Research and Design of Active Equalization System for Multi-stage Series Li-ion Battery

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Abstract: In view of the obvious phenomenon of the difference between the single cells of the series battery pack after multiple cycles of recycling, it is necessary to adopt balanced control to extend the working life of the battery pack, improve the energy utilization rate, and ensure the safety and stability of the battery pack. This paper proposes a single battery voltage as the control variable, adopts staged equalization, charge-discharge two-level equalization protection and isolated flyback converter circuit to realize the active equalization of battery pack energy, and designs the corresponding equalization control circuit. Through the comparison of a variety of control methods, the application of this system can achieve the final voltage balance. Tests show that the proposed equilibrium system can make full use of the larger capacity monomers, quickly improve the energy imbalance in the battery pack, and can effectively extend the working life of the battery pack and improve energy utilization.

1. Introduction

As one of the energy storage methods widely used by humans, Li-ion batteries have the advantages of low self-discharge ratio, fast cycle charge and discharge speed, and no memory effect. In addition, Li-ion batteries mostly exist in series in actual high-voltage and high-capacity applications. However, the series connection of batteries will be affected by many factors such as the capacity of single cells, internal resistance, and electrochemical characteristics, which can cause imbalance in the battery pack. If the imbalance in the battery pack is not dealt with in time, it will lead to overcharge and overdischarge of the battery pack, accelerated polarization, low energy utilization, shorten the life of the battery pack, and cause safety hazards, etc.¹, so the research on the balance control of the battery pack is particularly important.

At present, and domestic foreign companies and related scholars have studied the balance control of battery packs, and most of them use capacity, voltage, state of charge, etc. as control variables.² In the literature [3], a switch resistor topology is used for capacity balance control, which is relatively simple and low cost, but a large amount of power waste will be generated during the balance process and the actual working time will be shortened. In literature [4], a parallel non-isolated conversion circuit is used to balance the voltage at the single battery end. In industrial applications, the battery voltage is often used as the criterion. Compared with the former, this method uses an active balance method to achieve efficient use of electrical energy, But it can only complete the energy transfer between adjacent cells and is not suitable for multi-level battery series. The literature [5-6] regards the state of charge as the research control object. The state of charge is an important reference for measuring the real-time status of the single battery, but it cannot be directly measured. It is mostly used in the simulation stage. The estimation accuracy depends on the accuracy of the algorithm, and easily affected by the external...
environment.

Based on the analysis of the above balance control, and taking into account the system loss, as well as the safety and service life of the battery, it is necessary to ensure that the voltage of the single battery cannot be greater than 4.25V and less than 2.75V. Therefore, this paper adopts the directly measurable voltage value as the control variable, combined with staged balance, charge-discharge two-level balance protection and isolated flyback converter circuit to achieve the purpose of fast and active balance and full utilization of battery pack power. First of all, build and analyze the principle of the overall architecture of the active balance control system of the battery pack. Secondly, research and design the equalization process control circuit and algorithm. Finally, verify and analyze the adopted control system by building a balanced experimental platform.

2. The overall architecture and principle of the active balance control system

2.1. The overall architecture of the active balance system

On the one hand, the active balance control method adopted in this paper avoids the energy loss caused by passive balance using energy-consuming components. On the other hand, it uses staged balance, charge-discharge two-level balance protection and isolated flyback converter circuit to ensure the safe and fast balance of the control method. The overall architecture of the battery pack active balance control system is shown in Fig. 1. The battery pack consists of multiple single ternary Li-ion batteries with a nominal voltage of 3.7V and different power levels. The main controller uses its own internal analog-to-digital conversion (ADC) interface to realize the collection of the voltage of each cell in the battery pack and the first-level equalization protection control. The Li-ion battery charge and discharge protection IC implements secondary protection for the charge and discharge and equalization process according to the preset overcharge voltage threshold and overdischarge voltage threshold. The PWM control IC directly drives the NMOS switching element on the flyback converter side by outputting a PWM signal of a certain frequency to realize the energy conversion in the battery pack. Among them, the flyback converter is actually a Buck/Boost circuit that combines electrical isolation, voltage matching, and energy storage. This article uses a 100KHz PWM signal to drive the flyback converter. Therefore, when the PWM control IC outputs a high level, the flyback converter stores energy, and when the PWM control IC outputs a low level, the flyback converter releases energy.

