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Research on Energy Control Strategy based on Improved Hybrid Energy Storage System

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Abstract: With the rapid development of globalization, problems such as resource depletion have become increasingly prominent, and new energy technologies will become a new way for humans to alleviate the energy crisis, resulting in a large number of new energy devices. The application of a large number of new energy devices has led to unstable power in the power grid. Therefore, this paper proposes an energy control strategy based on an improved hybrid energy storage system to improve power grid stability. By integrating a traditional single battery energy storage system into a supercapacitor energy storage system and combining it into a battery capacitor hybrid energy storage system, the power of the hybrid energy storage system is distributed to compensate for fluctuating power. Simulation results show that the energy management control strategy of the improved hybrid energy storage system can effectively smooth out the occurrence of power in independent microgrid systems. The issue of power fluctuations, this further proves the feasibility and correctness of the control strategy.

Keywords: Battery; Power Fluctuation Suppression; Hybrid Energy Storage; Energy Management; Supercapacitors.

1. Introduction

In recent years, with the depletion of energy and the increasing greenhouse effect caused by traditional energy sources, the country has proposed a "dual carbon" policy to achieve carbon neutrality. Therefore, technologies and equipment related to clean energy have developed rapidly. Among them, when distributed power sources are connected to the grid for power generation, power fluctuations may occur, causing equipment damage and reducing power quality. Therefore, a hybrid energy storage system is added to the independent microgrid system to smooth out power fluctuations and improve the stability of power transmission.

As a new type of energy storage method, hybrid energy storage system combines the advantages of different types of energy storage devices to achieve efficient management and optimized control of energy. At the same time, it can effectively control the volatility of renewable energy when connected to the grid, effectively solving the interference of intermittency and volatility of renewable energy on the power grid.

Scholars from various countries have conducted extensive research on control strategies for hybrid energy storage systems. In reference [3], the innovation of HESS for multiple energy storage systems was introduced, and Eckert et al. proposed coordinated control strategies for multiple HESS systems. Simulation results showed that the coordination between the systems was significantly optimized under various cyclic operating conditions. In reference [4], a detailed study was conducted on the key components of hybrid energy storage and the DC/DC power conversion circuit. An efficient energy management strategy was developed based on the control strategy of the hybrid energy storage system. The feasibility of the proposed energy management control strategy was verified through MATLAB simulation experiments, and it was ultimately concluded that the hybrid energy storage system with the combination of "supercapacitor battery" can effectively achieve the "peak shaving and valley filling" function, while also effectively limiting the battery output current and protecting the energy storage equipment. In reference [5], a hybrid energy storage system consisting of iron aluminum phosphate batteries and supercapacitors was proposed as the energy component of new energy electric vehicles, and fuzzy control strategy and logic gate control strategy were adopted for the control strategy. The effectiveness and feasibility of the proposed control strategy were verified through simulation experiments. A novel control strategy based on model prediction was proposed in reference [6], which does not require PI controllers and filters for frequency division control of batteries and supercapacitors. Compared with traditional control methods, the model prediction control strategy has a faster response and lower computational complexity when the steady-state operating point of the system changes, effectively achieving voltage regulation and power allocation. A hybrid energy storage control strategy based on smooth control was proposed in reference [7], and a method for pre controlling the voltage at the supercapacitor terminal was designed. The charging and discharging power of the supercapacitor and battery can be adjusted according to the remaining electrical energy, achieving the goal of smoothing power fluctuations.

Based on the above research, this article proposes a control strategy for a hybrid energy storage system based on an improved "supercapacitor battery" to address the issue of stable integration of distributed power sources into the power grid and avoid damage to grid equipment caused by power fluctuations. An improved hybrid energy storage system has been designed, which can redistribute the system energy based on the remaining electrical energy of the battery and supercapacitor, achieving the goal of smooth grid connection, while effectively protecting the battery and supercapacitor from overcharging and discharging. Finally, a simulation model of a hybrid energy storage system based on "supercapacitor battery" was built in MATLAB/Simulink, and the model was simulated to further verify the feasibility and correctness of the proposed control strategy.

