Research on a Supercapacitor Power Controller Based on Buck-Boost Circuit

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Abstract: Supercapacitors are widely used in energy storage systems due to their high power density, long life, and fast charging and discharging characteristics. However, during the charging and discharging process and during the switching of operating modes, the voltage of the supercapacitor will fluctuate significantly, which poses a challenge to the stability and safety of the system. In order to solve this problem, a supercapacitor power controller based on Buck-Boost circuit is designed in this paper. The controller adopts three closed loop control strategies, which realize the precise balance of voltage and dynamic replenishment of power through the voltage loop and current loop with power loop limiting, so as to ensure that the system can respond quickly and maintain stable operation when the load changes and voltage changes. In this paper, the effectiveness of the scheme is verified by MATLAB simulation, which further proves its superior performance under load change.

Keywords: Supercapacitor; Hybrid Energy Storage; Closed-Loop Control; Buck-Boost Converter; Power Control

1. Introduction

With the transformation of the global energy structure and the widespread application of renewable energy, energy storage systems have become increasingly important in fields such as smart grids, electric vehicles, and distributed power generation [1]. Although traditional chemical batteries have high energy density, their low power density, slow response speed, and limited number of charge-discharge cycles make them difficult to meet the application requirements of fast dynamic response [2]. In contrast, supercapacitors have the advantages of high power density, fast charge-discharge speed, and long cycle life, making them ideal fast-response supplements in energy storage systems [3]. However, supercapacitors have low energy density and cannot independently undertake long-term energy supply tasks.

To simultaneously meet the requirements of high energy density and high power density, the battery-supercapacitor hybrid energy storage system (HESS) has emerged. Leveraging its characteristic of flexibly allocating energy according to dynamic load demands, this system achieves a balance between dynamic performance and endurance, thus becoming a research hotspot in the current energy storage field.

In the research on energy management strategies, the fuzzy logic control strategy demonstrates unique advantages. By real time monitoring of key parameters such as load power, voltage, and current, and constructing a fuzzy rule base to intelligently judge the load state, this strategy coordinates the output power of batteries and supercapacitors, enabling efficient collaborative operation between the two [4]. Alternatively, model predictive control (MPC) takes a different approach. It establishes an accurate mathematical model of the bidirectional DC - DC converter, predicts the future state of the system, and optimizes control variables based on the prediction results, significantly enhancing the dynamic response performance and operational stability of the system [5].

Regarding the optimization of topological structures and control technologies, the topological optimization of the Buck-Boost converter structure effectively improves the energy conversion efficiency and power density by improving the layout of circuit components, optimizing the selection of switching devices, and adjusting the control timing [6]. The control strategy based on state-of-charge (SOC) and current feedback dynamically adjusts the charging and discharging currents by obtaining real time SOC information and current data of supercapacitors, greatly enhancing the energy utilization efficiency of supercapacitors [7]. The multi-mode switching control method intelligently switches between multiple working modes according to the characteristics of different working conditions, significantly enhancing the adaptability and robustness of the system under complex conditions [8].

Despite the numerous advancements achieved in the mentioned research, current mainstream studies predominantly focus on simple closed loop control systems. These systems suffer from issues such as slow response speed, poor control accuracy, and high energy consumption, which are insufficient to meet the stringent requirements of high performance energy storage systems for rapid response and efficient energy management. Therefore, the development of more advanced control strategies and system architectures is urgently needed to further promote the technological development of hybrid energy storage systems.

Based on this, this paper proposes a battery-supercapacitor hybrid energy storage control scheme based on the Buck-Boost circuit. The scheme adopts a voltage and current closed loop control structure with power limitation, and employs a four switch converter to achieve dynamic voltage balancing of supercapacitor banks and efficient energy flow management. The proposed scheme is simulated on the MATLAB Simulink platform to verify its fast response and high-efficiency performance during bidirectional power flow, providing theoretical support and practical basis for the engineering application of hybrid energy storage systems.

