

Dynamic Resistance Battery Equalization for Capacity Optimization of Parallel-Connected Cells

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Abstract - This paper proposes a dynamic resistance equalization for parallel battery configuration, which can improve the equalization performance, optimize the battery capacity, and reduce loss dissipation. From the estimated SOC rate of battery cells, the switches in the equalization circuit are controlled to change the equivalent series impedance of individual branches, which regulates the current flow to maximize SOC utilization. The performance of the proposed technique is verified by simulations of a parallel connected configuration of four 18650 Li-ion battery cells with 3.7V/2.6Ah individually. The results show that the SOCs are balanced within 1% difference, all cells are fully charged or discharged at the same time, and the branch current is confined to safety range with less power dissipation over the conventional method.

Keyword: Battery equalization, dynamic resistance, state of charge (SOC), parallel-connected cells.

1. INTRODUCTION

In renewable energy application, battery cells are connected in series to increase the operating voltage. Even with the same operating condition, the behavior of battery cells in a series-connected configuration are different due to the uneven battery impedance and mismatched SOCs, which is so-called battery inconsistency. To address this issue, various battery equalization techniques for series-connected battery cells are reported in [1]. On the other hand, the parallel-connected configuration is used to increase the system capacity with extended working time. However, just a few studies about battery equalization for parallel-connected cells have been done, and parallel configurations are usually constructed by similar impedance battery cells relying too much on the self-balancing ability of parallel connection. Therefore, the battery inconsistency still exists and may cause the

unequal working current in parallel branches, which reduces the overall utilization of the battery system.

As a trend, capacity optimization for the battery system is becoming a key issue in the market, which requires an effective parallel equalization as well as series equalization. The characteristics of battery cells in a recent parallel application is reported in the literature [2]-[3], where the inconsistency becomes more serious during calendar aging as the impedance of battery cell changes.

To overcome this issue, fuzzy logic control is used in [4] to automatically adjust the number of cells attached to the DC bus in accordance with the load demand and SOC rate. However, the equalization performance is reduced as more battery cells are connected to the DC bus due to increased load demand. Another solution uses an additional resistor in series with each battery cells to relax the difference in the impedance of an individual cell. This method is popularly used due to its simplicity, low cost, and small size [5]. However, the efficiency is low due to power dissipation in the balancing resistor and the equalization performance is not satisfactory due to the difference between individual self-discharging rate. As a result, an improved equalization technique for parallel-connected battery configuration needs to be investigated.

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

2. PROPOSED ARCHITECTURE

2.1. Inconsistency issue in parallel battery configuration

To analyze the characteristic of the parallel-connected configuration, three parallel-connected battery cells are modeled in Fig. 1, where the current in each branch is calculated by (1), (2), and (3).

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

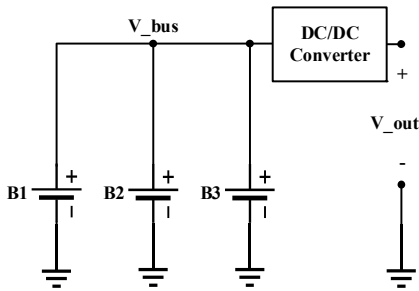
$$I_2 = \frac{I_{load} R_{b1} R_{b3}}{R_{b1}(R_{b2} + R_{b3}) + R_{b2} R_{b3}} + \frac{OCV_2(R_{b1} + R_{b3}) - OCV_1 R_{b3} - OCV_3 R_{b1}}{R_{b1}(R_{b2} + R_{b3}) + R_{b2} R_{b3}} \quad (2)$$

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

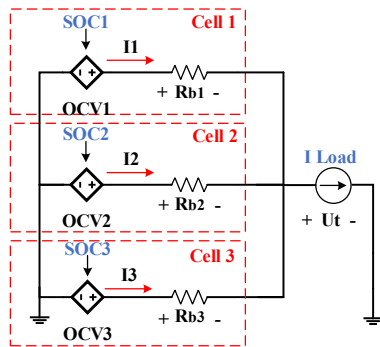
According to them, the branch current is dependent on the open circuit voltage (OCV_i) and the impedance of the battery cells (R_{bi}), all of which change during calendar aging. In addition, there is unregulated energy transfer between cells, which is so-called the self-balancing effect, even when the battery system is in idle mode. As a result, the battery may generate additional internal heat and cause over-charging or over-discharging risks.