2. Independent DC Microgrid System Structure with Hybrid Energy Storage

2.1. Structure of Independent DC Microgrid System with Hybrid Energy Storage

The independent DC microgrid in this article adopts a hybrid energy storage system, as shown in Figure 1, which consists of four modules: hybrid energy storage system, distributed power generation, load, and inverter. In Figure 1, P_{HESS} represents the total power provided by the hybrid energy storage system; PWind is the total power provided by the wind power generation system; The total power provided by P_{PV} for photovoltaic power generation systems; P_{Load} is the total power consumed by independent microgrid loads.

The wind power generation system and photovoltaic power generation system used in distributed power sources in independent DC microgrid systems usually operate at the maximum power point. As they obtain natural energy and have the characteristic of real-time changes, hybrid energy storage systems are added to microgrid systems to maintain stable system operation. The main function of supercapacitors is to smooth out high-frequency power fluctuations, and the main function of batteries is to smooth out low-frequency power fluctuations, in order to reduce the number of charging and discharging cycles of batteries and extend their service life.

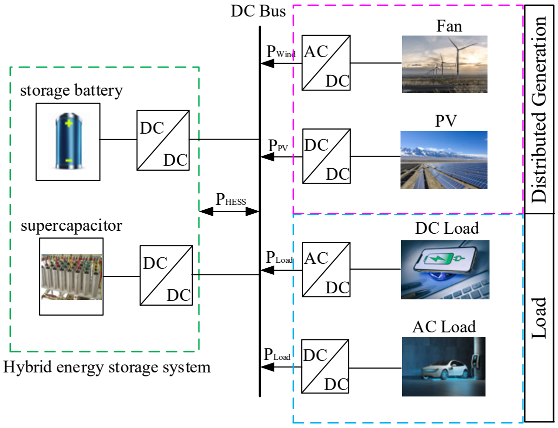
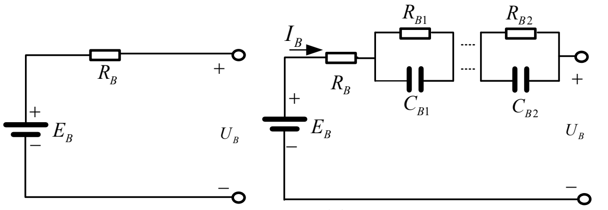
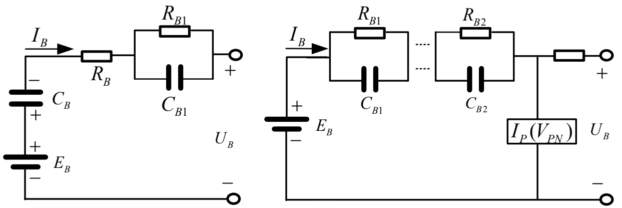


Figure 1. Independent DC microgrid system structure with hybrid energy storage

2.2. Mathematical Modeling of Batteries



(a) Internal resistance model (b) Thevenin model



(c) PNGV model (d) Massimo Ceraolo model

Figure 2. Equivalent circuit model of battery

As an efficient energy conversion device, batteries are widely used in various power systems. The basic principle circuit model diagram of commonly used batteries is shown in Figure 2. Due to the complex chemical changes involved inside the battery, the relevant parameters cannot be accurately calculated. After comparing the basic equivalent model circuit diagrams of the other three types of batteries, this paper chooses the second-order RC circuit in Figure (b) as the research object to reduce the computational complexity and improve the accuracy of relevant parameter calculations.

Among them, E_B is the electromotive force of the battery, I_B is the constant pulse discharge current, R_{B1} and R_{B2} are the polarization internal resistance, R_B is the ohmic resistance of the battery pack, C_B, C_{B1}, and C_{B2} are the polarization capacitance [8]. The mathematical relationship between them is:

$$\begin{cases} U_B = E_B - I_B R_B - I_B R_{B1} - I_B R_{B2} \\ I_B = \dfrac{U_{B1}}{R_{B1}} + C_{B1}\dfrac{dU_{B1}}{dt} \\ I_B = \dfrac{U_{B2}}{R_{B2}} + C_{B2}\dfrac{dU_{B2}}{dt} \end{cases} \tag{1}$$

Due to the fact that the equivalent model of the battery mentioned above did not consider SOC, it is necessary to optimize the model. Therefore, a universal circuit model was obtained, as shown in Figure 3.

