing current of the cell-equalizer, v_{pack} is the voltage of the pack, and v_i is the voltage of the cell. The current through the target cell, I_i, is determined as

$$I_i = I_{bal} - I_p. \tag{2}$$

The current through the other cells in the pack equals the pack current $I_1 = I_2 = ... = I_n = -I_p$, with n is the number of cells.

On the other hand, the main purpose of the pack-charger is to adjust the SOC level of the whole pack to a targeted level. The battery pack is charged or discharged by a constant current, I_c. During the cooperative operation between the cell-equalizer and the pack-charger, the operating current of each cell has to be lower than the maximum current rating, I_{max}, which is provided by the manufacturer.

$$I_i + I_c \leq I_{max}. \tag{3}$$

III. Theoretical Operation Analysis

In the ideal condition without SOC inconsistency, in order to adjust the SOC level of the battery pack only, the pack-charger needs to operates until the SOC level reached the target. However, in the practical SOC inconsistency conditions, a cooperative operation between pack-charger and cell-equalizer is essential.

A. Theoretical Analysis of Cooperative Algorithm

First, to analyze the cooperative operation of the pack-charger and cell-equalizer, the available capacity of each battery cell is denoted by Q_{A_i} (i = 1,2, . . . , n; n is the number of cells in the series string), which means that each battery cell could have a different available capacity. The cell index, i, is assigned in the descending order of the battery cell. And the remaining capacity of a battery cell, $Q_i(t)$, is expressed as

$$Q_i(t) = SOC_i(t).Q_{A_i} \tag{4}$$

where $SOC_i(t)$ is the state of charge of one cell at t.

According to [16], assuming that the Coulomb efficiency is unity, the SOC level of i^{th} cell at t, is determined as

$$SOC_i(t) \;= SOC_i(t_0) + \frac{I_i(t-t_0)}{Q_{A_i}}100\% \tag{5}$$

where $SOC_i(t_0)$ is the initial SOC at t_0, and I_i is the current pass through the cell.

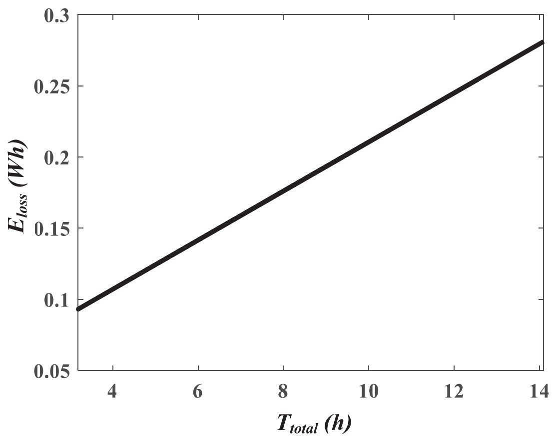

Fig. 3: Relationship the energy loss E_{loss} and the total processing time T_{total}

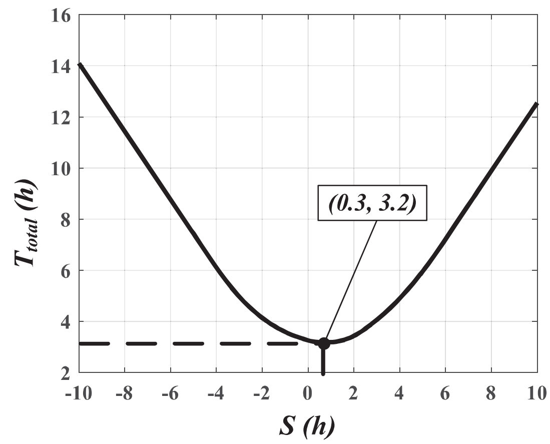

Fig. 4: Optimizing curve for the total processing time and S

In the SOC estimation studies, there are several methods such as Open Circuit Voltage (OCV) [17], Electrical Circuit Model-Based Estimation (ECM) [18], or Artificial Neural Networks (ANN) [19], etc. In this paper, Open Circuit Voltage (OCV) curve modeling method is used for the initial SOC estimation as

$$SOC_i(t_0) = f^{-1}(OCV_i). \tag{6}$$

where $f^{-1}(OCV_i)$ is the mapping function from SOC to OCV. With the SOC inconsistency, the initial SOCs are different, so it is useful to introduce average initial SOC values, SOC_{avg}, presented as

