

Design of Voltage Balancing Circuit for Power Batteries in New Energy Vehicles

Yiwen Liu^{1, *}, Rui Zhou¹, Shiyun Hong¹, Siyu Han², Jiawen Pan²

¹College of Electrical and Information Engineering, Jiangsu University of Technology, Changzhou, China

²College of Mathematic, Jiangsu University of Technology, Changzhou, China

*Corresponding Author: Yiwen Liu

ABSTRACT

Aiming at the issue of inconsistent cell voltages in series-connected power battery packs for new energy vehicles, this paper investigates voltage balancing circuits, with the goal of preventing the degradation of overall battery pack performance and service life caused by this problem. The study investigates a passive balancing circuit using resistors as energy dissipation components and an active voltage balancing circuit employing capacitors as energy storage and transfer devices. Simulation analyses of both balancing circuits are carried out in the MATLAB environment. The results demonstrate that the single-capacitor method exhibits distinct advantages in terms of energy efficiency, balancing speed, and system reliability, thus providing a more advanced and practical solution for voltage balancing of power batteries in new energy vehicles.

KEYWORDS

Lithium-ion battery; Voltage balancing; Active balancing; Resistive balancing; Capacitive balancing.

1. INTRODUCTION

Since the 21st century, clean energy sources such as solar and wind energy have been rapidly emerging and becoming the dominant force in reshaping the global energy landscape. China's new energy vehicle market has expanded rapidly, effectively accelerating the trend of electrification in the transportation sector. In this transformation, lithium-ion batteries, with their outstanding energy storage capacity, strong instantaneous power output, low daily maintenance requirements, and wide environmental adaptability, have become the core power source of electric vehicles. As the heart component of the vehicle, the battery directly determines the range, long-term reliability, and driving safety of the entire vehicle[1]. However, to achieve high-voltage and high-power output, battery packs usually require dozens of individual cells to be connected in series[2]. Due to manufacturing differences, aging and environmental reasons, the voltage, internal resistance and capacity of each cell naturally vary, which often leads to performance degradation, reduces the available capacity of the entire pack, accelerates cell aging and even poses a risk of thermal runaway[3]. Efficient voltage balancing circuits can mitigate the voltage deviations between cells, so the research on battery balancing technology has profound significance for improving the performance ceiling and safety bottom line of battery packs.

Based on different energy handling modes, battery balancing technologies are divided into passive balancing and active balancing. The two technologies have essential differences in energy flow and control logic. The resistive voltage balancing circuit is the typical representative of passive balancing. Its basic mechanism is energy dissipation. By connecting bypass resistors in parallel with high-

voltage cells, excess energy is released in the form of heat, thus equalizing the cell voltages[4]. This solution features a simple topology, low hardware cost and simple control strategies, and is widely used in medium and low-power new energy vehicles[5]. However, the physical characteristic of dissipating energy in the form of heat determines its inherent limitations. A trade-off exists between heat dissipation capacity and balancing speed, making it difficult to meet the requirements for balancing efficiency and thermal management in high-rate conditions. Capacitive balancing, a type of active balancing, adopts a core technology that breaks through the limitation of unidirectional energy flow. It uses energy storage components as energy buffer carriers and power conversion circuits such as DC/DC converters to transfer energy from high-voltage cells to low-voltage cells[6]. Compared with passive balancing, this solution has significant advantages in balancing speed and energy utilization efficiency, but it also faces challenges such as complex topology, higher system cost and greater difficulty in designing control strategies.

This paper compares the applicability and effectiveness of the two in battery voltage balancing, and the results show that the resistive method is limited by the heat dissipation mechanism, and there is a mutual restraint contradiction between its balancing speed and heat dissipation capacity; while the capacitive method, by leveraging the energy transportation capacity of capacitors as energy carriers, has advantages in balancing efficiency and system thermal load control, and can significantly extend the service life of battery packs and improving the battery utilization rate.

2. DESIGN OF VOLTAGE BALANCING CIRCUIT FOR LITHIUM-ION BATTERY PACK

2.1. Passive voltage balancing circuit design

2.1.1. Topology design of resistive balancing circuit

This paper first uses resistors as the core components to achieve voltage balancing among the individual cells of the lithium-ion battery pack. The resistive balancing circuit, as a typical implementation of passive balancing technology, operates based on the energy dissipation mechanism. When the voltage of a certain cell in the battery pack is higher than that of the other cells, by connecting a controllable switch in parallel with the bypass resistor, an additional discharge path is opened for that cell, allowing the excess energy to be dissipated as heat across the resistor, thereby suppressing the further rise of the cell's voltage. The voltage of this cell can then match that of other cells during charging, or decrease gradually in a static state, ultimately achieving voltage balance among all cells. The topology of the balancing circuit is shown in Figure 1.

