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ORIGINAL ARTICLE

Coordinated operation algorithm of pack-chargers and cell-equalizers for SOC adjustment in second-life batteries

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Abstract
Investment for battery energy storage systems (BESS) is rapidly growing. However, cost is still a major barrier. Since a retired battery pack from an electric vehicle can be re-utilized for BESS, second-life battery energy storage systems (SL-BESS) have become a promising option. However, SL-BESS applications require more intensive care in terms of battery maintenance due to the increase in the characteristic differences of aged cells. Therefore, the SOC adjustment process is essential both for maintenance and shipping. This study proposed a coordinated operation algorithm for the calibration process with an optimal processing time. In addition, the effects of pack and cell currents on adjustment speed have been investigated. Experimental results verify the performance of the calibrator by a sequence of test scenarios. The battery cells are equalized and adjusted to the target SOC level within a 14 mV error, while the processing time is reduced by 20% when compared to the traditional method.

Keywords Battery calibration · Cell-balancing · Cell equalizer · Second-life battery · SOC adjustment

1 Introduction

In the last decade, vehicles have been gradually electrified due to the demand for gas emission reduction [1, 2]. However, due to the lifetime limitations of battery packs, the number of retired batteries grows higher every year. Various studies have proposed material recycling options [3–5]. However, the economic effectiveness of such endeavors is controversial due to the high labor burden of recycling. In addition, almost 80% of the available capacity remains after the retirement of EV battery packs [6]. This capacity can be re-utilized for other purposes. Two approaches that can be considered for second-life battery (SLB) utilization are: by cells (dismantling) or by modules (direct use). In the dismantling approach, the retired battery packs are dismantled into individual cells, which are categorized based on their characteristics and then re-assembled for electric bikes, electric golf carts, etc. This approach can ensure the performance of the re-assembled batteries, but the labor cost offsets its practical feasibility. In the direct use approach, the retired battery pack can be directly re-used for stationary energy storage systems after a minimal inspection process [7]. Direct re-utilization is more promising since it reduces the efforts of classification.

These days, most studies focus on two fields of research, charging and balancing. In charging, they mainly consider how to reduce the charging time. Meanwhile, in balancing, they consider the equalization performance and time. Both the charging and balancing processes are independent, hence, the total time of operation is increased. A number of studies have reported on a combination of the charging and the equalization processes at the same time. In first-life batteries, this operation combination is not necessary since imbalances among batteries rarely occur. However, in second-life batteries, the inconsistency of the battery cells becomes more significant. Moreover, SL-BESS applications require another step called SOC adjustment during the screening process, which is also essential for the purpose of maintenance and shipping. For example, the SOC level of a battery pack is required to be aligned to less than 30% SOC level to ensure safety before shipping [8, 9].

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Generally, cells should be equalized before they are charged or discharged to adjust the SOC level to the target set point. Cell-balancing methods are classified into passive and active methods [10, 11]. The passive methods are commonly used in industrial applications due to their low cost, circuit compactness, and simple control [12]. However, passive methods show a poor equalization performance in SLB applications, where the individual cells can have huge characteristic differences [13]. On the other hand, the active balancing methods transfer energy between cells and can be classified by the energy transfer elements. The switched-inductor methods transfer energy between adjacent cells.

[14] or cell to cell by inductors [15]. However, bulky size and low efficiency are their limitations. To reduce the volume of the equalizer, switched-capacitor equalizers are alternative candidates [16, 17]. However, the equalization current is strongly dependent on the voltage difference between cells, which reduces the equalization speed.

Therefore, converter-based methods are more desirable for SL-BESSs due to their high equalization performance and speed [18–20]. However, converter-based cell-balancing methods are not suitable for calibration purposes due to their non-optimized speed and lack of freedom in terms of the target SOC. To optimize speed, a bi-directional equalizing algorithm based on particle swarm optimization (PSO) is introduced in [21]. However, the study does not address its lack of a target SOC freedom feature. In addition, the computation burden and total operation time become huge when the number of series connections increases. Thus, their practical feasibility is relatively limited.

To mitigate these issues, this study proposes a coordinated operation algorithm to combine a pack-charger and a cell-equalizer in the SOC adjustment process to minimize the balancing time without resorting to an iterative calculations optimization algorithm. The circuit configuration and overall control flow are introduced in Sect. 2. A theoretical analysis of the calibration process is presented in Sect. 3 and verified in Sect. 4. Finally, some conclusions are made in Sect. 5.

2 Proposed methods

2.1 System configuration

The architecture of a calibration system for a second-life battery pack is illustrated in Fig. 1, where the battery cells are equalized by a uni-directional dc–dc converter that transfers the charge from the battery pack to the cell. The voltages of the cells are monitored by battery monitoring integrated circuits (BMICs) and they are delivered to the MCU for analyzing of the SOC level. Battery cells are alternatively connected to the output of the converter through the switch

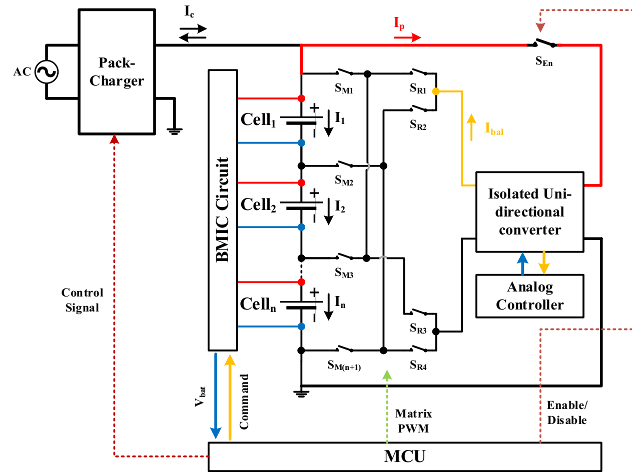

Fig. 1 System configuration of the proposed method

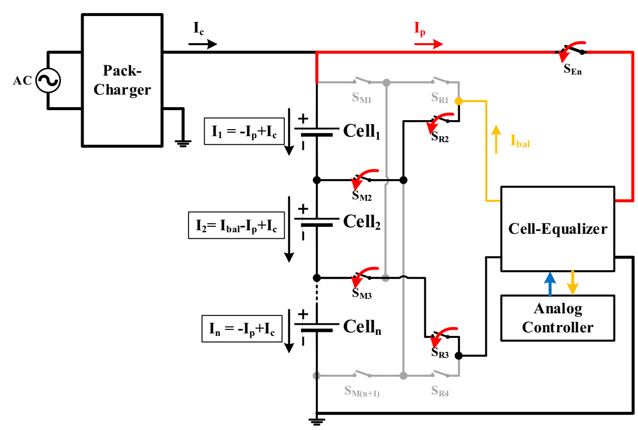

Fig. 2 Operation principle of the pack-charger and cell-equalizer

matrix by MCU decisions based on SOC information, while the input port is connected to the whole pack.

Meanwhile, another bi-directional source, called a pack-charger, charges or discharges the battery pack from the ac line, which helps speed up the calibration process and adjust the SOC level of the cells to the target set point. The pack-charger supplies the battery pack with a constant positive or negative current in accordance with the cell-equalizer operation. The operations of the pack-charger and the equalizer are well-coordinated according to the proposed algorithm as shown in Sect. 2.3

2.2 Operation principle

The co-operation of the pack-charger and the cell-equalizer is illustrated in Fig. 2. The pack-charger directly charges/discharges the whole battery pack with a constant current, I_c. It also plays the role of adjusting the SOC level of the whole battery pack. By determining the available capacity of the whole pack, it is possible to calculate the amount of required capacity to be charged or discharged.

Meanwhile, the cell-equalizer distributes energy from the whole pack to individual cell to increase their SOC level. For example, if $Cell_2$ has the lowest-SOC level, it is re-charged first. The switches S_{M2}, S_{M3}, S_{R2}, and S_{R3} are turned on while the other switches are kept off. As a result, $Cell_2$ is connected to the output of the cell-equalizer for an equalization process. After the cell-equalizer is enabled, the cells are discharged by a constant current, I_p, while $Cell_2$ is re-charged by I_{bal}. The switching pattern is held during the equalization time before the pattern is changed to connect the other cells to the cell-equalizer. By repeating the procedure for the cells one by one, the SOC difference is equalized. Thus, the final cell-SOC levels are adjusted to the target level. It can be observed that the equalization times for each of the cells are different and are analyzed in Sect. 3.2.

2.3 Coordinated control algorithm

Without coordination between the pack-charger and the cell-equalizer, the SOC adjustment could fail to meet the target, which would lead to extra time and excessive energy loss due to repeating the calibration. Instead, this study proposes a coordinated operating algorithm for the cell-equalizer and the pack-charger that can optimize the processing time by executing the cell-balancing and pack charging or discharging process concurrently in a more cooperative way.

A flowchart of the coordinated operation algorithm is illustrated in Fig. 3. First, the voltages of the cells are measured, and the initial SOCs of cells are estimated by applying the OCV–SOC curve in Fig. 4. In the second step, the SOC levels are sorted in ascending order and the cells are connected to the output of the cell-equalizer in that order. In the third step, the operating times for each of the cells are obtained by charge transfer calculations. Finally, the switching patterns are decided. Therefore, only n process steps are required to calibrate the battery pack, where n is the total number of cells in the pack. The pack-charger supplies a positive constant current to the pack if the target SOC level is higher than the initial average SOC, or it sinks.

draws a constant current from the pack if the target SOC is lower than the initial average SOC. The process is terminated after the equalization steps end.

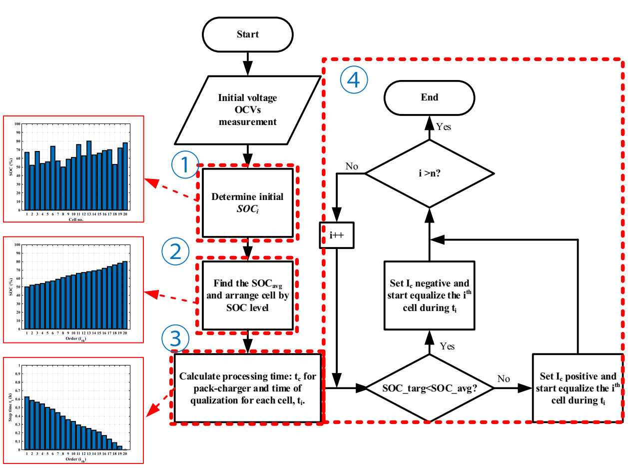

Fig. 3 Flowchart of the coordinated operation algorithm

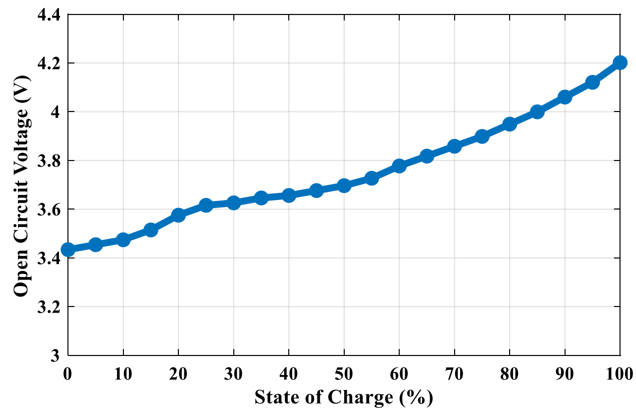

Fig. 4 OCV–SOC relationship used in this study

3 Theoretical analysis

3.1 State of charge of battery cells

Assuming that every cell has an available capacity Q_{A_i} and the coulombic efficiency is 1, the remaining capacity of a battery cell is defined as

$$Q_i(t) = SOC(t_0)Q_{A\_i} + \int_{t_0}^{t} I(\tau)d\tau. \quad (1)$$

The SOC of a battery cell is expressed through (1) as

$$SOC_i(t) = SOC_i(t_0) + \frac{1}{Q_{A\_i}} \int_{t_0}^{t} I(\tau)d\tau. \quad (2)$$

3.2 Charge transfer calculation

In each step of the calibration process, the cell-equalizer provides a constant current to an individual cell to increase its capacity and to balance the SOC difference. If the cell-balancing current, I_{bal}, which is defined by the output current of the cell-equalizer, is uni-polar and constant as shown in Fig. 5, the pack current, I_p, is determined by

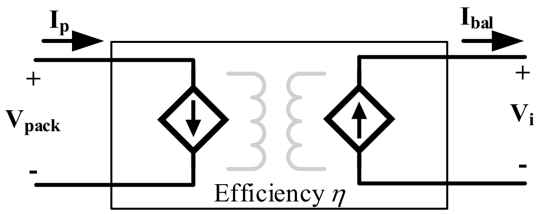

Fig. 5 Current equalization of a cell-equalizer

$$I_p = \frac{v_i.I_{bal}}{\eta.v_{pack}} \tag{3}$$

where v_i is the voltage of the ith cell, v_{pack} is the voltage of the battery pack, and η is the efficiency of the cell-equalizer. By assuming that the pack-charger current, I_c, is bi-polar and constant while passing through n cells of a battery pack, the actual current flowing through the ith cell, I_i, is given by

$$I_i = I_{bal} - I_p + I_c. \tag{4}$$

On the other hand, the operating currents of the remaining cells are calculated by

$$I_1 = .. = I_{i-1} = I_{i+1} = .. = I_n = -I_p + I_c. \tag{5}$$

Note that I_c can be positive or negative depending on the preset target. For the safety of the battery, the cell current should be lower than the maximum allowable current level in the datasheet.