2.2. Conventional equalization methods for parallel cells

Conventionally, a SOC-based switch sequencing in Fig. 2(a) alternately disconnects battery cells from DC bus to balance the SOC. A micro-controller unit (MCU) measures the bus voltage, the load current, and the SOC of battery cells to decide the switching order. When the load demand is higher than 1C rate, multiple battery cells are connected at the same time to prevent over-charging or over-discharging. Although the utilization of battery system increases, the cell

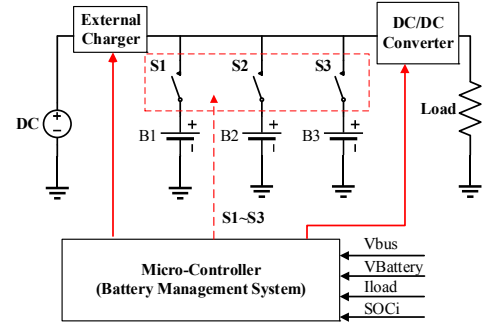


(a)

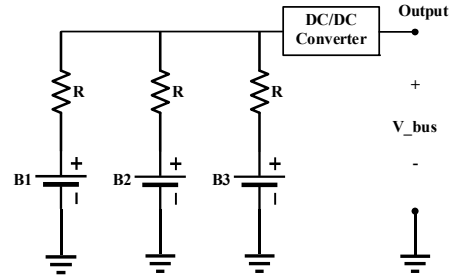


(b)

Figure 1: Parallel-connected battery network (a) three cells configuration; (b) equivalent model.



(a)



(b)

Figure 2: Conventional methods: (a) SOC based switch sequencing [4]; (b) fixed-resistance balancing [5].

inconsistency makes the equalization performance poor and a pulsating battery current flows at the switching instant due to the mismatched SOC.

Another equalization circuit in Fig. 2(b) adopts an external resistor in series with each battery cell. When the equalization resistance is sufficiently larger than the internal impedance of battery cells, the cell inconsistency can be nearly eliminated and the current of each parallel branch become nearly equal. However, achieving such a small current difference results in a large power loss in the equalization resistor. The equalization performance further decreases as the SOC become mismatched due to the unequal battery self-discharging rate.

2.3. Proposed equalization technique

The proposed equalization circuit in Fig. 3 adopts 2 resistors and 1 switch connected in series with each battery cell. By Coulomb counting method, the SOC of all cells are estimated and are used to decide the switching order. The bi-directional converter charges the battery or delivers energy from battery to the load. By controlling the switches, S_1, S_2, S_3 , the impedances of parallel branches are adjusted to regulate the current flow in each branch.

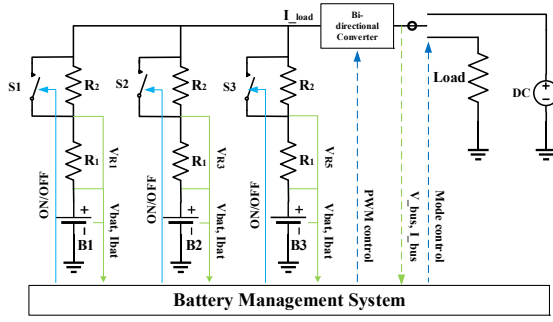


Figure 3: Proposed dynamic resistance equalization.