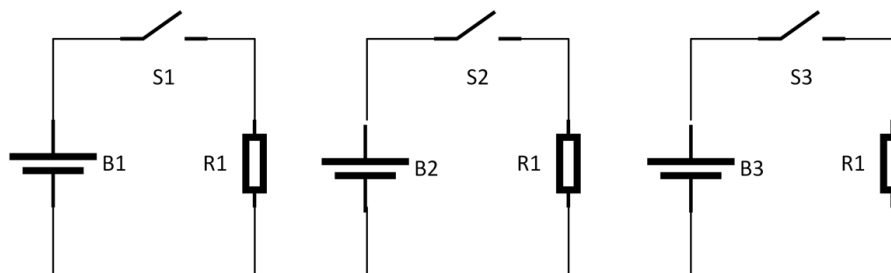


Figure 1. Topology of voltage balancing circuit for lithium-ion battery pack using single resistor method

2.1.2. Analysis of resistance-based balancing principle

Take the balancing circuit of three batteries as an example. The working process of the resistive balancing circuit can be divided into three stages: differential voltage detection, dynamic energy dissipation, and voltage balance achievement. The state transition of each stage is realized by

adjusting the on-off states of the switching transistors. The specific working sequence and current path are as follows.

Assume that the voltage of B2 is higher than that of B1 and B3. The voltage-time waveform diagrams of the control switches S1, S2, and S3 are shown in Figure 2.

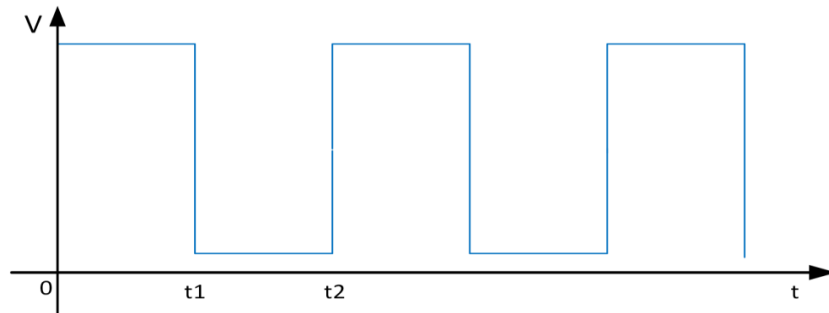


Figure 2. Schematic diagram of the voltage and time waveforms for the opening and closing of the three switches

During the 0 - t₁ stage, the sampling circuit samples the terminal voltages of B1, B2 and B3 in real time, and the control unit determines that $U_2 > U_1 > U_3$. Then, the switching transistor S2 corresponding to B2 is triggered to conduct, while S1 and S3 remain off. At this point, the balancing system enters the energy dissipation mode.

The current path in this stage is as follows: B2 positive electrode → switching transistor S2 → balancing resistor R2 → B2 negative electrode. During this stage, a closed energy dissipation loop is formed, allowing the excess energy of the high-voltage battery B2 to be converted into heat energy through R2, and its terminal voltage shows a slow downward trend; while B2 and B3 have no effective current path, so their voltages remain stable and they do not participate in energy dissipation. As shown in Figure 3.

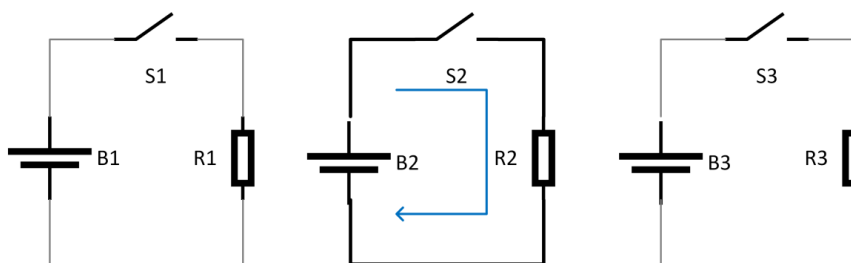


Figure 3. Schematic diagram of the current flow direction during the 0 - t₁ period

During the time period from t₁ to t₂, if the voltage of B2 is balanced, S2 is turned off. If the voltage of B1 is too high at this moment, S1 is triggered to conduct to balance the voltage of B1. When the voltage of B1 drops to a level close to that of B2 and B3, S1 is turned off and the balancing process is paused. If the voltage of any individual cell is detected to be too high again, the above process is repeated. As shown in Figure 4.