Based on the circuit model shown in Figure 3 and combined with Kirchhoff's voltage law, the following mathematical expression can be obtained:

$$\begin{cases} E = E_0 - K\dfrac{Q}{Q - \int i_{bat}dt} + A\exp\left(-B\int i_{bat}dt\right) \\ V_{bat} = E - R.i_{bat} \end{cases} \tag{2}$$

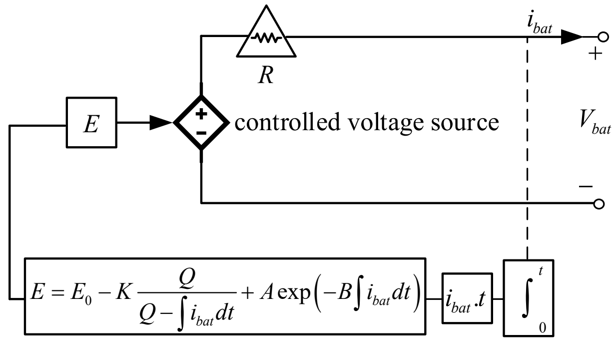


Figure 3. General Circuit Model for Batteries

Among them, E_0 is the battery voltage coefficient; E is the no-load voltage; Q is the battery capacity; K is the polarization voltage; B is the reciprocal of the time coefficient of the exponential interval; A is the amplitude of the index interval; ibat is the constant current of the battery; V_{bat} is the battery voltage; R is the internal resistance of the battery; $\int i_{bat}dt$ is the actual battery level [9].

Based on the above analysis and combined with the discharge characteristic curve of the battery, as shown in curve ab in Figure 4, the terminal voltage of the battery drops rapidly in the initial stage of discharge, and then enters a stable decline stage, as shown in curve bc in the figure, which is the intermediate stage of discharge. After point c, the battery discharge enters the tail stage, and the discharge curve shows a rapid drop.

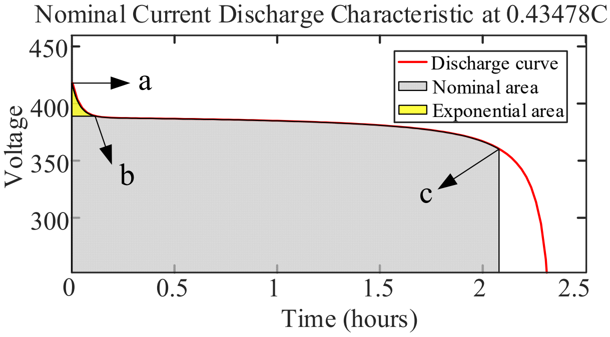


Figure 4. Typical discharge curve of Besti battery

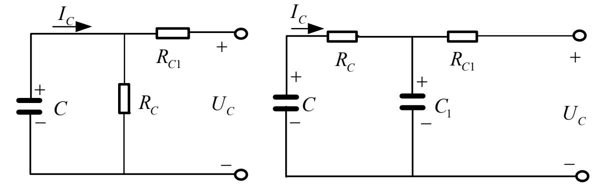
From the above analysis, it can be concluded that the relevant parameters of the battery can be calculated through the following mathematical expressions:

$$\begin{cases} A = E_{Full} - E_{Exp} \\ B = \dfrac{3}{Q_{Exp}} \\ K = \dfrac{\left(E_{Full} - E_{Nom} + A\left(\exp\left(-BQ_{nom}\right) - 1\right)\right).\left(Q - Q_{nom}\right)}{Q_{nom}} \end{cases} \tag{3}$$

In the formula: E_{Full} is the full load voltage of the battery; E_{Nom} is the real-time voltage during battery operation; E_{Exp} is the terminal voltage at the end of the battery index range; Q_{Exp} is the total discharge amount of the battery from the cut-off zone to the end of the index zone; Q_{nom} is the total amount of electricity discharged from the battery from the cut-off zone to the end of the normal operating zone[10].