The remaining capacity for each of the cells can be expressed as follows:

$$Q_i = SOC_i(t)Q_{A\_i} \tag{6}$$

where SOC_i is the individual SOC level of the ith cell. Since the initial SOC level of the ith cell can be estimated using OCV_i information

$$SOC_i(t_0) = f(OCV_i), \tag{7}$$

the SOC level of the cells after t_i is given by

$$SOC_i(t_i) = SOC_i(t_0) + \frac{I_i(t_i - t_0)}{Q_{A\_i}}. \tag{8}$$

Under ideal conditions when no energy loss effect occurs, the SOC level after equalization is the average of the initial SOC levels. The initial average SOC level of the cells, SOC_{init_avg}, is given by

$$SOC_{init\_avg} = \frac{\sum_{i=1}^{n} SOC_i(t_0)}{n}. \tag{9}$$

Meanwhile, considering the efficiency of the cell-equalizer, the equivalent SOC loss is estimated by

$$SOC_L = \frac{\left(\frac{1}{\eta} - 1\right) \sum_{i=1}^{n} \frac{v_i}{n} I_{\text{bal}} t_{\text{total}}}{v_{\text{pack}} Q_{A\_avg}} \tag{10}$$

where Q_{A_avg} is the average available capacity of the cells, and t_{total} is the sum of the processing time of every step.

$$t_{\text{total}} = \sum_{i=1}^{n} t_i. \tag{11}$$

Since the pack-charger compensates the SOC loss and steers the SOC level to the target SOC value SOC_{targ}, the processing time of the pack-charger, t_c, is expressed as

$$t_c = \frac{(SOC_{targ} - SOC_{init\_avg} + SOC_L)Q_{A\_i}}{I_c} \tag{12}$$

where a negative t_c reverses the polarity of I_c.

In every time step, only one cell is charged by the cell-equalizer (I_{bal}). Meanwhile, the other cells are discharged by I_p. The pack-charger current, I_c, also regulates the SOC levels of the cells. Hence, the capacity change from the initial SOC level to the target SOC level for the 1st cell after the overall processing time is calculated by

$$\begin{aligned}&(I_{bal} - I_p)t_1 - I_p t_2 - \dots - I_p t_n + I_c t_c \\ &\quad = (SOC_{targ} - SOC_1(t_0))Q_{A\_1}.\end{aligned} \tag{13}$$

Likewise, the capacity change for the *ith* cell is given by

$$\begin{aligned}&- I_p t_1 - \dots + (I_{bal} - I_p)t_i - \dots - I_p t_n + I_c t_c \\ &\quad = [SOC_{targ} - SOC_i(t_0)]Q_{A\_i}.\end{aligned} \tag{14}$$

At this stage, it is only necessary to solve (14) to obtain the optimal step time t_i for each cell and pack-charger.

3.3 Processing time calculation

Some of the solutions of (14) result in negative values, which have no meaning in a practical sense. Hence, a constraint $t_i \geq 0$ must be imposed to guarantee the existence of feasible solutions. Under this constraint, the calculation is given as follows.

First, from (11) and (14), (15) is derived as

$$\begin{aligned}&- I_p(t_1 + \dots + t_i + \dots + t_n) + I_c t_c + I_{bal} t_i \\ &\quad = -I_p t_{total} + I_c t_c + I_{bal} t_i = [SOC_{targ} - SOC_i(t_0)]Q_{A\_i}.\end{aligned} \tag{15}$$

Then, using (12) to replace $I_c t_c$, the change of the charge in the *ith* cell is re-arranged from (15) to

$$I_{bal}t_i - I_p t_{total} = [SOC_{targ} - SOC_i(t_0)]Q_{A\_i} - [SOC_{targ} - SOC_{init\_avg} + \mathrm{SOC}_L]Q_{A\_avg} \tag{16}$$

where t_{total} is already defined in (11). Hence, the processing time, t_i, is expressed as

$$t_i = \frac{[SOC_{targ} - SOC_i(t_0)]Q_{A\_i}}{I_{bal}} - \frac{[SOC_{targ} - SOC_{init\_avg} + SOC_L]Q_{A\_avg} - I_p t_{total}}{I_{bal}}. \tag{17}$$

Since the initial SOCs of the cells are known and in order, the operation time for each step is $t_1 \geq t_2 \geq \ldots \geq t_n$ as shown in Fig. 6, where the calculated processing time for each step is shown as an example. The negative values after the 16th step represent the fact that the balancing current of the cell-equalizer needs to be reversed as shown in Fig. 6a. However, the uni-directional cell-equalizer adopted in this paper does not provide a negative current. Instead, a time offset is introduced. In other words, the processing times are increased by the value of t_n, which nullifies t_n. Since t_n is designed as zero, the individual processing times, t_i $(i = 1, 2, \ldots, n)$ are non-negative. Thus, t_n is calculated as

$$t_n = \frac{[SOC_{targ} - SOC_n(t_0)]Q_{A\_n}}{I_{bal}} - \frac{[SOC_{targ} - SOC_{init\_avg} + SOC_L]Q_{A\_avg} - I_p t_{total}}{I_{bal}}. \tag{18}$$

By equating $t_n = 0$, t_{total} is expressed as

$$t_{total} = \frac{[SOC_{targ} - SOC_{init\_avg} + SOC_L]Q_{A\_avg}}{I_p} - \frac{[SOC_{targ} - SOC_n(t_0)]Q_{A\_n}}{I_p}. \tag{19}$$

From (3), (17), and (19), the processing time of the *ith* cell is finally derived as

$$t_i = \frac{[SOC_{targ} - SOC_i(t_0)]Q_{A\_i}}{I_{bal}} - \frac{[SOC_{targ} - SOC_n(t_0)]Q_{A\_n}}{I_{bal}}. \tag{20}$$

In general, it is a challenge to monitor the individual capacities of cells since they are operated under the same conditions. Instead, every cell has the same available capacity. Thus, with (3) and (10), t_{total} is re-arranged by cell voltages and I_{bal} as

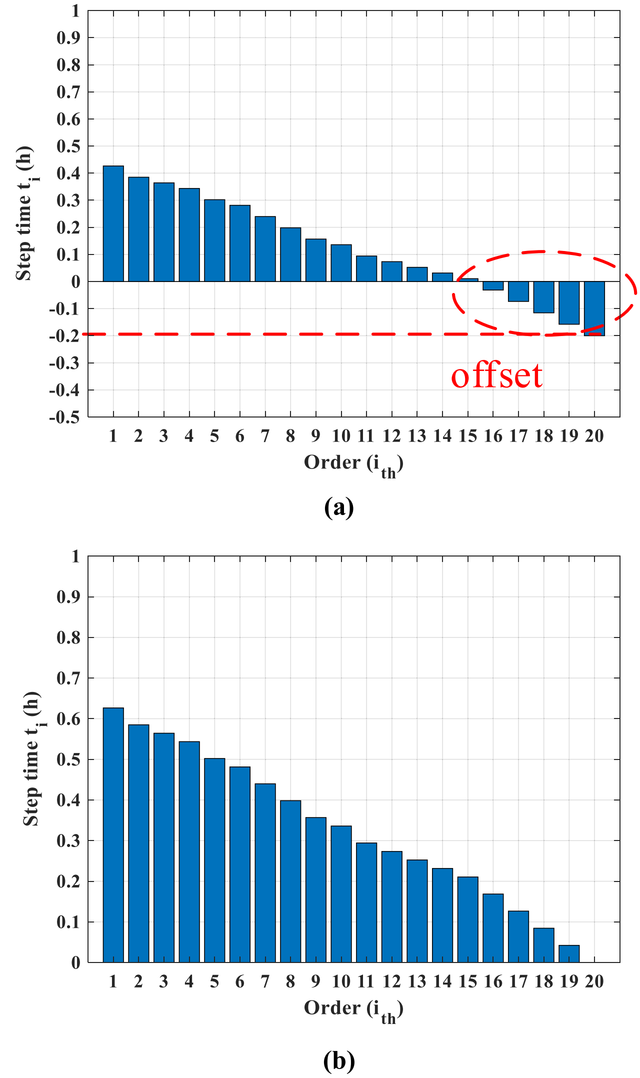

Fig. 6 Processing times for individual cells: **a** before an offset; **b** after an offset

$$t_{\mathrm{total}} = \frac{[SOC_n(t_0) - SOC_{init\_avg}]v_{pack}Q_{A\_n}}{\left[\left(\frac{1}{\eta} - 1\right)\sum_{i=1}^{n}\frac{v_i}{n} + \frac{v_i}{\eta}\right]I_{bal}}. \tag{21}$$

The processing time of the *ith* cell is finally derived as

$$t_i = \frac{[\mathrm{SOC}_n(t_0) - \mathrm{SOC}_i(t_0)]Q_{\mathrm{A}}}{I_{\mathrm{bal}}}. \tag{22}$$

Therefore, n sequential schedule chargings of the individual cells achieve SOC adjustment to the target point according to (22).

4 Performance verification

4.1 Test setups

To verify the proposed method, simulation tests were carried out in PSIM for a Li-ion battery string consisting of 20 series-connection (18,650–3.6 V/2.9Ah). The cell-equalizer in the test is an output current-controlled flyback converter that has an efficiency of around 80% during operation and can handle power up to 12.5 W (5 V/2.5A). In PSIM, the equalizer is modeled by a uni-polar constant current source, and the pack-charger is replaced by a bipolar.

constant current source. The cell-balancing current, the input current of the cell-equalizer, and the pack charging current are listed in Table 1, where the tests are performed for three SOC targets.

- Target #1: The SOC level is reduced to 25% for the purpose of shipping.
- Target #2: All of the cells are equalized at the medium SOC level (45%) for maintenance.
- Target #3: The battery pack is adjusted to 60% SOC for almost full charging.

The initial SOC levels of the cells are configured randomly from 30 to 60%, as shown in Fig. 7 and as summarized in Table 2. After the initial SOC levels of the cells are estimated, the SOC levels of the 20 battery cells are sorted in ascending order, and the cell-equalizer is connected to cells based on their order. The performance of the proposed method is compared with the traditional method, which was called the equalize-min-cell method in [20]. In the traditional method, the lowest voltage cell is equalized first, and the min-cell role is dynamically changed due to the change of the SOC level. During the operation, the cell voltage is traced every 15 s. The lowest voltages are detected, and the switching pattern is changed based on the voltage of the cells until the voltage difference between the cells is less than 15 mV. For a fair comparison with the proposed method, after the cells are equalized, the equalized voltages are measured and the SOC levels are estimated again. After that, the charging process time is calculated, and the battery pack is charged (or discharged) to achieve the target SOC level.

Experiments were also carrier out to further verify the performance of the proposed method as shown in Fig. 8. The battery parameters of the cells are similar to those of the simulation. The battery voltages are logged by a Hioki LR8402-20 and plotted by MATLAB. A Kernel BTU-1601 bi-directional power supply is used as the pack-charger, and a uni-directional output current-controlled flyback converter serves as the cell-equalizer. Two BMIC circuits are used to monitor the cell voltages.