2. Four-switch Buck-Boost circuit

Traditional Buck, Boost, and single switch Buck-Boost topologies have application potential in specific scenarios [9], but their inherent unidirectional power flow, efficiency bottlenecks, or polarity reversal drawbacks make them difficult to meet the complex requirements of hybrid energy storage systems [10]. Therefore, this design employs a four switch Buck-Boost circuit as the core topology of the hybrid energy storage system. By combining a full-bridge structure with synchronous rectification technology, it achieves high efficiency, wide-range voltage regulation, and seamless bidirectional energy transfer. The following sections focus on analyzing the working principle, dynamic characteristics, and parameter design methods of this topology, supplemented by formula derivation and waveform analysis, to clarify its performance advantages over traditional schemes.

The four-switch Buck-Boost circuit is composed of two pairs of complementary power switches (M1/M2 and M3/M4), an energy storage inductor L, and an output filter capacitor C. Figure 1 shows the circuit topology diagram.

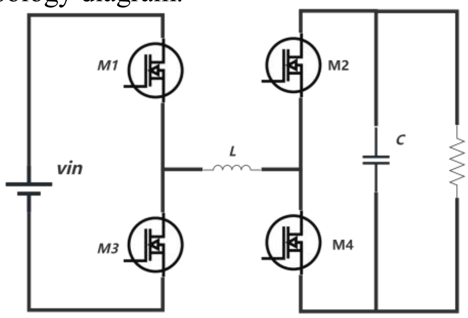

Figure 1. Topology of the Four-Switch Buck-Boost Circuit

Its core innovation lies in integrating the Buck and Boost modes into the same topology through switching logic reconstruction, while maintaining the same polarity of input and output voltages.

2.1 Buck Operating Mode

When the input voltage V_{in} is much higher than the output voltage V_{out}, the switch M2 remains always on and the switch M4 remains always off, putting the circuit into the Buck step-down mode. During the charging phase, M1 is turned on, M3 is turned off, M2 remains on, and M4 remains off, causing the inductor current to rise continuously. During the discharging phase, M1 is turned off, M3 is turned on, M2 and M4 remain unchanged, and the inductor current decreases continuously.

2.2 Boost Operating Mode

When the input voltage V_{in} is much smaller than the output voltage V_{out}, the converter switch M1 remains always on and the switch M3 remains always off, placing the circuit in the Boost step-up mode. During the charging phase, M2 is turned off, M4 is turned on, M1 remains on, and M3 remains off, causing the inductor current to rise continuously. During the discharging phase, M2 is turned on, M4 is turned off, M1 and M3 remain unchanged, and the inductor current decreases continuously.

2.3 Buck-Boost Operating Mode

When the input voltage V_{in} is close to or equal to the output voltage V_{out}, the converter's working process can be divided into three stages. In the initial stage, the converter has not yet entered the Buck-Boost hybrid mode, and its behavior is basically similar to that of a traditional Buck step-down converter. At this time, the system mainly adjusts the switches to charge and discharge the inductor, thereby achieving voltage regulation. As the operation progresses, the converter gradually enters a hybrid mode between Buck and Boost. It initially maintains the charging characteristics of the Buck mode and then switches to the charging process of the Boost mode, with the inductor current continuously rising. When the system detects suitable conditions, it switches back to the Buck mode and enters the discharging stage. Since the input and output voltages are relatively close, the converter frequently switches between the Buck and Boost states within a clock cycle, forming a dynamic transition mode. If the input voltage is detected to be significantly lower than the output voltage, the control logic causes the converter to fully switch to the Boost step-up mode. In this stage, the Buck clock signal no longer causes any action, and only when the Boost mode clock is triggered are the relevant switches activated to complete the inductor discharging and voltage boosting actions. At this time, the converter completely leaves the previous transition mode and switches to a stable Boost operation state.

