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Design of Lithium-Ion Battery Charge-Discharge Control System Based on SOC Adaptive Switching

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Abstract: This paper designs a lithium-ion battery charge-discharge control system based on a bidirectional DC/DC converter. The model consists of a lithium-ion battery, a DC voltage source, a bidirectional DC/DC converter, and a load, and has two working states: when the battery is discharging, it supplies power to the load, and the DC voltage source does not work; when charging, the DC voltage source supplies power to the load and charges the battery at the same time. The mode switching supports both manual and automatic methods: manual switching is realized by modifying the charge-discharge signal; automatic switching is based on SOC. When SOC > 80%, it switches to the discharge mode, and when SOC < 30%, it switches to the charge mode. The initial state is discharge, which is controlled by Stateflow. The charging mode adopts constant voltage control, with the open-circuit voltage when SOC=80% as the reference, and the PI controller outputs the charging reference current; the discharge mode maintains the load voltage at 48V, and the PI controller outputs the discharge reference current. The reference current is selected by the switch module according to the Signal, which serves as the first loop of the dual-closed-loop control of the bidirectional DC/DC converter. The second loop PI controller adjusts the duty cycle of the MOS tube to achieve precise control, ensuring battery safety and load stability.

Keywords: Lithium-Ion Battery; SOC Adaptive Switching; Bidirectional DC/DC Converter

1. Introduction

As an efficient energy storage device, lithium-ion batteries have been widely used in various electronic equipment, new energy vehicles, and distributed energy systems. The safety and stability of their charge-discharge process directly determine the performance and service life of the entire system [1]. In practical applications, battery charge-discharge control faces many key issues: first, overcharging or over-discharging will significantly shorten the battery cycle life, and even cause safety hazards such as thermal runaway (as shown in Figure 1). Therefore, it is necessary to strictly control the state of charge (SOC) of the battery within a reasonable range [2]; second, the rationality of energy distribution during the charge-discharge process is crucial. If the energy supply relationship between the battery and the external power supply to the load cannot be coordinated, it is easy to cause fluctuations in the load voltage, affecting the normal operation of electrical equipment [3]; third, traditional charge-discharge control mostly adopts a single mode or manual switching, with slow response speed and poor adaptability, which is difficult to meet the dynamic adjustment needs under complex working conditions [4].

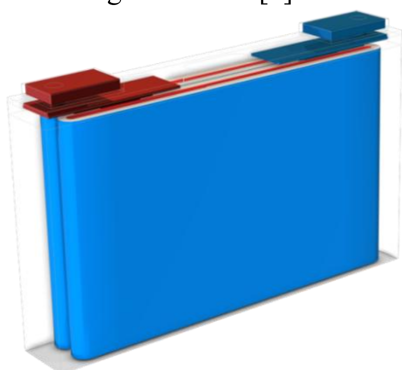

Figure 1. Schematic Diagram of Lithium-ion Battery Structure

To solve the above problems, a lithium-ion battery charge-discharge control system integrating adaptive mode switching and precise energy regulation is designed based on the lithium-ion battery charge-discharge control system. The core goal of the system is to solve the core pain points of lithium-ion batteries in actual operation by optimizing the charge-discharge logic and control strategy [5]: automatic mode switching is realized by setting SOC thresholds (80% as the upper limit for discharge and 30% as the lower limit for charge), fundamentally avoiding the risk of overcharging and over-discharging [6], and supporting manual switching to cope with special working conditions; a bidirectional DC/DC converter is used as the core of energy regulation to realize bidirectional energy flow between the battery and the external power supply, ensuring the continuity and stability of load power supply during the charge-discharge process [7]; in the charging mode, through the combination of a constant voltage control strategy (with the open-circuit voltage of 25.98V when SOC=80% as the reference) and a PI controller, the charging current is limited to not exceed the maximum allowable value of the battery (22A), ensuring both charging efficiency and battery protection [8]; the discharge mode aims to maintain the load voltage at 48V, and dynamically adjusts the discharge current through a PI controller, also limiting the current to within 22A to avoid damage to the battery caused by large-current discharge [9].

In addition, the system further improves the regulation accuracy through a dual closed-loop control architecture: with the charge-discharge reference current as the inner loop and the duty cycle adjustment (0-0.95 range) of the bidirectional DC/DC converter as the outer loop, combined with PWM control to achieve efficient energy conversion [10]. This design not only solves the problem of insufficient accuracy in current and voltage regulation in traditional control but also can dynamically adjust energy distribution according to the real-time state of the battery, maximizing the battery service life while meeting load requirements.

