Switching control strategy for an energy storage system based on multi-level logic judgment

Sun Donglei[1], Sun Yi[1], Sun Yuanyuan[2]*, Liu Rui[1], Wang Xian[1] and Wang Yao[1]

[1]Economic and Technology Research Institute, State Grid Shandong Electric Power Company, Jinan, China, [2]School of Electrical Engineering, Shandong University, Jinan, China

Energy storage is a new, flexibly adjusting resource with prospects for broad application in power systems with high proportions of renewable energy integration. However, energy storage systems have spare capacity under stable working conditions and may be idle for some periods. These actions are primarily selected for peak shaving and valley filling, frequency regulation, and voltage regulation as the only control target; thus, energy storage cannot be used effectively, which weakens the effect of energy storage on grid support. To improve the utilization rate and economic benefits of the energy storage system and enhance the support performance of energy storage for the safe operation of the power grid, this article proposes a switching control strategy for an energy storage system based on multi-layer logic judgment to maximize energy storage benefits and ensure safe and stable power grid operation. First, this study analyzed the potential multi-ancillary service operation requirements of the energy storage system, combined with the auxiliary compensation benefits of the energy storage power station. Using this information, the study proposed a comprehensive index that considers the economy of the energy storage system and the stable operation of the power grid to support the evaluation needs of energy storage control. Based on this, the study then pre-set multi-layer judgment logic for the operation control of the energy storage system. A multi-objective judgment and smooth switching strategy for the coordinated operation of the energy storage system was proposed based on the typical operating conditions of the energy storage system participating in the grid peak shaving and valley filling, frequency regulation, and voltage regulation. This switching control method effectively utilized the idle capacity of the energy storage system and improved the energy storage system's support effect on the power grid. Through the improved energy storage control model based on MATLAB/Simulink, this study also verified the effectiveness of the proposed smooth switching strategy of the energy storage system.

KEYWORDS

energy storage, multi-objective control, toggle control, energy storage utilization, economic benefits

1 Introduction

The rapid scale-up of new energy power generation and the reduction of the proportion of non-clean energy have improved the green and low-carbon levels of the energy industry (Zhu et al., 2022; Sun et al., 2021a). The intermittency, volatility, and uncertainty of renewable energy generation bring new problems to the safe and reliable operation of the power grid (Xiao et al., 2022). To address the challenge of high-efficiency utilization of

new energy with high proportions and power replacement with high proportions under the background of carbon peak (Sun et al., 2021b), the demand for power systems for auxiliary power services such as peak and frequency regulation has increased significantly in recent years (Ma et al., 2021). Energy storage systems can further enhance the regulation potential of existing resources through bidirectional power and energy storage characteristics. Meanwhile, energy storage systems can support safe and stable power grid operation by using their flexible and rapid adjustment ability for active power and non-function, which can be widely used for frequency modulation (Li et al., 2019; Yan et al., 2021; Jiang et al., 2020), peak cutting and valley filling (Ma et al., 2022), and voltage regulation (Chen et al., 2021; Guo et al., 2019; Xu et al., 2017) of the power grid, and other scenarios (Huang et al., 2021).

At present, research on control strategies in energy storage systems has mainly focused on the fields where the energy storage converter is the control object and peaking and valley cutting or frequency and voltage regulation are the control objectives. In terms of peak cutting and valley filling, Zhou et al. (2021) proposed an optimization model and algorithm for a battery energy storage system based on the traditional constant power control strategy. The authors reported a real-time constant power charge and discharge strategy of the battery through the secondary analysis and processing of predicted load data. Regarding the energy storage involved in the frequency modulation of the power grid, Ma et al. (2019) and Li et al. (2017), reported the influence of characteristics including virtual sagging and virtual inertia control on power grid frequency and proposed an optimization control method. Based on the frequency regulation requirements of the power system, the optimal control strategy is selected to allow the coordinated operation and complementary advantages of the two control strategies. In terms of energy storage participation in the voltage regulation of the power grid, Wang et al. (2021) proposed a control strategy given the improvement of the power grid voltage quality and utilization rate of the energy storage system. The strategy adopted a timing coordination method to coordinate the participation of reactive power sources and energy storage power stations for power grid voltage regulation. Chen et al. (2022) proposed a division method and switching index for different working conditions of peak regulation and frequency modulation based on the state of charge of the energy storage system. This method proposed a coordinated control strategy to allow ES switching between peak regulation and frequency modulation control to improve the utilization rate of the energy storage system. Shi et al. (2017) proposed an economic optimization model of the joint peaking benefit and frequency regulation benefit of the energy storage system, proving that the benefit of joint peaking and frequency regulation control was greater than the sum of the two individual benefits, and analyzed the feasibility of peaking and frequency regulation cooperative control from the perspective of economics. However, the authors did not consider the specific control strategy. Although control strategies for energy storage peak regulation and frequency modulation, as well as voltage regulation, have been partially applied in demonstration projects, the multi-objective control strategy of the energy storage system is still early-stage research as the control of a single objective (Li and Wang, 2021). Thus, the idle capacity of the energy storage system

cannot be maximized during operation and the supporting effect of energy storage on the power grid is weakened. Moreover, the economic benefits of energy storage systems are lost.

Therefore, to address the problems of the current energy storage system, such as poor system benefits and weak power grid support caused by single-control objectives, this article proposed a smooth switching control strategy for energy storage systems based on multi-layer logic judgment to achieve real-time optimal control of energy storage systems. First, demand analysis was carried out for different grid auxiliary service scenarios in which energy storage participated in frequency modulation, peak regulation, and voltage regulation to clarify the operation state of energy storage under different control objectives. Second, considering the auxiliary compensation income and safe and stable operation requirements of the energy storage power station, a comprehensive index system was proposed, which considers the economy of the energy storage system and the stable operation of the power grid to support the evaluation requirements of the energy storage switching control. Finally, based on the typical operating conditions of the energy storage system participating in power grid peaking and valley filling, frequency modulation, and voltage regulation, the multi-layer judgment logic of the energy storage system under different operating conditions was preset, and a smooth switching control strategy of the energy storage system based on the multi-layer logic judgment was proposed.

2 Basic operation principle and demand analysis of the energy storage system

2.1 Operation principle of the power conversion system

The power conversion system (PCS) allows the two-way interaction of DC power-side energy storage and AC grid-side energy, in addition to the charging and discharging of DC power on the energy storage side, tracking of grid-side load power, and operation mode switching control by changing the control strategy. As the interface device between the energy storage medium and grid and load, the PCS realizes the control function of the energy storage medium and is the core part of the energy storage system. PCS references the phase voltage vector on the AC network side. It changes the phase relationship between the phase voltage and the phase current on the AC network side by controlling the voltage vector on the AC network side to realize the four-quadrant operation of PCS (Yin et al., 2023). Figure 1 describes the vector diagram when PCS presents different load characteristics.

