Cell-balancing Algorithm for Paralleled Battery Cells using State-of-Charge Comparison Rule

Phuong-Ha La* and Sung-Jin Choi**
School of Electrical Engineering, University of Ulsan, South Korea
*laphuongha@gmail.com, **sjchoi@ulsan.ac kr

ABSTRACT

The inconsistencies between paralleled battery cells are becoming more considerable issue in high capacity battery applications like electric vehicles. Due to differences in state-of-charge (SOC) and internal resistance within individual cells in parallel, charging or discharging current is not appropriately balanced to each cell in terms of SOC, which may shorten the lifetime or sometimes cause safety issues. In this paper, an intelligent cell-balancing algorithm is proposed to overcome the inconsistency issue especially for paralleled battery cells. In this scheme, SOC information collected in the sub-BMS module is sent to the main-BMS module, where the number of parallel cells to be connected to DC bus is continuously updated based on the suggested SOC comparison rule. To verify the method, operation of the algorithm on 4 paralleled battery cells are simulated on Matlab/Simulink. The simulation result shows that the SOCs of paralleled cells are evenly re-distributed. It is expected that the proposed algorithm provides high reliable and prolong the life cycle and working capacity of the battery pack.

Keywords – Lithium-ion Battery; Paralleled Battery Cells; Battery Modeling; State-of-Charge (SOC); Depth-of-Discharge (DOD).

1. INTRODUCTION

With the soaring development of renewable energy, batteries are considered as the first choice for energy storage solutions as in electric vehicles (EVs) or battery energy storage system (BESS). To reach the operation voltage and energy capacity, hundreds of cells are connected in series and parallel in the battery pack.

Although it is possible to balance each cell by applying passive or active techniques for series-connected cells [1], few studies have been done for cell balancing issues in the parallel-connected cells. As shown in Fig. 1, the inconsistency in parallel-connected cells is still a big technical challenge, which may cause over-charging and over-discharging of the battery cells [2]-[3]. In [4], a cell balancing architecture employing unregulated DC bus has been introduced, where switches are embedded into the parallel branches and connecting the battery to the bus according to the voltage dropdown of the battery. This method is simple but the battery still has a risk to reach the over-discharge limit. To increase the performance, a regulated DC bus control architecture has been introduced in [5], where a buck-boost converter for each battery cell regulates the discharging current of the cells. Although the system can still supply power to the load without interrupting the system, the SOC of battery cells is imbalanced at the end due to the limitation of the scheduling control algorithm and go through overload condition. In [6], a Fuzzy logic strategy is applied to adjust the number of active cells in accordance with the load demand. While it presents a cost-effective control scheme for parallel-connected battery network, computation burden increases too much when the number of parallel connection increases.

It goes without saying that placing a dedicated equalizer for each parallel cell greatly improves the cell balancing performance. A similar architecture is already common in the energy management system having a mixture of different kind of energy source/storage like fuel cell generation, battery, and ultra-capacitor [6]. If the dedicated equalizer is to be adopted for the parallel-connected battery cells, an effective cell balancing algorithm that is simple, fast, and accurate, is essential. Therefore, this paper presents an intelligent equalizer for parallel-connected battery cells with integrated charger/discharger.

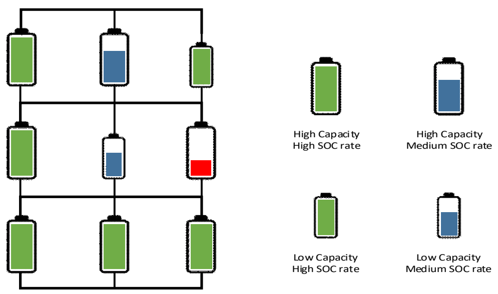


Figure 1. The inconsistency in cells' capacities and states of charge of series-parallel battery cells network.

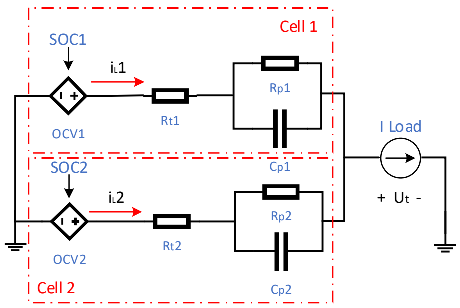


Figure 2. Battery modeling of parallel-connected battery cells.

2. PROPOSED CELL-BALANCING ALGORITHM

2.1. *Inconsistency of battery cells in parallel-connected network*

To analyze the characteristics of parallel-connected battery cells, a lumped parameter model is shown in Fig. 2, where each cell is modeled by single RC network. The imbalance current between battery cells mainly caused by mismatch in the internal parameter such as ohmic resistance R_t, polarization capacitance C_p, resistance R_p, and open circuit voltage (OCV). The electrical behavior of the modeling is expressed as:

$$SOC_k = SOC_{init} - \frac{\int i_{Lk} * dt}{C}$$

$$SOC_{avg} = \frac{\sum_{1}^{n} SOC_k}{n}$$

$$\begin{cases} \dot{U}_{Ck} = -U_{Ck}/R_{pk}C_{pk} + i_{Lk}/C_{pk} \\ U_{Ck} = OCV_k - U_{Ck} - i_{Lk}R_{tk} \\ U_t = OCV_k - U_{Ck} - i_{Lk}R_{tk} \end{cases} \qquad (k = 1, 2)$$