$$SOC_{avg} = \frac{\sum_{i=1}^{n} SOC_i(t_0)}{n}. \tag{7}$$

Therefore, the amount of energy required to be transferred to the battery pack by the pack-charger is the difference between the target SOC level, SOC_{tg}, and the average initial SOC level, SOC_{avg} and is calculated from (5) as

$$SOC_{tg} - SOC_{avg} = \frac{I_c T_c}{Q_{A_i}} \tag{8}$$

where T_c is the period of time needed for pack-charger operation. And T_c is determined by re-expressing (8) as

$$T_c = \frac{(SOC_{targ} - SOC_{avg})Q_{A_i}}{I_c}. \tag{9}$$

For the cell-equalizer operation, because the cooperative algorithm considers the bi-directional way of energy flow, the analysis is based on the following polarity convention: the positive I_c means the charging process of the battery pack while the negative one denotes the discharging process. Accordingly, the positive I_{bal} represents the pack-to-cell mode while the negative I_{bal} corresponds to the cell-to-pack mode. In Fig. 2, the principles of operation of bidirectional cell-equalizer are shown, where α denotes the polarity of the balancing current and is expressed as

$$\alpha_i = sign(I_i) = \begin{cases} -1, & \text{for charging} \\ +1, & \text{for discharging} \end{cases}. \tag{10}$$

With n cells in a pack, the operation is divided into n operating steps. For each step, only one cell is connected to the cell-equalizer and the pack-to-cell or cell-to-pack energy exchange occurs during a precalculated time span for each cell. During that time, the selected battery cell current becomes αI_{bal}, and the pack current is αI_p. Therefore, the amount of charge transfer of the i^{th} battery cell equating (2), (5), and (7) is expressed as

$$\begin{aligned} SOC_{avg} - & SOC_i(t_0) \\ & = \frac{\alpha_i I_{bal} T_i - \alpha_1 I_p T_1 - ... - \alpha_n I_p T_n}{Q_{A_i}} \end{aligned} \tag{11}$$

where T_i is the processing time of i^{th} step, and α_i is the polarity of the current representing the charge or discharge status of the i^{th} step. If we denote S as the weighted sum of the processing time like in

$$S = \sum_{i=1}^{n} \alpha_i T_i, \tag{12}$$

the (11) is re-expressed by (12) as

$$SOC_{avg} - SOC_i(t_0) = \frac{\alpha_i I_{bal} T_i - S I_p}{Q_{A_i}}. \tag{13}$$

Considering the loss of the cell-equalizer during processing time, the corresponding SOC loss for each cell during the process is determined as

$$SOC_{L_i} = \frac{(\frac{1}{\eta} - 1)\frac{v_i}{v_{pack}} I_{bal} T_{total}}{Q_{A_i}} \tag{14}$$