As shown in Figure 1, the energy storage system can be presented with four characteristics: pure inductance, pure capacitance, positive resistance, and negative resistance, by changing the control strategy to meet the system requirements. As shown in Figure 1A, the voltage phase at the AC network side is the same as that of the electromotive force of the power network, and the phase current lags the voltage by 90°. PCS absorbs reactive power, showing pure inductance characteristics. As shown in Figure 1B, the phase current is in the same phase as the electromotive force of the grid. PCS absorbs active power from the AC busbar on the grid side, showing positive resistance characteristics, and the energy storage system is charging. As shown in Figure 1C, the phase current is 90° ahead of the grid voltage, and PCS releases reactive power,
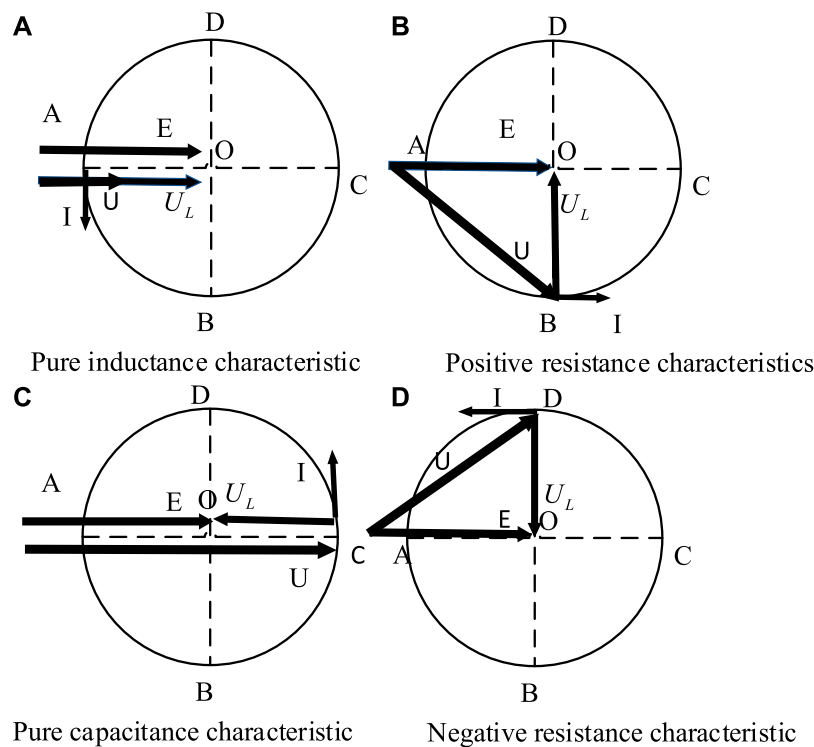
FIGURE 1
Vector diagram of the different load characteristics. E: Grid voltage; *I*:AC network side phase current; *U*:AC net-side voltage; U_L:Load Voltage; O: zero point of the coordinate system; A,B,C,D: The critical working point of the four quadrants. **(A)** PCS absorbs reactive power, showing pure inductance characteristics. **(B)** PCS absorbs active power from the AC busbar on the grid side, showing positive resistance characteristics. **(C)** PCS releases reactive power, showing pure capacitance characteristics. **(D)** PCS transmits active power from the AC bus at the grid side, showing negative resistance characteristics.

showing pure capacitance characteristics. As shown in Figure 1D, the phase of the grid-side phase current is opposite to the electromotive force of the grid. PCS transmits active power from the AC bus at the grid side, showing negative resistance characteristics, and the energy storage system is in a discharged state (Xiao et al., 2021; Li et al., 2023a).

2.2 Demand analysis and control principle of ESS

As an emerging flexible regulation resource, energy storage can further enhance the regulation potential of existing resources and better support the power grid to adapt to the rapid development of new energy through its bidirectional power characteristics. It has a broad application prospect in new power systems and can play an essential role in new systems with high proportions of renewable energy access (Sun et al., 2020).

2.2.1 Peak shaving and valley filling

In recent years, the proportion of new energy installations with intermittency and uncertainty, such as wind power and photovoltaic sources, has been growing, increasing the pressure of system peaking and the difficulty of grid operation control. Currently, the task of peaking in the power system is mainly undertaken by traditional generating units such as thermal power. Still, many challenges could be solved with conventional units for peaking, mainly including 1)

operational safety, in which the sudden load change caused by the traditional unit output changes results in an abnormal loss of unit components, affecting the stable operation of the unit. 2) Cost-effectiveness, in which the peaking cost of thermal power units is higher, including the fuel consumed by frequent start-up and shutdown and the operating energy consumed by prolonged rotating standby. 3) Peaking performance, in which thermal power units cannot quickly increase output power, resulting in long regulation response times and affecting regulation performance (Sun et al., 2022).

Due to the huge peak-to-valley differences in the demand for electricity between times and seasons, energy storage can effectively provide demand-side management with its good charging and discharging capability. Energy storage can allow direct profit through low storage and high generation. Moreover, energy storage also reduces system operation costs, saves investment in peaking units, improves the daily load rate of the power system, and significantly improves the utilization rate of power generation equipment. By reducing system operating costs and saving investments in peaking units, the daily load rate of the power system is improved, and the utilization rate of power generation equipment is greatly enhanced, thus improving the overall operating efficiency of the power grid, reducing the cost of power supply, and generating considerable economic benefits. The energy storage system can also participate in grid peaking by using a constant power charging and discharging control strategy; that is, the battery storage system makes charging and discharging rules according to the

historical load curve and provides continuous power to charge and discharge the grid, independent of the real-time load changes.

2.2.2 Frequency regulation

Under the current trend of large-scale grid-connected development of highly proportional distributed energy sources, the imbalance between power supply and demand due to forecast errors and other factors has become more significant and the traditional frequency regulation method based on automatic generation control (AGC) systems to adjust generator output are facing substantial challenges, including 1) rapid output changes to accurately track load changes; 2) small response power reserve margins; 3) battery storage power in response to frequency fluctuations in floating charge state, compared to the peak and valley load of the power grid in depressed areas require deep battery charging and discharging, with limited impact on battery life.