2.2. *Control architecture*

To overcome the cell inconsistency problem, one of the conventional solutions is to make the cells alternately connected to the bus. This kind of conventional architectures is illustrated in Fig. 3, where a micro-controller measures bus voltage, load current, and battery SOC. Due to load demand and SOC information, battery cells are connected to the bus one after another (Fig. 3.a) or the discharging current are shared independently though buck-boost converters (Fig. 3.b). Depending on the cells that are connected to the bus, the bus voltage is inherently unregulated and thus an external charger is always required to interface with the DC source.

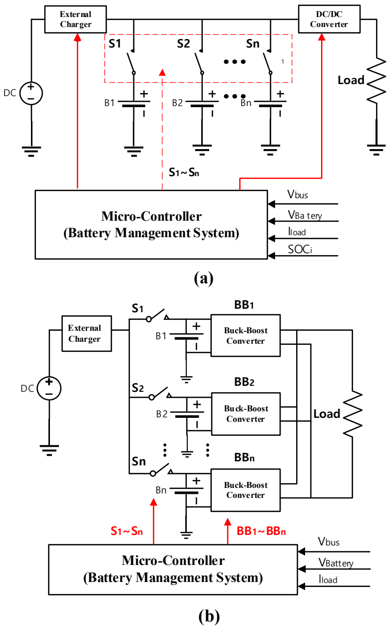


Figure 3. Conventional control architecture: (a) in ref. [4],[6] (b) in ref. [5]

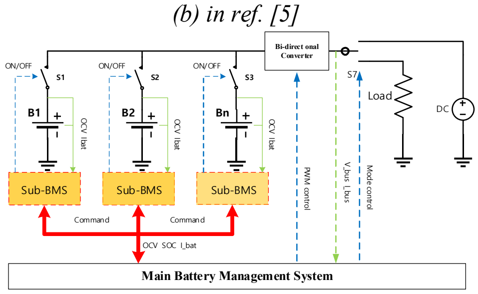


Figure 4. Proposed control architecture.

Fig. 4 shows the control architecture of the proposed system. Each battery cell is connected to the unregulated DC bus through a single switch which is controlled by a sub-BMS. The sub-BMS is responsible for measuring the cells' status and control the switch. All sub-BMSs communicate with the main-BMS to send cell status and receive control commands by I2C protocol which is integrated into all modern MCU. The DC bus is connected to a bi-directional converter which works as a charger or voltage regulator. By transferring the centralized control to distributed control architecture, the computational burden of main-BMS is reduced. Thus, the proposed control architecture can individually control battery cell, eliminate the external addition charger, and increase the overall computation speed.

2.3. *Cell-balancing algorithm*

The proposed cell-balancing algorithm is based on SOC comparison rule. Sub-BMSs are working independently with main-BMS. From the sensed information such as OCV and battery current, SOC is calculated and sent to main-BMS. With collected data, the number of cells connected to the dc bus is decided and the bi-directional converter charge the battery (charging process) or deliver the power to the load (discharging process) by main-BMS. Fig. 5 shows the control flowchart of main-BMS and sub-BMS.

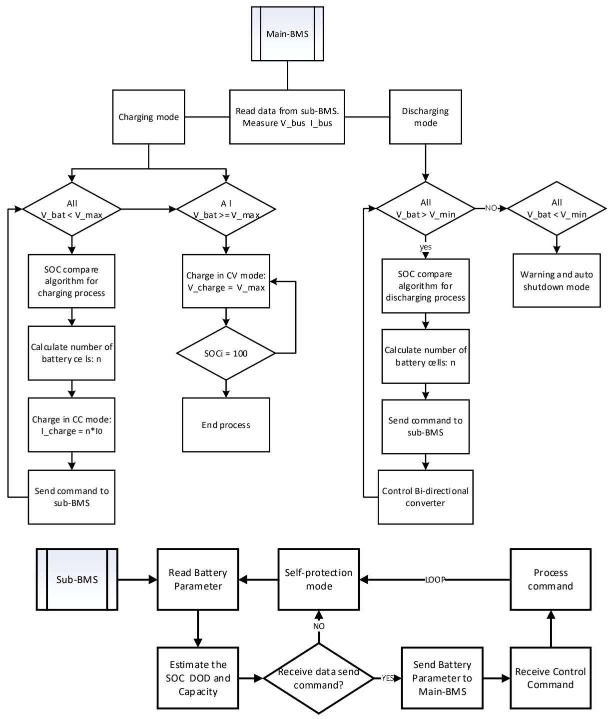


Figure 5. Control flowchart

To decide the number of the battery cell that is connected to the DC bus, we propose some control scenario working modes and power flows, which is summarized in *Tables I* and *II*. Assume that the switches, S_1, S_2, …, S_n are turned on when $S_i = 1$ and off when $S_i = 0$ (with i = 1, 2, …, n). It is noticeable that only single battery cell is activated to be discharged in the lightest load condition during discharging process. As the load demand increases, additional battery will be connected to the DC bus to maintain the DC bus voltage. It is also clear that and the minimum SOC cell has the priority to be turned off.