where T_{total} is the total processing time of equalizing opera-

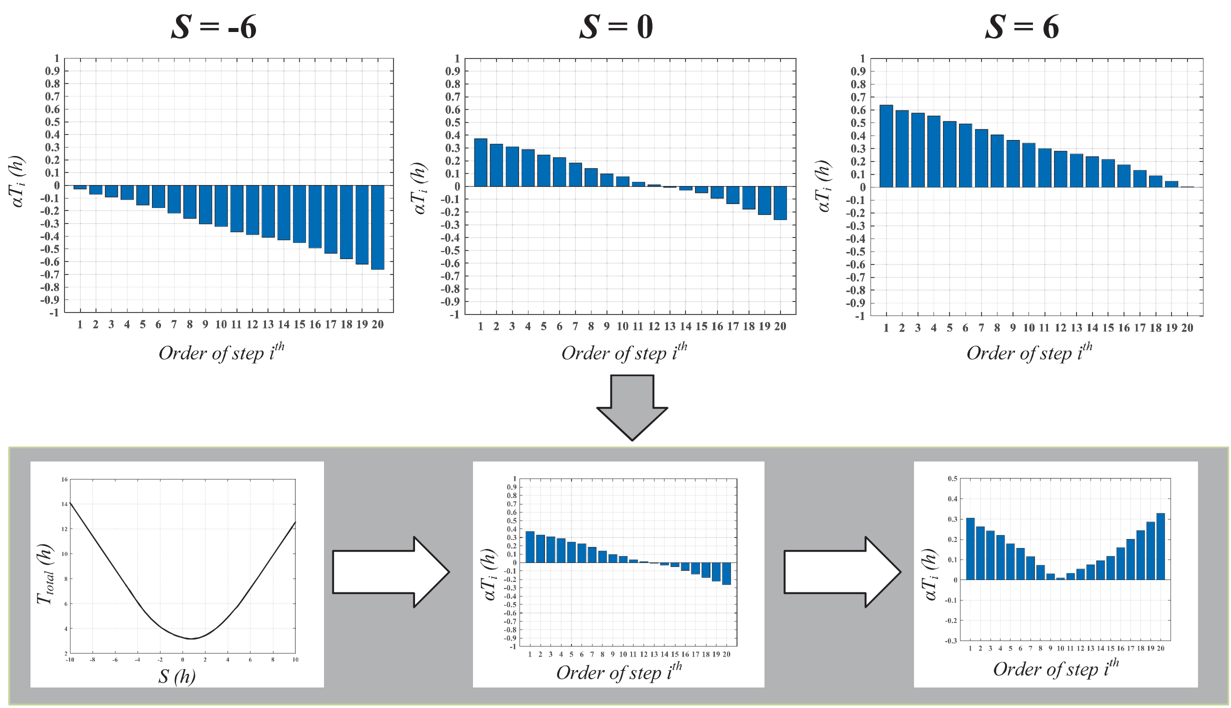

Fig. 5: Processing time according to S

tion and expressed as

$$T_{total} = \sum_{i=1}^{n} T_i. \tag{15}$$

Finally, by combining (13) and (14), the processing time within SOC loss assigned for the i^{th} cell, T_i, is calculated as

$$\begin{aligned} T_i &= |\alpha_i T_i| \\ &= \left| \frac{(SOC_{avg} - SOC_i(t_0) - SOC_{L_i})Q_{A_i} + SI_p}{I_{bal}} \right| \end{aligned} \tag{16}$$

and this will be used as a key equation for the processing time optimization to be discussed in the next section.

B. Processing time optimization

1) Energy loss of batteries: In the SL-BESS, the energy loss becomes more serious, since the second-life battery has the slightly higher internal resistance leading to more heat and more energy loss. Denoting that R_b is the total internal resistance of the battery, the energy loss of the n-cell battery pack during the total processing time is calculated as

$$\begin{aligned} E_{loss} &= \int_0^{T_{total}} P_{loss}(\tau) d\tau \\ &= nR_b(I_c - I_p)^2 T_c + nR_b I_b^2 (T_{total} - T_c) + R_b I_{bal}^2 T_{total}. \end{aligned} \tag{17}$$

Fig. 3 is the relationship the energy loss E_{loss} and the total processing time T_{total}. This curve shows that as the total processing time T_{total} is smaller, the energy loss E_{loss} of batteries becomes reduced. Therefore, by minimizing the processing time, the cooperative algorithm can achieve high efficiency.

2) Time step analysis: From (12), (15) and (16), we can see that the processing time is strongly dependent on S. By choosing S, the set of T_i is established and the total processing time T_{total} is optimized. Fig. 4 illustrates the optimizing curve for the total processing time and S based on the test settings in Table I. The curve shows that a strong positive S causes a higher T_{total} since the cell-equalizer is mostly operated in the pack-to-cell mode. In contrast, a strong negative S results in a higher T_{total} since the cell-equalizer is mostly operated in the cell-to-pack mode. It is found that for most SOC initial scenarios, the S versus T_{total} curve is a concave function, where there is always a value of S that makes the total processing time minimum. In Fig. 4, the initial SOC is randomly scattered from 30% to 60% and the T_{total} has the minimum value of $3.2h$ when S equals 0.3.

