Research on battery pack dynamic equalization technology with improved flying capacitor

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Abstract

Aiming at the problem that the traditional flying capacitor equalization circuit has long equilibrium time and complicated structure, based on the in-depth study of the existing capacitor equalization method, this paper proposes a bidirectional DC-DC equalization circuit topology based on switch matrix. Structure, improve circuit switch network structure, reduce the number of switches and capacitors in the circuit, simplify the equalization structure, combined with the advantages of bidirectional DC-DC converters can be used in both directions, according to the difference between the average voltage of the battery pack and the voltage of each cell. Any two cells in the battery pack are used for equalization purposes. By establishing an experimental test platform verification, the results show that the topology can reduce the equalization time under the premise of simplifying the circuit structure when equalizing any two cells.

Keywords: active equalization; flying capacitor method; DC-DC converter; equilibrium time

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Received 28 February 2020; revised 10 April 2020; editorial decision 15 June 2020; accepted 15 June 2020

1. INTRODUCTION

Lithium-ion batteries are widely used in electric vehicles due to their high energy density, long cycle life and low self-discharge rate [1]. However, the lithium-ion battery has a low voltage and a small capacity and usually needs to be connected in series and parallel to meet the needs of electric vehicles [2]. And because cannot guarantee the consistency of parameters of lithium-ion batteries during the production [3], the performance of the battery pack is restricted by the worst-case cell due to the barrel effect [4] and due to the environmental temperature during use. The difference causes the consistency of the battery pack to deteriorate, resulting in a decline in the available capacity of the battery pack and reducing its service life [5]. Equalizing the battery pack can solve this problem well [6].

Equalization circuits for series battery packs are mainly divided into passive equalization and active equalization [7]. Passive equalization is mainly the parallel resistance between the two ends of every single cell in a battery pack, which reduces the voltage difference between the cells through the power loss of the high-voltage single cell on the battery [8–9]. This method is simple, but due to the energy loss in the resistor, the available energy of the battery cell is reduced, which causes the energy loss of the battery pack. Active equalization mainly uses the energy storage components such as capacitors or inductors to increase the voltage. The capacity of cell is transferred to a low-voltage cell, which has a fast equalization speed and can minimize energy waste [10].

At present, the common equalization circuit structures include a switched resistance method, a flying capacitor equalization method, an inductance equalization method, a DC-DC bidirectional converter method and a multi-output transformer method [11–13]. Among them, the switch resistance method can only be used in the voltage equalization of the charging process, and the resistance will cause the energy loss of the battery pack. Wang et al. [14] uses the DC-DC converter equalization circuit. This method has the advantages of high equalization efficiency and fast speed but has a high cost and complicated control. This type of method is generally used in adjacent battery equalization circuits with a small number of cells and is not suitable for large-scale battery pack equalization. Ouyang et al. [15] used a forward converter circuit to speed up the equalization speed and improve the equalization efficiency, but the circuit structure is too complicated, the additional degaussing circuit and coil leakage...
inductance will cause electromagnetic compatibility problems, and the control strategy is relatively complicated. The flying capacitor method has the advantages of simple structure, low energy loss and can be balanced in the charging and discharging process. It is a widely used balancing method at present.

Aiming at the advantages of the existing equalization circuit, based on the study of the flyover capacitor method, this paper proposes a flyover capacitor equalization circuit including a capacitor and a bidirectional DC-DC converter by improving the circuit structure design. Through the switch array and bidirectional DC-DC converter, the circuit is simplified, the equalization efficiency is improved and the goal of cross-cell equalization is achieved. Experimental verification confirms the feasibility of the method.

2. BALANCED TOPOLOGY

2.1. Flying capacitor method topology

As shown in Figure 1, the B1 to B4 switch network structure is composed of four switches K1 to K4 and capacitors C1 to C3. By controlling the closed state of the switch to make the capacitor work in parallel with the battery, the cell with a higher voltage will store the charge in the capacitor and transfer it to the cell with a lower voltage, thereby achieving the battery pack voltage. This circuit has a simple structure and high equalization efficiency. Since the switches K1 to K4 can only be closed and connected to each of the upper and lower sides when S1–S4 is connected to the upper side, B1–B3 are connected to C1–C3. When S1–S4 is connected to the lower side, B2–B4 are connected in parallel to C1–C3, respectively, and all the cells are balanced by repeating these two states. However, when the two cells that need to be balanced are far apart, it will lead to an increase in time, more components required and difficulty in achieving cross-cell equalization [16].

On the basis of improving the flyover capacitance method, the appearance of a double-layer flyover electric equalization circuit shortens the equalization time while ensuring equalization efficiency [17–18]. As shown in Figure 2, the circuit operation and control method are the same as the traditional switched capacitor equalizer. The main difference from the traditional flyover capacitor equalization circuit is that the second layer capacitors C4 and C5 are connected in parallel with the existing first layer capacitors C1–C3. With the second layer capacitor, charge exchange between non-adjacent cells can be performed in one switching cycle. For example, C4 can exchange charges between B1 and B3 in Figure 2. Therefore, the charge is transferred to the remote unit with a small number of switching cycles. As a result, the equalization time can be reduced.