3. SIMULATION RESULTS

To verify the proposed method, a simulation for 4 parallel-connected 18650 battery cell has been performed in Matlab/Simulink. The simulation results are separately obtained for charging and discharging process.

Table I: Control scenario – Charging process

CC charging mode	*CV charging mode*
$\Delta SOC_i = SOC_i - SOC_{\max}$ If $\Delta SOC_i = 0$ ➔ $S_i = 0$; n = n - 1; If $\Delta SOC_i < 0$ ➔ $S_i = 1$; n = n + 1; *Total charging current:* $I\_\text{charge} = n * I_0$	*For all switches:* $S_i = 1$; $V\_\text{charge} = V\_\max$

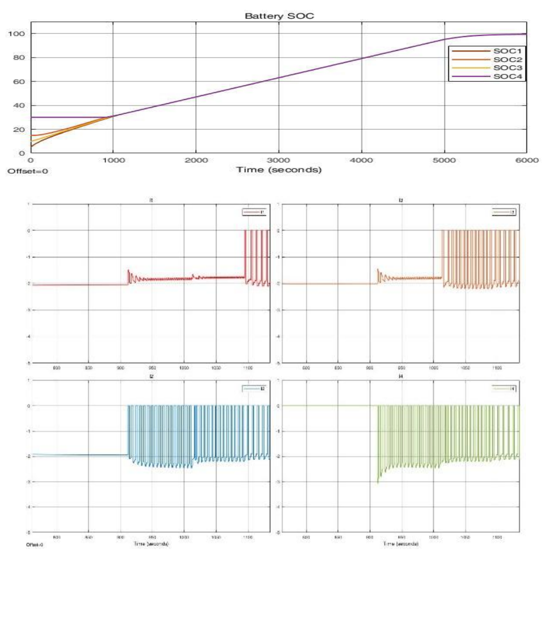
Table II: Control scenario – Discharging process

Light load condition *I_load ≤ 0.75C*	*Heavy load condition* *I_load > 0.75C*
$\Delta SOC_i = SOC_i - SOC_{\max}$ If $\Delta SOC_i = 0$ ➔ $S_i = 1$ If $\Delta SOC_i < 0$ ➔ $S_i = 0$	$\Delta SOC_i = SOC_i - SOC_{avg}$ If $\Delta SOC_i > 0$ ➔ $S_i = 1$ If $\Delta SOC_i < 0$ ➔ $S_i = 0$

3.1. *Charging process.*

In this test, it is assumed that all cells have the same capacity of 2600mAh but their initial SOCs are different: $SOC_{1,2,3,4}$ = 5, 15, 10, 30 %. The standard charging current for single cell, I_0 is 2A (0.75C). The simulation result is shown in Fig. 6. The charging process is divided into pre-balancing and post-balancing phases. In pre-balancing phase, the highest SOC battery cell is not connected to DC bus and but is waiting for the other cell to be conneted. After activation of the balancingalgorithm, all parallel cells are alternatively turn off according to the SOC comparison rule..

The zoomed view shows that the charging current of each battery is confined within safety region. Total charging time is around 1.6 hr, which is reasonable speed with 0.75C charging current.



(a)

(b)

Figure 6. SOC balancing (a) and current of each cell (b) in the charging process

3.2. *Discharging process.*

In this test, 4 parallel-connected battery cell is discharged with constant current of 4A (1.5C). Assume all cells have the same capacity of 2600mAh with different initial SOC of 80, 100, 90, and 70%, the simulation results are shown in Fig. 7. It is also clear that the discharging current is shared according to the SOC comparison rule.

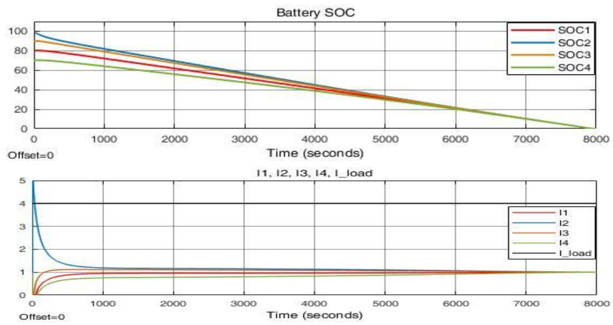


Figure 7. SOC balancing (a) and current of each cell (b) in discharging process

4. CONCLUSION

With a novel SOC comparison rule with distributed control architecture, the proposed scheme can be applied to any number of parallel connections of battery cells. Simulation results with 4 paralleled 2600mAhr 18650 Li-ion battery cells show that all battery cells are balanced evenly and the required balancing time is also fast. Due to distribuited computational burden between master and sub-BMS, the computing speed is increased and the complexity of the control system is reduced. It is expected that the proposed algorithm provides high reliable and prolong the life cycle and working capacity of the battery pack.

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