IV. Verification

In order to verify the algorithm, simulation is implemented by PSIM with a 20-cell battery (18650-3.6V/2.9Ah) connected in series. The conventional algorithm in [9] and the proposed algorithm are implemented under the same conditions as

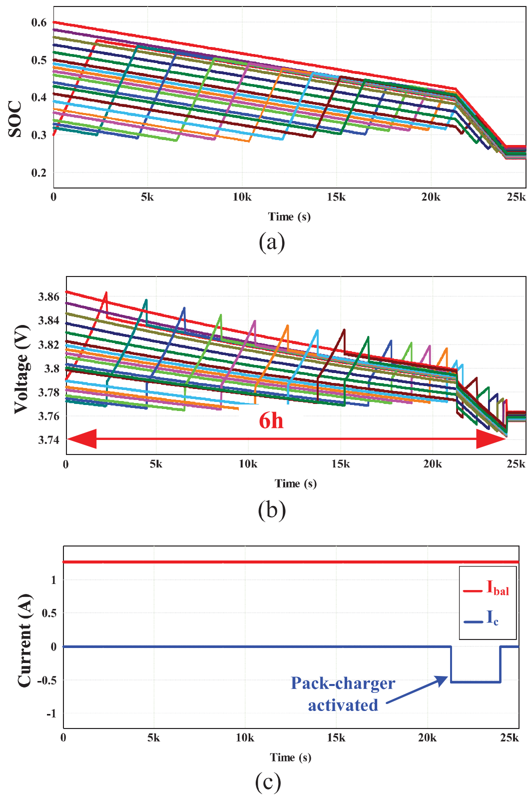

Fig. 6: Simulation waveforms of the conventional method

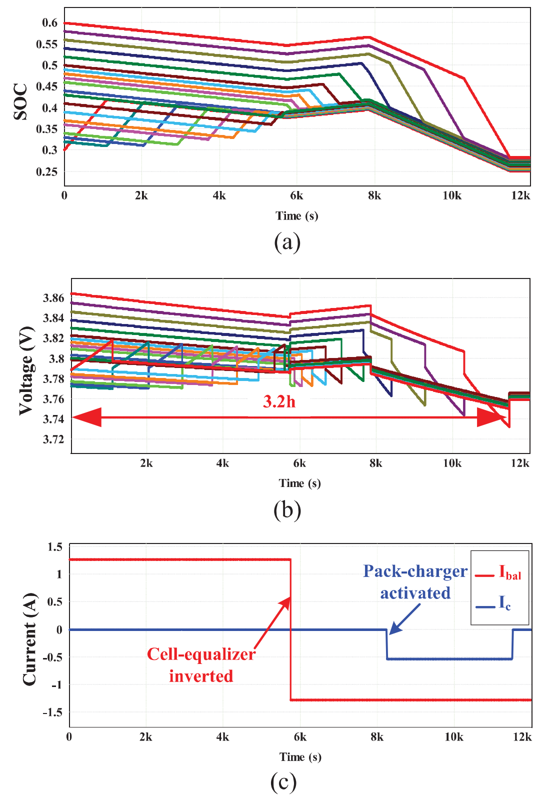

Fig. 7: Simulation waveforms of the proposed method

shown in Table I. The various initial SOC levels of the cells between 30% and 60% are tested while the target SOC point is fixed to 25%. The parameter S is set at the minimum value of 0.3 when compared with the conventional method, respectively. In the conventional method, the equalizer is operated only in the unidirectional charging mode. On the contrary, with the proposed method, the converter is operated in the bi-directional charging/discharging mode when S is set to 0.3 to achieve the minimum processing time.

In order to see the effects and differences between the two methods, the order of steps is re-arranged base on ascending SOC level of battery cells. Fig. 5 illustrates the processing time of each step according to the parameter S. It shows that the conventional operation in [9] can be also possible just by adjusting S. The cells are only uni-directionally charged by the pack when S equals 6. In the case of S = 0, the first-half steps of the cell-equalizer are operated in the pack-to-cell mode, and the second half steps are in cell-to-pack mode. When S is -6, the cell-equalizer works with all steps in cell-to-pack mode.

The SOC, voltage, and current profiles of the conventional and proposed methods are applied are illustrated in Fig. 6 and Fig. 7, respectively. Both methods can equalize the SOCs of the cells within a 3% of SOC level and adjust the SOC level of the whole pack to the target point of 25%. However, the proposed method only requires 3.1h to finish the calibration process while the conventional method took 6h. The SOC and voltage profiles in Fig. 6(a), Fig. 6(b), Fig. 7(a), and Fig. 7(b) reflect the difference between the two algorithms. The conventional method only charges every cell even though the pack-charger discharges the whole pack. On the other hand, the proposed method charges the lower-SOC cells and discharges the higher-SOC ones when it is required. The current profiles in Fig. 6(c) and Fig. 7(c) explain the current directions and operations mode changes.