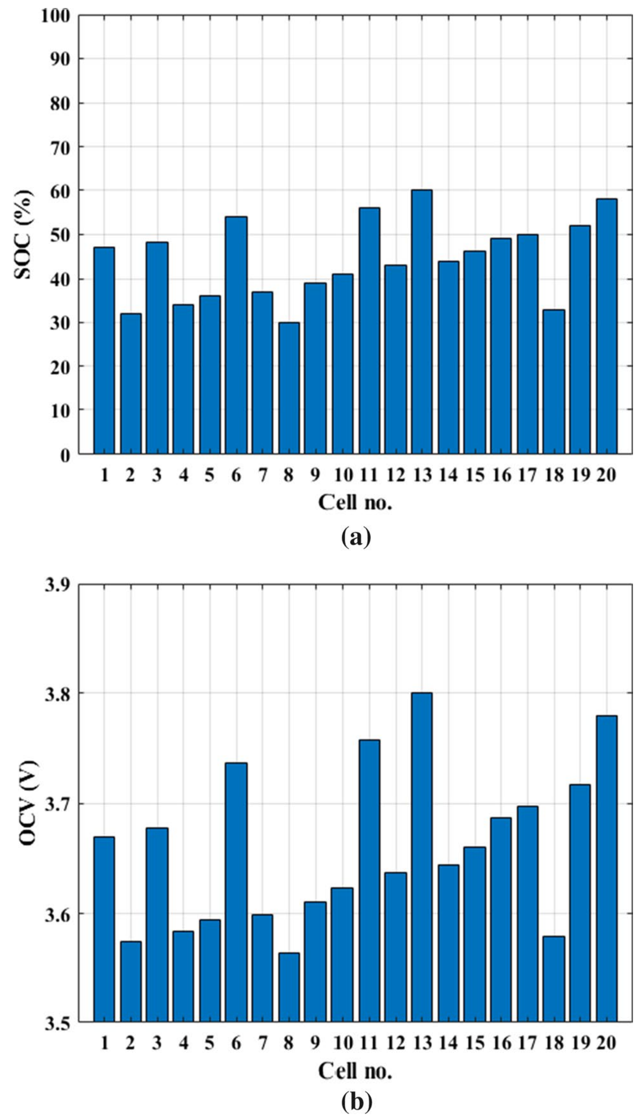

Fig. 7 Initial status of cells: **a** initial SOCs; **b** initial voltages

Table 1 System Configuration

	Target #1	Target #2	Target #3
SOC target	25%	45%	60%
Configuration	*20S1P* (18,650–3.6 *V*/2.9*Ah*)		
I_c	0.53*A*		
I_{bal}	1.3*A*		
I_p	0.1*A*		

Table 2 Experiment Results Summary—SOC and Voltage of Individual Cells

Cell no		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16	#17	#18	#19	#20
SOC_{init} (%)		47	32	48	34	36	54	37	30	39	41	56	43	60	44	46	49	50	33	52	58
V_{init} (V)		3.67	3.57	3.68	3.58	3.59	3.74	3.60	3.56	3.61	3.62	3.76	3.64	3.80	3.64	3.66	3.69	3.70	3.58	3.72	3.78
Proposed method																					
Target #1	SOC_{final} (%)	25.5	24.6	25.8	25.3	25.1	25.5	25.2	24.8	24.8	25.0	25.1	24.9	25.2	25.1	25.6	25.5	26.0	26.0	26.0	24.8
	V_{final} (V)	3.53	3.53	3.54	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.54	3.53	3.54	3.54	3.54	3.53
Target #2	SOC_{final} (%)	45.6	45.2	45.8	45.6	45.5	45.6	45.5	45.2	45.2	45.2	45.4	45.2	45.2	45.2	45.1	45.5	45.1	45.1	45.1	45.9
	V_{final} (V)	3.67	3.66	3.67	3.67	3.66	3.67	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66
Target #3	SOC_{final} (%)	63.3	63.1	63.4	63.4	62.9	62.9	62.8	62.3	62.8	62.6	62.8	62.1	62.6	62.7	62.2	62.4	63.3	63.3	63.6	63.3
	V_{final} (V)	3.83	3.83	3.83	3.83	3.83	3.83	3.83	3.82	3.83	3.83	3.83	3.82	3.83	3.83	3.82	3.82	3.83	3.83	3.84	3.83
Traditional method																					
Target #1	SOC_{final} (%)	23.0	23.4	23.4	23.6	23.5	24.0	23.7	23.7	23.7	23.7	23.6	23.7	23.8	23.7	23.9	23.7	23.8	23.4	23.3	23.6
	V_{final} (V)	3.51	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
Target #2	SOC_{final} (%)	45.4	45.5	45.5	45.6	45.5	45.5	45.4	45.6	45.6	45.5	45.5	45.4	45.5	45.5	45.5	45.3	45.3	45.2	45.5	45.4
	V_{final} (V)	3.65	3.66	3.66	3.66	3.66	3.66	3.65	3.66	3.66	3.66	3.66	3.65	3.66	3.66	3.66	3.65	3.65	3.65	3.66	3.65
Target #3	SOC_{final} (%)	62.5	62.7	62.6	63.0	62.9	62.9	63.2	63.3	63.3	63.2	63.3	63.2	63.1	63.2	63.3	63.2	63.3	62.7	62.9	62.8
	V_{final} (V)	3.82	3.83	3.83	3.83	3.83	3.83	3.83	3.83	3.83	3.83	3.83	3.83	3.83	3.83	3.83	3.83	3.83	3.83	3.83	3.83

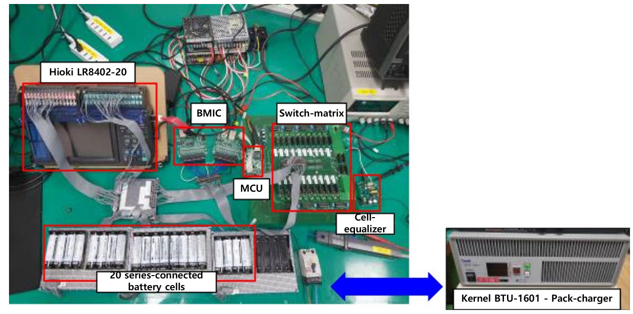

Fig. 8 Experiment setup

4.2 Results and discussion

Before discussing the test results, it should be noted that the operation of the pack-charger can affect the safety of cells. To assess the influence of the sequence of activation, simulations were conducted for the SOC decrement process of 20 series-connected battery cells. Assume that the SOC levels of the cells need to be adjusted to a 25% SOC level set point. In addition, the operation of the pack-charger is executed from the beginning, in the middle, and in the last steps of the calibration process. Since the cells are equalized by a constant 1.3A current, the battery pack is discharged under two pack-current scenarios: 2A and 0.5A. The SOC profiles of the test simulations are shown in Figs. 9 and 10, which reveal some interesting results. Although the equalization is achieved within 3% and the operation times are similar in all of the tests, the high current of the pack-charger can lead the SOC of some cells to go below the safety limitation as shown in Figs. 9a, b. This means the safety of the cells is compromised when the operation of the pack-charger is executed from the beginning or in the middle of the calibration process.

On the other hand, the amplitude of the pack-charger current also affects the safety of the cells. When the pack-chargers current is reduced to 0.5A, as shown in Fig. 10, the SOC levels of the cells are always higher than the limitation level regardless of when the operation of the pack-charge is executed. To ensure the safety and performance of the proposed method, the operation of the pack-charger is executed in the last steps of the process and the least amplitude of the current is used.

In Fig. 11, the results of an experiment on the equalization process of the traditional method are shown. Figure 11a shows the voltage profiles of 20 series-connected battery cells. Meanwhile, Fig. 11b illustrates the SOC profiles after equalization. Although the cells are equalized within a 3% SOC difference and a 10 mV voltage difference, the final SOC level of the cells (35% SOC) is lower than the expected average SOC level (44% SOC). The 9% SOC loss is the result of unnecessary switching during the equalization process. It goes without saying that the equalization process has no freedom in the SOC set point.

The performance of the proposed algorithm is further assessed by comparing it to the traditional method. The final SOC and voltage of individual cells are summarized in Table 2, which shows a good equalization performance for both methods. The cells are equalized to within a 3% SOC difference and a 14 mV voltage difference as shown in Figs. 12 and 13. Figure 12 shows voltage profiles of the traditional method with an additional charging process for a fair comparison. Meanwhile, Fig. 13 demonstrates voltage profiles of the proposed method. The voltage profiles of the

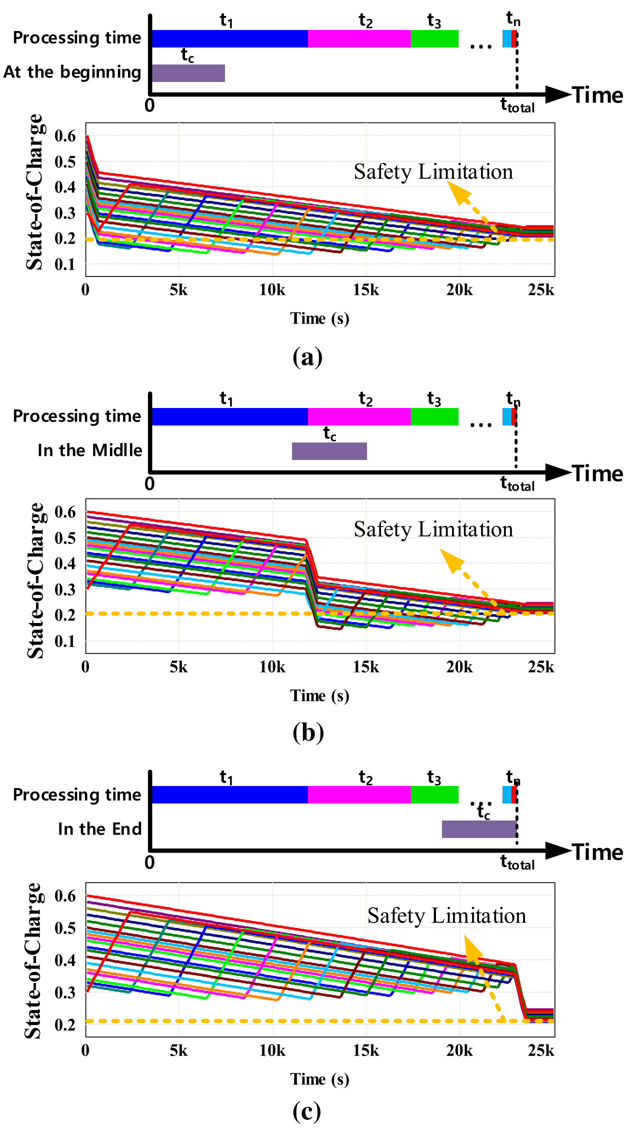

Fig. 9 Impact of the 2A constant current of a pack-charger on calibration when it is activated: **a** from the beginning; **b** in the middle; **c** in the last steps

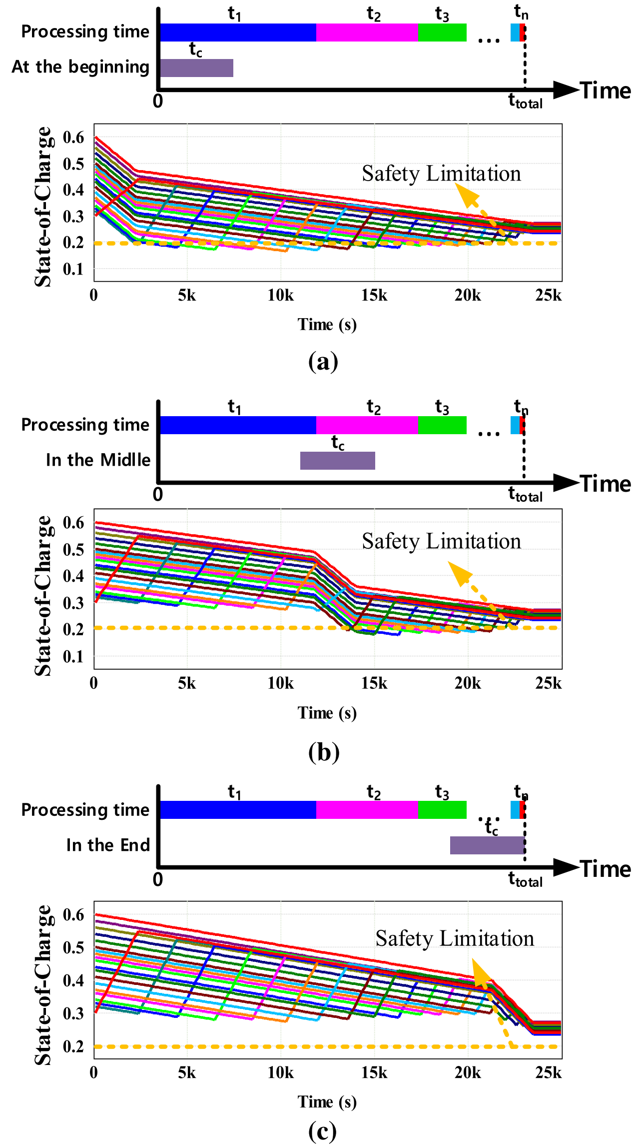

Fig. 10 Impact of the 0.5A constant current of a pack-charger on calibration when it is activated: **a** from the beginning; **b** in the middle; **c** in the last steps

cells distinguish the control strategies of the traditional and the proposed methods. While the traditional method alternatively changes the switching pattern every 15 s and requires 0.5 h–1.5 h for the additional charging process, the proposed method only changes the switching pattern 19 times and only requires 6.5 h for all of the processes. Hence, the proposed method is less sensitive to battery impedance differences and false voltage measurements in the BMIC due to the polarization effect.