3. The Controller Design

To achieve comprehensive control over the voltage, current, and power during the charging and discharging processes of capacitors, this paper proposes a universal power control strategy based on the Buck-Boost topology. A three-stage closed loop control framework is introduced into the controller structure. This strategy organically integrates the power loop, voltage loop, and current loop to balance system stability and dynamic performance, making it particularly suitable for supercapacitor control in scenarios with drastic load changes or rapid energy release. Figure 2 shows the designed control block diagram.

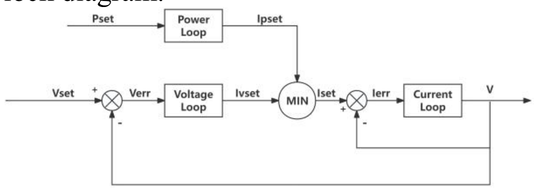

Figure 2. Dual Closed-Loop Control Block Diagram with Power Limitation

The control system is constructed using a positional PI regulator. The voltage loop and current loop are based on characteristics of simplicity, stability, and ease of implementation, while a hierarchical nesting of functional modules forms a refined adjustment system. In the design, the voltage loop takes the error between the capacitor output voltage and the set reference voltage as input. After regulation by the PI controller, it outputs a current reference value. If the corresponding error signal is $e_v = V_{ref} - v_{sc}$, the voltage loop PI output current is:

$$i_{ref} = K_{pv} e_v + K_{iv} \int e_v dt \tag{1}$$

Among K_{pv} and K_{iv} are tuned by the pole placement method to ensure that the bandwidth of the voltage loop $f_{bw_v} \leq 1/10$.

The current loop, acting as the inner loop, performs dynamic compensation to rapidly track the reference current i_{ref} and suppress inductor current ripple. Its error signal is defined as $e_i = i_{ref} - i_L$ the duty cycle control variable, which is calculated via the PI controller:

$$d = K_{pi} e_i + K_{ii} \int e_i dt \tag{2}$$

The transfer function of the current loop is expressed as:

$$G_i(s) = \frac{K_{pi} s + K_{ii}}{Ls + R_{\text{sense}} + K_{pi}} \tag{3}$$

The proportional gain K_{pi} and integral gain K_{ii} are tuned using the frequency-domain response method to ensure that the phase margin of the current loop exceeds 45°, thereby achieving fast dynamic response and stable control. The power loop takes the set power as input and calculates the corresponding current reference value based on the power-current-voltage relationship. The maximum power is constrained as:

$$P_{max} = V_{sc} I_{max} \tag{4}$$

When the v_{sc} drops, the amplitude limiting P_{max}/v_{sc} threshold is automatically raised to avoid control failure caused by traditional fixed amplitude limiting. Therefore, the limitation of maximum power is achieved under the premise of ensuring voltage stability. This mechanism not only enhances the anti-interference capability of the system but also effectively prevents the output current from overshooting or exceeding the set safety range.

In the specific design of the PI controller, to fully leverage the left-right symmetry of the Buck-Boost topology, the system employs a universal PI structure that adapts to different operating modes by dynamically switching the reference input signal and its feedback channels. When the system is in Buck mode (step-down), the controller uses the criterion that the input voltage is higher than the output voltage to designate the Buck-direction current path as the main control object. When transitioning to Boost mode (step-up), the control logic adjusts the reference channel accordingly, shifting the control target to stabilizing the output current during the step-up process. When the input and output voltages are close, the system automatically enters a transition region, where the controller intelligently determines the current priority mode based on the output difference between the power loop and voltage loop, ensuring the entire control system exhibits smooth transition capabilities under different operating conditions.