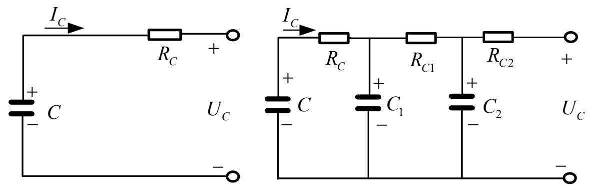
2.3. Circuit Equivalent Model of Supercapacitors

The most important characteristic of a capacitor is that it neither generates nor consumes energy. In the power system, it can both smooth out power fluctuations and improve power quality. Due to the complex discharge characteristics inside supercapacitors, as shown in Figure 5, the classical resistance capacitance model in Figure 5(a) is considered as the research object. Due to its simple structure and easy availability of relevant parameters, it is the primary focus of this article.



(a) Classic Resistive Capacitive Equivalent Circuit Model

(b) Second order RC equivalent circuit model



(c) Equivalent circuit model of internal resistance

(d) Multi branch RC equivalent circuit model

Figure 5. Equivalent Circuit Model of Supercapacitors

Considering the complex calculation parameters of high-order RC circuit models, this paper adopts the internal resistance model as the equivalent model of capacitors [11].

2.4. Mathematical Modeling of Hybrid Energy Storage Systems

The topology diagram of the hybrid energy storage system circuit used in this article is shown in Figure 6. The circuit topology diagram consists of a front-end circuit and a back-end circuit. The front-end is a bidirectional DC/DC circuit topology diagram, which is used to complement the electrical energy of the battery and supercapacitor in real time; The topology diagram of the downstream circuit is a three-phase voltage type PWM converter, which converts the collected voltage signal into a pulse signal to control the on/off of the IGBT switch. By controlling the entire circuit topology, a hybrid energy storage system combining batteries and supercapacitors can effectively suppress the power generated by renewable energy sources, achieving stable power integration into the grid.

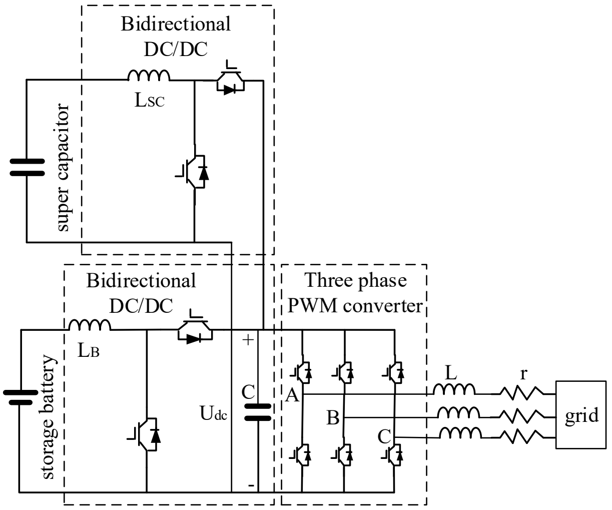
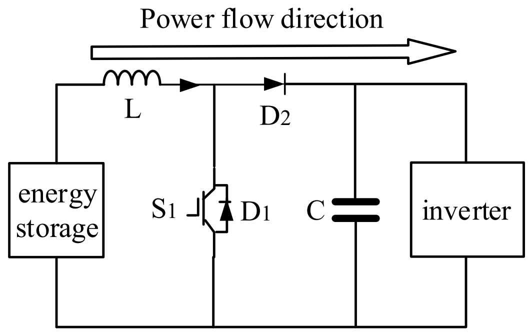
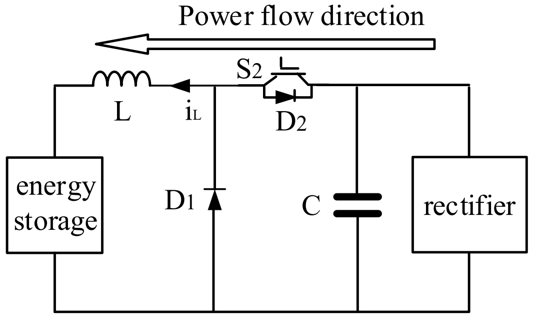


Figure 6. Topology of main circuit in hybrid energy storage system



(a) Equivalent circuit during discharge



(b) Equivalent circuit during charging

Figure 7. Equivalent circuit of bidirectional DC/DC during charging and discharging

In Figure 6, the front-end bidirectional DC/DC converter serves as the interface circuit between the energy storage system and the grid side AC/DC, playing an important role in rectification and inversion, ensuring a more stable and rapid flow of system energy.

