Research on a balanced circuit and control strategy

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Abstract

For reducing the inconsistent state of charges (SOC) of lithium-ion battery cells and making the full use of battery packs, effective battery balancing technology should be used. In order to achieve the goal of balancing any single cell in the battery pack expeditiously and considering the cost and the balance efficiency, a balanced circuit is proposed. By changing the action state of single-pole double-throw relay connected to each of the single cell battery, the balanced single-cell battery is in a state of non-load power supply, at this point, the balanced battery is in ‘charging’ state compared with other batteries in the battery pack, thus achieving the balance target of the battery pack. On this basis, this paper also proposes a new balancing control strategy; it is different from the traditional control strategy to balance the SOC of the single cell to the SOC average of the battery pack, considering the different SOC change rates of the cells with different capacity in the battery pack. The balanced control strategy proposed in this paper allows the set condition of the single cell to end the equilibrium process in advance so as to reduce the unnecessary balance time and then improve the equilibrium speed. In order to verify the feasibility of the proposed circuit and control strategy, 18650 batteries with different initial SOC in series are experimentally verified. The experimental results show that the balanced circuit proposed in this paper can well balance the cell of each single cell and make the battery pack reach a balanced state.

Keywords: battery equalization; 18650 cell; single-pole double-throw relay; equalization strategy

1. INTRODUCTION

Lithium-ion batteries are widely used because of their excellent performance [10]. However, a single lithium-ion battery has low voltage and capacity. It is usually necessary to connect multiple batteries in series to meet load voltage and power requirements [3]. In order to improve the capacity of the battery and reduce the risk of cell overcharge or overdischarge, it is necessary to balance the lithium-ion battery pack [4, 7, 14].

Passive equalization is widely applied, but there are some disadvantages such as energy waste and difficulty in heat management [12]. The performance of the traditional active equilibrium circuit is not good [13, 15]. Zheng et al. [16] put the equalizer in different layers to improve the speed and efficiency of equalization, but the cost is high. Morstyn et al. [11] used the oscillator circuit resonant circuit to achieve a faster balancing speed, but it is not convenient to balance any single cell in the battery pack. Kim and Lee [8] used bi-directional flyback converter, which can balance battery more conveniently, but the equilibrium speed is slower. Kim et al. [9] assigned different force coefficients for each battery and balanced the arbitrary single-cell battery in the battery group. It has a good performance in equilibrium efficiency and equilibrium speed but the cost is high. For the balancing method, [1, 5, 6] usually balances the state of charges (SOC) to the target.

An equalization circuit is proposed in this paper. By controlling the operation state of the single-pole double-throw (SPDT) relay, the battery pack can be well balanced. At the same time, considering that the battery capacity in the battery group are different compared with the traditional equilibrium method, there is a certain margin where the battery is balanced and the balance speed
is accelerated indirectly on the premise of achieving the balance of the battery group. The experiment is carried out to verify the feasibility of the equalization circuit and the equalization method.

2. ANALYSIS OF EQUILIBRIUM CIRCUIT

2.1. Equilibrium circuit

Figure 1 shows a balanced circuit containing N cells. B1 corresponds to the SPDT relay K1, which determines whether the B1 is supplied to the load. B2 corresponds to the SPDT relay K2, which determines whether the B2 is supplied to the load, and so on.

For the convenience of expression, as shown in Figure 2, all the SPDT relays are normally closed on the left side (normal connected (NC)), the right is normal open (NO), the middle is the common terminal (common (COM)). When an SPDT relay does not receive the trigger instruction, the COM is connected with the NC. When the SPDT relay receives the trigger instruction, the COM terminal is connected to the NO terminal.

As shown in Figure 1, under normal circumstances, the anode of each single cell is connected to the NC terminal of the corresponding SPDT relay. By controlling the operation state of the SPDT relay corresponding to each single cell, it is possible to decide whether the single battery is supplied to the outside power. So as to control the change of the SOC value of the corresponding single cell, and ultimately achieve the purpose of equalization for the battery pack.

2.2. Analysis of working principle

In order to facilitate the analysis of the working principle of the balanced circuit, it is assumed that the SOC value of B1 in the battery group is low and needs to be balanced; the SOC value of the other batteries is higher and does not need to be balanced. In order to achieve the target of balancing B1, only change the action state of SPDT relay K1 corresponding to B1, so that the COM terminal of the SPDT relay K1 is connected to the NO terminal, as shown in Figure 3.

As shown in Figure 3, all batteries except B1 are supplied for load. It can be considered that B1 is in the 'off' state at this time. During this period, the SOC value of B1 remained unchanged while the SOC value of other batteries gradually decreased. Take B2 as an example, when B1 is in the 'disconnected' state.
The variation of the SOC value of B2 battery:

\[
\Delta SOC_{B2} = -\frac{1}{Q_{B2}} \int_{0}^{T} I_{out} \, dt,
\]

where

- \(\Delta SOC_{B2}\) is the SOC change of B2 battery;
- \(Q_{B2}\) is the capacity of B2 battery (Ah);
- \(T\) is the equilibrium time (h);
- \(I_{out}\) is the current provided by the battery pack for the load (A).