Additionally, due to the significant voltage variations of supercapacitors during charging and discharging, traditional fixed reference value methods often fail to precisely regulate output power or voltage, prone to causing dynamic response delays or system oscillations. To address this issue, the PI parameter design in this control strategy adopts a bandwidth allocation principle of "fast inner loop-slow outer loop," where the current loop responds faster than the voltage loop, thereby enhancing the system’s overall response performance. During load transients or operating mode switches, the current loop rapidly completes feedback correction, while the voltage loop provides buffering and correction, with both loops collaborating to achieve precise control over the dynamic behavior of supercapacitors. Meanwhile, as an outer protective mechanism, the power loop further ensures safe system operation under extreme conditions by limiting the current reference value. This control strategy not only achieves multi-dimensional coordinated control of power, voltage, and current but also demonstrates excellent versatility, adaptability, and robustness.

4. System Simulation and Result Analysis

To verify the feasibility and effectiveness of the proposed supercapacitor power control strategy based on the Buck-Boost topology, this paper designs a comprehensive system simulation model using the MATLAB/Simulink platform. The model systematically integrates four key components: the four-switch main circuit of the Buck-Boost converter, a supercapacitor module, a closed-loop controller implementing the designed three-stage feedback framework, and a dynamic load model capable of simulating abrupt power demand changes. This configuration enables comprehensive investigations of the system under multiple scenarios, including Buck-mode step-down conversion, Boost mode step-up conversion, and hybrid-mode transitions when input and output voltages are close.

The simulation model incorporates critical physical parameters to enhance fidelity, such as parasitic resistances and inductances of passive components (inductors and capacitors), on-state resistances and switching delays of power transistors, and the equivalent series resistance (ESR) of supercapacitors. Additionally, the initial state-of-charge (SOC) of the supercapacitor is explicitly parameterized to study its impact on dynamic performance during charging and discharging cycles. These details ensure the model accurately reflects real-world operating conditions, bridging the gap between theoretical design and engineering application.

As shown in Figure 3, the constructed simulation circuit visually demonstrates the interconnection structure of subsystems, highlighting the signal flow among different components.

The parameters set for the simulation circuit are shown in Table 1.

To further validate the stability and scalability of the control strategy, the simulation introduces perturbation signals such as increased capacitor ESR, control delay, and sampling noise to conduct robustness tests against disturbances. During the system startup phase, after the controller detects the load power, it rapidly calculates the target current reference value through the power loop, and the voltage loop and current loop jointly control the switch duty cycle to quickly establish the system output. As shown in the Figure 4, the supercapacitor voltage rises rapidly from the initial level with a fast response, no obvious overshoot, and oscillation, verifying that the designed three-stage closed-loop control strategy exhibits high stability and rapidity during system startup.

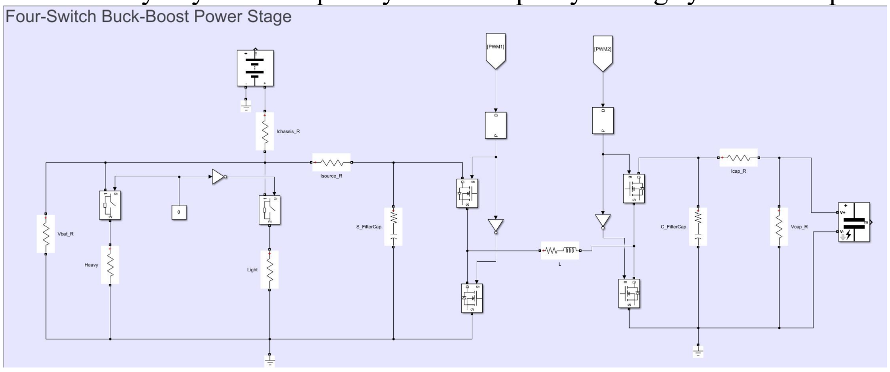

Figure 3. Constructed Simulation Circuit Diagram

Table 1. Core Parameters of the Buck-Boost Simulation Circuit

Buck-Boost Circuit Parameters	Numerical value	Unit
Power Supply Power	96	W
Low-Power Load	60	W
High-Power Load	180	W
Initial Voltage of Supercapacitor	5	V
Maximum Voltage of Supercapacitor	28	V
Inductor L	5.62	mH
Load Capacitor	1	mf