As a high-quality flexible resource, participation in system fast frequency regulation is an important application scenario for energy storage. The droop control strategy shown in Eq. 1 can be used for the participation of an energy storage system in grid-assisted frequency regulation. When the system frequency deviation crosses the set regulation dead zone, the energy storage starts to work and adjusts the power in real time, according to the charging and discharging rules, to maintain frequency stability. In contrast, the energy storage system is idle and does not work when the system frequency deviation is within the dead zone (Stroe et al., 2017; Wu et al., 2015).

$$P = \begin{cases} P_0 + k(\Delta f - f_0), & (\Delta f > f_0), \\ P_0 + k(\Delta f + f_0), & (\Delta f < -f_0), \end{cases} \quad (1)$$

where P is the charging and discharging power of the battery storage; k is the gain factor of the battery storage, Δf is the frequency deviation of the system; f_0 is the set deadband value, in which the battery storage does not work; and P_0 is the charging power of the battery storage at the set regulation deadband.

2.2.3 Voltage regulation

Energy storage has millisecond power response speeds, four-quadrant power regulation capability, and high-power regulation accuracy. It can effectively control the system voltage, and its emitting/absorbing reactive power occupies only the PCS capacity without affecting the charge state of the energy storage system. Thus, the use of energy storage to participate in grid voltage regulation when there is remaining PCS capacity can improve the utilization rate of energy storage power plants.

Few measures are available on the grid side to manage voltage transients. These usually rely on the user side to install management devices to alleviate voltage transients. By moderately charging reactive power through energy storage, the demand for reactive power compensation can be met while ensuring that the voltage does not cross the limit, which provides a new idea for transient voltage management on the grid side.

$$U_{PCC} = U_S + \frac{(P - P_L)R + (Q - Q_L)X}{U_S}, \quad (2)$$

$$Q_{ref} = \frac{U_{PCCN}}{X}\left[(U_{PCCN} - U_2) + \left(\frac{PR + QX}{U_{PCCN}} - \frac{PR + QX}{U_2}\right)\right]. \quad (3)$$

First, the power flow analysis of the parallel network of the energy storage system, considering that the voltage transverse component is much smaller than its longitudinal component, is used to obtain the voltage of a similar network as in Eq. 2. A sizeable reactive power shortage or fault occurring in the grid will cause PCC bus voltage fluctuation and affect the regular grid operation. When the PCC bus voltage is transformed to U_2, the reactive power quantity Q_{ref} required to support the PCC point voltage to recover to the rated value U_{PCCN} is shown in Eq. 3, where U_{PCC}, U_{PCCN}, and U_S are the energy storage grid point voltage, grid voltage rating, and system voltage, respectively. U_2 is the grid connection voltage, P and Q are the active and reactive powers issued by the energy storage system, and P_L and Q_L are the active and reactive powers of the load, respectively. When the grid has a reactive power shortage, or a fault occurs, if the energy storage emits the corresponding reactive power as in Eq. 3, it can precisely compensate for the missing reactive power of the grid and support the PCC parallel network voltage to restore the rated value (Lee et al., 2017).

3 Multi-target judgment and smooth switching control

Based on the participation of the energy storage system in typical operating conditions such as peak shaving, frequency regulation, and voltage regulation, the multi-layer judgment logic of energy storage system operation control under different operating conditions was preset. A multi-objective judgment and smooth switching strategy was proposed, as shown in Figure 2, which effectively utilized the idle capacity of the energy storage system, improved the grid power quality, and provided the optimal control of energy storage that considered both technical and economic aspects.

3.1 Multi-level logic judgment

The energy storage system mainly applies to active power output scenarios such as peak shaving, valley filling, and fluctuation smoothing. Therefore, energy storage and peak regulation were the original control targets. The multi-layer logic judgment was made through the constructed energy storage and grid connection evaluation index to determine the optimal control target of energy storage and complete the control strategy switching.

3.1.1 First level of judgment

First, the output data of energy storage units and grid connection status were collected and analyzed to determine the actual demand for energy storage from the grid and obtain the power command of energy storage by intelligent algorithm prediction (Li et al., 2023b; Sun et al., 2023; Sun et al., 2021a). The first layer of judgment aimed to quickly identify whether the voltage and frequency of the energy storage grid connection are in normal condition and assess the need for emergency energy storage support. In this case, if the voltage or frequency is in the emergency support state, the corresponding control strategy is switched without regard for the economic index, as the capacity allows.

The real-time voltage and frequency deviation is selected as the first level judgment index for switching the control strategy of the
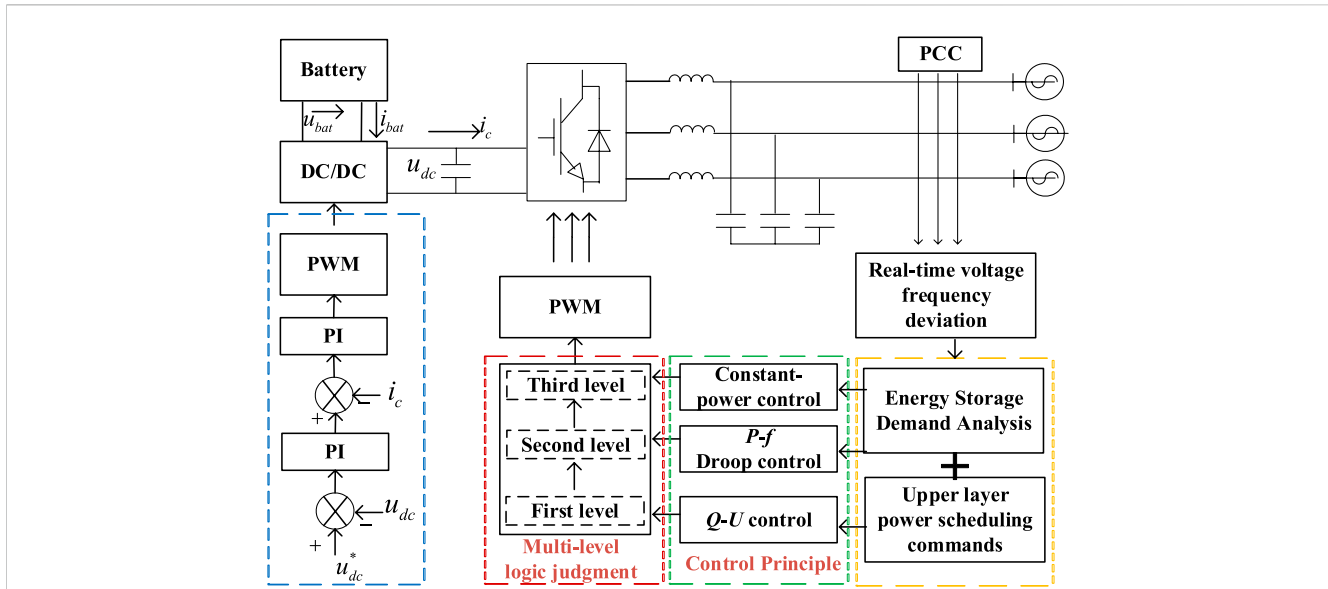
FIGURE 2
Block diagram of the energy storage system converters for multi-objective control.