The structure of the bidirectional DC/DC converter used in this article is shown in Figure 7. When the circuit operates in a discharge state, as shown in Figure 7 (a), electrical energy flows from the energy storage system to the grid, and the amount of power released by the energy storage system is controlled through a feedback mechanism; When the circuit operates in charging mode, as shown in Figure 7 (b), electrical energy flows from the grid to the energy storage system, and the charging power of the energy storage system is controlled through a feedback mechanism [12].

The three-phase PWM converter in this article is provided by the Matlab/Simulink model library, and the coordinate transformation used is also provided by the software model library. The principles of model construction will not be elaborated one by one.

3. Power Allocation Strategy for Hybrid Energy Storage System

3.1. Energy Management Strategy for State of Charge of Supercapacitors

The key to energy management strategy in hybrid energy storage systems is to balance the power between the battery and supercapacitor. Usually, a low-pass filter is used to process P_{HESS}, and the filtered power is used as battery power compensation, denoted as P_{b1}. Its mathematical relationship expression is shown in Equation 4; The remaining power is used as a compensating supercapacitor, denoted as P_{sc1}, and its mathematical expression is:

$$P_{b1} = P_{HESS} \bullet \frac{1}{st_s + 1} \tag{4}$$

$$P_{sc1} = P_{HESS} - P_{b1} = P_{HESS} \bullet \frac{st_s}{st_s + 1} \tag{5}$$

In the formula: ts is the time constant of the low-pass filter; P_{b1} and P_{sc1} are the compensation power obtained from the initial distribution of batteries and supercapacitors [13].

In a hybrid energy storage system, the battery is a vulnerable consumable. When designing the control strategy for the energy storage system, the charging and discharging power will be limited. By compensating for the low-frequency part of the battery's fluctuating power, the service life of the battery can be extended. Specifically, by adding a filtering time constant adjustment module and redistributing power, the reference compensation power for the battery and supercapacitor is P_{b2} and P_{sc2}, whose mathematical relationship is expressed as:

$$P_{b2} = P_{HESS} \bullet \frac{1}{s(t_s + \Delta t) + 1} \tag{6}$$

$$P_{sc2} = P_{HESS} - P_{b2} = P_{HESS} \bullet \frac{s(t_s + \Delta t)}{s(t_s + \Delta t) + 1} \tag{7}$$

In the formula, Δt is the time coefficient adjustment value of the low-pass filtering process.

By compensating for low-frequency power fluctuations as described above, it is possible to effectively limit the absorption and release of energy by the battery, thereby effectively extending its service life.

3.2. Coordination Control Strategy for Overcharge and Over Discharge

Due to the limited capacity of batteries and supercapacitors, overcharging or overdischarging may occur when the capacity is insufficient, causing equipment damage. Protective mechanisms are added in the design to prevent these phenomena from occurring. Generally, the protection function is achieved by adjusting the discharge power. Specifically, when the supercapacitor and battery are in the discharge warning zone, the mathematical relationship between the adjustment rules is:

$$P_{\mathrm{dx}}' = P_{dx} \bullet \max\left\{0, \frac{SOC_x - SOC_{\min}}{SOC_{low} - SOC_{\min}}\right\} \tag{8}$$

In the formula: P_{dx}' is the power value after overcharge and overdischarge protection; P_{dx} is the power value without overcharge and over discharge protection.

When the state of charge of the battery and supercapacitor is in the charging alert zone, adjust the mathematical relationship as follows:

$$P_{\mathrm{cx}}' = P_{cx} \bullet \max\left\{0, \frac{SOC_{\max} - SOC_x}{SOC_{\max} - SOC_{high}}\right\} \tag{9}$$

In the formula: P_{cx}' is the power value after overcharge and overdischarge protection; P_{cx} is the power value without overcharge and over discharge protection.

According to equations (8) and (9), it can be seen that when the battery or supercapacitor is fully charged, the charging power decreases to 0 and the energy storage component will not continue to charge.