![Overall architecture of active balance control system](image)

Fig. 1. Overall architecture of active balance control system

2.2. Principles of Active Balance Control

Since the battery pack is recycled for many times, based on the manufacturing process and the difference in electrolyte, there are obvious differences in the single cells in the pack, showing a phenomenon of different capacity values. During the charging and discharging process, the battery voltage is positively correlated with the remaining power. During the period, the battery with a smaller capacity value usually takes the least time to reach the cut-off voltage (4.25V, 2.75V) [7]. However,
whether the charging and discharging process is terminated often depends on the monomer with a smaller capacity value, that is, the "barrel effect". This results in a monomer with a larger capacity value that can never be filled or discharged. Therefore, it is of great significance to prevent the cells with small capacity values from reaching the cut-off state and ensure the balance of power in the group, which is of great significance for extending the working life of the battery pack and improving the energy utilization rate. The working principle of the flyback converter is: when the NMOS switching element is in the on state, the two sides of the coils L1 and L2 have opposite polarities, so the diode on the secondary side of the converter is reversely cut off, and the converter stores energy at this time. When the NMOS switching element is in the off state, the diode on the secondary side of the converter is turned on, and the converter releases energy.

The specific control principle is: in the charging and discharging state, when the voltage of the single battery collected by the main controller presents an extremely unbalanced state. And a single battery voltage is higher than 4.1V or lower than 3V, the main controller immediately triggers the first level of equalization protection, and sends out the equalization protection high-level enable signal to the enable terminal of the PWM control IC. Since the enable end of the PWM control IC is high-level effective, it triggers the flyback converter to execute the high-voltage single battery power flow to the low-voltage single battery. Until the voltage of the single cell in the battery pack reaches the overcharge cut-off voltage of 4.25V or the overdischarge cut-off voltage of the Li-ion battery charge-discharge protection IC, the Li-ion battery charge-discharge protection IC starts to implement secondary protection. When the battery pack is in a static state and the voltage of the single cells is in an unbalanced state, the main controller directly sends a balanced enable high-level signal to the enable terminal of the PWM control IC. Then trigger the flyback converter to execute the higher-voltage single battery power flow to the low-voltage single battery until the voltage difference between the maximum single battery voltage value and the minimum single battery voltage value in the battery pack is lower than 0.05V, which is considered to be balanced.

3. Balanced circuit design and control process
In order to reduce the complexity of circuit design and verify the feasibility of the active balance control system used in this article, the circuit design and control are mainly aimed at four-string, 3000mAh rated capacity ternary Li-ion Battery with nominal voltage 3.7V, respectively. Variable acquisition circuit, charge and discharge protection circuit, energy balance topology circuit, balance control algorithm design.

3.1. Control variable acquisition circuit

For the collection of the voltage of the control variable, the internal ADC of the main controller is used. This article uses the CMS8S5885 chip as the main controller. It has multiple built-in AD conversion channels and the conversion digits are 10 bits, including 1.2V, 2.0V, 2.4V, 3.0V 4 kinds of reference voltages (Vref) are available, based on the maximum voltage value of the four-string Li-ion battery pack is about 17V, Vref=2.4V is selected as the reference voltage (the minimum resolvable input voltage change is 2.3mV), and use the voltage divider resistance to measure the voltage to collect the voltage,
the voltage collection circuit is shown in Fig. 2. According to the 30KΩ voltage divider resistance:

\[ V_{\text{Bat}x} = V_{\text{By}} \times \frac{30K + 210K}{30K} \]  

(1)

\[ V_{\text{CELL}1} = V_{\text{Bat}+} - V_{\text{Bat}1} \]  

(2)

\[ V_{\text{CELL}2} = V_{\text{Bat}1} - V_{\text{Bat}2} \]  

(3)

\[ V_{\text{CELL}3} = V_{\text{Bat}2} - V_{\text{Bat}3} \]  

(4)

\[ V_{\text{CELL}4} = V_{\text{Bat}3} - 0 \]  

(5)