The equalization process is divided into 3 intervals. All switches are turned on during interval 1 and the highest and the lowest SOC cells are identified. Next, only the corresponding switch of the highest (in charging mode) or the lowest (in discharging mode) SOC cell is turned off provide a high impedance path to the branch. The current in each parallel branch during interval 1 is determined by (4), (5), and (6) where the branch impedances are given by $Z_i(t) = Z_{ON} = R_{bi} + R_1 + (R_{ds,ON})//R_2$ (when switches are turned on) or $Z_i(t) = Z_{OFF} = R_{bi} + R_1 + R_2$ (when switches are turned off) with $i = 1, 2, 3$.

Interval 2 start when the equalization is achieved in more than two cells. The corresponding switches are turned on and off alternatingly to regulate the branch currents and maintain the equalization status. When the SOC of all cells are equalized, all switches are turned on to provide a low impedance path to the branches during interval 3. The branch current is calculated by (7) where N is the number of parallel branches.

$$I_1 = \frac{I_{load} Z_2 Z_3}{Z_2(Z_1 + Z_3) + Z_1 * Z_3} + \frac{OCV_1(Z_2 + Z_3) - OCV_2 Z_3 - OCV_3 Z_2}{Z_2(Z_1 + Z_3) + Z_1 * Z_3} \quad (4)$$

$$I_2 = \frac{I_{load} Z_1 Z_3}{Z_1(Z_2 + Z_3) + Z_2 * Z_3} + \frac{OCV_2(Z_1 + Z_3) - OCV_1 Z_3 - OCV_3 Z_1}{Z_1(Z_2 + Z_3) + Z_2 Z_3} \quad (5)$$

$$I_3 = \frac{I_{load} Z_1 Z_2}{Z_2(Z_1 + Z_3) + Z_3 * Z_1} + \frac{OCV_3(Z_1 + Z_3) - OCV_1 Z_2 - OCV_2 Z_1}{Z_2(Z_1 + Z_3) + Z_3 Z_1} \quad (6)$$

$$I_1 = I_2 = I_3 = \frac{I_{load}}{N} \quad (7)$$

3. VERIFICATION OF THE PROPOSED METHOD

To verify the proposed equalization method, a simulation for parallel-connected four 18650 battery cells (3.7V/2.6Ah) has been implemented in Matlab/Simulink. The equalization resistor is set as $R_1=25m\Omega$; $R_2=1\Omega$ for the proposed method and $R=1\Omega$ for the conventional fixed-resistance balancing. The

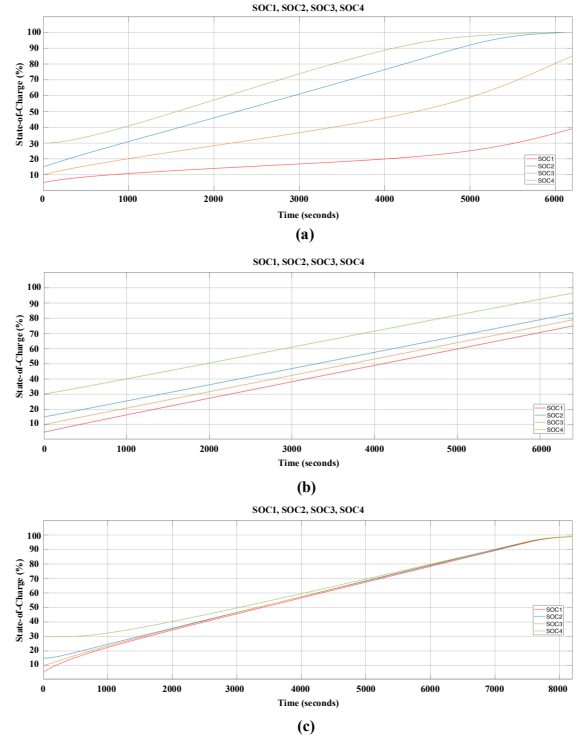


Figure 4: Charging process - battery SOC: (a) SOC based switch sequencing [4]; (b) fixed-resistance balancing [5]; (c) proposed method.

simulation results are separately obtained for a charging and a discharging process.