energy storage system. The energy storage has fast power output and accurate tracking capability, which can make up for the response speed and regulation capability of traditional units and address the sudden change in system frequency. By detecting the real-time voltage and frequency deviation of the energy storage parallel network, energy storage was classified into two working states (emergency support and non-emergency support) based on the deviation value. The first level of evaluation was performed by the first level of the judgment index. When the real-time deviation value exceeded the grid standard, the energy storage system directly switched the control strategy to regulate grid voltage or frequency. Eq. 4 shows that the first level of evaluation indicators were set according to the real-time deviation value to determine whether the grid voltage and frequency required emergency support, i.e., when the energy storage system cannot meet the grid standards. If there is an indicator in the voltage or the frequency for the emergency support state, the energy storage system switches to the corresponding active support control.

$$\begin{cases} \Delta u(t) = u(t) - u_{PCC}, \\ \Delta f(t) = f(t) - f_{PCC}. \end{cases} \tag{4}$$

3.1.2 Second level of judgment

When the voltage and frequency of the energy storage grid connection point meet the grid connection criteria, a second layer of judgment must be constructed through economic and stability assessment indexes to obtain the optimal control target that simultaneously considers the economic benefits and the grid connection status of energy storage.

First, the stability assessment index of the grid-connected operation state of energy storage was defined: the deviation coefficient of the voltage and frequency of the grid-connected network of energy storage relative to the international standard

of grid-connected, in which the larger the deviation coefficient, the weaker the support ability of the system, and the higher the priority of voltage/frequency regulation.

$$S_u = \sqrt{\frac{(u(t) - u_{\text{ref}})^2}{u_{\text{dead}}}}, \tag{5}$$

$$S_f = \sqrt{\frac{(f(t) - f_{\text{ref}})^2}{f_{\text{dead}}}}, \tag{6}$$

where u_{dead} indicates the voltage regulation deadband, S_u the voltage regulation stability index, and u_{ref} the rated energy storage voltage to the grid. f_{dead} indicates the frequency regulation deadband, S_f the frequency regulation stability index, and f_{ref} the rated frequency of energy storage to the grid.

The economic index of energy storage is defined as considering the compensation standard of auxiliary services under different revenue modes in the power market, comprehensively comparing the economic benefits of energy storage under peak regulation, frequency regulation, and voltage regulation, and providing economic evaluation criteria for achieving optimal control of energy storage.

In terms of peak and valley shaving, the energy storage system buys and stores electricity from the grid in the low valley, releases electricity, and sells it to customers in the peak, using the peak–valley price difference to realize arbitrage and gain income from differences between the purchase and sale prices (Zhao et al., 2022). At present, Europe, including Germany, the United Kingdom, France, and other countries, has introduced carbon-neutral policies to provide opportunities to develop energy storage to allow energy storage to participate in the scoring mechanism. Grid companies are similarly reducing the threshold of the wholesale power and power balancing markets. The United States introduced a relevant decree in 2018 to support
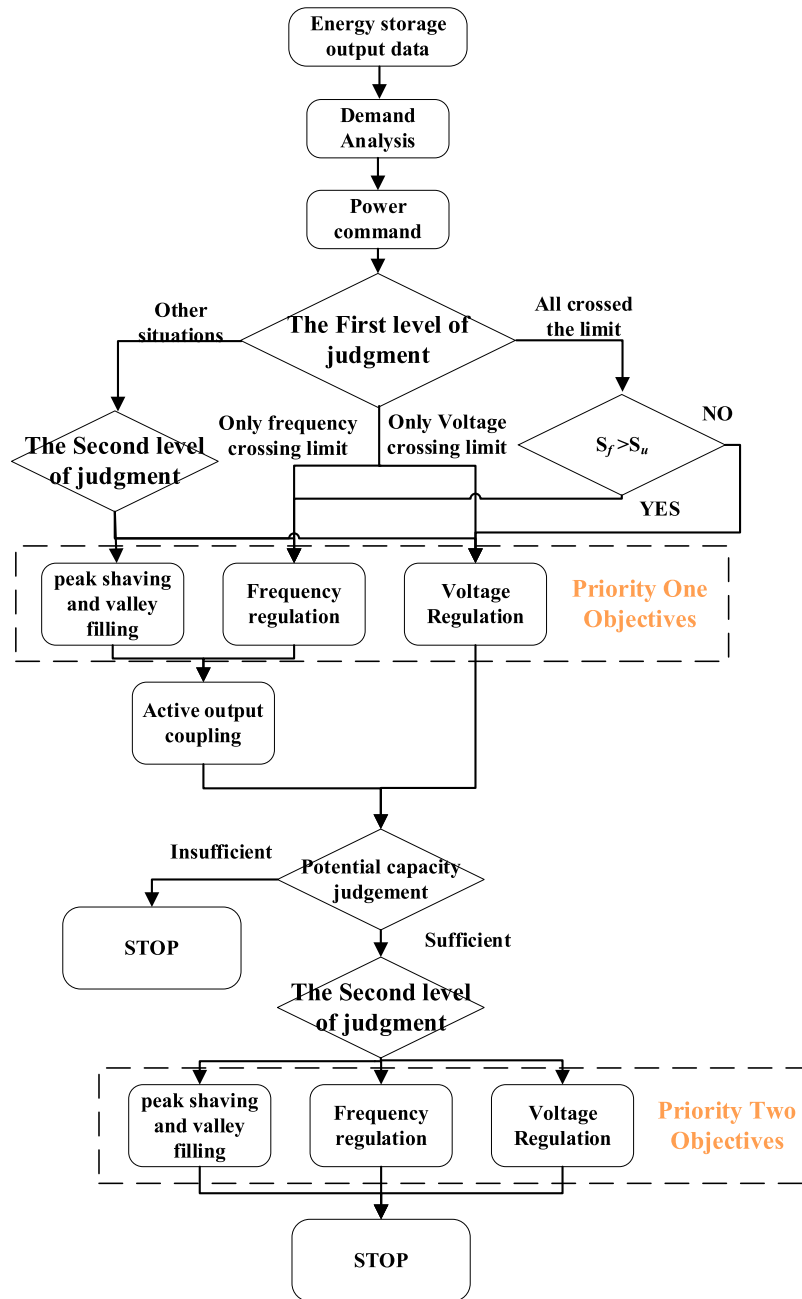
FIGURE 3
Flow chart of the control strategy for energy storage system switching.

the participation of energy storage companies in the wholesale power market, laying the foundation for developing energy storage business models.