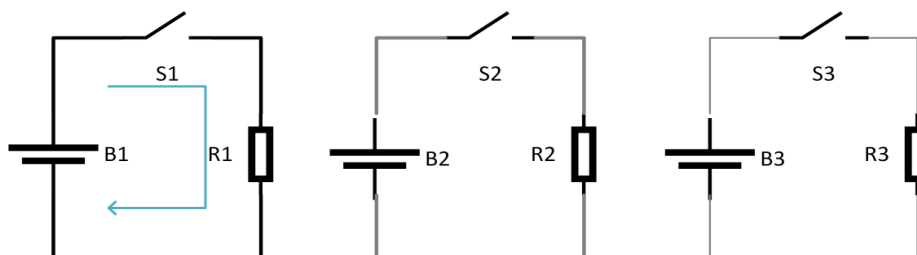


Figure 4. Schematic diagram of the direction of current flow during the time period from t₁ to t₂

With a monitoring period of 0 to t_2 , real-time voltage sampling is conducted for each individual cell of the battery pack within each cycle. If there is a cell with excessively high voltage, the corresponding bypass switch is activated to release the energy of that cell until the voltage drops within the threshold range. Therefore, when designing the control method, it is necessary to first determine the cell with the highest voltage in the battery pack and check whether it exceeds the allowable voltage deviation range, thereby deciding whether to start the balancing process.

2.1.3. Design of resistance-based balancing circuit control method

Based on the above analysis, in this section, a control method based on the voltage comparison method is designed, taking the voltage balancing circuit of three battery cells as an example. This control method compares the voltages of all cells and turns on the bypass switches of the cells whose voltages exceed the average value, thus allowing the excess energy of the high-voltage cells in the battery pack to be dissipated through the corresponding balancing resistor.

The control method is as follows: V_1 , V_2 , and V_3 are the voltages at the ends of B1, B2, and B3 respectively. The control logic is shown in Table 1.

Table 1. Relationship between battery voltage and switch on-off in the passive balancing circuit

Voltage relationship	State of S1 conduction	State of S2 conduction	State of S3 conduction	Voltage relationship
$V_1 > V_2 > V_3$	conducting	off	off	$V_1 > V_2 > V_3$
$V_1 > V_3 > V_2$	conducting	off	off	$V_1 > V_3 > V_2$
$V_2 > V_1 > V_3$	off	conducting	off	$V_2 > V_1 > V_3$
$V_2 > V_3 > V_1$	off	conducting	off	$V_2 > V_3 > V_1$
$V_3 > V_1 > V_2$	off	off	conducting	$V_3 > V_1 > V_2$
$V_3 > V_2 > V_1$	off	off	conducting	$V_3 > V_2 > V_1$
$V_1 = V_2 = V_3$	off	off	off	$V_1 = V_2 = V_3$

According to the above regulation, after several control cycles, energy is continuously dissipated from the cell with the highest voltage through the resistor, and the voltages of all cells gradually approach each other until they ultimately achieve balance. When the voltages of the three cells are equal, S1, S2, and S3 all remain in the off state, and the balance is completed.

2.2. Active voltage balancing circuit design

2.2.1. Capacitive balancing circuit topology design

Capacitors are used as the core component to achieve voltage balancing between the cells of the lithium-ion battery pack. The control system monitors the terminal voltages of each cell in real time, when the voltage of a certain cell is detected to be higher than the average voltage of the battery pack, the control system turns on the corresponding switch. This enables the high-voltage cell to form a discharge circuit with the capacitor, releasing excess electrical energy to the capacitor, which then charges the low-voltage cells until the voltage of the high-voltage is basically consistent with that of other cells in the group. During this process, the capacitor plays the role of a channel for energy storage and exchange. By selectively bypassing high-voltage cells, the circuit enables the overall voltage of the battery pack to gradually achieve balance. The topology of the balancing circuit is shown in Figure 5[7].

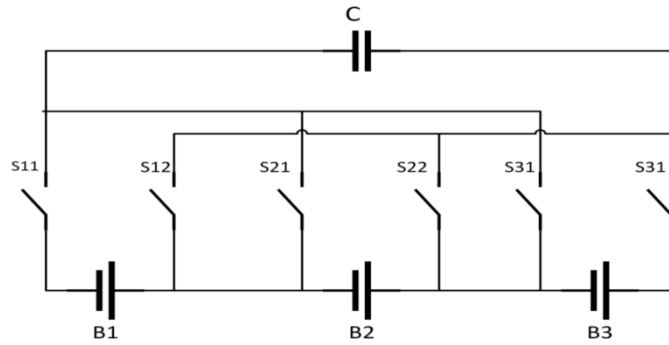


Figure 5. Topology of voltage balancing circuit for lithium-ion battery pack using a single capacitor

2.2.2. Analysis of capacitive balancing principle

Taking the balancing circuit of three batteries as an example, it is assumed that the voltage of B1 is higher than the average level and that of B3 is lower than the average level. The on-off characteristics of the control switches S11, S12, S31 and S32 are shown in Figures 6. and 7.