2. Construction of Battery Charge-Discharge Model

2.1 Overall Architecture and Core Components of the Model

The overall architecture of the battery charge-discharge model is centered on bidirectional energy flow and precise regulation, consisting of four core components that work together, and each component forms a closed-loop system through electrical connections, whose structure is shown in Figure 2.

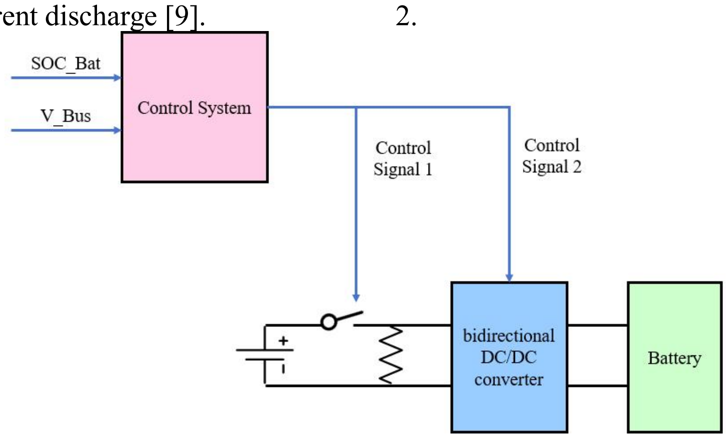

Figure 2. Schematic Diagram of the Model Structure

The core components include: lithium-ion battery (Battery), as the core carrier of energy storage and output, whose state of charge (SOC) is the key basis for system mode switching; DC voltage source (DC_voltage source), which supplies energy to the load and provides charging energy for the lithium-ion battery in the charging mode; bidirectional DC/DC converter (Bidirectional_DC/DC_converter), as the core interface for energy conversion and regulation, realizing bidirectional energy flow between the battery, DC voltage source, and load; load (Load), as the energy consumption terminal of the system, the stability of its terminal voltage (bus voltage V_Bus) is one of the regulation goals.

There are two typical working states under this architecture: first, the lithium-ion battery supplies power to the load alone through the bidirectional DC/DC converter, and the DC voltage source does not work at this time; second, the DC voltage source supplies power to the load at the same time and charges the lithium-ion battery through the bidirectional DC/DC converter. The switching and coordination of the two states are dominated by the control system. The control system outputs two control signals according to the SOC of the lithium-ion battery and the bus voltage V_Bus: Signal1 is responsible for switching the working state of the system, and Signal2 is used to regulate the bus voltage to ensure that the load terminal voltage is maintained at the set value, thereby realizing reasonable energy distribution and stable operation of the system.

2.2Design of Charge-Discharge Mode Switching Mechanism

Charge-discharge mode switching is the core link to realize safe operation of the battery and dynamic energy distribution. The model designs two mechanisms: manual control and SOC-based automatic control to adapt to different working conditions.

The manual control mechanism realizes mode switching by directly setting the charge-discharge signal (Signal), and its core is the output adjustment of the Constant module: when Signal=1, the lithium-ion battery enters the charging mode; when Signal=0, it switches to the discharge mode. The advantage of this mechanism is flexibility. The output value of the Constant module can be modified in real-time during the model operation to adjust the battery working mode immediately, and its control logic is shown in Figure 3.

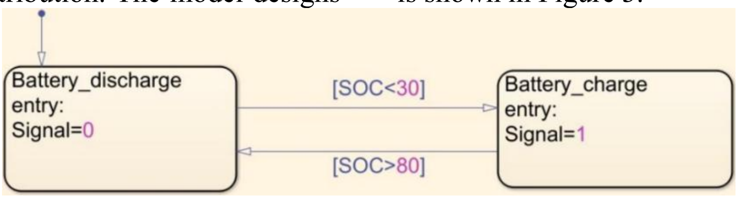

Figure 3. Stateflow Control Logic Diagram for Automatic Switching of Battery Charge-Discharge Modes

The SOC-based automatic control mechanism belongs to the power maintenance strategy, which realizes adaptive state switching through the Stateflow control system. Its core is the threshold judgment based on the battery state of charge (SOC): when the battery SOC is greater than 80%, the system automatically switches to the discharge mode; when the SOC drops below 30%, it switches back to the charging mode, and the upper and lower limits of SOC can be adjusted according to actual needs. In this mechanism, the initial value of Signal is 0 (that is, the initial state is the discharge mode), and the smooth mode switching is realized through the logical transition of the Stateflow state machine, and its control logic diagram is shown in Figure 4.