Taking a Chinese province as an example, the government has constructed an energy storage market with a peak-to-valley tariff, where the peak tariff reaches 0.5 RMB/kWh. The valley tariff reaches 0.4 RMB/kWh, and I_1 is defined as the revenue from the participation of energy storage in peaking, C_1 is defined as the peaking service capacity in MWh, B_1 is the paid peaking of the price of energy storage facilities in peak hours, B_2 as the paid peaking of the price of energy storage facilities in trough hours, η_d is the

discharge efficiency of the energy storage system, t_1 is the peaking time of energy storage in peak hours, and t_2 is the peaking time of energy storage in trough hours.

$$I_1 = \sum_{t=1}^{T} \left[B_1 \left(P_c + P_d \eta_d \right) t_1 + B_2 \left(P_c + P_d \eta_d \right) t_2 \right], \tag{7}$$

where P_c and P_d denote the average power of the energy storage system during charging or discharging periods, respectively.

The main compensation of frequency regulation includes mileage and capacity compensations, which are mainly calculated based on the frequency regulation mileage and the calling capacity,

TABLE 1 Pseudo-code and control schemes for multi-layered logical judgment.

Algorithm 1: Energy storage switching control scheme
Input: Energy storage grid-connected state
Output: Optimal control of energy storage
If $\Delta f(t) < f_1$ and $\Delta u(t) < u_1$ then
return Strategy I
elseif $\Delta f(t) >= f_2$ and $\Delta u(t) >= u_2$ then
if $S_f > S_u$, then
return Strategy II
else
return Strategy III
end
elseif $\Delta f(t) < f_2$ and $\Delta u(t) < u_2$ then
if $s_1 > s_2 > s_3$
return Strategy IV
elseif $s_1 > s_3 > s_2$
return Strategy V
elseif $s_2 > s_1 > s_3$
return Strategy VI
elseif $s_2 > s_3 > s_1$
return Strategy VII
elseif $s_3 > s_1 > s_2$
return Strategy VIII
elseif $s_3 > s_2 > s_1$
return Strategy IX
end
end
end

respectively. This article analyzed mileage compensation as an example (Liu et al., 2021).

$$I_2 = \sum_{t=1}^{T} \left(MD_t \sqrt{K_t} B_f \right), \tag{8}$$

where I_2 is defined as the revenue brought by the participant of energy storage in frequency regulation, B_f is the paid frequency regulation clearing price of energy storage facilities, D_t is the frequency regulation mileage, K_t is the frequency regulation performance index, and M is the regulation factor, adjusted according to the market operation, tentatively $M = 1$.

The economic benefits of energy storage participation in grid voltage regulation are mainly capacity compensation benefits, including the compensation obtained from the reduction of active output and the savings obtained from the removal of reactive power compensation equipment. When a voltage warning occurs on the grid, the grid company will release the grid-connected active limit C_{pmax}, compensation tariff B_3, a reactive power demand absorbed or issued by the storage system, and the reactive power tariff B_Q. When the active output of the storage system is greater than the active limit, it will not receive the auxiliary service benefit of active reduction; on the contrary, the storage system will receive the corresponding benefit according to the active reduction. The energy storage system emits or absorbs reactive power according to the actual grid demand and obtains the reactive auxiliary service revenue I_3.

$$I_3 = B_3 \left(C_{Pmax} - C_P \right) t_3 + B_Q C_Q t_3, \tag{9}$$

where C_P, C_Q, and t_3 are the stored active output capacity, reactive output capacity, and the time involved in voltage regulation, respectively.

The energy storage involved in frequency regulation of the dispatching active output and participation in voltage regulation of the reactive production due to the existence of the peaking plan is not an algebraic superposition of the binding relationship; the need to participate in frequency regulation of energy storage and peaking auxiliary service active output coupling calculation, and then further analysis of the coupling of energy storage involved in voltage regulation of the available PCS capacity. When the absolute value of the active output decreases after superposition, the reactive margin of the energy storage increases, which is beneficial to voltage regulation; in contrast, when the absolute value of the active output increases after superposition, the reactive margin of the energy storage decreases, thus reducing the voltage regulation capacity. The final actual active power output and actual reactive power output of the energy storage are related to the PCS capacity; therefore, the capacity index of the energy storage system should also be considered.

$$\eta_C = \frac{1}{T} \int_0^T \frac{\sqrt{(P_{\text{real}} + Q_{\text{real}})^2}}{S_{PCS}}, \tag{10}$$

$$\sqrt{(P_{\text{real}} + Q_{\text{real}})^2} \leq S_{PCS}, \tag{11}$$

where η_C denotes the capacity indicator, P_{real} and Q_{real} denote the energy storage system's active and reactive output values, respectively, and S_{PCS} is the PCS capacity.

The comprehensive evaluation index is defined as a comprehensive index that considers the system economy, the state of energy storage on the grid, and the utilization rate of energy storage capacity to obtain stable and economic grid operation. First, the hierarchical analysis method sets the influence weights of the three graded indicators on the comprehensive evaluation index of peak regulation. Based on an in-depth analysis of the problem, the objectives at each level, the system benefits considered, the technical factors, and the control objects are decomposed into different hierarchical structures. The priority weights of each element of each level on the previous level are then obtained by solving the judgment matrix eigenvectors. Finally, the final weights of the indicators at each level to the integrated target are determined by weighted summation (Jafari et al., 2019). According to the comparison of the influence degree of each index, the comparison matrix A is obtained as follows:

TABLE 2 Control strategy descriptions.

Control strategy	Strategy description
Strategy I	Energy storage with peak regulation as the target. When the voltage and frequency are in the normal ranges and meet the grid connection criteria, the energy storage system operates with peak regulation as the target
Strategy II	Energy storage with frequency regulation as the target, when the voltage is normal and meets the grid standard. Frequency is in an emergency, urgent active support, energy storage system operates with frequency regulation as the target
Strategy III	Energy storage aims to regulate voltage when the frequency is standard and meets the criteria for grid connection. The voltage is in an emergency state and reactive power support is urgently needed, and the energy storage system is operated to regulate the voltage
Strategy IV	When voltage and frequency do not need emergency support, and the comprehensive index of peak regulation is better than frequency and voltage regulation, energy storage prioritizes peak and auxiliary frequency regulation
Strategy V	When the comprehensive index of peak regulation is better than that of frequency and voltage regulation, then energy storage gives priority to peak and auxiliary voltage regulation
Strategy VI	The comprehensive index of frequency regulation is better than that of peak and voltage regulation when energy storage is given priority over frequency and auxiliary peak regulation
Strategy VII	The comprehensive index of frequency regulation is better than peak and voltage regulation when energy storage takes priority over frequency and auxiliary voltage regulation
Strategy VIII	The comprehensive index of voltage regulation is better than frequency and peak regulation when energy storage takes priority over voltage and auxiliary peak regulation
Strategy IX	The comprehensive index of voltage regulation is better than frequency and peak regulation when energy storage is given priority over voltage and auxiliary frequency regulation

TABLE 3 Simulation parameter table.