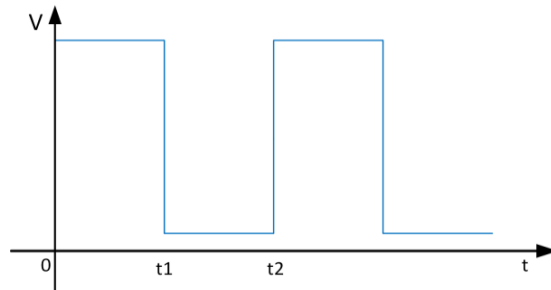


Figure 6. Opening and closing processes of S11 and S12(left)

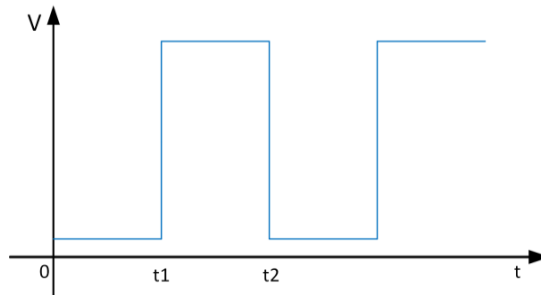


Figure 7. Opening and closing processes of S31 and S32(right)

During the time period from 0 to t_1 , S11 and S12 are turned on, while S31 and S32 are turned off. B1 is connected in parallel with capacitor C, and energy is transferred from B1 to C. Capacitor C is rapidly charged from its initial state, and its voltage rises until it is equal to the voltage of B1. When the voltage reaches a balanced state, capacitor C is in an open-circuit state. At this point, capacitor C has stored the corresponding energy and is ready to charge B3 in the next step. As shown in Figure 8.

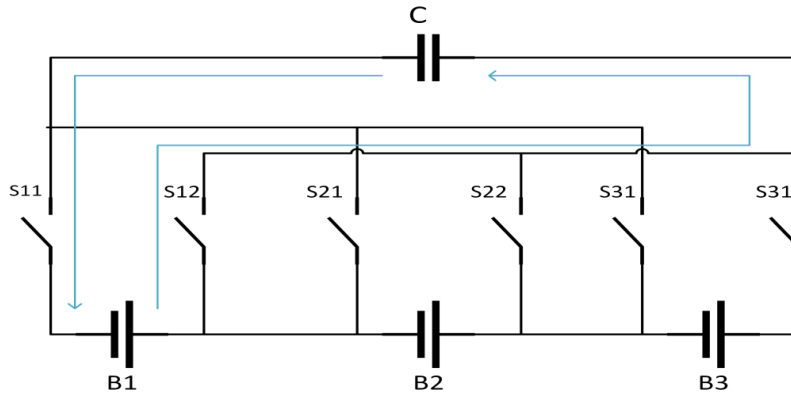


Figure 8. Schematic diagram of the direction of current flow during the period 0 to t_1

During the time period from t_1 to t_2 , S11 and S12 are turned off, while S31 and S32 are turned on. At this point, the voltage of capacitor C is equal to that of B1 and higher than that of B3. Current flows from C to B3, and the energy stored in C from B1 is gradually transferred to B3. As shown in Figure 9.

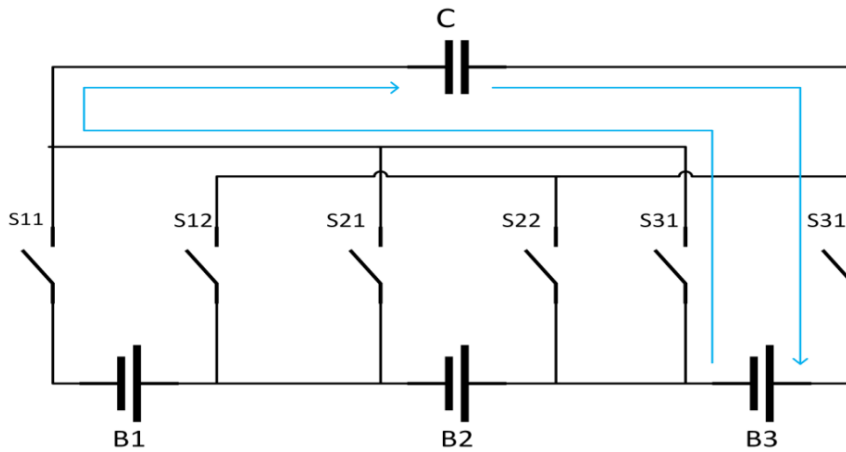


Figure 9. Schematic diagram of the direction of current flow during the time period from t_1 to t_2

Taking the period from 0 to t_2 as a complete working cycle, the circuit can achieve voltage balance between B1 and B3 by alternately turning on and off the corresponding control switches in this cycle. The control logic of the balancing circuit composed of multiple batteries is basically the same as the above process, with the difference being that the balancing target is extended from two adjacent cells to the cells with extreme voltages in the entire pack, namely the cell with the highest voltage and the cell with the lowest voltage, followed by energy transfer between them. Therefore, in the process of formulating the control strategy, it is necessary to first identify the cell with the highest and lowest voltages in the pack, then execute the balancing process and construct the energy transfer path between them, so that the voltages of all cells in the battery pack reach a consistent level [8].