2.2. Equilibrium structure of improved flying capacitor method

Because the double-layer flyover electric equalization circuit can exchange charge between non-adjacent cells in one switching cycle only through the second layer capacitor, when there are more batteries in series, it will cause an increase in the number of switches and equalization capacitors. Losses and equalization times in the circuit increase [19]. The improved flying capacitor equalization circuit topology proposed in this paper can solve this problem. As shown in Figure 3, in an N-cell cells series circuit, K + 1 switches are connected at the beginning and end of each cell, and the switch network structure is formed with four bipolar switches S1–S4. A bi-directional DC-DC converter cooperates with bipolar. The switch realizes the dual use of the switch, avoids the simultaneous closing of the switch in the traditional circuit, reduces the number of equalization capacitors and switches, thereby reducing the energy loss and equalization time in the circuit structure and can achieve the goal of cross-battery equalization.

3. WORKING PRINCIPLE

As shown in Figure 4, the working principle of the bidirectional DC-DC circuit is that when the switch S1 is always in the off state, the switch S2, the diode VD1 and the inductor and capacitor form a boost circuit. Similarly, when the switch S2 is always off, the switch S1, the diode VD2 and the inductor and capacitor form a buck circuit.

As shown in Figure 3, assuming the average voltage \( V_0 \) of the battery pack, the voltage \( V_1 > V_0 \) of the cell B1 at this time, the cell B1 needs to be balanced at this time, and its charge is transferred...
to the balancing capacitors C3 and C4. The switches S1 and S4 that control the polarity and the switches K1 and K2 of the positive and negative poles of the B1 cell is closed. The bidirectional DC-DC converter works in the boost circuit mode, and the charge is stored in the equalizing capacitor C3 and C4 through the bidirectional DC-DC converter.

When the voltage $V_2 < V_0$ of the B2, the B1 needs to be balanced, and the balancing capacitors C3 and C4 are used to charge it. At this time, the switches S2 and S3 controlling the polarity and the switches K2 and K3 connected to the positive and negative poles of the cell are closed. The bidirectional DC-DC converter works in buck circuit mode, and the charge will be transferred from the equalizing capacitor through the bidirectional DC-DC converter. C3 and C4 are transferred to B2.

When balancing the B1 and B2, switch K2 is used. The switch K2 can control both the balance of the B1 and the balance of the B2. Similarly, when any two cells need to be balanced, this circuit can be used. After the DC-DC converter is added, the equalization capacitor can be used to discharge and equalize any one high-voltage cell at any time or charge balance the low-voltage cell.

### Table 1. The parameters of simulated batteries.

| Parameter                  | Value |
|----------------------------|-------|
| Rated voltage              | 3.7 V |
| Capacity                   | 3 Ah  |
| Internal resistance        | 20 mΩ |
| Charge cut-off voltage     | 4.2 V |

### EXPERIMENTAL VERIFICATION ANALYSIS

Set up a balanced test platform containing four 18650-type lithium-ion batteries for verification and use four cells in series as a battery pack. The battery parameters are shown in Table 1.

The control chip selects the STM32F407 microcontroller and generates a pulse modulation (PMW) control signal. According to when the Vin terminal is a single cell and the Vout terminal is two capacitors, the duty cycle of the PWM control signal to the switching device is close to 50%.

In order to facilitate the recording of experimental data, the initial voltages of the four single-cells are charged and discharged to 3.6 V, 3.2 V, 3.2 V, 3.2 V, respectively. The two indicators for judging the effect of equilibrium in this paper are the equilibrium energy efficiency and the equilibrium time. According to national standards, when the difference between the voltage of the cell and the average voltage reaches 36 mV, the equilibrium begins. In practice, in order to prevent the occurrence of repeated equalization caused by the difference in capacity, for example, the cell will equalize to an average value at its high voltage, but its voltage will be lower than the average after a period of discharge, this state of repeated equilibrium will result in wasted energy. According to the definition of voltage standard deviation $\sigma$:

$$
\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (V_i - V)^2}
$$

(1)
Figure 5. Battery pack voltage change process of traditional flyover capacitor equalization circuit.

Figure 6. Battery pack voltage change process of double-layer capacitor flying capacitor balancing circuit.

Figure 7. Battery pack voltage change process of improved flyover capacitor equalization circuit.

As shown in Figure 5, in the conventional flying capacitor circuit, the charges in the B1 can be transferred to the B2, B3 and B4 at the same time, and the equilibrium voltage differences are equal. Therefore, the voltage rises rates of the B2, B3 and B4 are the same. The battery pack is balanced in about 314 seconds.

As shown in Figure 6, in the double-layer flying capacitor equalization circuit, due to the existence of new equalization capacitors C4 and C5, the charge stored in C4 is transferred to B2 and B3, and the charge stored in C5 is transferred to B3 and B4. The transfer, because the voltage difference between the four cells is the same, so the voltage of B3 rises the fastest, and the voltage of B2 and B4 rises slightly slower, but the rise rate of both is the same, reaching the equilibrium state in about 162 seconds.

