Research Article

Research on Active Overbalanced Control Strategy for Lithium-Ion Battery

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In order to improve the voltage balancing effect of the lithium-ion power battery pack, a control strategy based on single-cell voltage overbalanced in the battery pack was proposed. In this method, the voltage of each battery is taken as the criterion of energy balance, and the analog switch and the energy storage inductor are used in the energy balance circuit. The PID control strategy of overequalization is proposed, which fully considers the self-recovery of voltage after the end of the charging process. The voltage balanced system of the lithium-ion power battery pack based on the voltage of a single-battery pack is realized, and the voltage maintains a stable equilibrium state after being balanced. The experimental circuit built in this paper verifies the effectiveness of the proposed method and gives the experimental waveform and data of the balanced charging module, which proves the scheme’s feasibility.

1. Introduction

At present, lithium-ion battery energy storage system has been widely used in mobile communication equipment, medical equipment, electric vehicle, military equipment, aerospace power supply, and other fields with its obvious technical advantages. However, for high-voltage and high-power applications such as electric vehicles and standby power supply, a single battery is difficult to meet the requirements in terms of power and voltage, and the battery packs are usually connected in series or parallel [1–3].

A single lithium battery cannot meet the requirements, so it is necessary to connect a single battery in a series or parallel operation. However, the difference in process and environment in the production process of the battery will lead to a difference in the internal performance of the battery, and the self-discharge phenomenon of the battery itself magnifies the inconsistency of the single battery. Therefore, the use process of the battery pack increases many practical problems compared with a single battery [4–6]. How to keep the consistency of the battery pack becomes the critical problem of battery pack application. In the process of using the lithium battery pack, the difficulty is to prevent battery overcharge and overdischarge. Once overcharge and overdischarge occur, the service life of the battery will be seriously damaged. It is not only necessary to ensure that the battery pack will not be overcharged and overdischarged within the limited range but also necessary to ensure that the single battery cannot be overcharged or overdischarged [7–11]. Therefore, lithium battery balanced control technology is particularly important, and it is necessary to monitor and manage the power of each battery in real time. If there is no balanced control, the capacity of the battery pack should be limited to the minimum capacity of the monomer during the charging and discharging process, so as to ensure that the battery pack and monomer will not be overcharged or overdischarged. As a result, the capacity utilization rate of the battery pack will be greatly reduced [12–18]. In order to solve this problem and improve the battery life and capacity utilization, the balance control of lithium batteries is particularly important.

Most electric vehicles adopt the parallel resistance balance method, which belongs to the energy dissipation balance method. When a battery is fully charged, the parallel
resistance switch of the battery is closed, making the battery in the full-charge bypass state. When the charging current decreases, the corresponding cell will discharge. This method mainly relies on the voltage difference at the end of the parallel single battery to balance the power transfer automatically, which limits the application of the capacitance method in the lithium battery system of electric vehicles [19–21]. The switching balance method of the cascaded capacitor is mainly composed of a series capacitor and single-pole double-throw switch. By controlling the corresponding SPDT switch, the corresponding capacitor and its two adjacent batteries are connected in series, and the energy is converted into a single battery until the adjacent battery pack has the same amount of electricity, and finally, the voltage balance is achieved. This method is also relatively simple, but because this method mainly depends on the voltage difference generated by the voltage difference of the parallel single-battery terminals, the application of the capacitance method in the lithium battery system of electric vehicles is limited [22–24]. In the induction parallel balancing method, a parallel module is added to the periphery of the battery. This method can store the excess energy of the higher battery in the adjacent battery and transfer the energy to the lower battery in the form of current. At the same time, the flyback converter is added at the end of the battery pack to feedback the energy of the battery to the end of the series battery so that the energy is transferred from high voltage to low voltage to realize balanced charging. The limitation of this method is that it can only balance between two adjacent cells, and the equalization time is long. However, compared with the capacitance method, energy transfer in the form of current is more efficient than that in the form of voltage and is easy to control. The induction parallel balance method has a wide application range [25–28]. The centralized transformer balanced method is composed of a magnetic core, the main winding, and several secondary windings, which are connected with each battery cell through rectifier diodes. The energy of the battery pack passes through the primary winding and secondary winding of the transformer to generate an equal voltage charging voltage and then flows to the corresponding cell unit through the rectifier diode. The induced current generated is inversely proportional to the secondary reactance so that it can be balanced. The advantage of this method is that there is no need to detect the state of a single cell and no need for closed-loop control and the balanced speed is fast. The disadvantage is that the transformer design is complex, and the single-cell battery cannot be flexibly increased. The balanced can only be carried out in one direction. The equilibrium current and SOC are not linear, which cannot guarantee the complete balanced of battery cells [29–33]. In the charging process of the switch array bypass balanced method, when the battery power reaches the maximum, the switch array is used to select the bypass cell and then continue to charge other cells. In the next balanced cycle, the single battery to be bypassed is detected again. When discharging, it is used to detect the single battery with the lowest power and bypass it. This method has the advantages of simple structure, no volume, and relatively high efficiency [34, 35]. In distributed monomer charging balanced method, every single battery is connected with an independent charging module in parallel, and each one is charged by its own charging control unit, so as to achieve balanced charging. The circuit is relatively complex [36, 37].

