Battery Equalization Method for Parallel-connected Cells Using Dynamic Resistance Technique

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ABSTRACT

As the battery capacity requirement increases, battery cells are connected in a parallel configuration. However, the sharing current of each battery cell becomes unequal due to the imbalance between cell's impedance which results the mismatched states of charge (SOC). The conventional fixed-resistance balancing methods have a limitation in battery equalization performance and system efficiency. This paper proposes a battery equalization method based on dynamic resistance technique, which can improve equalization performance and reduce the loss dissipation. Based on the SOC rate of parallel connected battery cells, the switches in the equalization circuit are controlled to change the equivalent series impedance of the parallel branch, which regulates the current flow to maximize SOC utilization. To verify the method, operations of 4 parallel-connected 18650 Li-ion battery cells with 3.7V-2.6Ah individually are simulated on Matlab/Simulink. The results show that the SOCs are balanced within 1% difference with less power dissipation over the conventional method.

Keywords – State of charge (SOC), Parallel-connected battery, Battery equalization, Dynamic resistance techniques.

1. INTRODUCTION

The lithium-ion battery is considered as the first choice for energy storage solution in renewable application due to its advantages such as high energy density, high reliability, and long lifetime. To prolong the working time, battery cells are connected in a parallel configuration. Despite of working in the same condition, the characteristic of individual battery cells in the parallel-connected configuration are different in the battery impedance and SOC rates, which so-called parallel battery inconsistency issue. This issue affects immediately on the unequal current sharing of battery in each parallel branch which is reported in the literature [1]. The inconsistency issue becomes more serious during calendar aging as the battery impedance changes. Therefore, battery balancing circuits are necessary to prevent all cells in parallel configuration from over-charging and over-discharging.

Although, there are a lot of cell balancing techniques for series configuration [2], the balancing system for parallel-connected cells is rarely adopted due to the limitation of space and cost; hence, just a few studies have been done. In [3], fuzzy logic control is used to adjust the number of cells which is connected to the DC bus in accordance with load demand and SOC rate. Although the SOC of all cells are balanced and the utilization is increased, but the system converges to a directly parallel connected network when more battery cells are connected to the DC bus at the same time due to the load demand increasing. To control the current of the parallel branch, a resistor is added in series with each battery cells. This method is popularly used for light-emitting diode (LED) due to its simplicity, stabilization, low cost, and small size [4]. However, the efficiency is low due to high power dissipation in the balancing resistor and the equalization performance are not satisfactory.

This paper introduces a dynamic resistance technique to improve the performance and efficiency of the equalization system. The balancing circuit is described in section 2, the simulations are performed in section 3, and the conclusion is made in section 4.

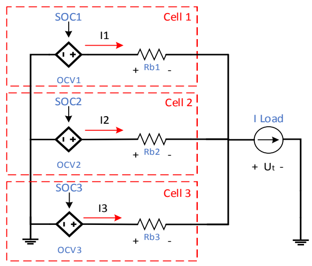

Figure 1. Battery modeling of parallel-connected battery cells.

2. PROPOSED METHOD

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

To analyze the characteristics of parallel-connected battery cells, a modeling of 3 parallel-connected battery cell is shown in Fig. 1, where the current through each battery branch a is calculated by (1), (2) and (3). According to the modeling, the current of each parallel branch is dependent on the open circuit voltage (OCV) and the impedance of the battery cells.

$$I_1 = \frac{I_{load} R_{b2} R_{b3}}{R_{b2}(R_{b1}+R_{b3})+R_{b1}R_{b3}} + \frac{OCV_1(R_{b2}+R_{b3}) - OCV_2 R_{b3} - OCV_3 R_{b2}}{R_{b2}(R_{b1}+R_{b3})+R_{b1}R_{b3}} \quad (1)$$

$$I_2 = \frac{I_{load} R_{b1} R_{b3}}{R_{b1}(R_{b2}+R_{b3})+R_{b2}R_{b3}} + \frac{OCV_2(R_{b1}+R_{b3}) - OCV_1 R_{b3} - OCV_3 R_{b1}}{R_{b1}(R_{b2}+R_{b3})+R_{b2}R_{b3}} \quad (2)$$

$$I_3 = \frac{I_{load} R_{b1} R_{b2}}{R_{b2}(R_{b1}+R_{b3})+R_{b3}R_{b1}} + \frac{OCV_3(R_{b1}+R_{b3}) - OCV_1 R_{b2} - OCV_2 R_{b1}}{R_{b2}(R_{b1}+R_{b3})+R_{b3}R_{b1}} \quad (3)$$