Parameter	Value
The reference value of active power for ESS/KW	20
The reference value of reactive power for ESS/KVar	0
Discharge efficiency of ESS (η)	90%
Peak-hour tariffs for ESS (RMB/KWh)	0.5
Low-hour tariffs for ESS (RMB/KWh)	0.4
Benefits of ESS for frequency regulation (RMB/MW)	6
Frequency modulation performance index (K)	2
Benefits of ESS for voltage regulation (RMB/MVarh)	1

3.2 Control strategy for energy storage system switching

With the participation of energy storage in peaking as the conventional operation scenario, from the long timescale, the energy storage system is divided into two operation scenarios: peaking and non-peaking. The short timescale of frequency regulation and peaking output is considered on this basis. However, due to the different control principles in different operation scenarios, direct switching between different control modes will usually lead to large disturbances or unsuccessful switching. To achieve smooth switching between different control modes, based on the proposed comprehensive index considering the stable and economic operation of the power grid, multi-objective priority ranking was performed using multi-layer judgment logic to obtain the control logic under nine operating conditions to provide multi-objective control and smooth switching of the energy storage system. The flow chart is shown in Figure 3.

(1) By judging $\Delta f(t)$, $\Delta u(t)$, identify whether the grid needs emergency active and reactive power support. If so, go to step (2); otherwise, go to step (3).
(2) If either the grid voltage or frequency requires emergency support, switch the response control strategy directly; if both voltage and frequency require emergency support, judge the comprehensive assessment and switch the response control strategy.
(3) Select the optimal control strategy for the stable and economic operation of the grid by judging the comprehensive index.
(4) Judging the capacity margin index, identify whether the energy storage can continue to work. If the capacity is sufficient, enter step (1). If the capacity is insufficient, stop working.
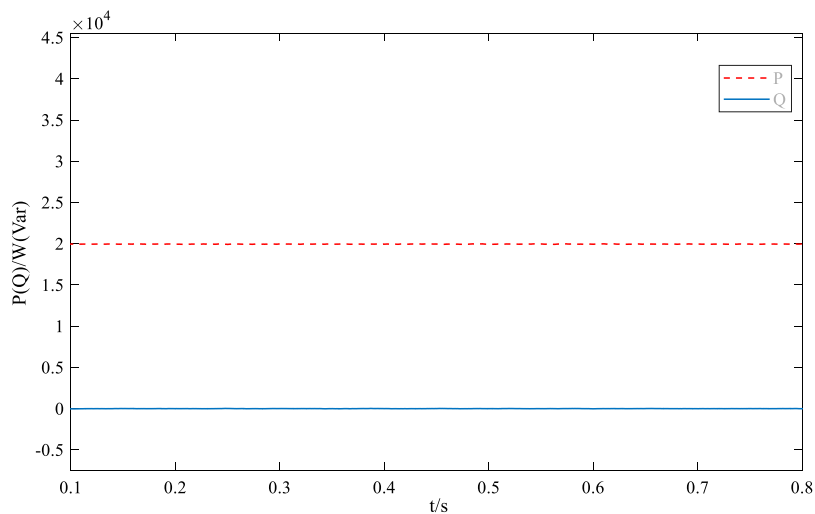
$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix}, \quad (12)$$

where $a_{ii} = 1$, $a_{ij} = 1/a_{ji}$ (i,j = 1, 2, 3, 4). After the consistency test of the judgment matrix, we can obtain the coefficients that satisfy each weighting coefficient of the test index.

S_1, S_2, and S_3 are defined as the comprehensive evaluation indexes of energy storage with peak regulation, frequency regulation, and voltage regulation as the control objectives, respectively. λ denotes the impact weight of indicators at each level.

$$S_1 = \lambda_{1,p} S_f + \lambda_{2,p} S_u + \lambda_{3,p} I_1 + \lambda_{4,p} \eta_C, \quad (13)$$

$$S_2 = \lambda_{1,f} S_f + \lambda_{2,f} S_u + \lambda_{3,f} I_2 + \lambda_{4,f} \eta_C, \quad (14)$$

$$S_3 = \lambda_{1,u} S_f + \lambda_{2,u} S_u + \lambda_{3,u} I_3 + \lambda_{4,u} \eta_C. \quad (15)$$

FIGURE 4
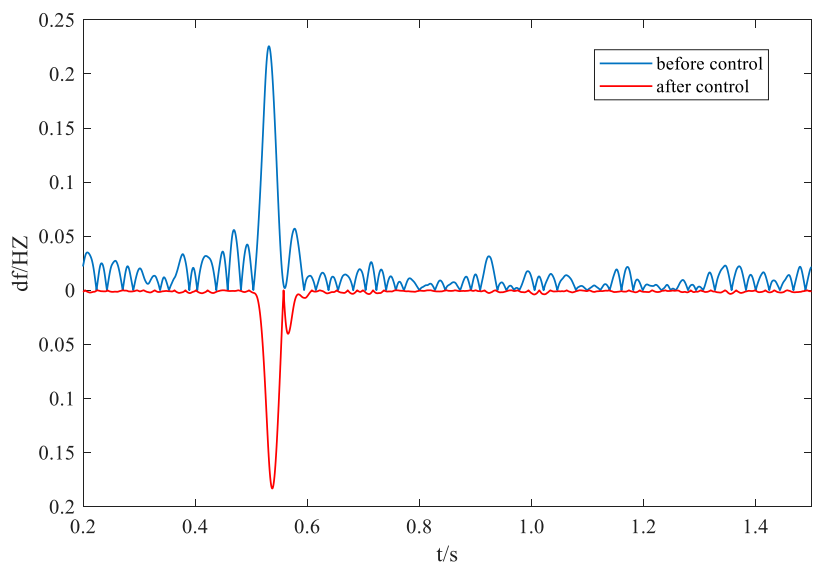Active and reactive power output curve of energy storage.

FIGURE 5
Grid frequency fluctuation curve.

The upper layer system switches the control strategy of the energy storage system according to different working conditions; therefore, the energy storage application scenario is specifically divided into nine working conditions, as shown in Table 1 according to the proposed two-layer judgment index. The corresponding energy storage output scheme is provided as pseudo-code.

The control strategies proposed in Table 1 are shown in Table 2.