In order to solve the above problems, this paper proposes an active overbalanced strategy for the lithium-ion battery pack. Aiming at the difference in performance parameters between individual batteries, efficient balanced charging and discharging measures can make the inconsistent battery pack return to the same performance index, which can effectively avoid the vicious cycle of the battery pack and improve the overall service life of the battery.

2. System Structure

2.1. Topology. The central topology of the overbalanced system is shown in Figure 1. In addition to the top and bottom circuits, the balanced module for each battery contains two inductors, a switch and a reverse diode. Two adjacent battery modules share an inductor. The topology structure is relatively simple and modular, which belongs to the balance between a single battery and other batteries, and the equalization efficiency is high.

This topology is based on the balanced bidirectional transformer-free structure between adjacent batteries. Its structure is simple and benefits from the strong current carrying capacity of switching devices, so it is suitable for electric vehicles.

In the scheme used, it is assumed that the battery voltage of \( B_x \) is higher than that of other cells due to manufacturing reasons. During the charging process, it will be fully charged soon. However, since other batteries in the battery pack are still not fully charged, the charging process will continue and \( B_x \) will be overcharged. Therefore, it is necessary to equalize the \( B_x \) battery and control the opening and closing of \( S_x \) through the controller. When \( S_x \) is turned on, its equivalent circuit is shown in Figure 2. At this time, the charging current increases, and \( L_{x-1} \) and \( L_x \) start to charge and store energy.

After time \( t \), when the switch is turned off, the current of inductance \( L_{x-1} \) flows through \( D_{x-1}, D_{x-2}, \ldots, D_1 \), for \( B_{x-1}, B_{x-2}, \ldots, B_1 \) charging. The current of inductance \( L_x \) is supplied to \( B_{x+1}, B_{x+2}, \ldots, B_n \) by the continuous current. At the same time, there is current flowing through other inductors. The equivalent circuit when \( S_x \) is turned off and no diode is turned off is shown in Figure 3.

When the battery energy in the battery pack detected by MCU reaches the set equilibrium index, it controls the corresponding MOSFET to turn off and stop the battery balanced. Similarly, if it is detected that the energy of a single battery is high or low again, the above work shall be carried out until the requirements are met. This scheme has the advantages of simple structure and strong modularity in the research of lithium-ion battery pack balanced, and the balanced efficiency between the single battery and other batteries is high, which is suitable for the research of this subject.
2.2. Balanced Strategy. The basic performance of the balanced circuit of the lithium-ion phosphate power battery pack proposed in this project is as follows:

(a) Collect the voltage of each battery in the battery pack.
(b) According to the collected voltage parameters, the voltage of two adjacent cells is compared. According to the comparison of voltage, the microprocessor will output PWM pulse with corresponding duty cycle to control the power switch MOSFET on and off, so as to realize energy transfer and reduce the inconsistency of battery voltage and battery state of charge in battery pack.
(c) According to the switching and driving requirements of power switch MOSFET, the corresponding driving circuit is designed.
(d) The charging and discharging current of the battery pack and the temperature information of the battery pack are collected.

According to the above performance requirements, the circuit is basically divided into six parts: battery pack module, battery voltage acquisition module, CPU, drive circuit and balanced circuit, battery current acquisition module, and battery temperature acquisition module. The specific system structure is shown in Figure 4.