Moreover, even without no load demand, unregulated energy transfer between cells, so-called the self-balancing effect. This issue is illustrated in Fig. 2, where four Li-ion battery cells are connected in parallel during no-load mode. Battery #1 is forced to charge for the other cell, then its SOC is significantly reduced. Thus, it can generate additional heat dissipation and lead the system to over-charging or over-discharging risks.

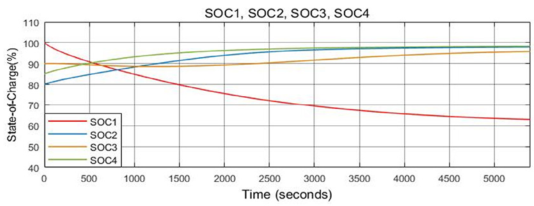

Figure 2. Self-balancing effect in parallel-connected battery network.

2.2. *Conventional method.*

To address the inconsistency issue, a SOC based switch sequencing in Fig. 3(a) alternatingly disconnects battery cells from DC bus to balance the SOC of them. A micro-controller unit (MCU) measures the bus voltage, load current, and SOCs of battery cells. Based on this information, the switching decision is made to balance the SOCs of battery cells. Although the utilization of battery system increases, the battery inconsistency and self-balancing effect still exist which may cause the thermal runaway, over-charging, and over-discharging for the weakest cell.

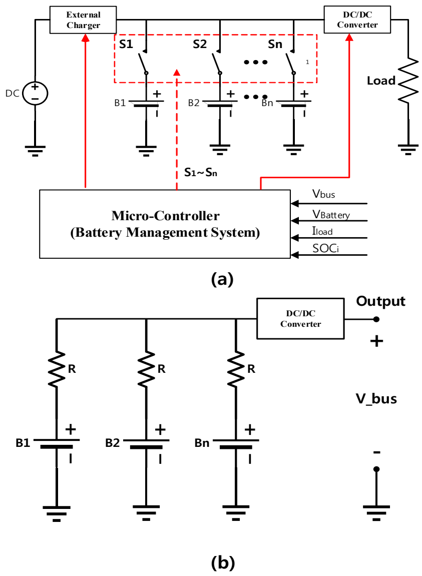

Figure 3. Conventional methods: (a) SOC based switch sequencing [3]; (b) fixed-resistance balancing [4].

The architecture in Fig. 3(b) is a simple equalization scheme which connects an external resistor in series with each battery cell. When the balancing resistance is larger than the impedance of battery cells, the battery inconsistency is nearly eliminated and the current of each battery branch become almost equal as (4). Despite this method is simple and easy to deploy, the current difference of each battery is inverse with a power loss of balancing resistor and the SOCs become unequal.

$$I_1 \approx I_2 \approx I_3 \approx \frac{I_{load}}{R} + \frac{OCV_1 - OCV_2}{R} \approx \frac{I_{load}}{R}; \quad (R \gg R_{b1}; R_{b2}; R_{b3}) \quad (4)$$

2.3. *Proposed method*

The proposed method adopts 2 resistors and 1 switch connected in series with each battery cell as in Fig. 4. By applying Coulomb counting techniques, the SOCs of all cells are estimated which is used to make the switching decision. A bi-directional converter is used to charge for the parallel battery or delivery energy from battery system to load. By controlling the switches, S1, S2, …, Sn, the impedance of the parallel branch is adjusted which changing the current of each branch.

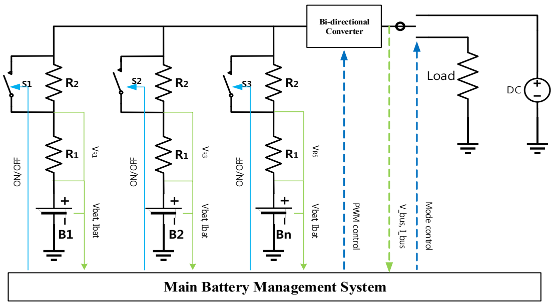

Figure 4. Proposed dynamic resistance balancing.