The actual compensation power differs from the initial fluctuation power P_{HESS}, and additional coordinated control strategies need to be added to adjust the power distribution between the battery and supercapacitor. The overall power flow of a hybrid energy storage system is generally complex, and the output power between the battery and supercapacitor conflicts with the current total power direction of the system. For ease of analysis, it is simplified into two situations:

1) When the SOC of the supercapacitor does not conflict with the total power compensation direction of the hybrid energy storage system, the mathematical expression of the compensation power value between the battery and the supercapacitor is:

$$\begin{cases} P_{b3} = 0 \\ P_{sc3} = P_{HESS} \end{cases} \tag{10}$$

In the formula, P_{b3} is the power reference value after coordinated control of battery overcharge and over discharge, and P_{sc3} is the power reference value after coordinated control of supercapacitor overcharge and over discharge.

2) When the SOC of the supercapacitor conflicts with the total power compensation direction of the hybrid energy storage system, the mathematical expression for the compensation power value between the battery and the supercapacitor is:

$$\begin{cases} P_{b3} = P_{HESS} - P_{nsc} \\ P_{sc3} = P_{nsc} \end{cases} \tag{11}$$

In the equation: P_{nsc} is the reference power value processed by equations (8) and (9).

The program flowchart designed based on the above formula is shown in Figure 8. Through the following program description, it can effectively make the total compensation power of the supercapacitor and the battery close to P_{HESS}, avoiding the problem of overcharging and discharging of the battery and supercapacitor.

As shown in Figure 8, Event 1 refers to a conflict between the SOC of only one energy storage device and its current self-power; Event 2 refers to the conflict between the SOC of two energy storage devices and their own reference instructions [14].

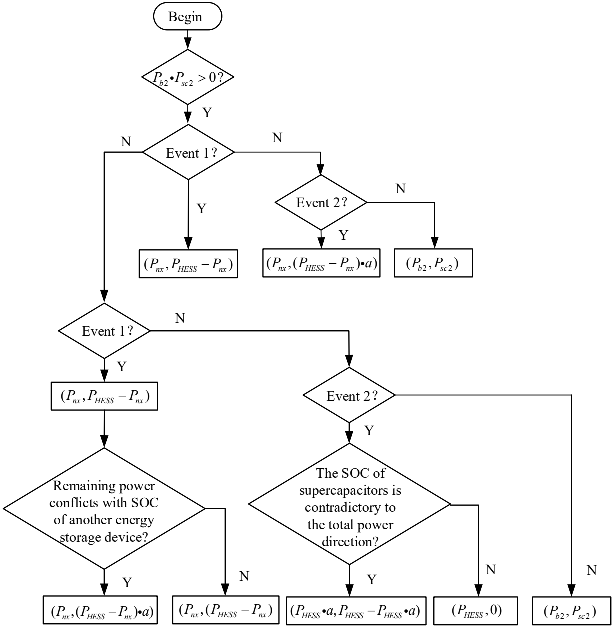


Figure 8. Coordination Control Flow Chart for Overcharging and Overdischarging of Hybrid Energy Storage System

3.3. Maximum Power Limit Strategy

The control strategy described in the previous section has effectively controlled the power fluctuation problem of hybrid energy storage systems. However, there are still some small power fluctuations in the actual system. Sometimes, the charging and discharging power of the battery and supercapacitor will reach their own limits, resulting in the inability to compensate for power and ultimately leading to phenomena such as overcharging and overdischarging. In order to further optimize the small power fluctuations, the power reference values of the battery and supercapacitor are modified to compensate at the maximum power, while the portion of power above the power limit is compensated by another energy storage device.

Table 1. Range of SOC_{sc} and SOC_b Values

P_e	SOC_{sc}	SOC_b
>0	≥0.3	≥0.4
<0	≤0.7	≤0.6

Make the maximum charging power of the battery P_{cbmax} and the maximum discharging power P_{dbmax}; The maximum charging power of the supercapacitor is P_{cscmax}, and the maximum discharging power is P_{dscmax}. The logic of maximum power limitation is: when the charging and discharging power of one energy storage device exceeds the limit value, it is operated at maximum power, and the other energy storage device determines whether to compensate for the excess power based on its own state of charge. As shown in Table 1, when the state of charge of the energy storage device meets the conditions of the table, another type of energy storage device can bear the excess power [15].