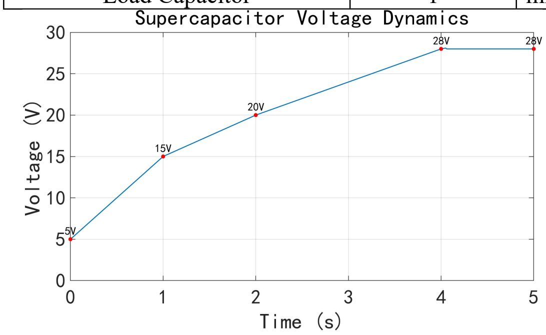

Figure 4. Dynamic Voltage of Supercapacitor

In the load step-change test, the system load abruptly increases from the minimum to the maximum between 5s and 10s to simulate drastic load variations in practical applications. The Figure 5 show that the system completes current reconfiguration and voltage regulation within 20ms after the load change, with a minimum voltage drop of no more than 5%, followed by a rapid recovery to the steady state. This performance is attributed to the fast response capability of the current loop and the current-limiting mechanism of the power loop, which effectively suppress overcurrent risks and demonstrate the system's excellent dynamic robustness.

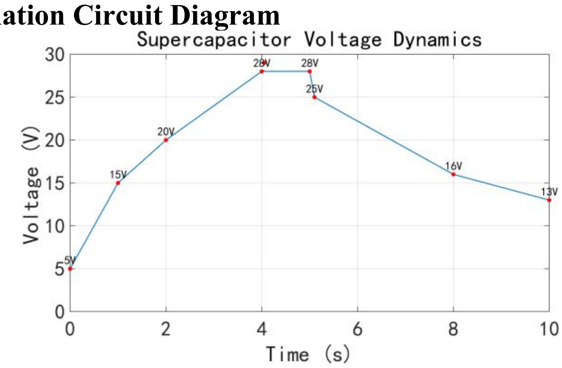

Figure 5. Dynamic Voltage of Supercapacitor

In addition, the simulation also tested the adaptability to input voltage disturbances. When the input voltage suddenly drops from 24V to 18V, which is the transition region from Buck to Boost, the system controller can automatically identify the current operating mode and achieve a smooth switch. During the transition from Buck to Boost, the system output voltage always remains near the set target, and there is no significant fluctuation in the current, indicating that the universal PI control structure has good adaptability and seamless performance in automatic mode switching. It is worth noting that in the region where the input and output voltages are close, the controller takes the outputs of the power loop and voltage loop as references, automatically adjusts the main control channel, and realizes stable control in the Buck-Boost hybrid mode without mode jitter or frequent jumps. When disturbances are added, the maximum fluctuation range of the system output voltage does not exceed 3%, all control variables remain within the stable range, and the overall performance of the system does not degrade significantly.

Moreover, the simulation further evaluated the system's adaptability to input voltage disturbances. As shown in Figure 6, when the input voltage suddenly dropped from 24V to 18V in the transition region between Buck and Boost operating modes, the controller automatically identified the current operating mode and achieved a smooth switch. During the transition from Buck to Boost, the system output voltage consistently remained near the set target, and the current showed no significant fluctuations, indicating that the universal PI control structure has good adaptability and seamless performance in automatic operating mode switching. It is worth noting that in the region where the input and output voltages are close, the controller uses the outputs of the power loop and voltage loop as references to automatically adjust the main control channel, achieving stable control in the Buck-Boost hybrid mode without mode jitter or frequent switching phenomena. Under the condition of adding disturbances, the maximum fluctuation range of the system output voltage does not exceed 3%, all control variables remain within the stable range, and the overall performance of the system does not undergo obvious degradation.