The minus sign indicates that the SOC value of B2 is declined. It can be understood that the SOC value of B2 varies from 0 to \(T\) is \(\Delta SOC_{B2}\) and the SOC value of B1 is 0. In turn, if the SOC value variation of B2 is 0 and the SOC value variation of B1 is shown in (2).

The variation of the SOC value of the B1 battery:

\[
\Delta SOC_{B1} = -\frac{Q_{B2}}{Q_{B1}} \Delta SOC_{B2},
\]

where

- \(\Delta SOC_{B1}\) is the SOC change of B1 battery;
- \(Q_{B2}\) is the capacity of B2 battery (Ah);
- \(Q_{B1}\) is the capacity of B1 battery (Ah);
- \(\Delta SOC_{B2}\) is the SOC change of B2 battery.

The minus sign indicates that the SOC value of B1 is in an ascending state compared to B2 at 0 to \(T\). It can be understood that between 0 and \(T\), the other batteries are not discharged, while B1 is in a ‘charging’ state. If the SOC value of B1 is \(SOC_{B1}\) before equalization, the SOC value of the B2 is \(SOC_{B2}\). To make the SOC value of the B1 and the SOC value of the B2 reach the same level, for B1, it is necessary to ‘charge’ \(Q_n\) as shown in (3).

\[Q_n \text{ should be ‘charged’ of B1 battery:}\]

\[
Q_n = Q_{B1} (SOC_{B2} - SOC_{B1}),
\]

where,

- \(Q_n\) is the B1 capacity change battery (Ah);
- \(Q_{B1}\) is the capacity of B1 battery (Ah);
- \(SOC_{B2}\) is the initial SOC of B2 battery;
- \(SOC_{B1}\) is the initial SOC of B1 battery.

When the SOC value of B1 reaches the set equilibrium completion condition, the COM terminal of the SPDT relay K1, which corresponds to the B1 battery, is connected to the NC terminal, ending the equalization process of the B1 battery.

Through the analysis of the balance process of the B1 battery, the balanced circuit proposed in this paper is to balance the corresponding single cell by changing the action state of the SPDT relay, so that the circuit can balance the battery of any single cell in the battery pack more conveniently. At the same time, it can be seen that, because there is no energy transfer process, it will not exist in the traditional active equilibrium circuit, when the battery pack is balanced, the loss is unavoidable and the equilibrium efficiency is not ideal. Therefore, the equilibrium efficiency can be close to the ideal value of the traditional active equilibrium circuit.

3. EQUILIBRIUM METHOD

Huang and Qahouq [6] show the following:

The SOC change of battery:

\[
\frac{\Delta SOC}{\Delta T} = \frac{I}{Q},
\]

where

- \(\Delta SOC\) is the SOC variation of the battery;
- \(\Delta T\) is the time variation (h);
- \(I\) is the current of the battery (A);
- \(Q\) is the capacity of the battery (Ah).

For each series battery, the SOC change rate of each battery is only related to its capacity Q. If the SOC value of B1 is larger than B2, the capacity Q is smaller. The SOC change of the two batteries when B2 is balance is shown in Figure 4.

The traditional equalization method will make the equalization circuit work to \(T_1\). But as shown in Figure 3, after \(T_1\), the dif-
Table 1. Battery capacity.

| Battery labeling | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|------------------|-----|-----|-----|-----|-----|-----|-----|
| Capacity, mAh    | 1214| 1122| 1206| 1187| 1214| 1247| 1225|

The difference between the SOC of B2 and B1 will gradually increase. At T2, if the difference between the SOC of B1 and B2 is equal, the equalization of B2 at T0 to T1 is unnecessary. Considering the battery parameters obey the normal distribution [2], when the equilibrium process of the battery is finished at the end of T0, about half of the battery will change to the target value because of the difference of the battery capacity.

In Figure 4, if the current at the time of 0 to T1 are not changed much, compared to T1, the equilibrium process of the balanced battery at the end of the T0 can save some time. In general, compared to the entire battery group, there are:

The equilibrium speed increased:

\[ V_{up} = \frac{T_0 - T_1}{2} \times 100\% \]

where

- \( V_{up} \) is the speed increased;
- \( T_0 \) is the time at T0 (s);
- \( T_1 \) is the time at T1 (s).

Obviously, the equilibrium method proposed in this paper can accelerate the equalization speed indirectly under the premise of achieving the goal of battery pack equalization.