In the Eq. (1), \( V_{\text{Bat}x} \) and \( V_{\text{By}} \) respectively represent \( V_{\text{Bat}+, V_{\text{Bat}0}} \); \( V_{\text{Bat}1}, V_{\text{Bat}2}, V_{\text{Bat}3}, V_{\text{Bat}4} \). In the Eq. (2), Eq. (3), Eq. (4), Eq. (5), \( V_{\text{CELL}1}, V_{\text{CELL}2}, V_{\text{CELL}3}, \) and \( V_{\text{CELL}4} \) represent the actual voltages of the single battery 1, single battery 2, single battery 3, and single battery 4, respectively.

3.2. Charge and discharge protection circuit

The voltage value of the Li-ion Battery must be monitored at all times during the charging and discharging process. According to the battery industry standard, the maximum battery voltage can be about 1.2 times the nominal voltage value. This article uses a Li-ion Battery with a nominal voltage of 3.7V. Therefore, when the voltage is higher than 4.25V, it is regarded as overcharging. Overcharging will cause a strong chemical reaction in the electrolyte inside, and the release of gas will cause the battery to bulge, reduce the capacity, or cause an explosion. When the battery voltage is lower than 2.75V, it is regarded as over-discharge, and continuous discharge will cause its internal material structure to dissolve, causing permanent damage to the battery [8]. Therefore, the design of the charge-discharge protection circuit can effectively prevent overcharge or over-discharge during the balancing process of the battery pack, avoid the overcharge and over-discharge of the single cells from affecting the performance of the entire battery pack, and ensure the safety and stability of the battery pack. The design of the charge and discharge protection circuit in this article is based on the R5432V404BA chip, which has the functions of protection, protection release, and battery equalization. The charging and discharging protection circuit is shown in Fig. 3. The circuit schematic diagram of this paper is drawn and simulated by Altium Designer software. In order to prevent excessive current from damaging the switching devices during the charging and discharging process, four groups of power NMOS transistors are used in the circuit design. During system operation, when overcharge or overdischarge is detected, corresponding protection actions will be executed. Until the voltage of the single cells in the battery pack is lower than 4.1V or higher than 3V, the charging and discharging protection restrictions are lifted.

![Charge and discharge protection circuit](image-url)
3.3. Energy balance topology circuit

In order to avoid the impact of hysteresis characteristics in the charging and discharging process of the battery pack [9], a phased equilibrium method is adopted, that is, the energy transfer balance in the charging and discharging phase and the energy transfer in the resting phase are balanced. Based on the state of the battery pack and the charging and discharging protection circuit, the main controller executes the corresponding energy balance algorithm to perform energy balance conversion. The energy balance topology circuit is shown in Fig. 4. Design four single battery sides to connect PWM control IC chips in parallel respectively. In the working state, the gate pin of the chip can output a PWM signal with a frequency range of 50KHz~1MHz and a pulse width of 0~85% according to the load current. In order to reduce the switching loss, this article uses a 100KHz switching frequency signal to drive the gate drive NMOS tube, And then control the flyback converter to perform energy conversion, C25, C26, C27, C28 used to eliminate the ripple voltage generated in the switching process. This balanced topology circuit has a simple principle and strong controllability. The use of staged balance can also avoid excessive magnetic loss and switch tube loss during the energy transfer process, and improve the balance efficiency.

In the charging (discharging) state, if the voltage of the single battery 1 is the highest and higher than 4.1V (if the voltage of the single battery 2 is the lowest and lower than 3V, and the voltage of the single battery 1 in the battery pack is the highest). The main controller controls b1EN to be high. At this time, the PWM control IC chip in parallel with the single battery 1 starts to work, the NM15 switching element starts to be turned on and off periodically, and the series flyback converter starts to perform the transfer of the single battery 1 power to the battery pack at the same time, that is, the battery 1 discharges, Battery 2, Battery 3, Battery 4 are charged. Until the voltage of single cell 1 is lower than the voltage of other single cells, b1EN returns to a low potential. The main controller continues to detect the battery voltage and loops this control until it detects that the single battery voltage is higher than 4.25V (lower than 2.75V), and the charge (discharge) equalization ends.