2.2.3. Design of capacitive balancing circuit control method

Based on the above analysis, a voltage comparison-based control method is designed in this section for the three-cell voltage balancing circuit as an example. Based on battery voltage comparison, this control method adjusts the on-off states of the switches corresponding to each cell and the capacitor, and realizes alternating conduction of the switches, thus enabling energy in the battery pack to transfer from higher-voltage cells to lower-voltage cells through the capacitor.

The control method is as follows: V_1 , V_2 , and V_3 are the voltages at the ends of B1, B2, and B3, respectively. The control logic is shown in Table 2.

Table 2. Relationship between battery voltages and switch on-off in the active balancing circuit

Voltage relationship	Switch on-off status	
$V1 > V3 > V2$	Alternating conduction	Shutdown
$V1 > V2 > V3$	S11,S12 and S21,S22	S31,S32
$V2 > V1 > V3$	S11,S12 and S31,S32	S21,S22
$V2 > V3 > V1$	S21,S22 and S31,S32	S11,S12
$V3 > V2 > V1$	S21,S22 and S11,S12	S31,S32
$V3 > V1 > V2$	S31,S32 and S11,S12	S31,S32

After several cycles through this process, energy continuously flows from the cell with the highest voltage to the cell with the lowest voltage through capacitor C. When $V1 = V2 = V3$, S11, S12, S21, S22, and S31, S32 all remain off, and the balancing is completed.

From the above process, it can be seen from the above process that the main method to achieve energy balance is to alternately turn to the bypass switches of the cells with the highest and lowest voltages. The bypass switches of the cells with intermediate voltages are turned off to avoid interfering with the energy flow between these two cells.

3. SIMULATION AND VERIFICATION

To verify the above-mentioned resistive and capacitive balancing circuits, this paper uses Simulink in the MATLAB environment to conduct simulation and comparative analysis. This study further analyzes the applicability and effectiveness of the two circuits in the voltage balancing of power batteries and draws relevant conclusions.

3.1. Simulation research of the resistive balancing circuit

A voltage balancing circuit for three series-connected lithium-ion battery cells is built in Simulink. Through the balancing resistors and switches connected in parallel with each cell, energy is discharged from the cell with the highest voltage, and the voltages of the three cells ultimately tend to balance[9].

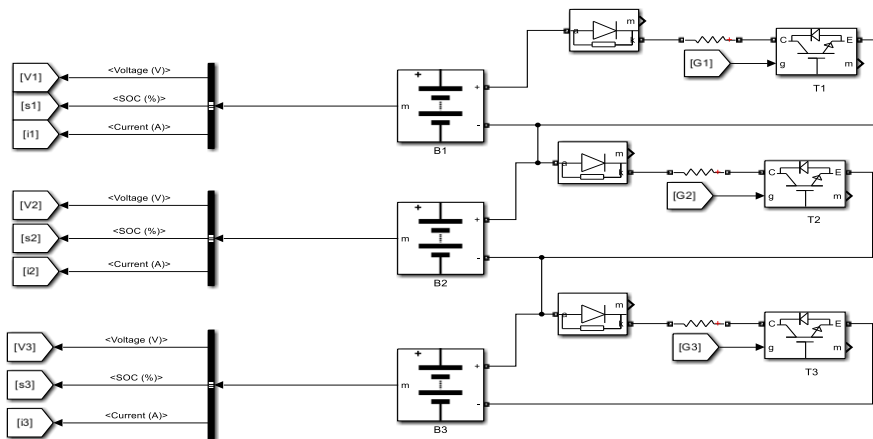


Figure 10. Simulation circuit for resistive voltage balancing of three-section lithium batteries

In Figure 10, G1, G2 and G3 are the gate drive signals of T1, T2 and T3 respectively; V1, V2 and V3 are the terminal voltages of the cells; S1, S2 and S3 are the state of charge (SOC) levels of the cells. Each cell has a rated voltage of 3.7 V and a rated capacity of 300 mAh. The sampling time step of the powergui module is 0.1 s. A balancing branch is connected in parallel at both ends of each battery. Each branch consists of a balancing resistor, a diode and an IGBT switching transistor connected in series. Figures 11, 12 and 13 show the variations in balancing speed and heat loss with different balancing resistor values.