The calculated energy loss of the conventional and the proposed methods for the simulation are 2.54Wh and 1.28Wh, respectively. By virtue of the bi-directional energy flow feature of the cell-equalizer, the processing time of the proposed method is significantly reduced, resulting in a 50% lower energy loss than the conventional method.

V. Conclusion

This paper proposes a high-speed target SOC alignment algorithm using cell-equalizer and pack-charger in second-life battery pack maintenance. According to the SOC level of the cells, the pack-charger and the cell-equalizer co-operates to

TABLE I: Test settings

Configuration	$20S1P$ $(18650 - 3.6V/2.9Ah)$
$\|\boldsymbol{I_c}\|$ $[\boldsymbol{A}]$	1.5
$\|\boldsymbol{I_{bal}}\|$ $[\boldsymbol{A}]$	2
$\|\boldsymbol{I_p}\|$ $[\boldsymbol{A}]$	0.1
SOC target [%]	25
Efficiency of cell-equalizer [%]	80
Initial SOC of the cells [%] (according to physical layout)	$47, 32, 48, 34, 36, 54, 37, 30, 39, 41, 56, 43, 60, 44, 46, 49, 50, 33, 52, 58$

achieve a fast SOC adjustment. The simulation results show that the proposed method can adjust the SOC level of the cells to the target set point within a 3% deviation in almost double the speed of the conventional method. In addition, the energy loss in the proposed method is significantly reduced by up to 50% of the conventional method. Furthermore, due to the algorithm simplicity, the proposed method can also be implemented by low cost computing devices and thus can make a convenient and flexible solution.

ACKNOWLEDGMENT

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High-speed Target SOC Alignment Algorithm for Second-life Battery Pack Maintenance

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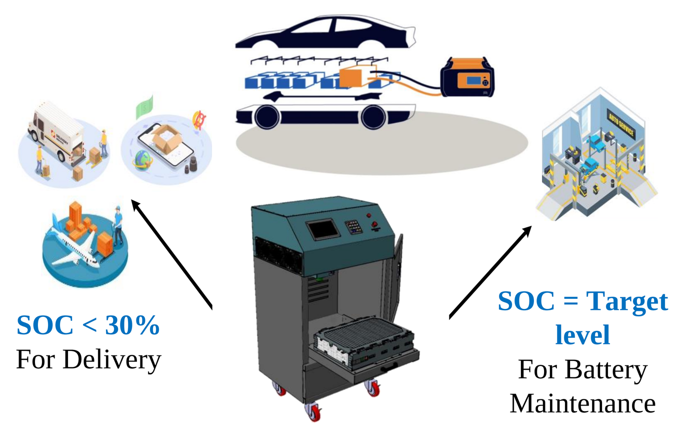
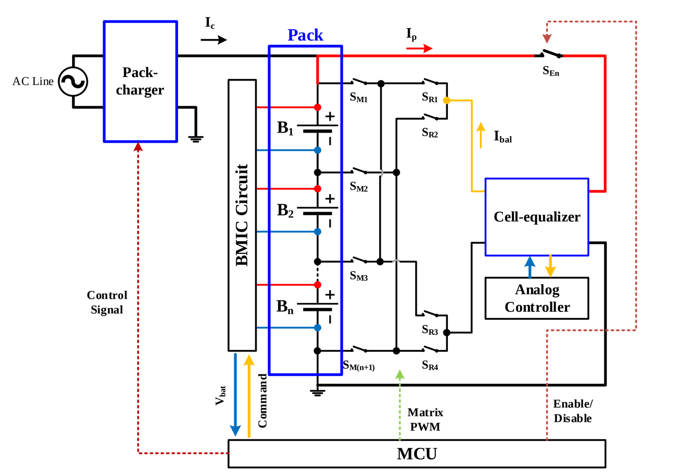
Abstract

- **Future trend – Necessity of SOC calibrator equipment:**
  - **Energy equalization and SOC adjustment features**
  - **SOC-set-point freedom**
- **Concept of SOC adjustment:**
  - **Bi-directional pack-charger** transfers energy between *DC bus and BESS.*
  - **Bi-directional cell-equalizer** transfers between *battery pack and cells.*
- **Proposed method features:**
  - **SOC-set-point freedom**
  - **Twice faster** than the traditional method
  - **50% energy loss reduction** than the traditional methods

Motivation

- **Requirements of SOC calibrator:**
  - SOC level must be adjusted to **under 30%** before **the shipping.**
  - SOC level need to be aligned **an arbitrary level** for the **maintenance.**





Conventional SOC calibrator architecture.