Although the voltage difference after the equalization of the traditional method is slightly lower than that of the proposed method, the high energy loss and long operation duration are the fundamental drawbacks of the traditional

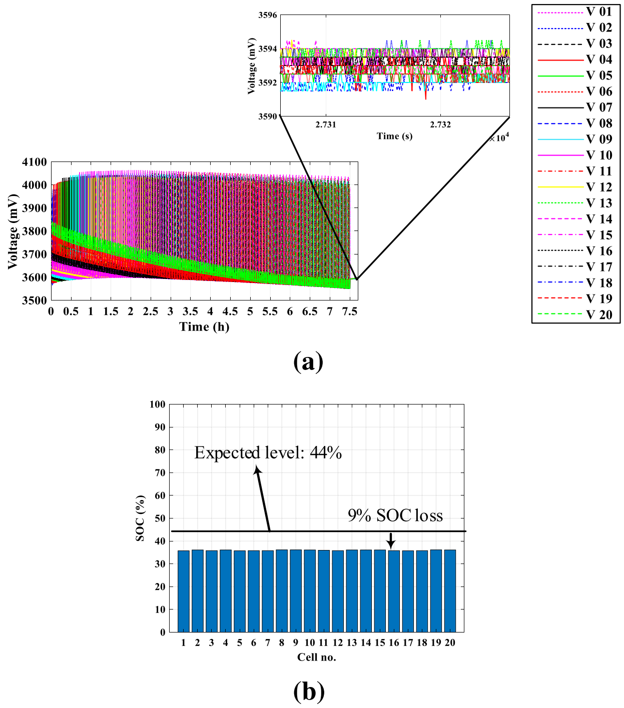

Fig. 11 Experimental results of equalize-min-first without a pack-charger: **a** voltage profiles; **b** SOC profiles

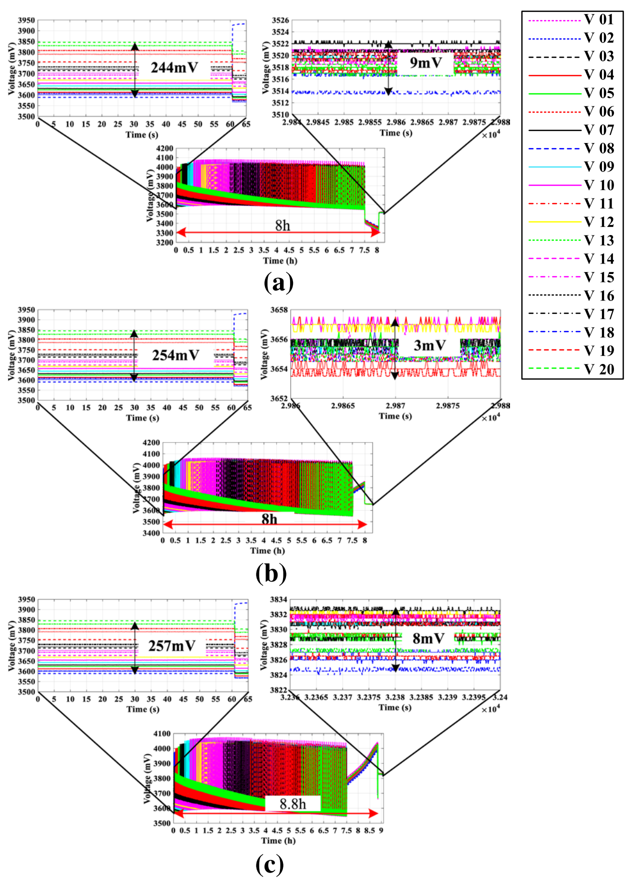

Fig. 12 Experimental results without the coordinated method—voltage profiles of the cells: **a** target #1; **b** target #2; **c** target #3

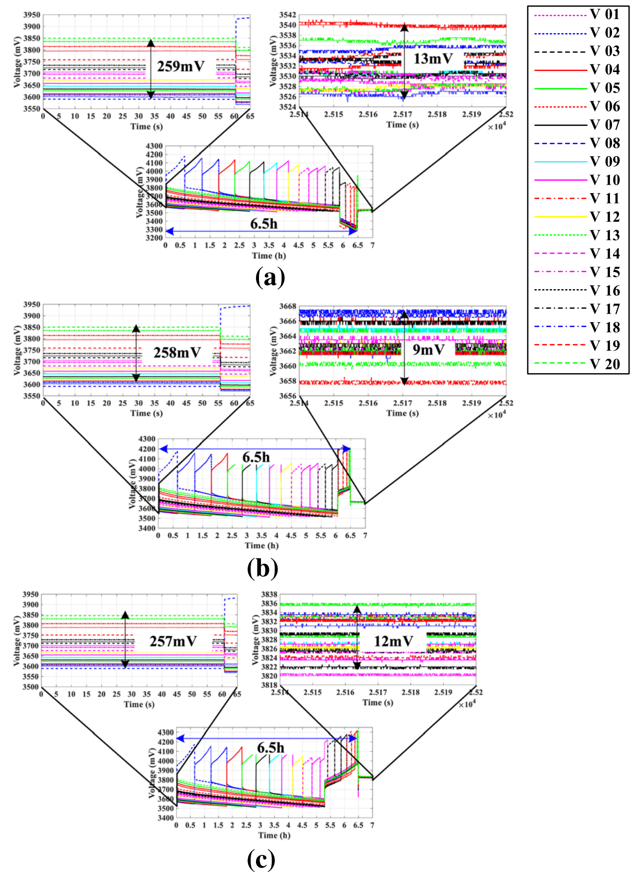

Fig. 13 Experimental results with the coordinated method—voltage profiles of the cells: **a** target #1; **b** target #2; **c** target #3

method. On the other hand, Fig. 14 and Fig. 15 show the final SOC levels of both methods in 3 test scenarios, respectively. Comparing the results, both methods can reach the target SOC and achieve balance. Although both achieve the target SOC level, the traditional method cannot predict the processing time. Meanwhile, the proposed method can predict the processing time, and optimize it.

However, it should be noted that it is difficult to directly compare the two methods using only the final voltage deviation because of the fundamental difference in the operating principles for the two methods. The traditional method is only designed for voltage equalization, not for target SOC adjustment. It is driven by voltage level information and does not utilize SOC information. However, the proposed method is operated by a charge transfer calculation to achieve the target SOC, and utilizes the SOC estimation of each cell. Thus, the operation performance is heavily dependent on the SOC estimation accuracy, which is the reason why the proposed method shows a slightly larger voltage deviation. Since a simple OCV–SOC lookup table is adopted in this paper, most of the errors are caused by the SOC estimation. The other factors that could affect the final deviation are the

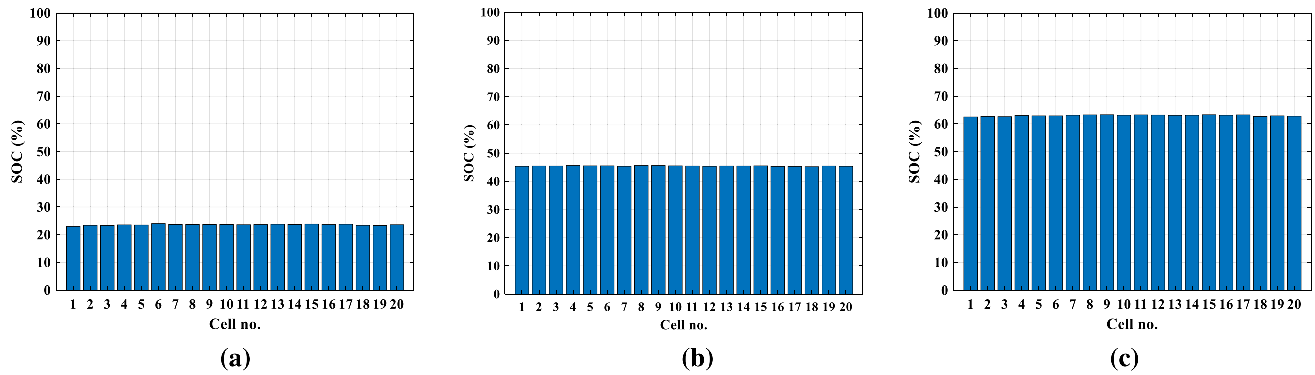

Fig. 14 Experimental results of the traditional method—SOC profiles of the cells: **a** target #1; **b** target #2; **c** target #3

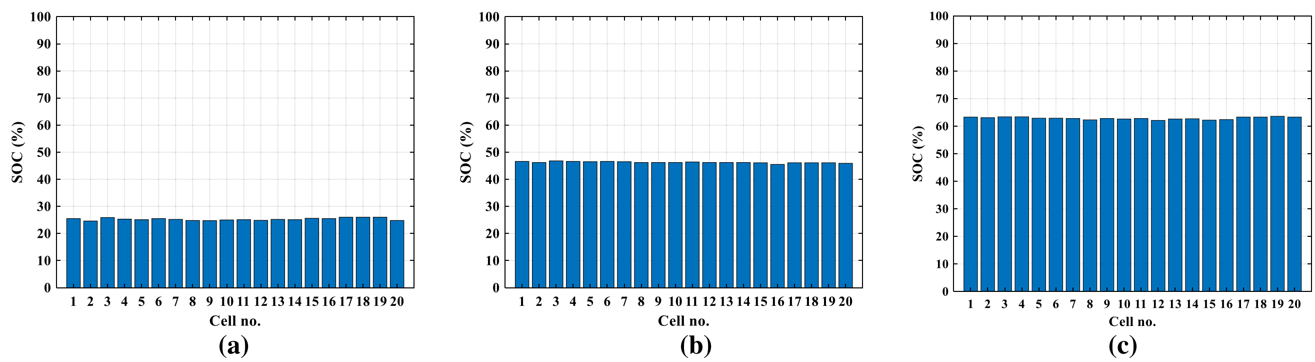

Fig. 15 Experimental results of the proposed method—SOC profiles of the cells: **a** target #1; **b** target #2; **c** target #3

many assumptions made during the calculation, such as the nominal capacity, cell-equalizer power efficiency, non-unity coulomb efficiency, etc.

5 Conclusion

In this study, the operation of a cell-equalizer and a pack-charger are coordinated for second-life battery maintenance and shipping. The proposed method can equalize and adjust the SOC level of the cells to an arbitrary target level. Test results show that the cells are equalized to within a 3% SOC difference, while the SOC levels reach the target level with a 2% tolerance. Individual processing times and switching patterns are calculated by successive calculations, which makes the proposed method easy to implement with a low-cost MCU due to the low computational burden. Charge transfer calculations provides optimal switching patterns to eliminate unnecessary switching patterns and to reduce the power loss in the circuit. In addition, the proposed method saves 20% of the total processing time when compared to the traditional non-coordinated method.

Acknowledgements This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (NRF-2020R1A2C2009303).

Funding National Research Foundation of Korea, NRF-2020R1A2C2009303.

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Coordinated Operation Algorithm of Pack-charger and Cell-equalizer for SOC Adjustment in Second-life Batteries

July 8th, 2021

Nguyen-Anh Nguyen*, Phuong-Ha La, and Sung-Jin Choi

University of Ulsan

Energy Conversion Circuit Laboratory

CONTENT

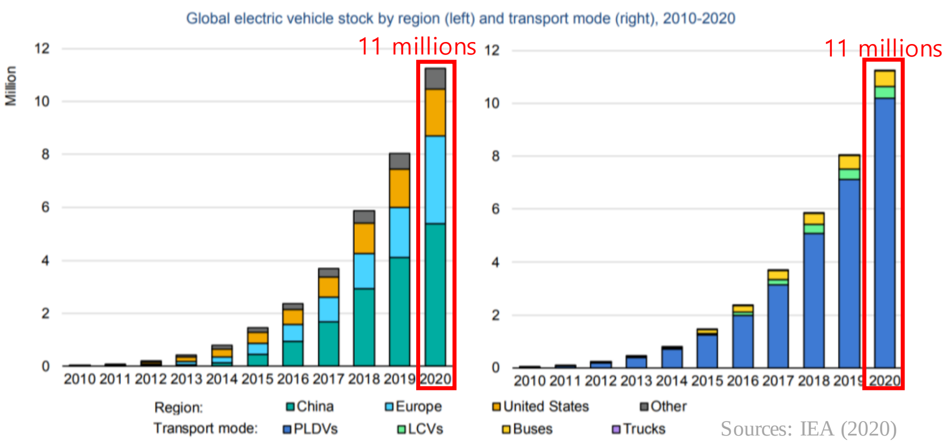
1. INTRODUCTION

❖ Opportunities for **Second-life Battery**

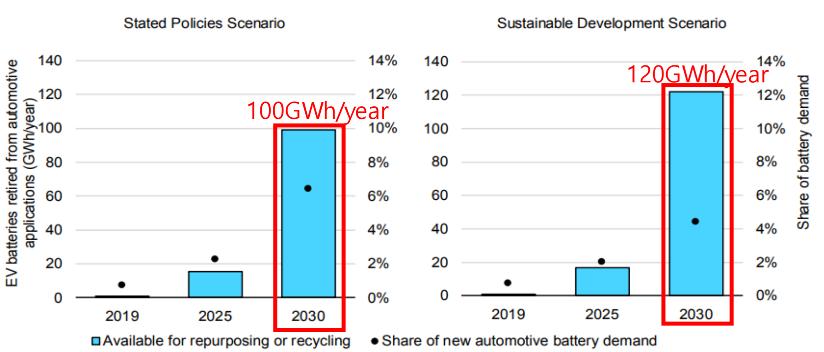
➢ The vehicle is gradually electrified due to the demand for emission reduction.