In Table 1, P_e represents the excess power, and the P_{xref} when compensating for additional power while meeting its own requirements is:

$$P_{xref}=P_{x3}+P_e \tag{12}$$

In the formula, P_{xref} is the reference power value.

Based on the above derivation, an energy control diagram for a hybrid energy storage system can be developed, as shown in Figure 9.

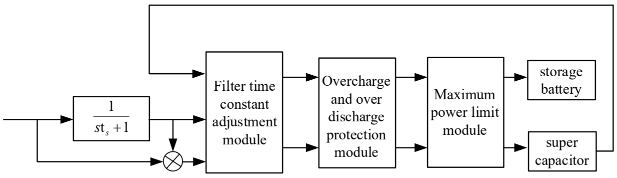


Figure 9. Energy Management Control Block Diagram of Hybrid Energy Storage System

4. Experimental Simulation

In order to verify the feasibility and correctness of the proposed control strategy, a hybrid energy storage system simulation model was built on the MATLAB/Simulink platform for simulation experiments in this paper.

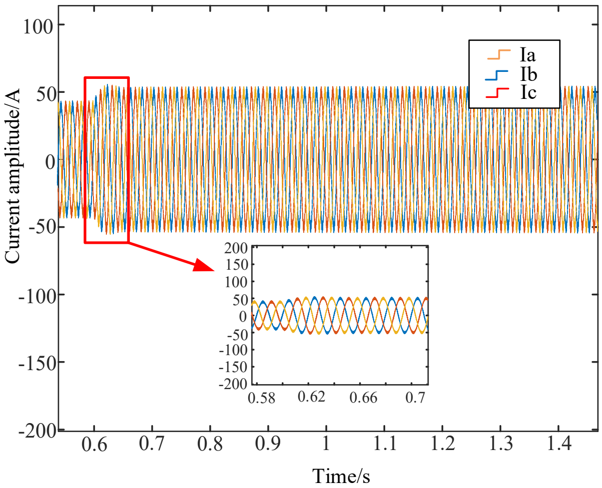


Figure 10. Grid connected current output waveform diagram

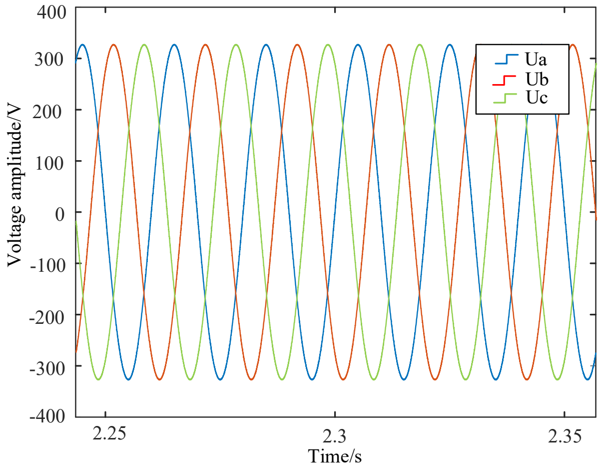


Figure 11. Grid connected voltage output waveform diagram

As shown in Figure 10, it is the waveform diagram of the grid connected current output. The amplitude of the output current in the figure is 50A, and the waveform is smooth, achieving the expected design effect.

As shown in Figure 11, it is the waveform diagram of the grid connected voltage output. The output voltage in the figure is 300V, and the output waveform is smooth. The control strategy has achieved the expected design effect.