Feature comparison of the conventional and proposed method

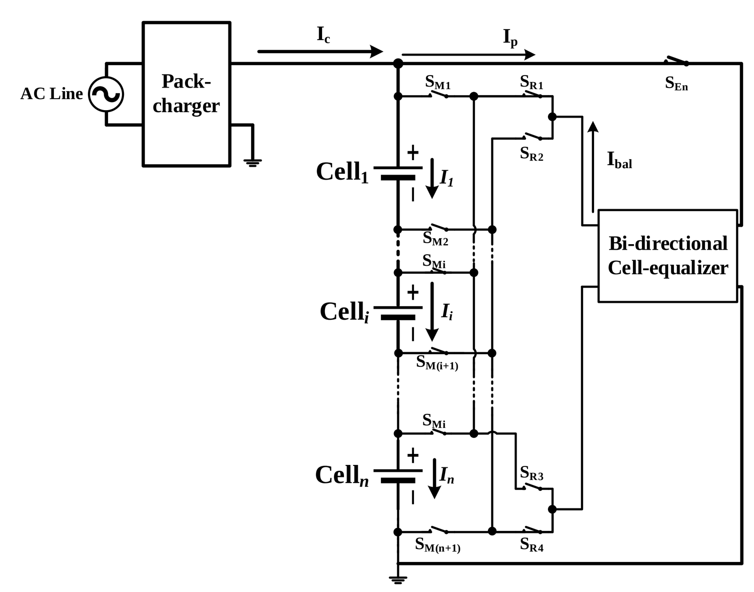
Features	Conventional method	Proposed method
Number of steps	Number of cells in pack	Number of cells in pack
Energy flow direction in equalization	Uni-directional	Bi-directional converter
SOC-set-point freedom	Yes	Yes
Balancing feature	Yes	Yes
Processing time optimization	No	Yes
Energy loss reduction optimization	No	Yes

Conclusion

- **Improved high-speed battery SOC adjustment algorithm is proposed for a new 2nd life battery.**
- **SOC-levels of the cells can be equalized and adjusted to a predefined level.**
- **Operation time is just a half of the conventional uni-directional method.**
- **Energy loss during the process is reduced to 50% by co-operation algorithm.**
- **Algorithm is simple enough to be implemented in the popular low-cost MCU.**
- **Full-duplex power flow accelerates equalization speed, reduces processing time and energy loss.**

Theoretical operation analysis

- **Key operation concept:**
  - **Processing** time of individual cells is optimized based on **the charge transfer calculation.**
  - **Switch-matrix and bi-directional converter** are controlled to **exchange energy** from cell to pack and vice versa.
  - **Bi-directional operations of the pack charger and bi-directional balancing process of the equalizer are coordinated.**



Configuration of the system.

- **Charge Transfer Calculation:**
  - **Polarity of the balancing current** of the i^{th} cell

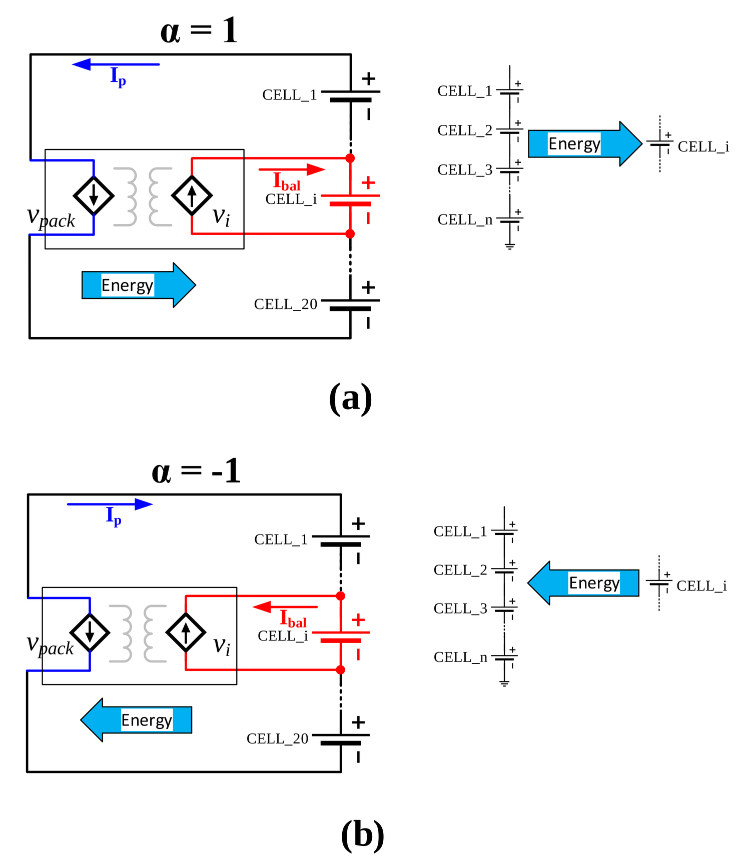
$$\alpha_i = sign(I_i) = \begin{cases} +1, & for\ charging \\ -1, & for\ discharging \end{cases}$$