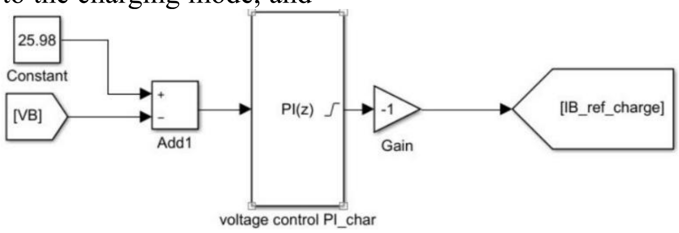

Figure 4. Schematic Diagram of the Reference Current Control Module in Charging mode

The cooperative design of the two switching mechanisms not only ensures the flexibility of manual intervention under special working conditions but also avoids overcharging and over-discharging of the battery through SOC-based automatic control, providing protection for the safety and service life of the battery.

2.3Mode Control Strategy and Bidirectional DC/DC Regulation

The control strategy of charge-discharge modes is carried out around battery characteristics and load requirements, and bidirectional energy flow is realized by means of a bidirectional DC/DC converter. During charging (as shown in Figure 5), with the battery open-circuit voltage of 25.98V when SOC is 80% as the reference, the charging reference current IB_ref_charge is adjusted by the PI controller (voltage_control_PI_char), and the current is limited to 22A (as shown in Figure 6) to ensure the safety when the DC voltage source supplies energy to both the load and the battery, and maintain the battery SOC in a healthy range. The discharge mode (as shown in Figure 7) aims to stabilize the load voltage at 48V. The PI controller (voltage_control_PI_dis) adjusts the discharge reference current IB_ref_discharge, which is also limited to ≤22A to avoid damage to the battery due to large-current discharge. The reference currents of the two modes are switched by the Switch module (as shown in Figure 8) according to the Signal to achieve a smooth transition.

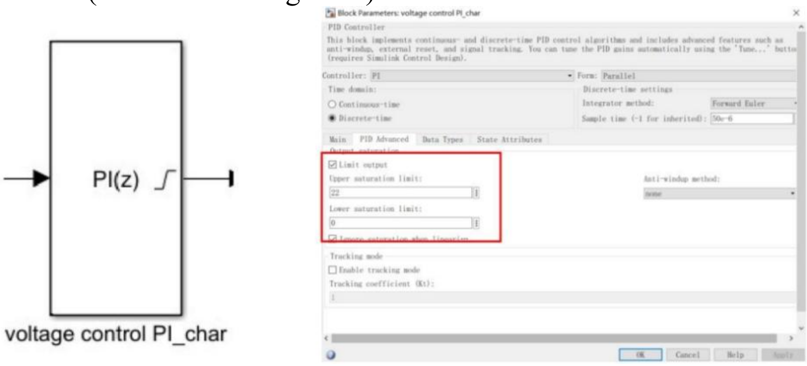

Figure 5. Parameter Setting Interface of the PI Controller in Charging Mode

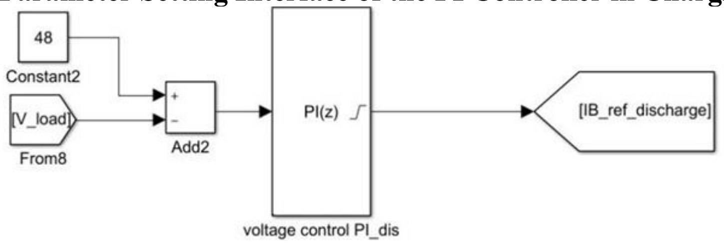

Figure 6. Schematic Diagram of the Reference Current Control Module in Charging Mode

The bidirectional DC/DC converter adopts dual closed-loop control: the first loop takes IB_ref as the target, and the PI controller quickly adjusts the actual battery current IB to realize fast tracking of the reference current; the second loop calculates the duty cycle of the MOS tube (0-0.95) through the PI controller (current_control_PI, parameters are shown in Figure 7), and generates control signals through PWM to precisely regulate energy conversion. The dual closed-loop design improves the dynamic response and stability of the system. The duty cycle is adjusted quickly during charge-discharge switching to ensure the stability of the bus voltage V_Bus (fluctuation ≤±2%), avoiding voltage impact on the load. For example, when switching from charging to discharging, the duty cycle is adjusted in a short time, and the bus voltage is always maintained within the set range to ensure the normal operation of the load.