The branch current equation of the proposed method for 3 parallel-connected cells in the discharging process is calculated in (5), (6), and (7) where $Z_i(\min,\max) = [R_1, R_1 + R_2]$ with (i = 1, 2, 3). The operation process is divided to 3 intervals when all switches are turned ON in interval 1; only the corresponding switch of highest (in charging process) or lowest (in discharging process) SOC cell is turned OFF in interval 2, and all switches are turned ON again in interval 3. When $Z_1 = Z_2 = Z_3 = Z = R_1 + R_2$, the SOC of all cells is balanced.

$$I_1 = \frac{I*Z_3*Z_2}{Z_1*Z_3+Z_2*(Z_1+Z_3)} + \frac{OCV_1*(Z_1+Z_3)-OCV_2*Z_3-OCV_3*Z_2}{Z_1*Z_3+Z_2*(Z_1+Z_3)} \quad (5)$$

$$I_2 = \frac{I*Z_3*Z_1}{Z_2*Z_3+Z_1*(Z_2+Z_3)} + \frac{-OCV_1*Z_3+OCV_2*(Z_1+Z_3)-OCV_3*Z_1}{Z_2*Z_3+Z_1*(Z_2+Z_3)} \quad (6)$$

$$I_3 = \frac{I*Z_1*Z_2}{Z_1*Z_3+Z_2*(Z_1+Z_3)} + \frac{-OCV_1*Z_2-OCV_2*Z_1+OCV_3*(Z_1+Z_2)}{Z_1*Z_3+Z_2*(Z_1+Z_3)} \quad (7)$$

The interval 2 starts when the SOC of some cells are equal. Hence, the SOC comparison algorithm dynamically change the order of cells. As a result, the highest SOC cell is charged by the lowest current in the charging process and the lowest SOC cell is discharged by the lowest current in discharging process which leading to balance SOC of all cells. Finally, when the SOC of all cells are equal, all switches are turned ON again and the branch current becomes (8) where $Z_1 = Z_2 = Z_3 = Z = (R_1 + R_2)$. Thus, all currents of the parallel branch are equal at the end of the process.

$$I_1 = I_2 = I_3 = \frac{I*Z*Z}{Z*Z+Z*(Z+Z)} = \frac{I}{3} \quad (8)$$

3. SIMULATION RESULTS

To verify the proposed method, a simulation for four parallel-connected 18650 battery cells (3.7V/2.6Ah) has been performed in Matlab/Simulink. The simulation results are separately obtained for the charging and discharging processn then compared with conventional methods.

3.1. *Charging process*

In this test, it is assumed that all cells have the same capacity of 2600mAh but have different initial SOCs: $SOC_{1,2,3,4}$ = 5, 15, 10, 30 %. Battery system is charged by CC-CV charging method with 4A constant current and 4.2V constant voltage. The charging process is stopped when there is one cell reach 100% of SOC.

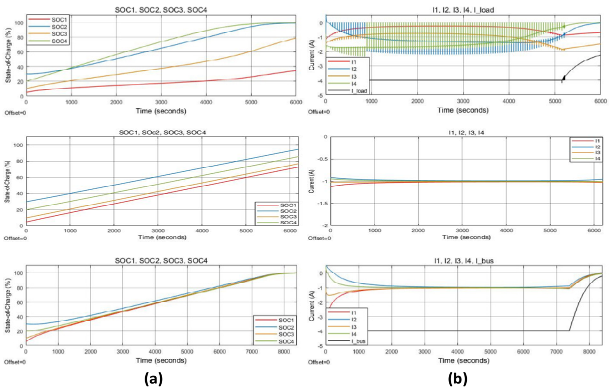

Figure 5. Charging process: (a) battery SOC; (b) battery current. (Top: conventional method I; Middle: conventional method II; Bottom: proposed method.)

The simulation results are shown in Fig. 5 which are compared with conventional methods. In both conventional methods (Fig. 5(a)-top and middle), the SOC of all cells is unequal when the charging process is stopped. On the contrary, the proposed method can balance the SOC by controlling the charging current of each parallel branch (Fig. 5(a)-bottom). Hence, all cells are fully charged when the process is stopped and the system capacity is maximally utilized.