Fig. 4. Energy balance topology circuit
In the static state, if the $V_{CELL4}$ voltage in the battery pack is the highest, the main controller controls $b4EN$ to be high, and the flyback converter starts to transfer the power of the single battery 4 to the battery pack. After a period of time, if the highest voltage of $V_{CELL2}$ is detected, the main controller controls $b2EN$ to be high, $b4EN$ returns to low, and the flyback converter starts to transfer the power of the single battery 2 to the battery pack. According to this equalization algorithm, the main controller continues to detect and control until the voltage of the single cells in the battery pack reaches equilibrium, and the equalization ends.

3.4. Balance control algorithm

The balance control algorithm is to perform corresponding balance control according to the state of the battery pack and the collected voltage. The process of the equalization algorithm used in this paper is shown in Fig. 5. The state of the battery pack is determined according to the detection value of the Hall current detection device MT9223 in series with the battery pack. When the MT9223 detects a current of about 1A, it is judged to be the charging and discharging stage, otherwise it is the resting stage.

![Fig. 5. Balanced algorithm flow](image)

4. Test verification

The balance experiment is carried out for a battery pack with four ternary Li-ion cells connected in series. The experimental platform includes electronic load meter, DC stabilized power supply,
high-precision multimeter, four-channel oscilloscope, etc. The equilibrium experiment device is shown in Fig. 6.

4.1. Balance test in resting state
For the balance test of the battery pack in the static state, the battery pack is first discharged using an electronic load machine at a rate of 0.2C for 1 hour. Due to the correlation between the terminal voltage and the state of charge of the battery in the resting state [10], the terminal voltage balance is the state of charge balance. Therefore, connect the equalization circuit after standing for a period of time, and use an oscilloscope and a high-precision multimeter to track the voltage of the battery pack in real time. The real-time voltage of the equalization process is shown in Fig. 7.

In Figure 7, VCELL1, VCELL2, VCELL3, and VCELL4 represent the real-time voltages of cells 1, 2, 3, and 4, respectively. It can be seen from the curve that although the voltage after the equalization of the control system fluctuates, the voltage difference between the maximum single cell voltage value and the minimum single cell voltage value starts to be lower than 0.05V after 3000s, that is, it tends to balance. It shows that the equilibrium system used in this paper has good performance and the overall equilibrium speed is relatively fast.

4.2. Battery pack working time comparison test
The battery pack working time test is divided into two groups. Discharge each single battery first, and then use a DC stabilized power supply at the same room temperature. The first group uses the equilibrium system of this paper to charge the battery pack to saturation at a rate of 17V/0.3C. The second group does not use the equalization system of this paper to charge at the same rate until a certain cell voltage is greater than 4.25V. After that, use an electronic load meter to discharge at a constant current of 0.2C to cut-off. The statistics of charging time and discharging working time adopts high-precision timer and manual monitoring method, and its accuracy can reach 99%. The test data is shown in TABLE 1

|                  | Charging time (h) | Discharge working time (h) |
|------------------|-------------------|-----------------------------|
| The first group (using this equalization system) | 3.28              | 4.26                        |
| The second group (not use this equalization system) | 3.05              | 3.97                        |

Tests show that the use of this balance control system is 0.29h longer than the unused working time. This data shows that the equilibrium control system in this paper can make full use of the larger capacity monomers, extend the working life of the battery pack, and improve energy utilization.
5. Conclusion
This article is based on a comprehensive analysis of various equilibrium controls. This paper proposes a single battery voltage as the control variable, adopts a staged equalization, charge-discharge two-level equalization protection strategy and an isolated flyback converter circuit to achieve active equalization control of battery pack energy. The circuit and algorithm required for equalization are analyzed and designed. In order to verify the feasibility of the active equalization control system used in this article, a test was conducted on a four-string ternary Li-ion battery pack. The test results show that the entire battery pack can be balanced for about 3000s in a static state. Compared with the unused balance control system, the working time of the balance control system in this article can be extended by 0.29h. The results show that the equilibrium system in this paper can make full use of the larger capacity monomers, quickly improve the energy imbalance in the battery pack, and can effectively extend the working life of the battery pack and improve the energy utilization rate.

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