3. System Hardware Circuit

3.1. Single Battery Voltage Acquisition Module. The requirement of the voltage acquisition system is to collect the
voltage of eight single batteries in the battery pack. The single-battery voltage acquisition circuit is shown in Figure 5. By switching the analog switch, the ports of the eight batteries are connected to the two ends of the charging capacitor in turn. In order to realize the isolation between a single-chip microcomputer and battery, an analog switch channel is used to read the voltage on the capacitor, that is, the terminal voltage of the battery. At the same time, it also saves the AD port of the MCU.

According to the analysis in Figure 5, when the two analog switches are switched to K1_1 and K2_1, the voltage at both ends of capacitor C is the terminal voltage of battery B1, and then the switch is switched to K1_0 and K2_0, the positive pole of the capacitor is connected to the output of channel 0, and the negative pole is grounded. At this time, the voltage output from channel 0 is processed by the signal processing circuit and then sent to the AD port of the single-chip microcomputer for relevant data processing. After AD acquisition, turn off the output of the analog switch, open the discharge circuit, charge the capacitor, and then select other channels of the analog switch to collect and process battery voltage in turn.

In addition, because the number of analog switch channels is not enough after using this method to collect the voltage of a single battery, so the negative pole of the fourth battery can be grounded directly for AD acquisition. The circuit is shown in Figure 6.

3.2. Overbalanced Circuit Module. The battery overbalanced system in this system is mainly composed of two parts: balanced module and drive module.

3.2.1. Overbalanced Circuit Module. The overbalanced circuit module is mainly composed of MOSFET Q, free-wheeling diode D, and energy storage inductor L. Taking the
balance circuit of four batteries as an example, the circuit diagram is shown in Figure 7.

3.2.2. Drive Module. The power MOSFET in the balanced circuit module needs a corresponding driving circuit. The driver of power MOSFET transistor in the balanced circuit of this system uses Infineon’s single-channel special driver 1ED02012–F2. It can be used to drive MOSFET with driving current up to 2A.

The system power drive circuit diagram is shown in Figure 8.

4. Control Strategy

The main tasks of the software part of lithium-ion power battery pack overbalanced system include system power on, system initialization, and battery data acquisition, including battery charge and discharge current acquisition, battery voltage acquisition, and battery temperature acquisition; battery voltage overbalanced control task and system information display task.

After the system is powered on, each register in the controller is initialized. Then, the whole system first collects the battery charge and discharge current, battery voltage, temperature, and other data. Then, according to this data, the MCU uses the software overbalanced control strategy to control the PWM wave drive output, balance the corresponding battery cell, and complete the overbalanced task. Finally, the current, voltage, temperature, and other data of the battery are displayed on the LCD.

4.1. Analysis of Overbalanced Control Strategy. According to the actual experimental verification, there is a period of voltage recovery time after the end of the charging and discharging process. Therefore, it is necessary to consider the self-recovery process of cell voltage when the cell voltage is used as the balanced standard. There is an error of 20 mV between the terminal voltage of the cell and the actual open circuit voltage in charging and discharging. The overbalanced control strategy adopted in this paper also takes the cell voltage as the balanced standard. Therefore, in the overbalanced control, in order to make the battery not be overcharged or excessive power, it is necessary to make the battery in the overbalanced state, that is, the condition that the voltage of the single battery is lower than the average voltage of the battery pack is the condition that the equilibrium process ends. The specific control methods of overbalanced control are as follows:

(a) After the system is started, the voltage of each battery in the battery pack is detected cyclically. When the voltage of a single cell is detected to be 50 mV higher than the average voltage, the balanced is turned on again.

(b) Both overbalanced and voltage detection are periodic. When it is detected that the voltage of the battery to be equalized is 10 mV lower than the average voltage of the battery pack, balanced stops.

(c) When the voltage of a single cell is detected to be 50 mV higher than the average voltage, the balanced is turned on again.

(d) Repeat the above steps in turn until the voltage of the entire battery pack is within the required range.

4.2. Overbalanced PID Algorithm. In order to make the balanced efficiency higher, the PID control part is added to the output PWM wave in the balanced process. PID control process in this system: in the process of balanced, when the battery voltage acquisition system detects the difference ΔV between the balanced cell voltage V and the average value V_avg, the difference ΔV is the system deviation, and the control value u is calculated by ΔV, so as to achieve the purpose of controlling the duty cycle of PWM wave with the actual measured cell voltage.