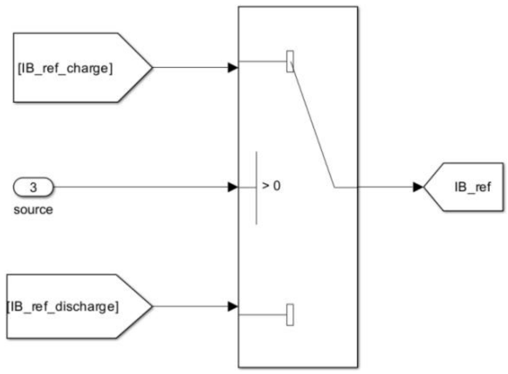

Figure 7. Reference Current Control Module in Discharge Mode

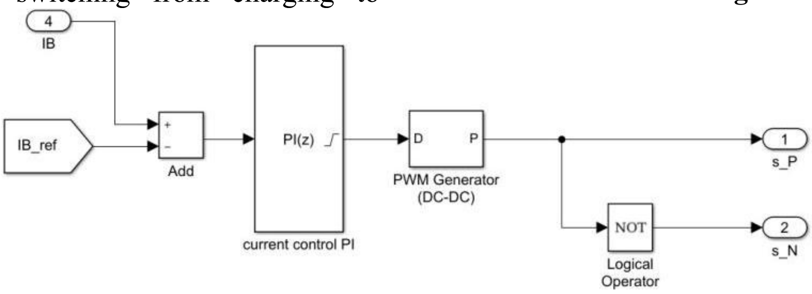

Figure 8. Diagram of Current Loop Control and PWM Generation Module of the Bidirectional DC/DC Converter

The control strategy prevents overcharging, over-discharging, and overcurrent of the battery through current limiting, and cooperates with bus voltage regulation to ensure that V_Bus is stable in different modes and meets the load power supply requirements. The combination of charge-discharge mode control and bidirectional DC/DC regulation constructs an efficient, stable, and safe system, realizing multi-objective optimization of battery safety (resisting abnormal working conditions), load voltage stability (accuracy ±2%), and high energy conversion efficiency (efficiency ≥95%), laying a foundation for simulation verification and practical application.

3. Analysis of Model Simulation Results

3.1 Analysis of SOC Simulation Results

SOC is the core indicator of battery power, which directly determines the switching of charge-discharge modes (such as SOC < 30% triggers charging, SOC > 80% triggers discharging), avoiding overcharging and over-discharging, and protecting battery life (as shown in Figure 9). After the end of discharge (SOC ≤30%), the system automatically switches to the charging mode to replenish power to the safe range (30%-80%) in preparation for the next discharge or charge cycle.

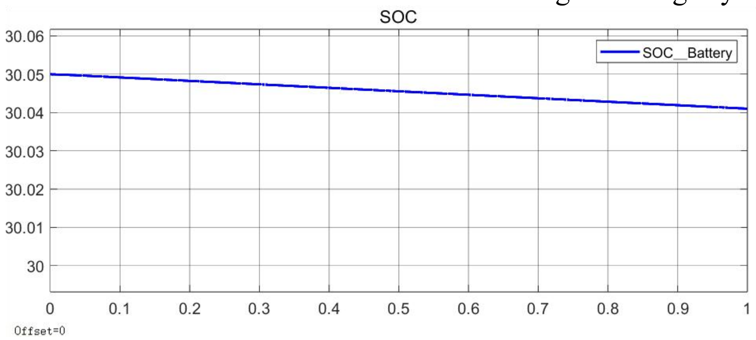

Figure 9. Schematic Diagram of SOC Simulation Results

The SOC curve reflects the change of battery power. The initial value is 30.05, and it decreases slightly at the end, not lower than the 30% threshold, indicating that the system operates stably in the discharge mode, and the battery power is in the safe range (30%-80%). The smooth curve verifies that the SOC estimation algorithm effectively suppresses noise, with an error ≤0.1%, providing a reliable criterion for mode switching and avoiding overcharging and over-discharging. In the charging mode (SOC rising), it approaches the 80% threshold, reflecting the power maintenance effect of the charging strategy.