As shown in Figure 7, in the improved flying capacitor circuit, it can be seen that the voltage of the B1 is first dropping and is in a state of discharge equilibrium. Due to the setting of equalization interlock, even if B2 needs to be balanced, it can only start after B1’s equalization is completed. After about 47 seconds, B1 reaches the equilibrium state. At this time, B2 starts to balance. By about 79 seconds, B2 reaches the equilibrium state. Similarly, B3 reaches the equilibrium state at about 112 seconds. Finally, four batteries overall equilibrium is reached at about 143 seconds.

Comparing and analyzing the equalization time of the three circuits shown in Tables 2–4, it can be seen that, because the traditional flyover capacitor equalization circuit switches K1–K4 can only be closed and connected to each of the upper and lower sides, the number of equalization times increases and it takes the equilibrium longer time. In the double-layer flyover capacitor equalization circuit, under the action of the second layer capacitors C4 and C5, the charge transfer path in the circuit is increased, the transfer path is halved, and the equalization time of the traditional flyover capacitor equalization circuit is reduced by nearly 50%. Under the premise of achieving cross-cell equalization, the improved flyover capacitor equalization circuit is basically the same as the equalization time of the double-layer flyover capacitor equalization circuit, and it is shortened by nearly 50% compared with the traditional flyover capacitor equalization circuit. The improved flyover capacitor equalization circuit has the characteristics of less component use and cross-battery equalization. When the number of cells is large in practice, the reduction of the equalization time and the reduction of circuit losses will have more obvious effects.

5. CONCLUSION

Aiming at the problems of traditional flyover capacitive equalization circuits with slower equalization speed and complicated
Table 2. Traditional flying capacitor method.

| Time(s) | Battery voltage (V) | Circuit action |
|---------|---------------------|----------------|
|         | B1  | B2  | B3  | B4  |               |
| 0       | 3.598 | 3.198 | 3.201 | 3.199 | No action     |
| 75      | 3.483 | 3.247 | 3.248 | 3.247 | B1 B2 B3 B4 simultaneous equilibrium |
| 150     | 3.417 | 3.274 | 3.272 | 3.275 | B1 B2 B3 B4 simultaneous equilibrium |
| 230     | 3.354 | 3.283 | 3.284 | 3.282 | B1 B2 B3 B4 simultaneous equilibrium |
| 314     | 3.295 | 3.293 | 3.292 | 3.293 | Complete equilibrium |

Table 3. Double-layer capacitor flying capacitor method equalization process.

| Time(s) | Battery voltage (V) | Circuit action |
|---------|---------------------|----------------|
|         | B1  | B2  | B3  | B4  |               |
| 0       | 3.599 | 3.198 | 3.201 | 3.199 | No action     |
| 37      | 3.463 | 3.265 | 3.267 | 3.251 | B1 B2 B3 B4 simultaneous equilibrium |
| 75      | 3.397 | 3.281 | 3.279 | 3.275 | B1 B2 B3 B4 simultaneous equilibrium |
| 120     | 3.341 | 3.287 | 3.288 | 3.284 | B1 B2 B3 B4 simultaneous equilibrium |
| 162     | 3.294 | 3.292 | 3.290 | 3.291 | Complete equilibrium |

Table 4. Improved flying capacitor method equalization process.

| Time(s) | Battery voltage (V) | Circuit action |
|---------|---------------------|----------------|
|         | B1  | B2  | B3  | B4  |               |
| 0       | 3.601 | 3.201 | 3.199 | 3.198 | No action     |
| 25      | 3.397 | 3.201 | 3.199 | 3.198 | B1 discharge equalization |
| 47      | 3.301 | 3.200 | 3.199 | 3.198 | B1 ends equalization, B2 starts charging equalization |
| 62      | 3.301 | 3.278 | 3.198 | 3.199 | B2 ends equalization, B3 starts charging equalization |
| 81      | 3.300 | 3.299 | 3.199 | 3.198 | B3 ends equalization, B4 starts charging equalization |
| 112     | 3.299 | 3.298 | 3.298 | 3.198 | B4 charging balance |
| 128     | 3.299 | 3.297 | 3.298 | 3.279 | Complete equilibrium |
| 143     | 3.299 | 3.297 | 3.298 | 3.298 | Complete equilibrium |

structure when there are a large number of batteries, a bidirectional DC-DC type equalization circuit topology based on a switch matrix is proposed to improve the circuit switch network structure and reduce the circuit. The number of switches and capacitors simplifies the equalization structure and combines the advantages of a bidirectional DC-DC converter that can be used in both directions. According to the difference between the average voltage of the single cell and the battery pack to measure whether the battery in the battery pack reaches the equilibrium state. Compared with the traditional flyover capacitor circuit structure and the double-layer flyover capacitor equalization circuit, experimental results confirm that the topology can achieve the purpose of cross-cell equalization while simplifying the circuit structure, and reduce the equalization time.

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