In order to simulate the charging and discharging process of the battery accurately, the relationship between EMF and SOC and the dynamic process of the battery should be considered. Therefore, the Thevenin model, also known as the first-order RC model, is adopted, as shown in Figure 9 that contains a voltage source and an RC parallel circuit. The loop composed of RS and CS is used to simulate the dynamic
The system block diagram of the inverter with voltage feedback single loop PID control is shown in Figure 10.

The control expression of the PID controller in Figures 9 and 10 is as follows:

\[ u(t) = k_p e(t) + \frac{1}{T_i} \int_0^t e(t) dt + T_d \frac{de(t)}{dt} \]  
(2)

\[ e(t) = V_{ave} - V = V_{ave} - E + U_C(s) * e^{-1/(R_s * C_s)} \]  
(3)

\[ G(s) = \frac{U(s)}{E(s)} = k_p \left( 1 + \frac{1}{T_i s} + T_d s \right) + k_i + k_d s. \]  
(4)

In equation (1), \( R_s \) is the equivalent polarization internal resistance, \( C_s \) is the equivalent polarization capacitance, and \( R_i \) is the equivalent internal resistance. In equation (2), \( k_p \) is the proportional coefficient, \( T_i \) is the integral time constant, and \( T_d \) is the differential time constant. \( e(t) \) is not only the system deviation but also the difference between the voltage \( V \) of a single cell and the average value \( V_{ave} \) as shown in equation (3). The transfer function \( G(s) \) is the ratio of the Laplace transform of the output \( u(t) \) to the Laplace transform of the input \( e(t) \) of the linear system under zero initial condition as shown in equation (4).

The closed-loop transfer function of the system can be deduced as follows:

\[ U_0(s) = \frac{k_d s^2 + k_p s + k_i}{(R_s C_s s + k_d) s^2 + (1 + k_p) s + k_i} V_{ave} \]  
(5)

\[ T_s s - \frac{R_s}{(R_s C_s s + k_d) s^2 + (1 + k_p) s + k_i} I_0(s). \]

The characteristic equation of the closed-loop system is the following equation:

\[ D(s) = (R_s C_s s + k_d) s^2 + (1 + k_p) s + k_i. \]  
(6)

The functions of each calibration link of the PID regulator are as follows:

(a) Proportional link: It can reflect the deviation signal \( e(t) \) of the control system in real time and proportionally. Once the deviation is generated, the regulator will immediately produce control action to reduce the deviation.

(b) Integral link: It is mainly used to eliminate static error and improve the error-free degree of the system. The strength of the integral action depends on the integral time constant \( T_i \). The larger \( T_i \) is, the weaker the integral action is, and vice versa.

(c) Differential link: It can reflect the change trend (change rate) of the deviation signal and can introduce an effective early correction signal into the system before the value of the deviation signal becomes too large, so as to accelerate the action speed of the system and reduce the adjustment time.

In order to improve the balanced efficiency, this system adopts the control strategy of overbalanced plus PID algorithm. The specific control flow chart is shown in Figure 11.

5. Experimental Test and Conclusion

According to the performance objectives of the system, in order to verify the feasibility of the system, the system was tested. The batteries in the experimental battery pack were lithium iron phosphate lithium-ion batteries with a capacity of 3,000 mAh and a nominal voltage of 3.2 V. The upper charging voltage and lower discharge voltage are 3.75 V and 2.35 V, respectively. In order to reflect the balanced effect of the overbalanced system, the voltage of some batteries was adjusted before the experiment, so that the voltage of each battery was different. The main technical parameters of a lithium-ion battery are shown in Table 1.

5.1. System Test Diagram. The overall test circuit diagram of the system is shown in Figure 12.

5.2. Driving Waveform and Current Waveform of MOS Transistor. The driving PWM wave of the MOSFET transistor is output by the PWM wave output of the single-chip microcomputer through the driving circuit, and its waveform is shown in Figure 13. Due to the reason of the driving chip itself, the rising edge of the driving waveform is not steep, but after measurement, the rise time has no effect on the MOS drive, and the whole driving waveform is relatively accurate. In the actual test, the driving circuit works normally and meets the experimental requirements. The comparison between the current waveform (CH2) and PWM wave (CH1) of MOSFET under PWM wave driving is shown in Figure 14. It can be seen from the waveform that when the PWM is high level, that is, when the MOS is on, there is a current on the MOS transistor. According to the analysis in Section 3, the current on the MOS transistor is proportional to the on-time.