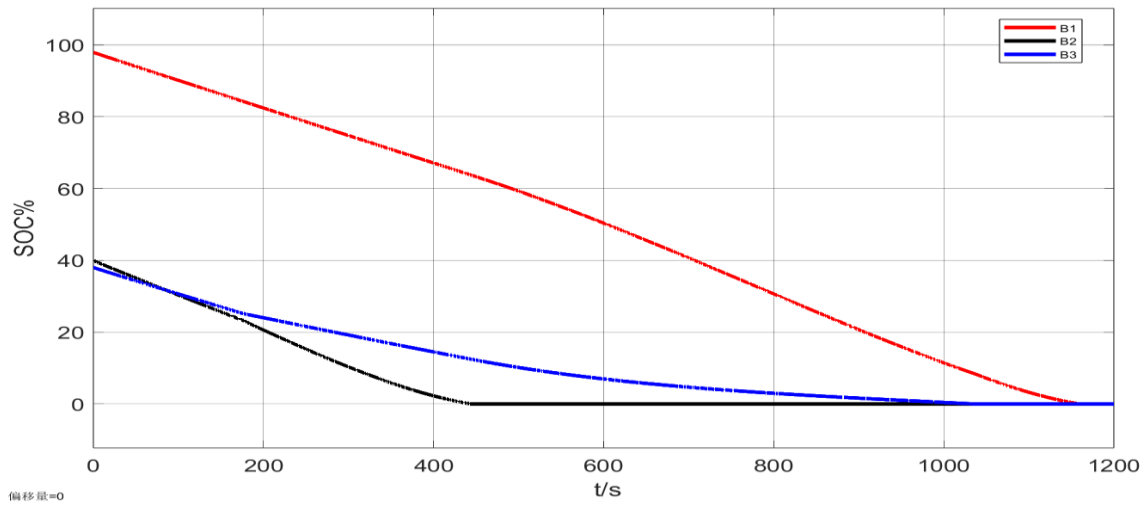


Figure 11. Battery capacity variation when the resistance value is set to 1Ω

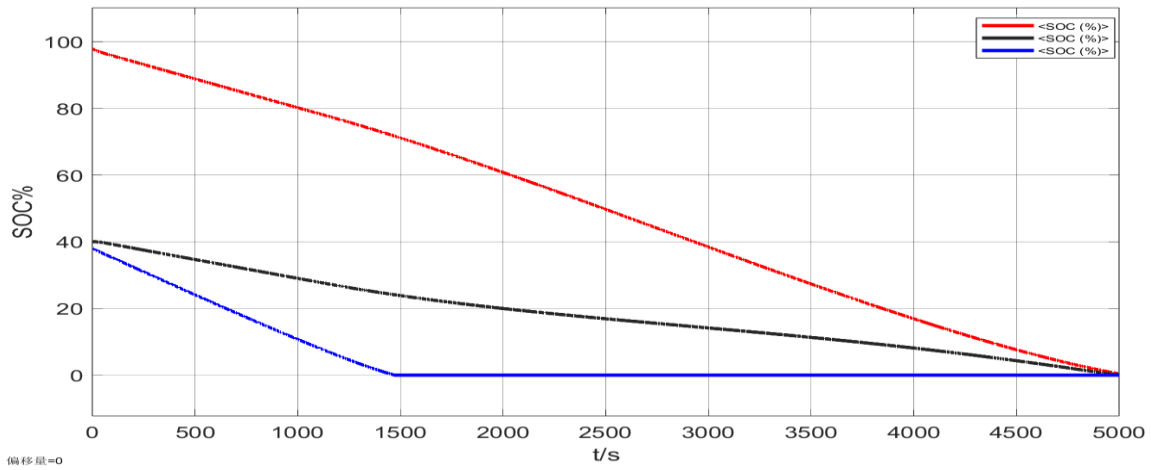


Figure 12. Battery capacity variation when the resistance value is set to 5Ω

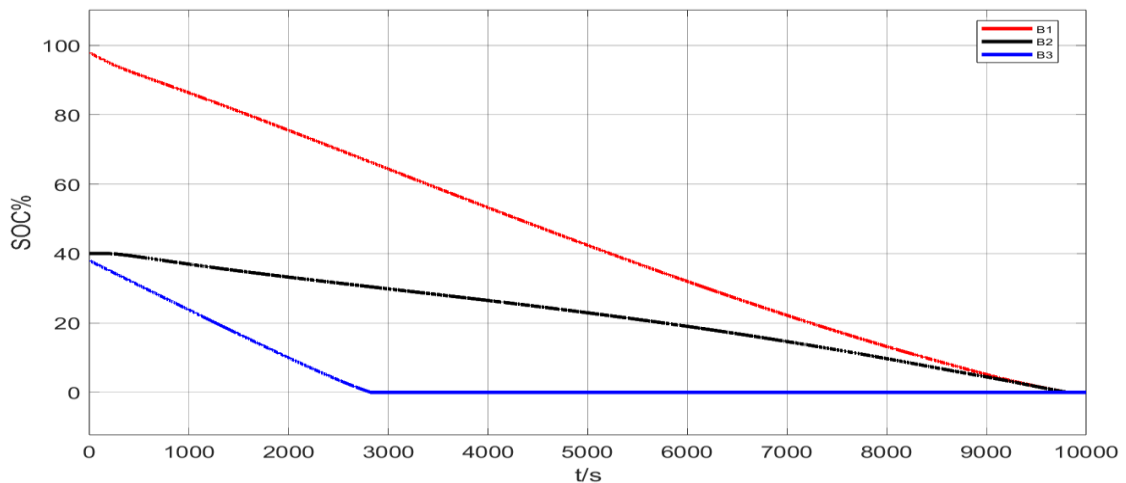


Figure 13. The variation of the battery capacity resistance value when it is set to 10Ω