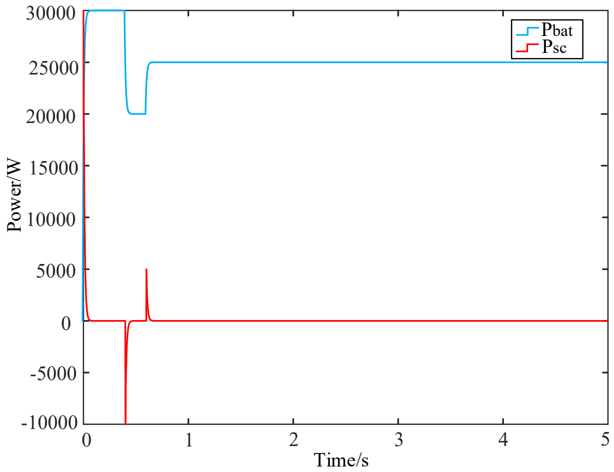


Figure 12. Low pass filter output power

As shown in Figure 12, it is the power waveform diagram of the battery and supercapacitor processed by a low-pass filter.

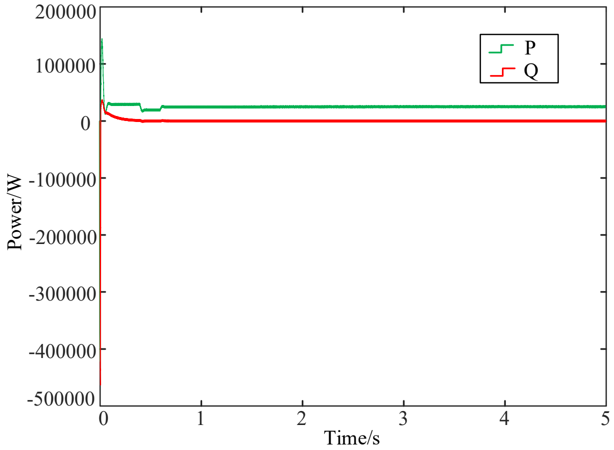


Figure 13. Waveform diagram of active and reactive power output

As shown in Figure 13, the waveform of active power and reactive power output of the hybrid energy storage system can be obtained. The green color in the figure represents active power, and the red color represents reactive power. The waveform is smooth without burrs, with fast response speed and smaller overshoot compared to traditional control strategies, reflecting the stability and flexibility of the hybrid energy storage system control strategy.

Figure 14 shows the FFT analysis waveform of the output current of the hybrid energy storage system after stable output power. After demonstrating the energy management control strategy, the grid connected current quality was good, and the waveform of current distortion was quickly restored to a stable state after the power curve suddenly changed. The figure shows that the *THD* is 4%, which is less than the national requirement of 5% and meets the grid connected requirements, further demonstrating the correctness and feasibility of the proposed hybrid energy storage system control strategy.

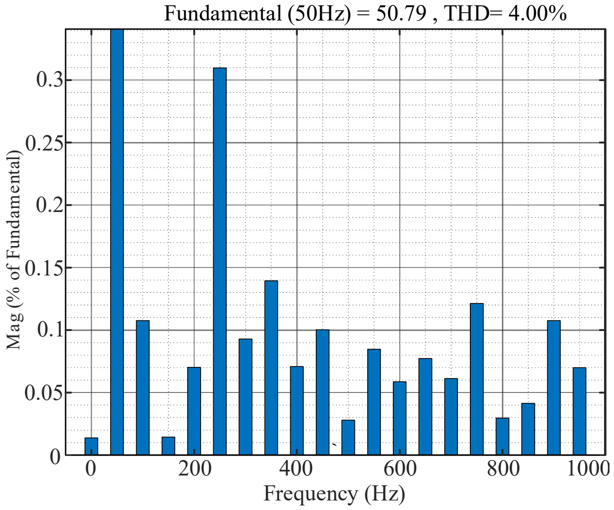


Figure 14. FFT analysis of VSG output current

5. Conclusion

Due to the huge scale of China's new energy market, a rich variety of power electronic devices have emerged. The connection and operation of these devices may pose challenges to the safe operation of the power grid. This article uses a hybrid energy storage system as a platform to study the role of batteries and supercapacitors in grid connection. Through the analysis of simulation results, research on energy management and control based on a hybrid energy storage system of batteries and supercapacitors is proposed in this article. The correctness of the proposed control strategy can be obtained through theoretical analysis and simulation experiments of supercapacitors and batteries. At the same time, the effects of adding supercapacitors and batteries are compared during grid connection, and it is concluded that supercapacitors can "peak shaving and valley filling", filter out harmonics, and make new energy power more stable when connected to the grid.

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