  - **Amount of charge transfer** of the i^{th} battery cell

$$SOC_{avg} - SOC_i(t_0) = \frac{\alpha_i I_{bal} T_i - \alpha_i I_p T_i - \ldots - \alpha_n I_p T_n}{Q_{Ai}}$$

  - **Weighted sum** of the processing time

$$S = \sum_{i=1}^{n} \alpha_i T_i$$



Principles of operation of bidirectional cell-equalizer: a) pack-to-cell, b) cell-to-pack.

  - **Processing time** considering coulombic loss of the i^{th} cell

$$T_i = |\alpha_i T_i| = \left| \frac{(SOC_{avg} - SOC_i(t_0) - SOC_{L_i})Q_{A_i} + SI_p}{I_{bal}} \right|$$

where $T_{total} = \sum_{i=1}^{n} T_i$ and $SOC_{L_i} = \frac{\left(\frac{1}{\eta} - 1\right)\frac{v_i}{v_{pack}} I_{bal} T_{total}}{Q_{A_i}}$

  - **Total energy loss, E_{loss},** of the *n-cell* battery pack

$$E_{loss} = \int_0^{T_{total}} P_{loss}(\tau) d\tau = nR_b (I_c - I_p)^2 T_c + nR_b I_b^2 (T_{total} - T_c) + R_b I_{bal}^2 T_{total}$$

  - **Weighted sum, S,** can be the optimized parameter to be adjusted the SOC level.

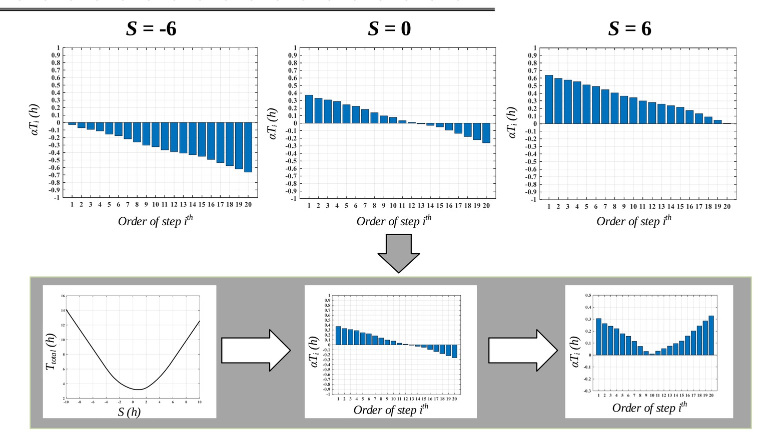
Verification

- Simulation is implemented by PSIM with **a 20-cell battery (18650-3.6V/2.9Ah) connected in series.**
  - Initial SOC levels of the cells are varied **between 30% and 60%.**

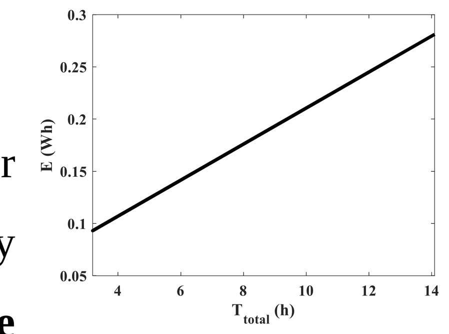
TABLE I: Test settings

Configuration	*20S1P (18650 – 3.6V/2.9Ah)*
$\lvert I_c \rvert$ [A]	0.53
$\lvert I_{bal} \rvert$ [A]	1.3
$\lvert I_p \rvert$ [A]	0.1
Efficiency of cell-equalizer [%]	80
SOC target [%]	25
Initial SOC of 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