3.1. Charging process

It is assumed that all cells have the same capacity of 2600mA, but different initial SOC rates ($SOC_{1,2,3,4} = 5, 15, 10, 30\%$). The battery system is charged by CC-CV method (4A/4.2V). The charging process is stopped when one of the cells reaches 100% of SOC. The simulation results are shown in Fig. 4 and Fig. 5 which are compared with the conventional methods. The SOC profile in Fig. 4 shows that the charging process is forced to stop before all cells are charged in the SOC-based sequencing (Fig. 4(a)) and fixed-resistance balancing (Fig. 4(b)). On the contrary, the SOC of all cells are equalized and the charging process is stopped in the proposed method when all cells are fully charged at the same time (Fig. 4(c)). Thus, the system capacity is maximally utilized.

The current profile in Fig. 5 further explains the situation. Due to the inconsistency, the charging current is contributed unequally by the individual cell in the SOC-based sequencing method as in Fig. 5(a). Hence, cell #4 is fully charged first then the charging process is forced to stop. In the fixed-resistance balancing method (Fig. 5(b)), the branch currents are

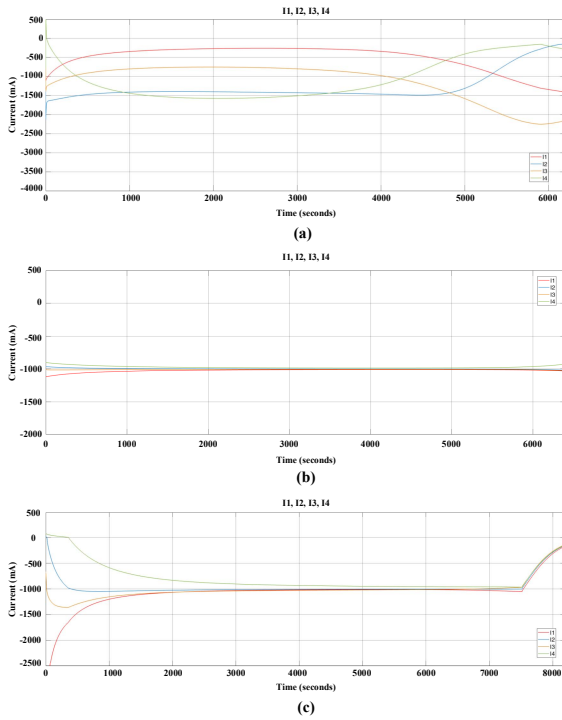


Figure 5: Charging process - battery current: (a) SOC based switch sequencing [4]; (b) fixed-resistance balancing [5]; (c) proposed method.

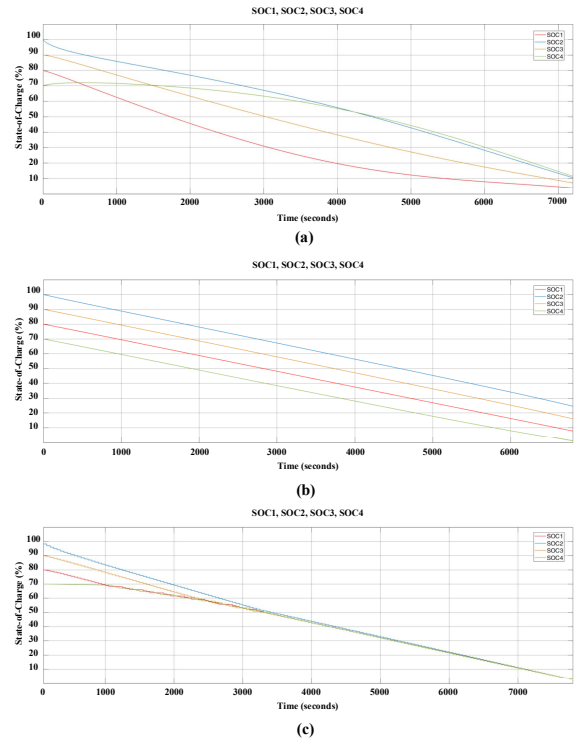


Figure 6: Discharging process - battery SOC: (a) SOC based switch sequencing [4]; (b) fixed-resistance balancing [5]; (c) proposed method.