➢ **Since 80% of available capacity** is remaining after retirement, it can be **re-utilized** for **other purposes**.

➢ **Such a repurposed battery** is called "**second-life battery.**"



Electric vehicles across all transport modes had steady growth over the last decade



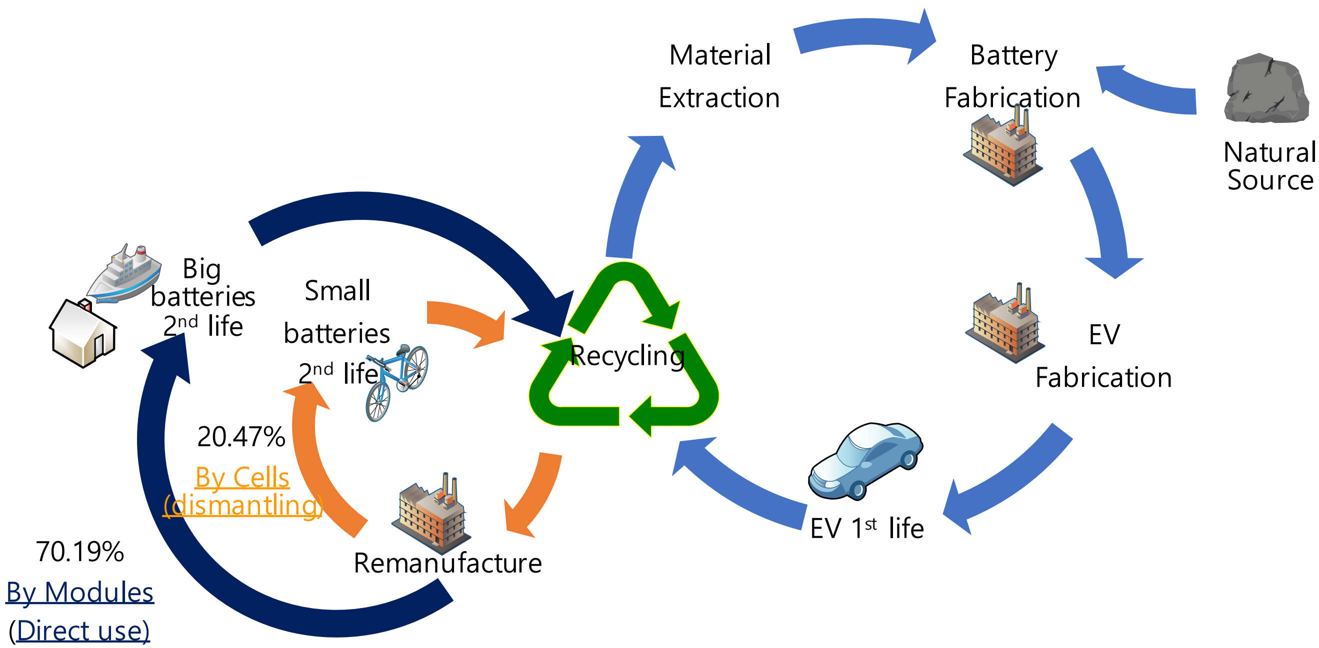
Automotive battery capacity available for repurposing or recycling, 2019-30

1. INTRODUCTION

❖ Two approaches for **re-utilization**:

➢ By cells (dismantling): **more energy-efficient**, but the labor cost offsets its practical feasibility.

➢ By modules (direct use): **more promising** because it **reduces** the **efforts of classification** significantly, and thus **more cost-effective.**



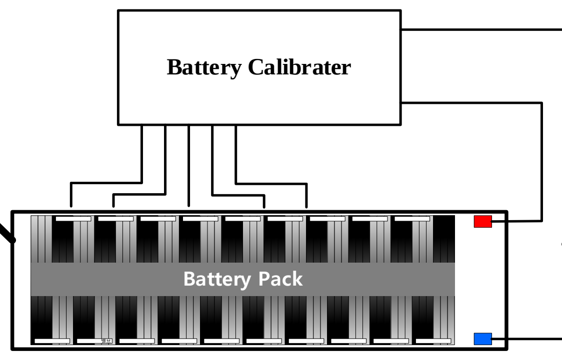
1. INTRODUCTION

❖ **Why is the SOC Alignment is needed for the second-life battery applications?**

➢ A calibration process is essential for **maintenance** and **shipping**.

- The SOC level must be aligned to **less than 30%** before shipping **for safety.**
- The SOC level needs to be set to **arbitrary level for the convenience of maintenance**.

SOC < 30%
For Delivery



SOC = Target level
For Battery Maintenance

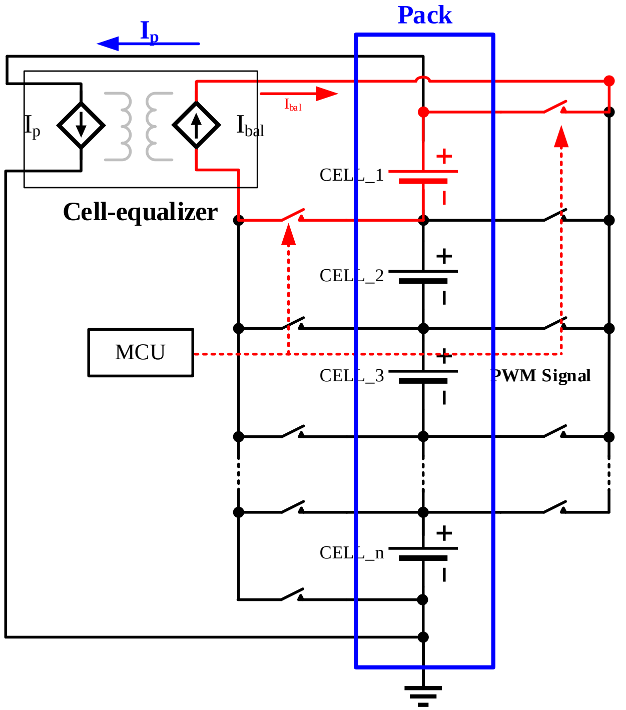
*Huo, Haibo, et al. "Safety requirements for transportation of lithium batteries." *Energies* 10.6 (2017): 793.

*Ahmadi, Leila, et al. "Environmental feasibility of re-use of electric vehicle batteries." *Sustainable Energy Technologies and Assessments 6* (2014): 64-74.

2. EXISTING STUDIES (I)

❖ Equalize-Min-Cell* method

- Operation principle
  - Uni-directional converter (Cell-equalizer) distributes the energy of the whole battery pack to the individual cells. (Input: battery pack/ Output: cells & switch-matrix)
  - The equalizer transfers the energy from the whole pack to the **lowest voltage cell.**
- Weakness:
  - No freedom of SOC set point
  - Switch-matrix operation is not optimized (leading to high energy loss)



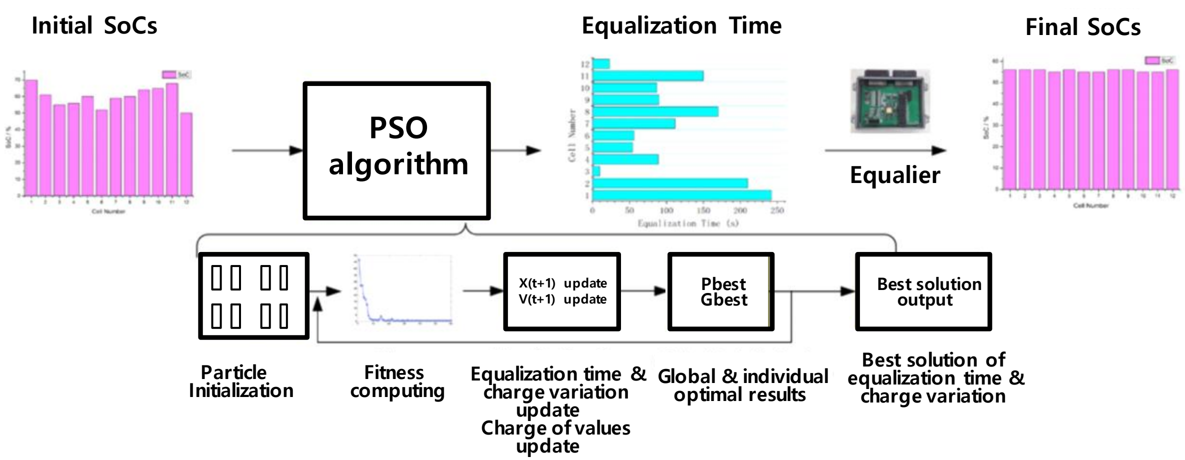
Topology of the traditional equalization method.

*Kim, Chol-Ho, et al. "Individual charge equalization converter with parallel primary winding of transformer for series connected lithium-ion battery strings in an HEV." *Journal of power electronics* 9.3 (2009): 472-480.

2. EXISTING STUDIES (II)

❖PSO (Particle Swarm Optimization)**

- Operation principle
  - Bi-directional converter is placed between pack and cells.
  - PSO algorithm reduces the **number of time steps** and **optimizes the equalization time.**
- Weakness: No freedom of SOC set point / Large computational burden (*not suitable for embedded system*)



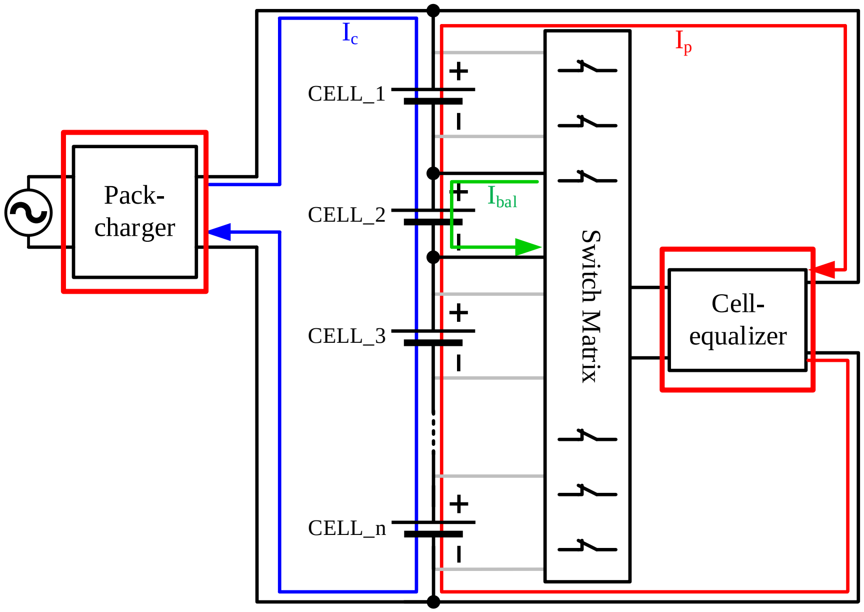
Flow charge of PSO equalization algorithm

**Sun, Jinlei, et al. "Development of an optimized algorithm for bidirectional equalization in lithium-ion batteries." *Journal of Power Electronics* 15.3 (2015): 775-785.