From the above figures, the initial SOC's of the three cells are 97.95%, 40% and 38% respectively. It can be seen that as the resistance value increases, the required balancing time becomes longer. This is because a larger resistance value results in a lower average current, and the SOC update rate depends on the internal current of the cell. Thus, the small current leads to a lower SOC change rate.

3.2. Simulation of the capacitive balancing circuit

A capacitive active balancing circuit for three series-connected lithium-ion battery cells, as shown in Figure 14, is built in Simulink. This circuit is equipped with independent half-bridge MOSFET switch pairs (T1-T2, T3-T4, T5-T6) for each cell, with dedicated gate drive signals (G1, G2, G3). A monitoring unit is used to sample the voltage, SOC and current of each cell in real time. The on-off states of the switches are controlled according to the balancing strategy, so that the voltages and SOC of the three cells eventually tend to be consistent with each other [8].

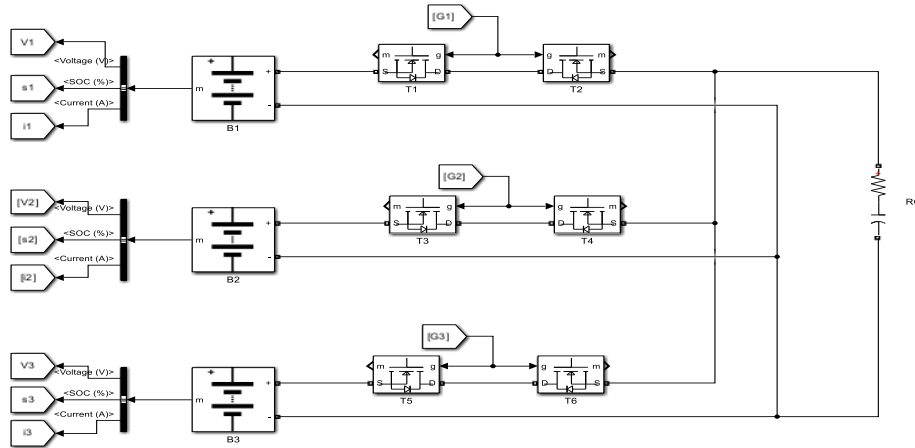


Figure 14. Simulation circuit for capacitive voltage balancing of three-section lithium-ion batteries. Each cell (B1, B2, B3) is equipped with an independent monitoring module, including voltage sampling ports (V1, V2, V3), state of charge (SOC) sampling ports (S1, S2, S3) and current sampling ports (I1, I2, I3). These sampling signals provide real-time state feedback for the control system.

Each cell is controlled by a pair of complementary MOSFET switching transistors. Specifically, B1 corresponds to switching transistors T1 and T2, B2 to T3 and T4, and B3 to T5 and T6. Each switch pair adopts a half-bridge topology, where the upper transistor (T1, T3, T5) and the lower transistor (T2, T4, T6) are connected in series, and their midpoint output is connected in parallel with the shared balancing capacitor C. Three independent gate drive signals G1, G2 and G3 serve as the control signals of the circuit, controlling the switch pair of the corresponding cell to realize independent control of the charging and discharging paths of each cell.