maintained almost equal during the process. However, due to the mismatch of the initial SOC rate, cell #2 is fully charged first and the remaining capacity of the other cells are wasted. Moreover, the power loss in the resistor becomes too high, which reduces the system efficiency.

On the other hand, the current profile of the proposed method in Fig. 5(c) inherits the advantages of the two conventional methods. Branches currents are distributed according to the SOC level. Once the equalization is achieved, the individual branches deliver the same branches current.

3.2. Discharging process

In this process, the battery system is discharged with a constant current of 4A and the initial SOC_{1,2,3,4} = 80, 100, 90, 70%. The discharging process is stopped when any battery cell gets fully discharged. The simulation results are shown in Fig. 6 and Fig. 7.

The discharging process is forced to stop in the fixed-resistance balancing method, due to the mismatched initial SOC rate. Cell #4 is fully discharged (Fig. 6(b)), but the remaining energy (10% capacity of cell #2, 20% of cell #3 and 30% of cell #1) are unused. It is because it only allows an equal discharging current in the individual branch as shown

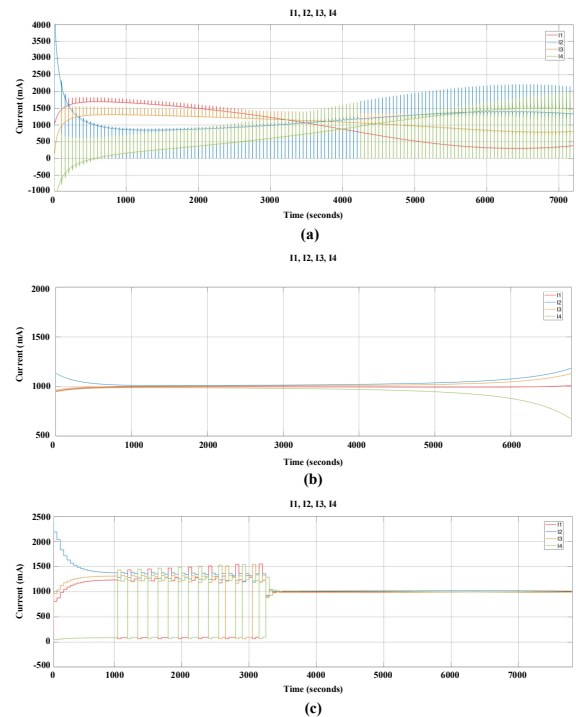


Figure 7: Discharging process - battery current: (a) SOC based switch sequencing [4]; (b) fixed-resistance balancing [5]; (c) proposed method.

in Fig. 7(b). Despite all cells are fully discharged at the same time, the currents of parallel branches are unequal (Fig. 6(a), and Fig. 7(b)) in the SOC-based sequencing method. In addition, there are current spikes at each switching time which increases the power loss. On the contrary, the proposed method can fully utilize the battery capacity (Fig. 6(c)) with the discharging currents are confined in the safety range.

The equalization algorithm is clearly described in the current profile in Fig. 7(c). Initially, battery cell #4 is facilitated to discharge with the lowest current (interval 1). At 2000 seconds, when SOC of cell #2 becomes equal to cell #4, the SOC comparison algorithm alternately discharge cell #2, and #4 with the lowest current to maintain the balancing status (interval 2). In the similar manner, the lowest current is assigned to cell #2, #3, and #4 successively. When the SOC of all cells are equalized with each other, all switches are turned on to evenly distribute the discharging current with the minimum power loss (interval 3). As a result, the cell inconsistency issue is completely eliminated and the battery capacity is maximally utilized.