3. PROPOSED METHOD

❖Key concept

- Coordinate operation between pack-charger and cell-equalizer
  - Pack-charger charges/discharges pack energy.
  - Cell-equalizer distributes the pack energy to individual cells through switch-matrix.
- **Advantages:**
  - Arbitrary target SOC level can be achieved. → **SOC set point freedom**
  - The total processing time can be optimized. → **optimal switching (low power loss)**
  - Only n* calculation for steps are required. → **low computational burden**



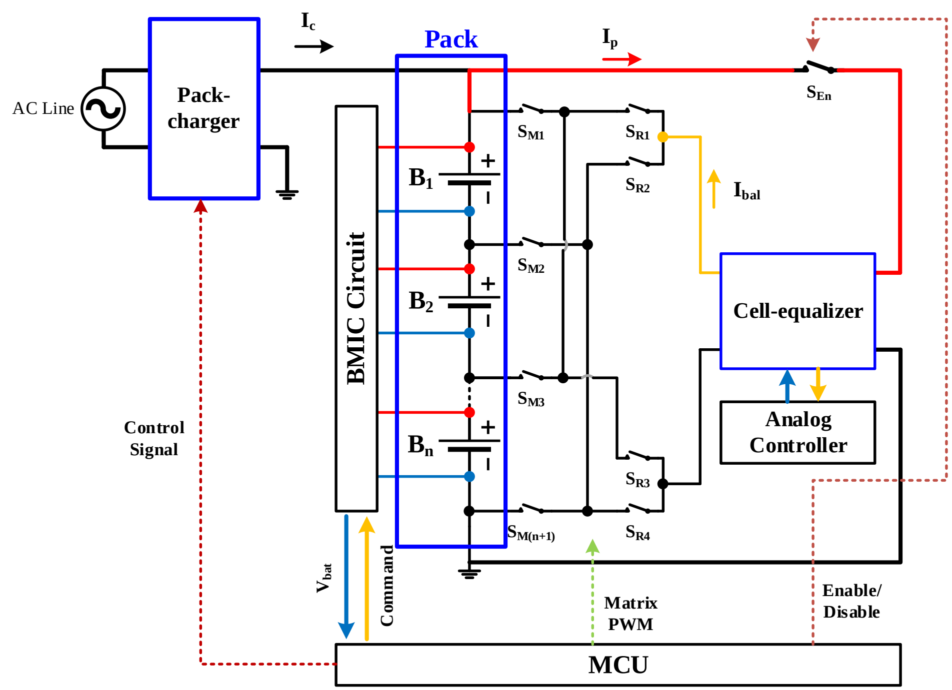
Key concept of proposed method.

n*: total number of cells

3. PROPOSED METHOD

❖ Basic building blocks

- **BMIC** monitors the **cell voltages**.
- **MCU** estimates the cell SOCs based on battery voltages and **decides** the **switching patterns**.
- A **uni-directional converter** and **a switch-matrix** equalize the battery cells.
- A **pack-charger** charge/discharges the whole battery pack to adjust SOC levels.



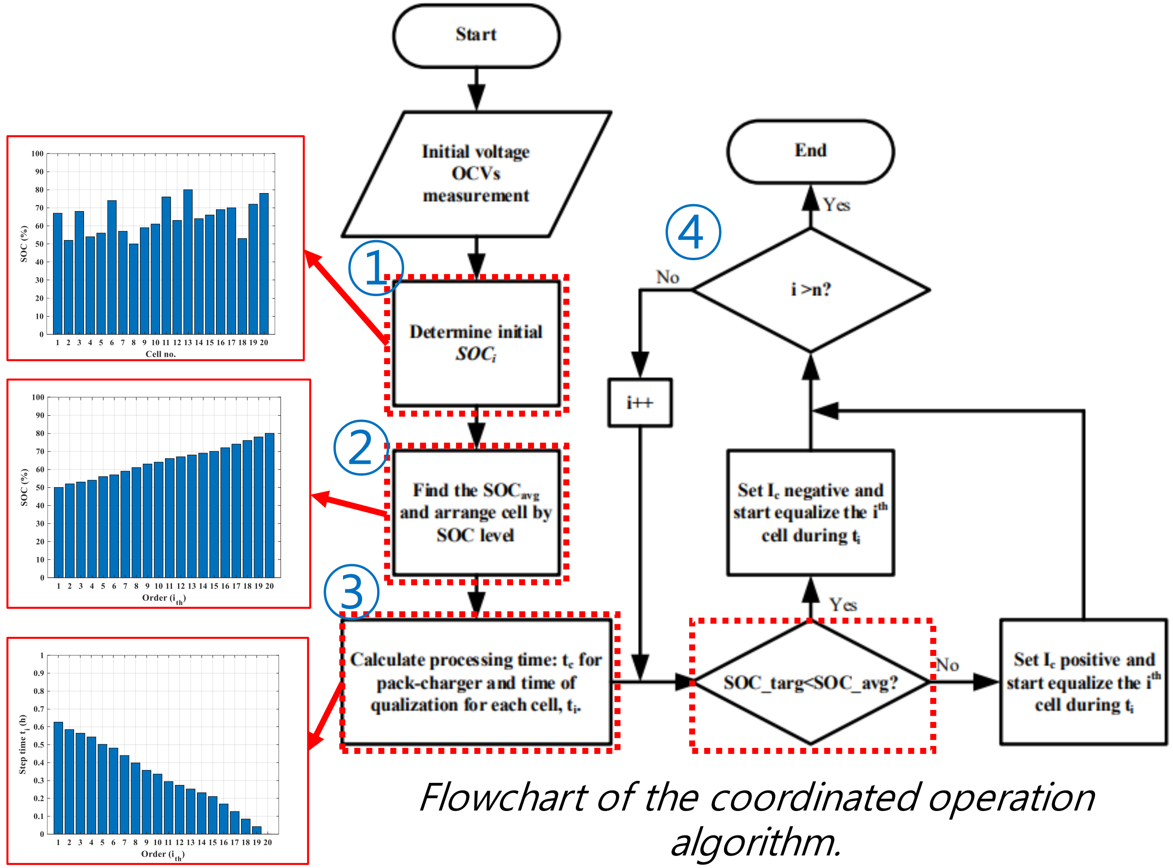
System configuration of the proposed method.

decide the direction of the current

3. PROPOSED METHOD

❖ Algorithm flowchart (I)

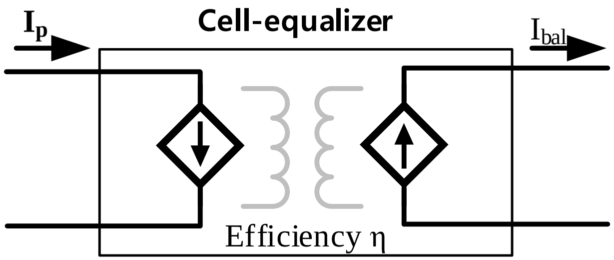
- ① **SOCs** are estimated by OCV-SOC look-up table.
- ② SOC levels are sorted in **ascending order**.
- ③ **Operating times** for each cell are obtained by **charge transfer calculation.**
- ④ **Switching patterns** are decided.



Flowchart of the coordinated operation algorithm.

4. THEORETICAL ANALYSIS

❖ Charge Transfer Calculation



- Let the **cell balancing current, I_{bal}** (defined by the output current of the cell-equalizer) is **uni-polar and constant**, the **pack current, I_p is determined by**

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

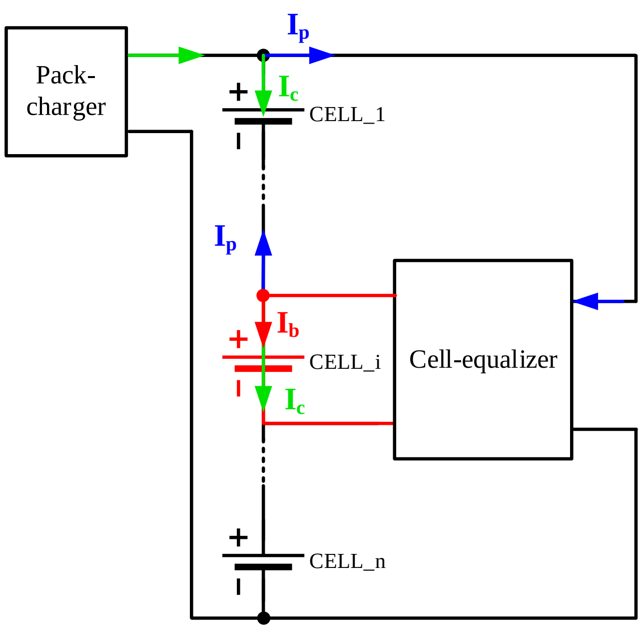
where v_i is the voltage of the i^{th} **cell**, v_{pack} is the **voltage of the pack** and η is the **efficiency of the cell-equalizer**.

- Besides, assume **the pack-charger current, I_c** is **bi-polar and constant.** When the switch-matrix is connected to the i^{th} cell, **actual current flowing** through i^{th} **cell is given by**

$$I_i = I_{bal} - I_p + I_c$$

- On the contrary, the **actual current flowing through** other disconnected cells are given by

$$I_1 = .. = I_{i-1} = I_{i+1} = .. = I_n = -I_p + I_c$$



4. THEORETICAL ANALYSIS

❖ Charge Transfer Calculation for pack-charger processing time (t_c)

- **SOC level** of the **cells after** t_i

$$SOC_i(t_i) = SOC_i(t_0) + \frac{I_i(t_i - t_0)}{Q_{nom}}$$

- **Initial average SOC level** of the cell

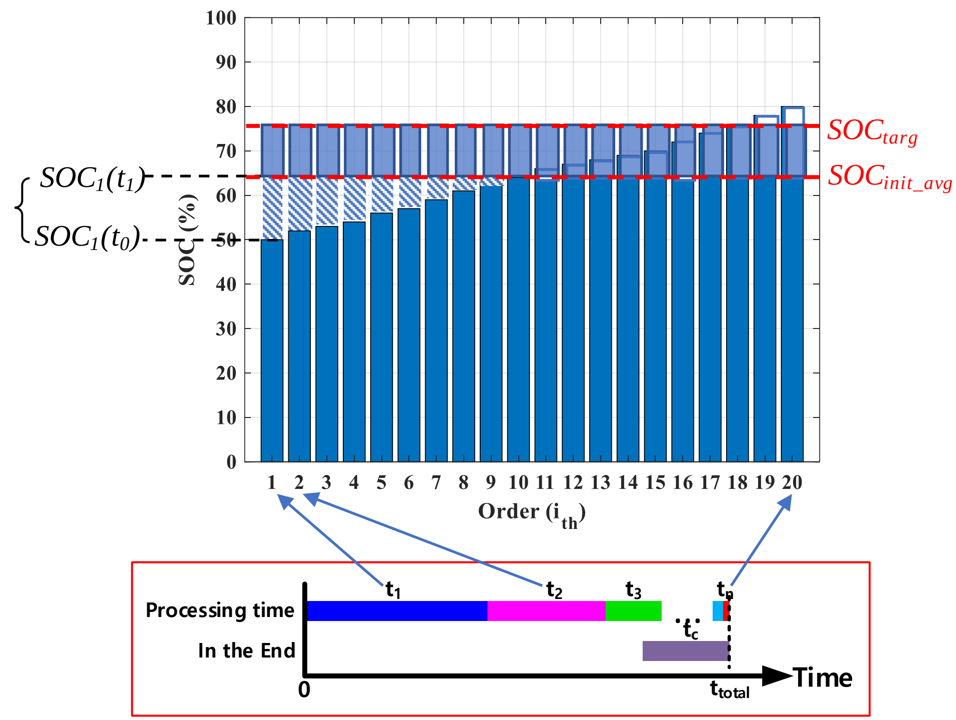
$$SOC_{init\_avg} = \frac{\sum_{i=1}^{n} SOC_i(t_0)}{n}$$

- **Equivalent SOC loss**

$$SOC_L = \frac{\left(\frac{1}{\eta}-1\right)\sum_{i=1}^{n}\frac{v_i}{n} I_{bal} t_{total}}{v_{pack} Q_{nom}}$$

- **Processing time of pack-charger**, t_c

$$t_c = \frac{(SOC_{targ} - SOC_{init\_avg} + SOC_L)Q_{nom}}{I_c} \quad (10)$$



- **Negative** t_c **reverses the polarity of** I_c.

3. PROPOSED METHOD

❖Charge Transfer Calculation for cell-equalizer processing time (t_i)

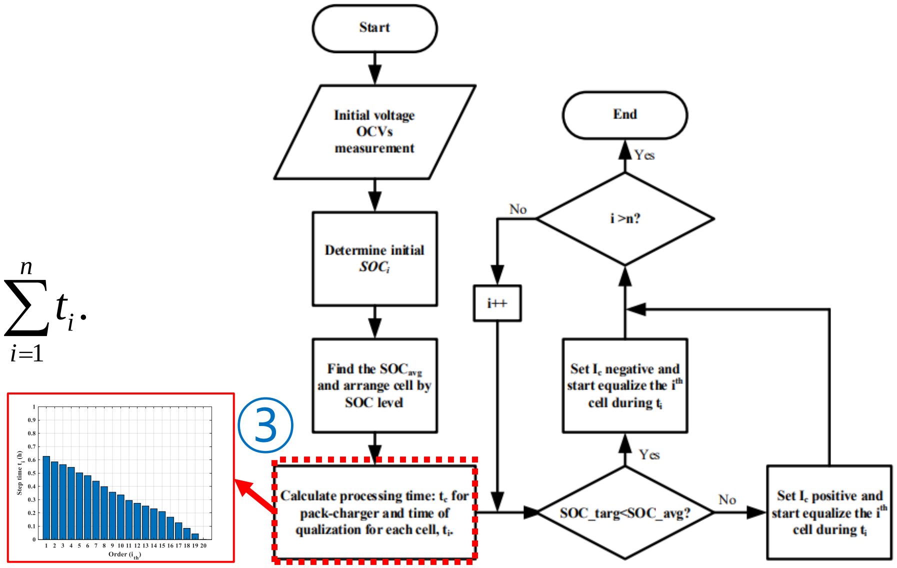
➢ **Capacity change** for the i^{th} **cell**

$$-I_p t_1 - \ldots + (I_{bal} - I_p) t_i - \ldots - I_p t_n + I_c t_c = (SOC_{targ} - SOC_i(t_0)) Q_{nom}$$

➢ **By introducing total processing time,** $t_{total} = \sum_{i=1}^{n} t_i.$

Equation (12) is re-arranged as

$$I_{bal} t_i - I_p t_{total} = (SOC_{init\_avg} - SOC_i(t_0) - SOC_L) Q_{nom}$$



Flowchart of the coordinated operation algorithm.