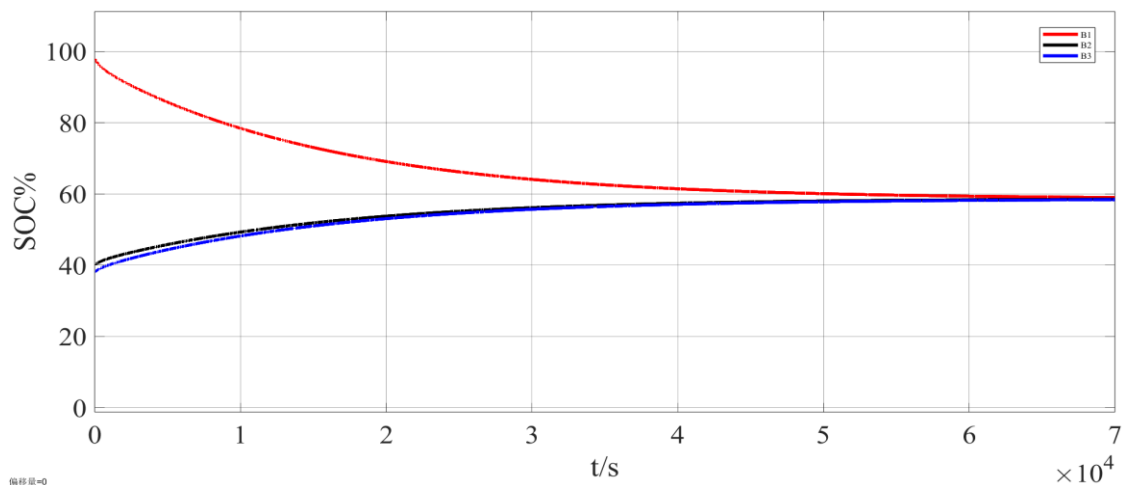


Figure 15. Simulation verification results of three-section lithium battery capacitive voltage balancing

In Figure 15, energy is transferred from B1 to B3 through capacitor C. When $V_3 > V_2$, energy is transferred from B1 to B2. Meanwhile, the voltage difference between V_2 and V_3 is very small, so the voltage of V_2 can exceed that of V_3 within a short time. Then, energy is transferred from B1 to B3 through capacitor C again, and this process is repeated until balancing is completed. From the figure, it can be seen that the SOC of the cells finally stabilizes at approximately 60%, achieving battery voltage balance successfully.

3.3. Performance comparison of two balancing circuits

Based on the systematic analysis of the principles, structures and performance characteristics of the resistive and capacitive balancing circuits above, the core performance indicators are summarized and compared in order to more intuitively reflect the differences in advantages and disadvantages between the two circuits, as shown in Table 3.

Table 3. Performance comparison of two battery balancing circuits

Performance	Resistive balancing circuit	Capacitive balancing circuit
Balancing direction	The energy can only be released from the high-voltage cell (through one-way dissipation)	Energy can be transferred bidirectionally between adjacent/multiple monomers.
Balancing speed	Slower, limited by resistance power and heat dissipation	Moderate, depending on the charge-discharge speed of the capacitor and the switching frequency of the transistors
Balancing time	The current is relatively low and balancing is mainly activated in the later stage of charging. The process is slow and often requires several hours or even longer.	It operates under any conditions, with a higher transfer current. The optimized topology can significantly shorten the time, especially when the initial voltage difference is large, the advantage is particularly obvious.
Balancing accuracy	It can achieve voltage consistency at the millivolt level, achieving stable Balancing through passive dissipation, but the capacity is limited by the weakest single unit.	With a reliance on the control algorithm, the flexibility is much higher, and the voltage difference can be controlled within a smaller range.
Energy efficiency	Low, the energy is dissipated in the form of heat, and the heat generation is obvious.	Higher, with only a small amount of loss, the energy is transferred and utilized between the battery cells, which is beneficial for extending the battery's lifespan.
Circuits complexity and cost	The structure is simple, requiring only a resistor and a switch; the cost is low, making it suitable for small-capacity applications.	The complexity is relatively high, requiring capacitors, multi-channel switches/driver circuits; the cost is slightly higher, but it is suitable for medium and large-sized battery packs.
Power consumption and heat generation	Continuous overheating and high power consumption during balancing state	Balanced operation results in low power consumption and low temperature rise.

In conclusion, the resistive-based balancing method is characterized by simplicity and low cost, but it has long time duration and low efficiency, making it suitable for low-performance requirement scenarios; the capacitive-based balancing method is superior in terms of time, efficiency and

applicability, and is suitable for high-performance battery systems. The actual selection should take into account factors such as capacity, inconsistency and cost.

4. CONCLUSION

This paper addresses the issue of voltage inconsistency among individual cells in series-connected battery packs for new energy vehicles, and designs resistive-based and capacitive-based balancing methods. MATLAB is used for simulation verification, and the following conclusions are drawn:

(1) The resistive-based voltage balancing method features a simple topology, low cost and simple control, but it has a small balancing current and low balancing speed. Energy is dissipated as heat during balancing, resulting in extremely low energy efficiency. It is suitable for small-capacity battery packs where low cost is prioritized and performance requirements are not high.

(2) Although the capacitive-based voltage balancing method has a complex topology and requires more switching transistors, it features a higher balancing speed, high energy transfer efficiency and low heat generation, which is conducive to extending the service life of battery packs. It is suitable for high-performance balancing requirements of medium and large-capacity lithium-ion battery packs.

(3) Compared with the resistive-based balancing method, the capacitive-based balancing method has significant advantages in balancing time, energy efficiency and operational adaptability. It can effectively reduce energy waste, alleviate the thermal management burden and improve the overall available capacity of battery packs.

Subsequent research will continue to focus on further improving the balancing performance, with in-depth exploration in two aspects: circuit topology optimization and control strategy improvement, to achieve better comprehensive performance in balancing speed, energy efficiency and system reliability.

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