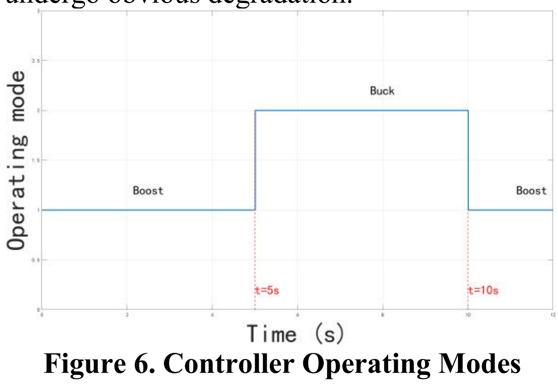

Figure 6. Controller Operating Modes

5. Conclusion

This paper presents a supercapacitor power control scheme based on the Buck-Boost circuit, and effectively addresses the voltage fluctuation issues of supercapacitors during charging and discharging processes through the design of a three-stage closed-loop control strategy. By introducing a dual closed-loop control consisting of a power loop, voltage loop, and current loop, the system can ensure fast response and stable operation under load variations and input disturbances. The proposed control strategy exhibits excellent dynamic performance and stability, particularly in scenarios involving abrupt load changes and input voltage fluctuations, enabling precise voltage regulation and current control. It avoids the hysteresis and overshoot phenomena inherent in traditional single-closed-loop control strategies, providing theoretical support and practical guidance for the engineering application of hybrid energy storage systems.

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References

[1] Li Jianlin, Li Xinran, Zou Fei, et al. Typical Engineering Demonstration and Grid-Related Characteristics Detection Technology of Grid-Forming Energy Storage. High Voltage Engineering, 1-15 [2025-04-27].

[2] Ai Wandong, Su Xing, Sun Junyong. Research on Charging and Discharging Control Strategy for Hybrid Power Supply System of Energy Storage Trams. Electric Locomotives and Urban Rail Vehicles, 2025, 48(01): 35-40.

[3] Bo Liming, Liu Xinyuan, Cheng Xueting, et al. Optimal Research on Hybrid Energy Storage Based on Variational Mode Decomposition for Wind-Solar Regulation Demand. Journal of North China Electric Power University (Natural Science Edition), 1-11 [2025-04-27].

[4] Zhou Wen. Research on Operation Control of Brushless DC Motor Powered by Battery-Supercapacitor Hybrid Energy Storage System. Zhejiang University, 2024.

[5] Yang Runan, He Jinwei, Wang Xiurui. Model Predictive Voltage Control of Three-Level Bidirectional DC-DC Converter. Journal of Power Sources, 2021, 19(02): 74-80.

[6] Cheng He, Li Pengsheng, Xu Kai, et al. Fully Integrated Magnetic Component Structure and Optimization Design of Dual Buck-Boost-CLLC Three-Port Converter. Transactions of China Electrotechnical Society, 1-16 [2025-04-27].

[7] Zhu Peng, Xie Zongchen. Research on Power Regulation Design of Source-Grid-Load Microgrid Based on Energy Storage SOC. Electrical Engineering Materials, 2024, (03): 28-32.
[8] Wang Hongbin, Chen Aobo, Xue Yuntao, et al. Research on Smooth Mode Switching Strategy for Four-Switch Buck-Boost Converter Based on Graphical Method. Journal of Power Sources, 1-14 [2025-04-27].
[9] Shi Jie, Wang Yu, Shi Yichen. A Buck-Boost Converter with High Voltage Conversion Gain. Electric Engineering, 2024, (20): 164-166.
[10] Guo Qiang, Zhang Fanyun, Li Haixiao, et al. Multi-Mode Control Strategy for High-Efficiency Four-Switch Buck-Boost Converter. Chinese Journal of Scientific Instrument, 2024, 45(11): 101-116.