3.3. Power loss comparison

Base on the simulation results, the power loss in the fixed-resistance balancing method and the proposed method are calculated and compared. In the conventional method, the root means square (RMS) current of each branch is calculated. The power loss in the equalization resistor is calculated by (8), where R is the equalization resistance, $i_i(t)$ is the current in the i^{th} individual branch.

In the proposed method, the switching decision is recorded to calculate the individual branch impedance at each time. The average power loss in the equalizer circuit is calculated by (9) with $i_i(t)$ is the measured current of each branch; $Z_i(t)$ is the impedance of each branch resistance; and T is the total working time.

The calculated power loss is compared in Table I. The results show that power loss in the proposed method is only 1/19 (in discharging process) and 1/40 (in charging process) of that in the conventional method.

$$P_{loss} = \sum_{i=1}^N \frac{R}{T} \int_0^T i_i^2(t) dt \quad (8)$$

$$P_{loss} = \sum_{i=1}^N \frac{\int_0^T i_i^2(t) Z_i(t) dt}{T} \quad (9)$$

Table I: power loss comparison

| Process | P_{loss} | Conventional method II | Proposed method |
|---------------------|-------------|------------------------|-----------------|
| Charging process | $P_1(W)$ | 1.0451 | 0.0312 |
| | $P_2(W)$ | 0.9959 | 0.0237 |
| | $P_3(W)$ | 1.0164 | 0.0268 |
| | $P_4(W)$ | 0.9447 | 0.0177 |
| | $\sum P(W)$ | 4.0022 | 0.0994 |
| Discharging process | $P_1(W)$ | 0.9886 | 0.0676 |
| | $P_2(W)$ | 1.0655 | 0.0340 |
| | $P_3(W)$ | 1.0264 | 0.0384 |
| | $P_4(W)$ | 0.9247 | 0.0627 |
| | $\sum P(W)$ | 4.0052 | 0.2027 |

3.4. Equalization performance

The equalization performance of the conventional and the proposed method in both charging and discharging process are evaluated by the SOC difference between cells during the equalization process. The comparison of equalization performance is shown in Fig. 8. In the SOC-based sequencing method, battery cell SOC are unequal and the SOC difference also becomes larger during the working process in both charging and discharging process. Because the fixed-resistance balancing method only maintains the equal branch current, the SOC difference is unchanged during the process. On the contrary, the proposed method controls the equalization process such that the SOC difference decreases time after time. To obtain a SOC difference of 5%, the proposed method takes about 2000 seconds (in charging process) and 2800 seconds (in discharging process). It means that the equalization speed of the proposed method is faster than the conventional methods. Besides, the SOC difference of proposed method approaches zero in the end of the charging and discharging process.

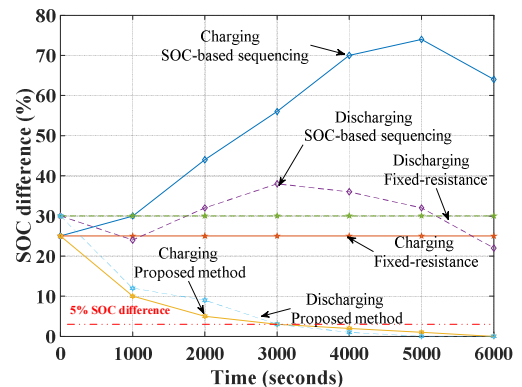


Figure 8: Equalization performance comparison

4. CONCLUSION

This paper proposes an equalization method for parallel-connected battery configuration using dynamic resistance technique. Based on the SOC status of battery cells, the switches are controlled to modulate the impedance of the parallel branches adjusting the branch current. The simulation shows that the battery capacity is maximally utilized in the discharging process and all cells are fully charged at the same time in the charging process. Consequently, the cell inconsistency issue is eliminated, which prolongs the battery life as well.

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