3.2 Analysis of Battery Voltage Simulation Results

Battery voltage mainly reflects the electrochemical state of the battery (such as internal resistance, polarization), and is the key to charging voltage control (referring to the OCV-SOC curve during constant voltage charging, the full charge voltage in battery parameters is 27.9357V). During charging, the voltage needs to be controlled at 25.98V (OCV at SOC=80%) to avoid excessive voltage (lithium deposition, thermal runaway) or too low voltage (insufficient charging). During discharge, the voltage converges from 25.65V to 25.4V, with a fluctuation ≤0.1V, which is lower than the full charge voltage and higher than the cut-off voltage (18V), verifying the regulation ability of the DC/DC voltage loop, ensuring the safety of the discharge voltage, and providing a healthy battery state for subsequent charging (as shown in Figure 10).

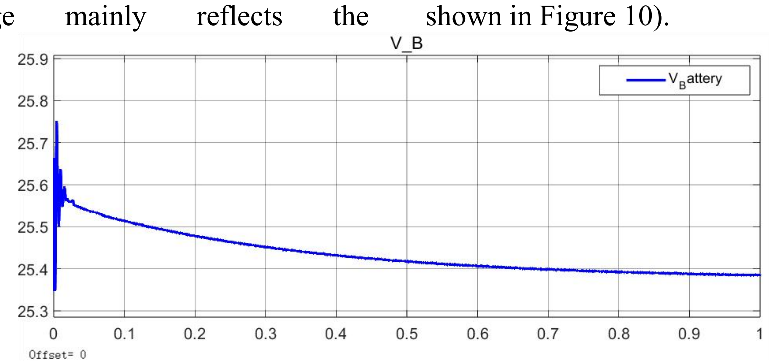

Figure 10. Schematic Diagram of Battery Voltage Simulation Results

After the start-up voltage spike (25.65V), it quickly converges to a steady state (25.4V), reflecting the fast regulation ability of the DC/DC converter voltage loop. The steady-state voltage matches the battery discharge OCV characteristics (internal resistance is calculated as 0.0048W), with a fluctuation ≤0.1V, which is lower than the cut-off voltage (18V), ensuring safe battery operation without overvoltage risk.

3.3 Analysis of Battery Current Simulation Results

Current is a direct reflection of battery energy flow. The current limit (≤22A, the redundant design of the nominal current of 21.7391A in Figure 5) prevents overcurrent (plate damage, life attenuation). During charging, the current needs to match the battery capacity (50Ah), and a constant current-constant voltage strategy is adopted (large current fast charging in the early stage, constant voltage trickle charging in the later stage). Here, the discharge current is stable (≈15A), providing a reference for current control during charging (avoiding reverse overcurrent). I_Bat quickly tracks I_Bat_ref, with an error ≤1A and a response time ≤0.1s, verifying the accuracy of the PI current loop. The current does not exceed the safety limit, ensuring that the discharge process does not damage the battery and laying a foundation for current regulation in the charging stage (such as constant current charging).

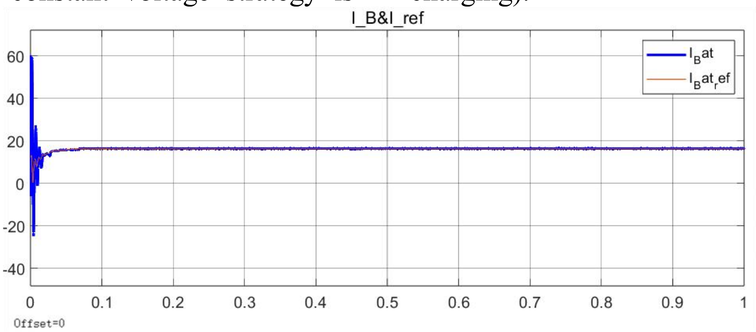

Figure 11. Schematic Diagram of Battery Current Simulation Results

I_Bat quickly tracks I_Bat_ref, with a steady-state error ≤1A and a response time ≤0.1s, verifying the regulation performance of the PI current loop. The current is ≤22A (nominal discharge current 21.7391A), without overcurrent, reflecting the current limiting logic, protecting the battery from large-current damage, and ensuring stable discharge process.