➢ **Individual processing time**

$$t_i = \frac{(SOC_{init\_avg} - SOC_i(t_0) - SOC_L) Q_{nom} + I_p t_{total}}{I_{bal}} \quad where\ i=1,2,\ldots,n \qquad (18)$$

4. THEORETICAL ANALYSIS

❖ Calculation

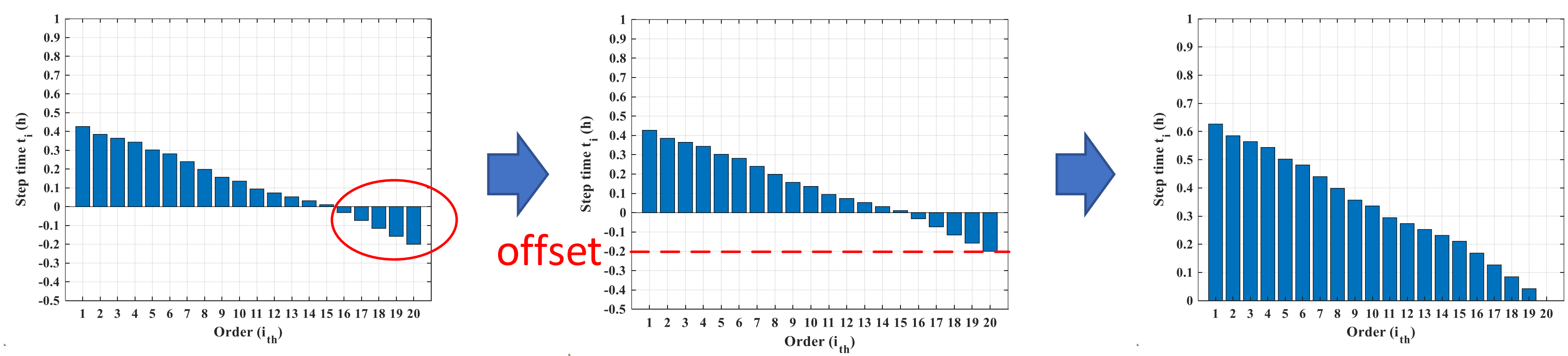
- Sometimes, the solution of (18) can be negative, so it should be avoided.
- Because $t_1 \geq t_2 \geq \ldots \geq t_n$, if t_n is designed as zero, it ensures that individual processing times, t_i (i=1,2,...,n) are **non-negative.**

- **By equating** $t_n = 0$

$$t_n = \frac{(SOC_{init\_avg} - SOC_{\max}(t_0) - SOC_L)Q_{nom} + I_p t_{total}}{I_{bal}}$$

- Then, the **total processing time is calculated as**

$$t_{total} = \frac{(SOC_{\max}(t_0) - SOC_{init\_avg})Q_{nom} v_{pack}}{v_i I_{bal}} \quad (21)$$



4. THEORETICAL ANALYSIS

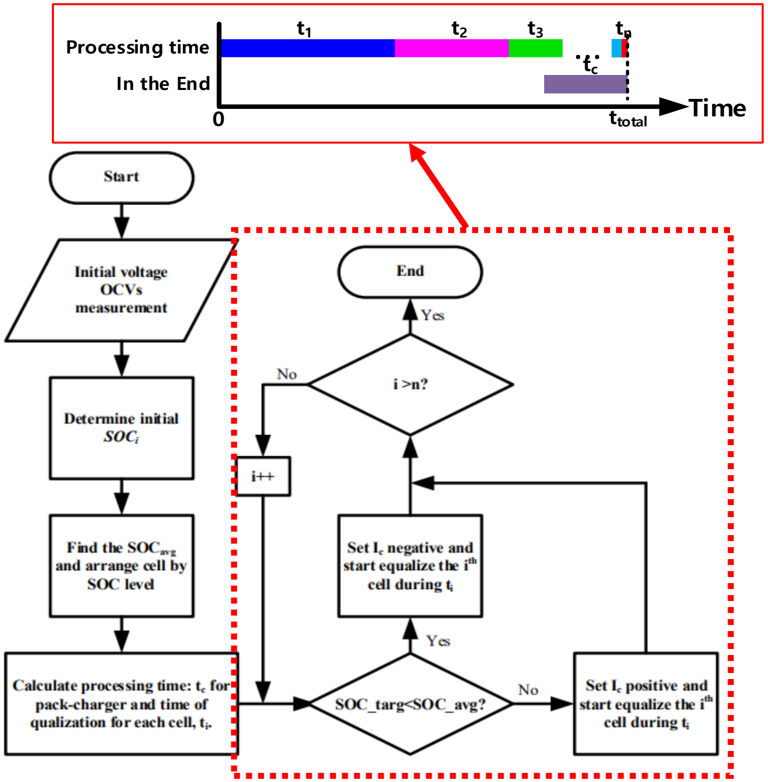
❖Individual Operating Time Calculation

- **Finally, base on t_{total}, the individual operating time of cells → non-iterative and simple calculation**

$$\begin{cases} t_i = \dfrac{(SOC_{init\_avg} - SOC_i(t_0))Q_{nom}}{I_{bal}} + \dfrac{(SOC_{max}(t_0) - SOC_{init\_avg})v_i Q_{nom}}{v_{pack} I_{bal}} \\ t_n = 0 \end{cases}$$

where i=1,2,…,n-1

- Eventually, **individual processing time** of all cells are derived, and the **switching patterns** are decided.

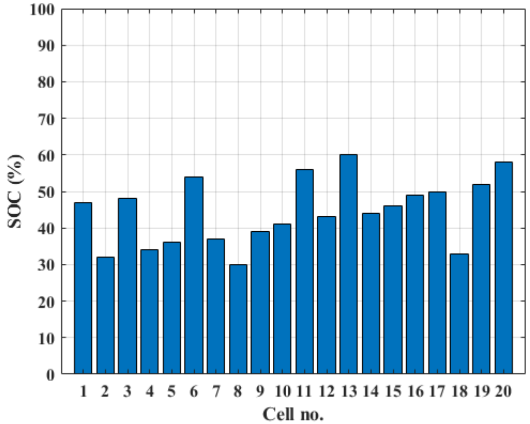


Flowchart of the coordinated operation algorithm.

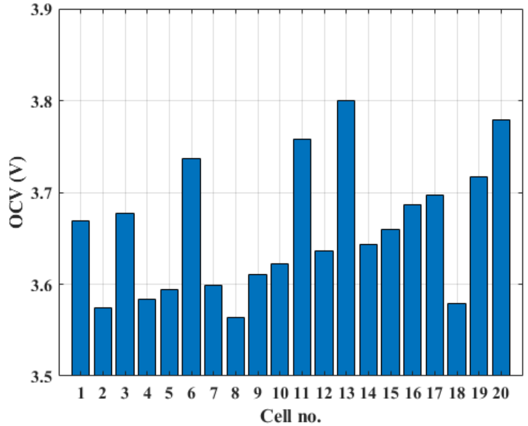
5. VERIFICATION RESULTS AND DISCUSSION

❖**Test setups:** Initial status of the cells

- The initial SOC levels of cells are randomly set between 30% and 60%.
- The initial voltage of cells are shown in the table below.



Initial SOCs



Initial voltages

The initial SOC and voltage values

Cell no.	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16	#17	#18	#19	#20
SOC_{init} (%)	47	32	48	34	36	54	37	30	39	41	56	43	60	44	46	49	50	33	52	58
V_{init} (V)	3.67	3.57	3.68	3.58	3.59	3.74	3.60	3.56	3.61	3.62	3.76	3.64	3.80	3.64	3.66	3.69	3.70	3.58	3.72	3.78

5. VERIFICATION RESULTS AND DISCUSSION

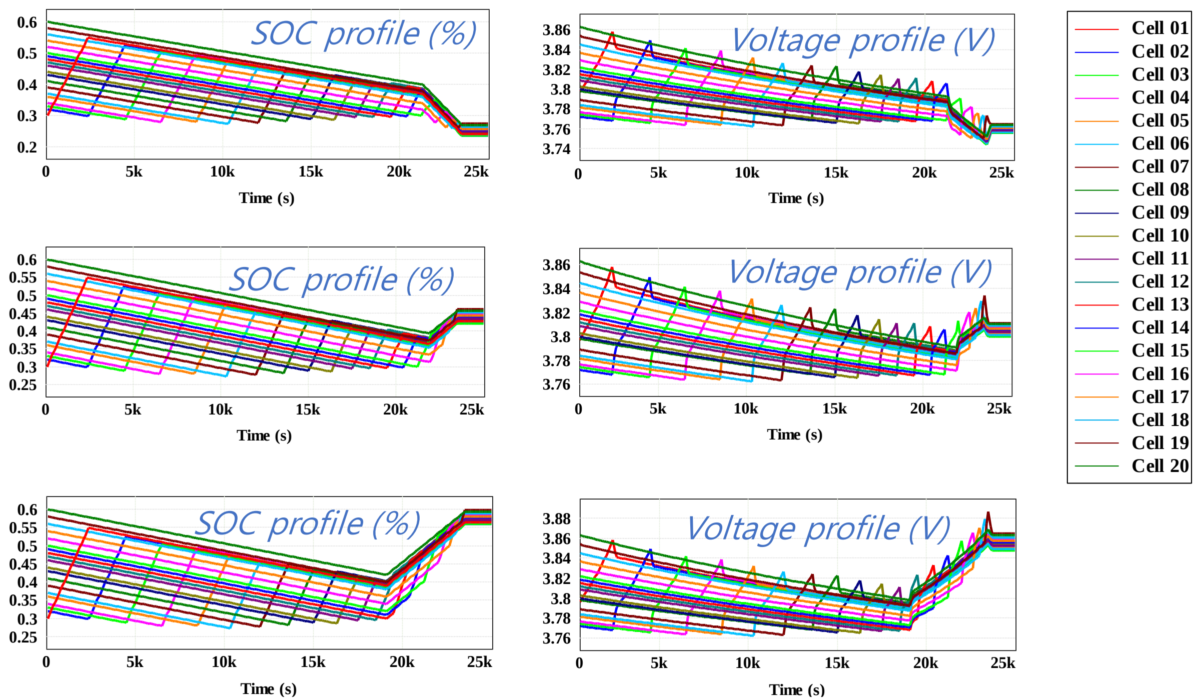
❖ **Simulation data for comparison:** Base on the initial setup

- The simulation is implemented on PSIM in **3 targets: 25%, 45%, and 60%.**
- In all tests, the SOC level and battery voltage are equalized within 3% SOC difference and achieved the final targets.

Target #1 – 25%

Target #2 – 45%

Target #3 – 60%



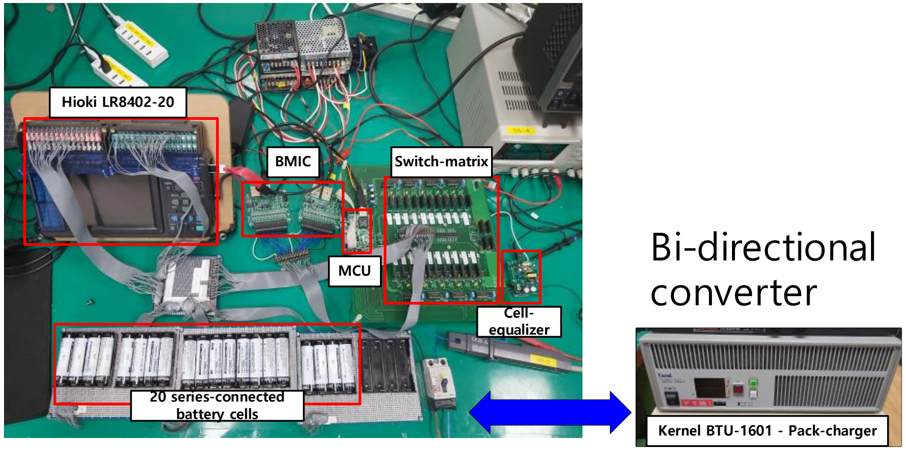
5. VERIFICATION RESULTS AND DISCUSSION

❖Experimental Setups

- **20 series-connected** battery cells **(18650-3.6V/ 2.9Ah).**
  - **Battery voltages** are logged by **Hioki LR8402-20** and plotted by Matlab. A **bi-directional converter** is used as the **pack-charger**.
- For conventional **Equalize-Min-Cell** method is implemented just for equalization.
  - After equalization was achieved, the **pack-charger** is activated to achieve the same SOC target set point for a fair comparison with the proposed method.