4 Discussion

4.1 Simulation analysis

Through MATLAB/Simulink, a simulation model of switching control of the energy storage system based on multi-layer judgment logic was built, as shown in Figure 2. The energy storage system was mainly involved in grid peaking as the long-timescale energy storage control target. The optimal control target was selected in real time
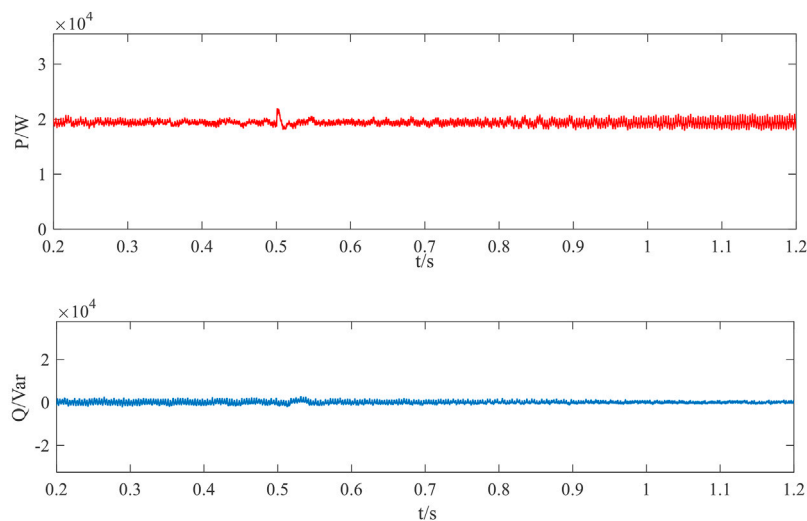
FIGURE 6
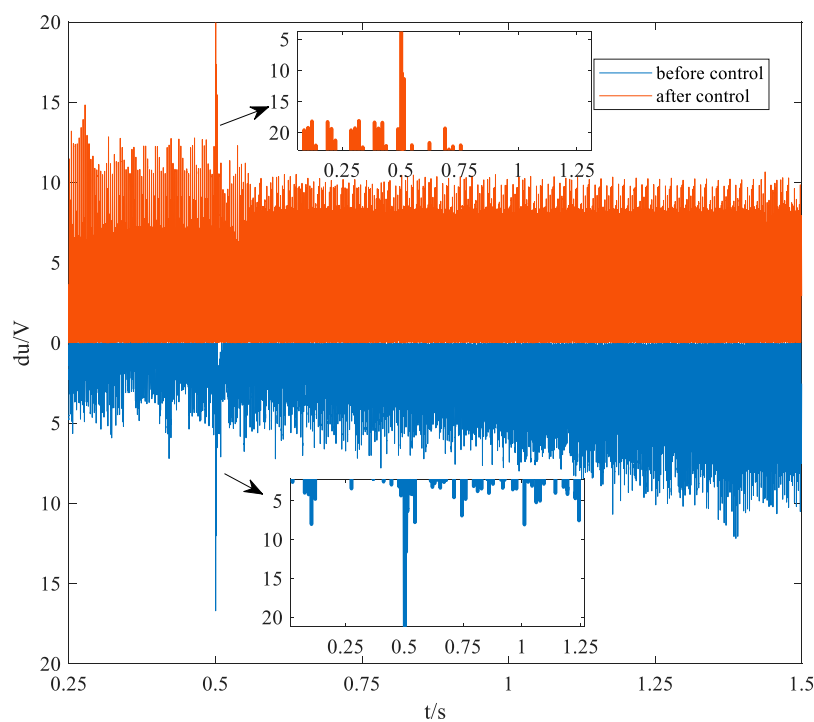Active and reactive power output curve of energy storage under frequency fluctuations.

FIGURE 7
Grid voltage fluctuation curve.

based on a comprehensive evaluation index. The power curve, grid voltage, and frequency fluctuation curve of energy storage were selected for analysis. The parameters are shown in Table 3.

First, we simulated the operation status of the energy storage system under normal operating conditions when the voltage and frequency aligned with the grid standard. The real-time power of the energy storage system is shown in Figure 4. At this time, the energy storage takes peak-shaving and valley-filling as the control target and runs according to the set power, and the energy storage runs in the constant power control mode.

To verify the frequency regulation effect of the energy storage system when frequency fluctuations occur in the power system, such
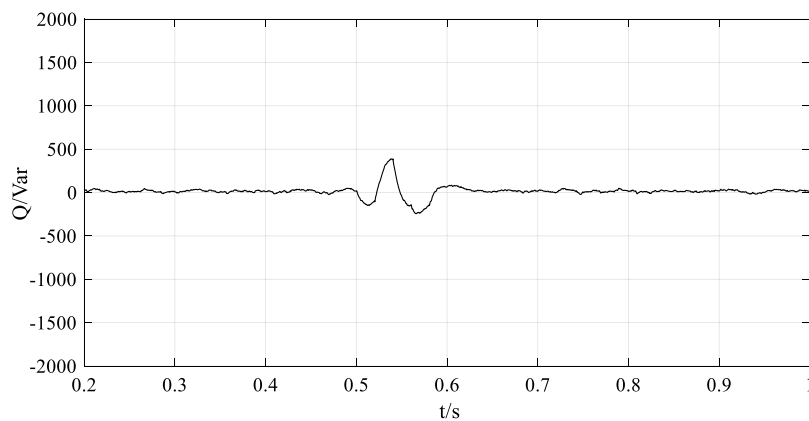
FIGURE 8
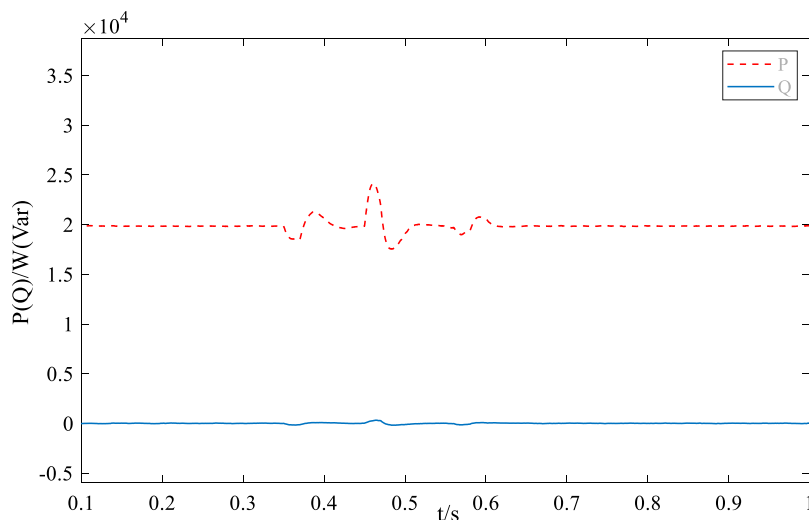Reactive power output curve of energy storage.

FIGURE 9
Energy storage power output when multiple voltage and frequency fluctuations occur in the system.

fluctuations in the actual power grid were simulated by load throwing and cutting. The frequency fluctuations are shown in Figure 5, in which the proposed control method has a suppression effect on the system frequency fluctuations, and the maximum and average values of the frequency fluctuations are reduced.