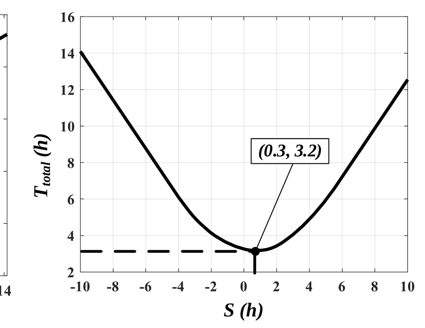
- ***Processing time** is strongly dependent on **S***
  - ***Strong positive S causes** a higher **T_{total}*** since the cell-equalizer is mostly operated **in the pack-to-cell mode (pack-charger prevails).**
  - **Strong negative *S*** results in a higher **T_{total}** since the cell-equalizer is mostly operated **in the cell-to-pack mode (pack-discharger prevails).**



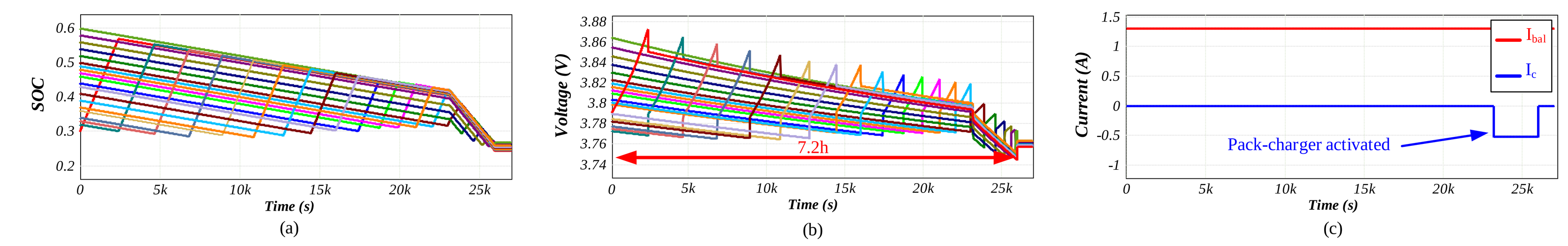
Processing time according to S



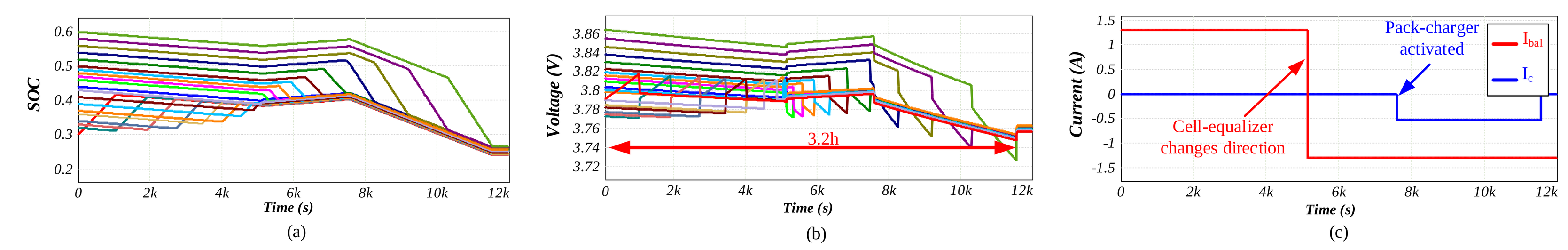
Relationship the energy loss E_{loss} and the total processing time T_{total}



Optimizing curve for the total processing time and S.



Simulation waveforms of the conventional method



Simulation waveforms of the proposed method with S = 0.3

- ***Both methods can adjust the SOC level** of the pack to the target point of 25% within equalization.*
  - ***For processing time optimization, T_{total}*** has the minimum value of 3.2h when **S** equals 0.3
  - **Proposed method only requires 3.2h** to finish the calibration process while the conventional method operate 6h (same as when ***S***=6).
  - **Energy loss** of the conventional and the proposed methods for the simulation are 2.54Wh and 1.28Wh, respectively.