5.3. Current Waveform on Inductance. According to the analysis of the hardware circuit in Section 3, in the balanced circuit, when the MOSFET transistor is in the on-state (i.e.,...
PWM is high level), there is a battery flowing through the inductors at both ends of the balanced battery, and the current is related to the battery voltage and inductance and is proportional to the PWM duty cycle. In other words, when PWM is at a high level, the current on inductors $L_1$ and $L_2$ increase linearly, and the corresponding waveforms are shown in Figures 15 and 16.

After PWM becomes low level, because the current on the inductor cannot change suddenly, the freewheeling current is carried out through the freewheeling diode. $L_3$ is charged under the action of $L_2$, $D_4$, and $D_3$ freewheeling until the next high level comes. The current (CH2) and PWM (CH1) on $L_3$ are shown in Figure 17.

5.4. Experimental Test and Analysis

5.4.1. Charge Balanced Experiment. The charging current is 1 A; the balanced current is 400 mA; and the charging time is 20 min. The experimental results are shown in Table 2.

5.4.2. Discharge Balanced Experiment. The power resistor is used as the energy dissipation device in the discharge experiment. The discharge current is 1 A; the equilibrium current is 300 mA; and the discharge time is 20 min. The
experimental results of discharge balanced are shown in Table 3.

### 5.4.3. Analysis of Equilibrium Experiment Results

According to the analysis of the above experimental results, before balanced, the difference between the cell voltage with the highest voltage and the average voltage of the battery pack is more than 100 mV. After the overbalanced circuit is added, the voltage difference between the four batteries is very small, and the difference between the voltage of the highest single cell and the average voltage is only 3.8 mV. The results show that in the process of charging, the battery with...
high single voltage transfers the remaining energy to the low-voltage single-cell so that the charging voltage of the whole battery pack is basically the same; after the discharge is terminated, the difference between the single-cell voltage and the average voltage is only 33.7 mV by overbalancing, which is acceptable in practical application. The experimental results show that the high-voltage battery will transfer part of the energy to the low-voltage battery after adding the balanced circuit in the discharge process, and other batteries will not overdischarge.

According to the comprehensive analysis of the above experimental waveforms and data, the overbalanced experiment achieves the expected experimental effect and meets the performance index of the system.

6. Summary
In this paper, a battery overbalanced circuit based on energy transfer is proposed. The inductor parallel balanced method is adopted, and the balanced module is added outside the battery. Each battery balance module contains two inductors, a switch and a reverse diode. Two adjacent battery modules share an inductor to store the excess energy of the high battery in the adjacent battery, and the current is transferred to the low battery. The topology of the battery pack balanced circuit is a bidirectional transformer-free structure based on balance between adjacent batteries. It has a simple structure and can be presented in the form of modules. It belongs to the balance between a single battery and other batteries, with relatively high balanced efficiency. At the same time, due to the strong current carrying capacity of the switching device MOSFET, it is very suitable for power lithium batteries used in new energy vehicles. The balanced circuit can flexibly control the direction of energy transfer and transfer part of the energy from the high-energy single-cell to the low-voltage single-cell in the battery pack, so as to achieve the purpose of balanced. In order to improve the balanced efficiency, this paper uses the control algorithm of overbalanced control and PID control. In the process of overbalanced, the difference between the voltage \( V \) of the balanced cell and the average value \( V_{\text{ave}} \) is detected by the battery voltage acquisition system, and the control value \( u \) is calculated by \( \Delta V \), so as to control the duty cycle of the PWM wave with the actual measured cell voltage. The experimental results show that the proposed balanced circuit and the control strategy are feasible and the balanced effect in the experiment is obvious. Under the premise of avoiding overcharge and overdischarge, the capacity of the battery pack is fully utilized.

Data Availability
The authors would like to declare that all the data in the manuscript were obtained by experiment and the data are true and effective in the manuscript.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

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References