With conventional method II, the branch currents in Fig. 5(b)-middle are equal most of the time while the inconsistency issue creates an unequal charging current in conventional method I. Moreover, Fig. 5(b)-top shows that the current spike appears whenever the switches commutates. This spike may generate additional internal heat dissipation which leading to thermal runaway issue. However, the proposed method as well as conventional method II (Fig. 5(b)-middle) controls the charging current (Fig. 5(b)-bottom); thus, prolonging the battery lifetime.

3.2. *Discharging process*

In this test, four parallel-connected battery cells are discharged with a constant current of 4A. Assume all cells have the same capacity of 2600mAh but different initial SOC of 80, 100, 90, and 70%. The simulation results of the proposed method are shown in Fig. 6(a) and (b)-bottom, which are compared with the conventional method I and II (Fig. 6(a) and (b) – top and middle).

In Fig. 6(a) and (b)-top, although all cells are fully discharged when the process is stopped, the current in each parallel branch are unequal. In addition, the discharging process in conventional method II have to be stopped before all cells are fully discharged (Fig. 6(a)-middle) and the remaining energy (10% capacity of cell #2, 20% of cell #3 and 30% of cell #1) are unused. On the contrary, the proposed method can utilize 100% of battery capacity (Fig. 6(a)-bottom) and the discharging current is confined to safety range (Fig. 6(b)-bottom). In other hand, due to the SOC comparison algorithm in the proposed method, the lowest SOC cell is facilitated to discharge with a lower current which can balance the SOCs. After 2000 seconds, SOC of cell #2 equal to that of cell #4, and then they are alternatingly discharged with the lowest current to maintain the balancing status. With the same scenario, the lowest current is alternatingly assigned for cell #2, #3, and #4 after SOC equalization. When the SOC of all cells are balanced, all switches are turned ON to evenly distribute the discharging current. As a result, the cell inconsistency issue is completely resolved and the lifetime of battery can be extended.

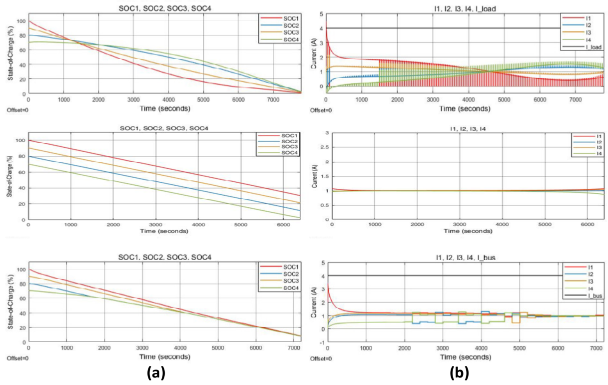

Figure 6. Discharging process: (a) battery SOC; (b) battery current. (Top: conventional method I; Middle: conventional method II; Bottom: proposed method.)

4. CONCLUSION

This paper proposes an equalization method for a parallel-connected battery using dynamic resistance techniques. Based on the SOC status and the load demand, the switches are controlled to modulate the impedance of the parallel branch which adjusts the branch current. The simulations show that all battery cells are fully charged when the charging process is stopped and 100% utilization of battery capacity is achieved in the discharging process. Moreover, the cell inconsistency issue of the parallel-connected battery is eliminated.

REFERENCE

[1] X. Gong, R. Xiong, C. C. Mi, *"Study of the Characteristics of Battery Packs in Electric Vehicles with Parallel-Connected Lithium-ion Battery Cells"*, IEEE Transactions on Industry Applications, Vol. 51, No. 2, March/April 2015.

[2] J. Qi, D. D. C. Lu, *"Review of Battery Cell Balancing Techniques"*, Australasian Universities Power Engineering Conference, AUPEC 2014, Curtin University, Perth, Australia. 28 September – 1 October 2014.

[3] C. Song, Y. Shao, S. Song, C. Chang, F. Zhou, S. Peng, and F. Xiao, *"Energy Management of Parallel-Connected Cells in Electric Vehicles Based on Fuzzy Logic Control"*, Energy 2017, 10, 404.

[4] M. Khatib, "Ballast resistor calculation—Current matching in parallel LEDs," Texas Instrument, Dallas, TX, Application Rep. SLVA325, 2009.