System configuration

	Target #1	Target #2	Target #3
Configuration	20S1P (18650-3.6V/2.9Ah)		
SOC target	25%	45%	60%
I_c	0.53A		
I_{bal}	1.3A		
I_p	0.1A		



Experiment setups

5. VERIFICATION RESULTS AND DISCUSSION

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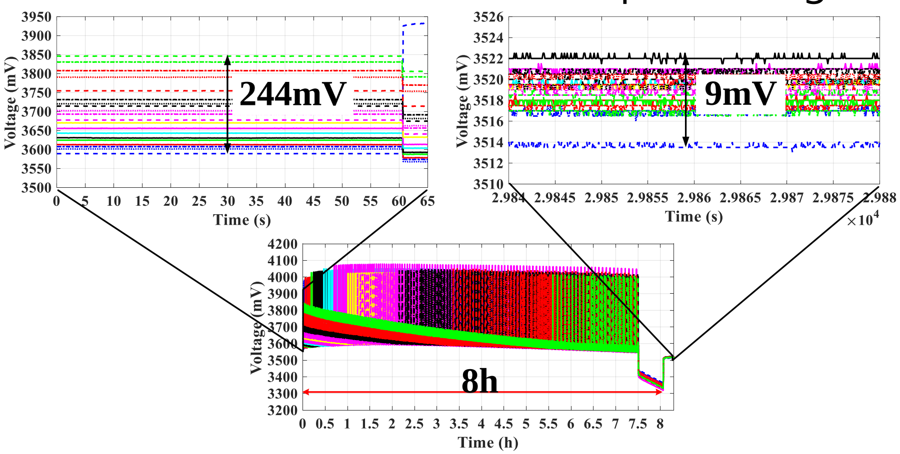
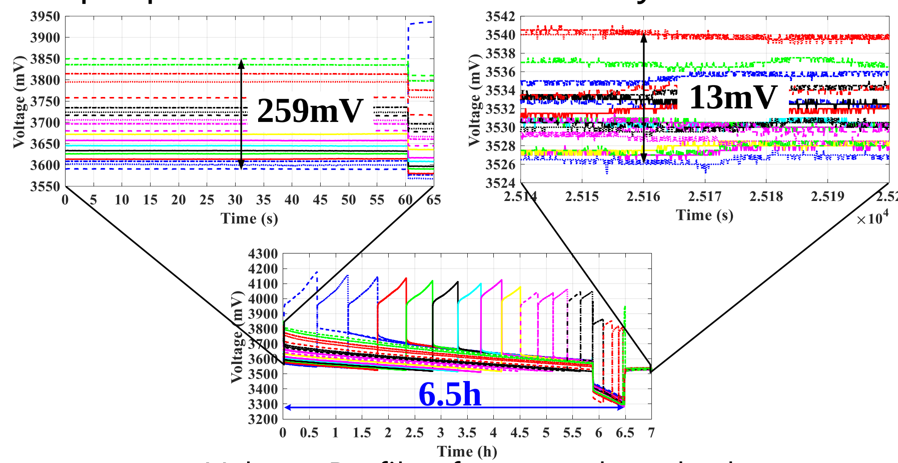
❖ **Experimental Results - Target #1:** achieved 25% SOC

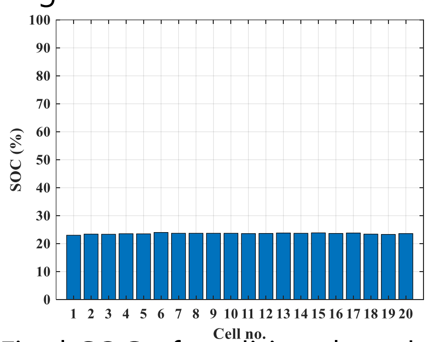
➢ The cells are equalized within **3% of SOC difference** and the **final voltage** is under 20mV difference. However, the processing time of proposed method is faster by 1.5hours.



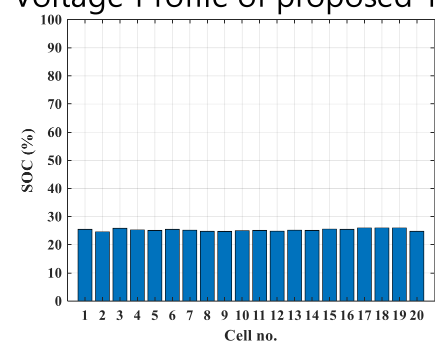
Voltage Profile of traditional method



Voltage Profile of proposed method



Final SOC of traditional method

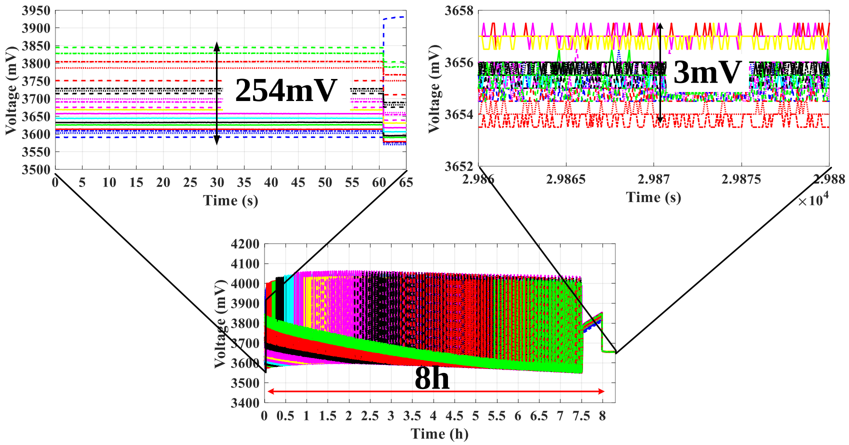


Final SOC of proposed method

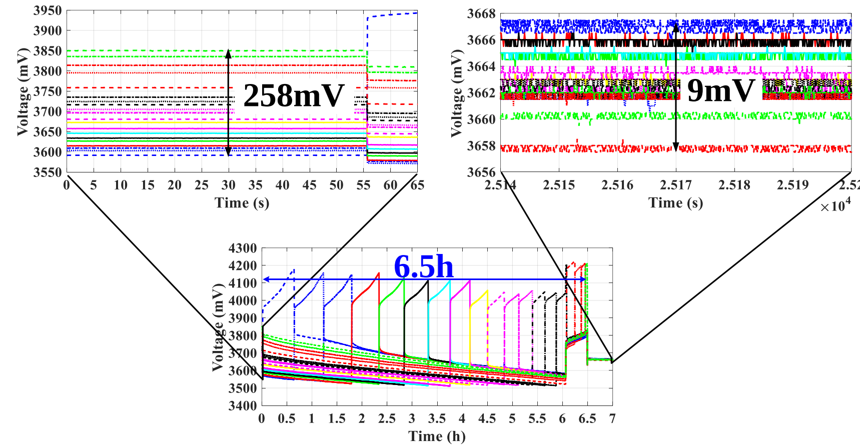
5. VERIFICATION RESULTS AND DISCUSSION

❖ Experimental Results - Target #2: achieved 45% SOC

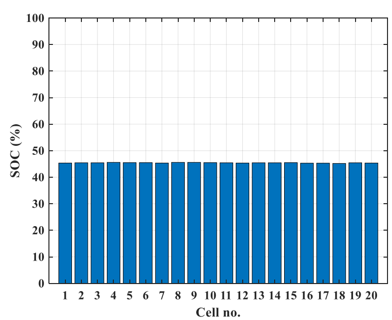
➢ The cells are equalized within **3% of SOC difference** and the **final voltage** is under 20mV difference. However, the processing time of proposed method is faster by 1.5hours.



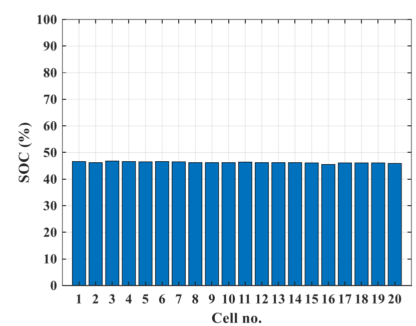
Voltage Profile of traditional method



Voltage Profile of proposed method



Final SOC of traditional method

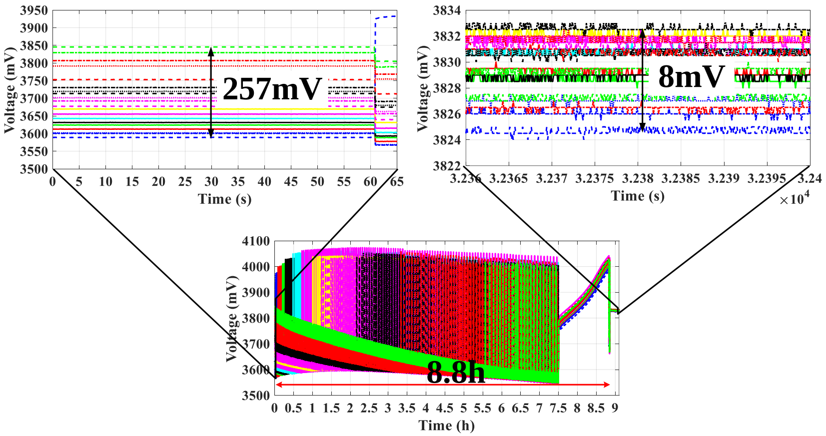


Final SOC of proposed method

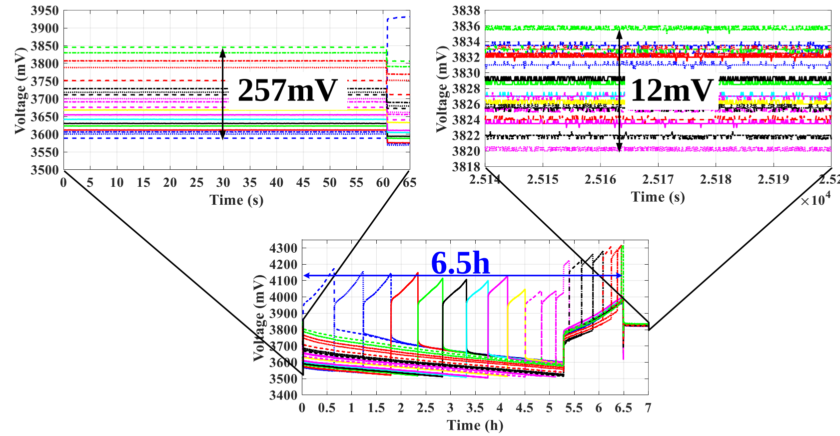
5. VERIFICATION RESULTS AND DISCUSSION

❖ **Experimental Results - Target #3:** achieved 60% SOC

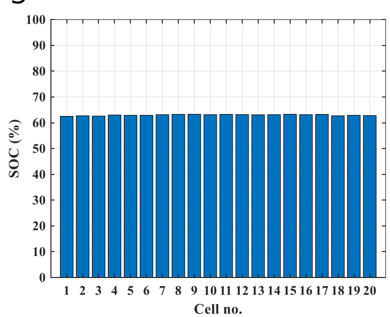
➢ The cells are equalized within **3% of SOC difference** and the **final voltage** is under 20mV difference. However, the processing time of proposed method is faster by 2.3hours.



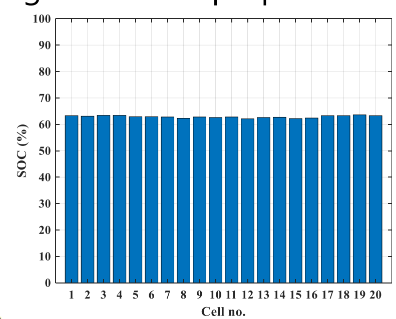
Voltage Profile of traditional method



Voltage Profile of proposed method



Final SOC of traditional method



Final SOC of proposed method

6. CONCLUSION

❖ In this paper, a cell-equalizer and pack-charger are cooperated to obtain the following merits which make it useful for second-life battery maintenance and shipping.

- The proposed method can equalize and adjust the SOC level of the cells to **an arbitrary target level.**
  - The test results show that the cells are equalized within **3% of SOC difference** and the SOC levels reach **the target level with 2% tolerance**.
- Individual processing times and switching patterns are calculated by successive calculations and thus it is easy to be implemented by low-cost MCU due to **low computational burden**.
- Charge transfer calculation provides optimal switching patterns to **eliminate the unnecessary switching pattens and reduces power loss in the circuit**.
- Besides, the proposed method can **save the total processing time** when compared to the traditional non-coordinated method.

Thank You
For Your Attendance!