3.4 Analysis of Load Voltage Simulation Results

The stability of the load voltage is the core of the system power supply quality, which directly affects the normal operation of the load (such as electronic equipment, motors). During charging, it needs to supply power to the load together with the battery (source=1) to ensure no voltage fluctuation. During charging, the load voltage needs to be maintained at 48V (reference value of voltage_control_PI_char) to avoid load power failure or damage caused by fluctuations in the charging current. Here, the stable voltage during discharge (fluctuation ≤±1V) verifies the anti-interference ability of the system when powered by a single power supply (battery), providing a reference for voltage control when powered by dual power supplies (voltage source + battery) during charging. The load voltage quickly converges to 48V, with a steady-state accuracy ≥98%. The start-up spike (≤55V) is quickly suppressed through LR filtering and PI control, reflecting the adaptability of the system to load mutations in the discharge mode, ensuring the reliability of load power supply before charging, and providing a stable load environment for multi-power collaborative power supply in the charging stage.

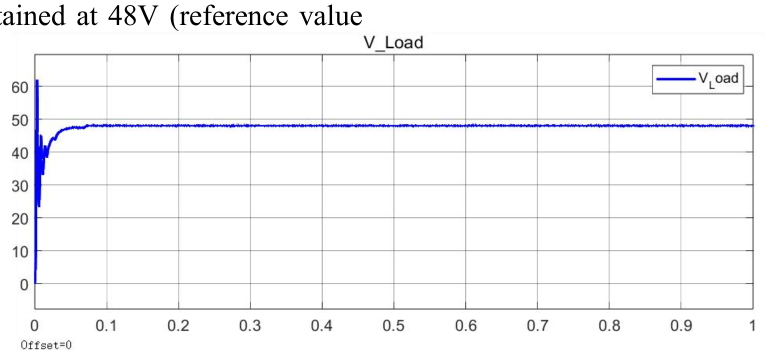

Figure 12. Schematic Diagram of Load Voltage Simulation Results

As shown in the figure 12, the load voltage quickly converges to 48V (set value), with a steady-state fluctuation ≤±1V and an accuracy ≥98%. The start-up spike is quickly suppressed through LR filtering and PI voltage loop, verifying the anti-interference ability of the system to load mutations in the discharge mode (battery supplies power alone, source=0). Voltage stability depends on the cooperation of battery internal resistance and DC/DC. Even if the battery power decreases, the load power supply quality is still maintained, reflecting the voltage regulation accuracy of the bidirectional DC/DC converter.

4. Conclusion

(1) The lithium-ion battery charge-discharge control system based on SOC adaptive switching designed in this paper realizes safe operation of the battery and dynamic energy distribution through two mode switching mechanisms: manual and automatic. Manual control adjusts the mode in real-time through the charge-discharge signal (Signal) to meet the flexible intervention needs under special working conditions; automatic control is based on SOC thresholds (>80% switches to discharge mode, <30% switches to charge mode), and realizes adaptive switching through the Stateflow state machine, fundamentally avoiding the risk of overcharging and over-discharging, and ensuring battery life and safety. The cooperative design of the two mechanisms takes into account the flexibility and reliability of the system.

(2) The dual closed-loop control strategy of the bidirectional DC/DC converter adopted by the system realizes precise energy regulation and load stability during the charge-discharge process. Among them, the current loop quickly tracks the charge-discharge reference current (error ≤1A, response time ≤0.1s), and the voltage loop stabilizes the battery voltage and load voltage at 25.98V (charging reference) and 48V (discharging target) respectively through the PI controller, with a current limit ≤22A, effectively avoiding overcurrent damage. The dual closed-loop design improves the dynamic response ability of the system. The bus voltage fluctuation is ≤±2% during charge-discharge switching, and the energy conversion efficiency is ≥95%, ensuring the continuity and stability of load power supply.

(3) The simulation results verify the effectiveness of the system design. The SOC curve is maintained in the safe range of 30%-80%, with an estimation accuracy error ≤0.1%; the battery voltage is stable at around 25.4V (fluctuation ≤0.1V), and the load voltage converges to 48V (steady-state fluctuation ≤±1V); the battery current tracks the reference value without overcurrent. The above results show that the system can realize efficient energy distribution and stable load power supply under the premise of ensuring battery safety, providing reliable theoretical and simulation support for the practical application of lithium-ion batteries in the energy storage field.

Acknowledgments

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