At 0.5 s, the system experiences large frequency fluctuations due to load throwing and cutting; the energy storage system judges the switching control target according to the comprehensive index and operates in frequency modulation mode, the PCS uses virtual sag control, and the real-time power is as shown in Figure 6. The traditional constant power control under peaking conditions does not allow adjustment of the system frequency by changing the energy storage power output for frequency fluctuations in the system. In contrast, the method in the present study can switch

the strategy in real time and change the energy storage power when the system frequency fluctuates to support the system frequency.

To verify the voltage regulation effect of the energy storage system during voltage fluctuations in the power system, voltage fluctuations in the actual grid were simulated by load throwing. For a load at 0.5 s, the grid voltage deviation is shown in Figure 7, indicating that the proposed method of control has a suppression effect on the system voltage fluctuation.

Currently, the energy storage system takes voltage regulation as the control target, and the PCS adopts reactive-voltage droop control, the reactive power output of which is shown in Figure 8. For the traditional constant power control under the peaking condition, when voltage fluctuation occurs in the system, no timely response is possible to allow the energy storage to participate in the regulation of the system voltage; however, the

TABLE 4 Economic performance index.

Time	Single target control/(RMB)			Method proposed in the present study/(RMB)			
	Peak shaving and valley filling	Frequency modulation	Voltage modulation	Peak shaving and valley filling	Frequency modulation	Voltage modulation	Total revenue
1:00	15,000	0	0	14,593	72	81	14,747
2:00	0	0	0	0	72	81	153
3:00	0	0	0	0	72	81	153
4:00	0	0	0	0	72	81	153
5:00	0	0	0	0	72	81	153
6:00	0	0	0	0	72	81	153
7:00	0	0	0	0	72	81	153
8:00	0	0	0	0	72	81	153
9:00	0	0	0	0	72	81	153
10:00	0	0	0	0	72	81	153
11:00	11,475	0	0	11,068	72	81	153
12:00	0	0	0	0	72	81	153
13:00	0	0	0	0	72	81	153
14:00	0	0	0	0	72	81	153
15:00	0	0	0	0	72	81	153
16:00	0	0	0	0	72	81	153
17:00	0	0	0	0	72	81	153
18:00	0	0	0	0	72	81	153
19:00	0	0	0	0	72	81	153
20:00	0	0	0	0	72	81	153
21:00	0	0	0	0	72	81	153
22:00	0	0	0	0	72	81	153
23:00	0	0	0	0	72	81	153
24:00	0	0	0	0	72	81	153
Total	26,475	0	0	25,662	1732	1951	29,346

strategy proposed in the present study can change the reactive power output of the energy storage in real-time to support the grid voltage according to the proposed index.

As shown in Figure 8, in this situation, the energy storage active power output according to the established plan, at 0.5 s due to the grid voltage fluctuations, switches to the voltage regulation mode, while the grid network voltage switches back to the grid standard and then to the peak regulation mode. Figure 9 shows the active and reactive power output of the energy storage system when the grid voltage and frequency fluctuate several times. The grid fluctuates at 0.35 s, 0.45 s, and 0.55 s, respectively, and the energy storage system switches the control target with the grid fluctuation of the power grid to change the power output of energy storage in real-time to effectively support the voltage and frequency of the system and realize real-time optimal control.

4.2 Economic benefit analysis

Using the actual power output data of a local energy storage power station as an example, the power station was charged and discharged at 0:00 and 10:00 to participate in grid peaking, charged with 100 MW power for 1 h at 0:00, and discharged with 85 MW to the grid for 1 h at 10:00. At other times, the power station energy storage was not working. In the actual engineering application, energy storage was not working most of the time, which led to a waste of energy storage resources. The switching control based on multi-layer logic judgment proposed in this article considered the short timescale conditions of frequency and voltage regulation, assuming that the energy storage was dispatched once every 5 min and the call ratio was 80%. In this article, although the energy storage frequency and voltage regulation occupied peak

capacity during peak hours, the frequency and voltage regulation services improved the total economic benefits of the energy storage system in short timescales during non-peak hours, which provided compensation benefits in the electricity market for the energy storage system. The results are shown in Table 4. Comparison with economic index I showed that the proposed method improved the economy of the energy storage system, with an approximately 10.8% increase in economic gain compared to the single-target control strategy, which only participates in grid peaking. In addition, the energy storage was deployed for grid frequency and voltage regulation during non-peak hours, which effectively utilized the idle capacity of the energy storage system and improved the energy storage utilization rate.

5 Conclusion

To meet the control requirements of energy storage systems under different power grid operating conditions, improve the energy storage utilization rate, and enhance the support role of energy storage in the power grid, this paper proposes a switching control strategy for an energy storage system based on multi-layer logic judgment to achieve the maximum benefit of energy storage and safe and stable operation of the power grid. First, we analyzed the current situation of multiple auxiliary services demanded by the energy storage system and proposed a comprehensive evaluation index to support switching control of energy storage by considering the economics of the energy storage system and the safe and stable operation of the power grid. Using this information, we proposed a multi-objective judgment and smooth switching strategy based on the participation of an energy storage system in typical operating conditions such as peak-shaving, frequency, and voltage regulation of the grid. The simulation results showed that compared with the traditional energy storage single-target control strategy, the proposed strategy allowed the energy storage system to switch its operation mode according to the real-time voltage and frequency states, which enhanced the support role of energy storage on grid voltage and frequency, improved the power quality of the grid, and effectively reduced the idle rate of the energy storage system to significantly improve the utilization rate of the energy storage system in typical operating conditions such as grid peak shaving, frequency regulation, and voltage regulation. The results of the analysis of the economic benefits showed that the proposed method improved the economic benefit by approximately 10.8% compared with those of the energy storage plant only for peak and valley reduction, which significantly improved the economic benefits of the energy storage system.

The economic efficiency of the energy storage system is an essential factor for its optimal control. This study focused on the benefit analysis of the energy storage system from two aspects: the whole life cycle cost of the energy storage system and the compensation income of the energy storage plant. However, the continuous switching of the energy storage control strategy will inevitably increase the energy storage system loss and its operation cost. Additional studies are needed to quantify the losses generated by this switching and fully consider the additional costs generated by energy storage in operation to meet the demand for the comprehensive benefits of energy storage containing a high percentage of renewable energy to the grid.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

SD: responsible for resources, software, formal analysis, and program compilation. SYi: responsible for methodology, project administration, and funding acquisition. SYu: responsible for writing the original draft. LR, WX, and WY: responsible for writing review and editing.

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Conflict of interest

Authors SD, SYi, LR, WX, and WY were employed by State Grid Shandong Electric Power Company.

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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