4. EXPERIMENTAL VERIFICATION

4.1. Experimental preparation

The experiment uses 3.7 V, 1200 mAh nominal capacity and 18 650 batteries. Seven batteries are labeled, from 1 to 7. The Arbin instrument was used to measure the capacity of the seven batteries. As shown in Figure 5.

Seven batteries used in the experiment are tested in the thermostat according to the following steps, of which the temperature of the thermostat is set to 25°C:

1. Charge the battery to 4.2 V at 0.5 C, then charge the battery at 4.2 V until the battery charging current is less than 0.02 C.
2. Discharge the battery to 3 V at 0.5 C, then discharge the battery at 3 V until the discharge current of the battery is less than 0.02 C.
3. Collect the capacity of batteries.

The capacity of the seven cells is shown in Table 1.

As shown in Table 1, even if the seven batteries have a capacity of 1200 mAh, the real capacity is also quite different.

After collecting the capacity of the seven batteries, a balanced experiment is conducted for these batteries. The equilibrium experimental diagram is shown in Figure 6.

The microprocessor we used is STM32F103, and the SOC of the seven batteries is estimated by the ampere integral method, which was displayed on the 3.2-inch TFT screen. The equalization is started when the difference between the maximum and minimum SOC of the battery pack is greater than 1%. The initial SOC of the seven cells used in the experiment is as shown in Table 2.

In the equalization process, the SOC value of the seven batteries is recorded every 10 s, and the time for the balance of the start and end of the battery in the battery group and the SOC value of the seven batteries at this time are recorded.

Table 2. Initial battery SOC.

| Battery labeling | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|------------------|-----|-----|-----|-----|-----|-----|-----|
| SOC, %           | 79.9| 80  | 79.8| 78.9| 79.7| 78.8| 79.9|

Figure 6. Balance experiment.

Figure 7. Experimental results use traditional balance methods.
4.2. Analysis of experimental results

When using the traditional equalization method, it is considered that the SOC value of the balanced battery can hardly be completely equal to the set target value, and the balance ends when the difference between the SOC value of the balanced battery and the set target value is less than 0.01%. At this point, the seven batteries’ SOC changes as shown in Figure 7.

As shown in Figure 7, the difference of SOC between batteries 2 and 6 reaches the setting condition; all batteries except battery 6 are loaded. Battery 6 is balanced at 75 s. Battery 4 is balanced in the same way until 143 s. At this point, the battery pack reaches a set equilibrium state and ends at equilibrium.

It can be seen that this circuit uses only seven relays, which completes the process of balancing the seven batteries. Because there is no transfer process of energy in the equilibrium process, the equilibrium conversion efficiency is ideal. Moreover, it can be seen that the balance of battery 6 or battery 4 only needs to control the relays related to the balanced battery, and the balance is more convenient.

In order to prove the superiority of the proposed equalization method, we use this equilibrium method to carry out the experiment again. That is to say, when the difference between the maximum and minimum SOC of the battery pack is greater than 1%, the balance will be started until the difference between the two SOC is less than 0.5%. At this point, the SOC change of the seven cells is shown in Figure 8.

As shown in Figure 8, battery 6 reaches the set conditions at 45 s and battery 4 reaches the set conditions at 79 s; the equilibrium process ends.

The definition of $X$:

$$X = SOC_2 - SOC_6, \quad (6)$$

where

Table 3. The value changes of $X$ and $Y$.

| t/s | X, % | Y, % |
|-----|------|------|
| 0   | 1.2  | 1.1  |
| 45  | 0.5  | 1.06 |
| 79  | 0.43 | 0.5  |
| 160 | 0.3  | 0.42 |

- SOC$_2$ is the SOC values of battery 2;
- SOC$_6$ is the SOC values of battery 6.

The definition of $Y$:

$$Y = SOC_2 - SOC_4, \quad (7)$$

where

- SOC$_2$ is the SOC values of battery 2;
- SOC$_4$ is the SOC values of battery 4.

At 0, 45, 79 and 160 s, the changes of X and Y are shown in Table 3.

As shown in Table 3, although the equilibrium method proposed in this paper does not balance the SOC value of batteries 4 and 6 to the target value, these batteries will gradually tend to ideal equilibrium over time, basically reaching the target of battery pack equilibrium.

When using the traditional equalization method to balance the battery, it takes 143 s, compared to 79 s we used. The equilibrium method proposed in this paper reduces the equilibrium time of 64 s and increases the equilibrium speed of about 44.8%.

5. CONCLUSION

The equalization circuit proposed in this paper can well balance the battery pack. Compared with the traditional equilibrium method of equalizing the SOC of the battery to the target value, the equilibrium method proposed in this paper take full account of the different battery capacities in the battery group. Therefore, by keeping the corresponding margin, the equilibrium speed can be improved on the premise of achieving the goal of equalization.

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