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Energy Storage Auxiliary Frequency Modulation Control Strategy Considering ACE and SOC of Energy Storage

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ABSTRACT As more and more unconventional energy sources are being applied in the field of power generation, the frequency fluctuation of power system becomes more and more serious. The frequency modulation of thermal power unit has disadvantages such as long response time and slow climbing speed. Battery energy storage has gradually become a research hotspot in power system frequency modulation due to its quick response and flexible regulation. This article first introduced the control method based on the signal of ACE (Area Control Error), which is the basic way of secondary frequency modulation and analyzed the features of the basic control mode. Then it zoned the signal of ACE and SOC of the battery energy storage system. On this basis, different frequency modulation methods were proposed according to the requirements of frequency modulation and the characteristics of the output of different regions. In addition, the fuzzy controller is used to smooth the output of the energy storage system under the normal adjustment of the regional control deviation and the normal charging and discharging state of SOC. Finally, a two-region interconnection simulation system was established based on the MATLAB simulation platform, and the simulation results verified the effectiveness of the proposed control strategy.

INDEX TERMS Energy storage frequency modulation, SOC, area control error, fuzzy control.

I. INTRODUCTION

In the face of increasingly serious environmental pollution and energy shortage, an increasing number of new energy sources, such as wind power, photovoltaic and solar thermal, have been used in the field of power generation [1]–[4]. However, unconventional energy output is prone to volatility and uncertainty, whose large-scale grid connection will pose a serious challenge to the stability of power system [5]–[7]. Therefore, it is a top priority to ensure the stability of power system frequency after new energy is connected to grid.

At present, China is still based on thermal power as the major way of modulating unit frequency. However, the frequency modulation of thermal power units has disadvantages such as long response time and slow climbing speed, so traditional frequency modulation method can no longer meet the current requirements of frequency modulation requirements [8]–[10]. In this context, battery energy storage system with high power response speed and high precision has quickly become a research hotspot of new auxiliary frequency modulation means [11]–[14]. Many domestic experts and scholars have also carried out in-depth research on the control strategy and frequency modulation in power grid assisted by energy storage. Reference [15] set the artificial dead zone through the frequency modulation interval of the energy storage system, and applied the adaptive control algorithm to adjust the coefficients of virtual droop control and virtual inertia control to reduce the mechanical wear caused by a high proportion of output power for long time in conventional thermal power units and improve the operation economical efficiency of the system. Reference [16] comprehensively considered the load demand of the power grid and the SOC of the energy storage system, and designed a control strategy for smoothing

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the output of the energy storage system with an intelligent algorithm controller. Reference [17] analyzed the feasibility and economical efficiency of the energy storage system involved in the frequency modulation of traditional thermal power units, and proposed various network connection modes of the energy storage system. Reference [18] proposed a coordinated control strategy that considers the size and SOC of the energy storage system, which could extend the service life of the energy storage system and allow wind power plants to provide auxiliary frequency modulation assistance. By optimizing the energy storage system involved in the frequency modulation strategy of thermal power units, the frequency modulation performance of the system can be effectively improved and the cost of the frequency modulation can be reduced, which has a certain practical significance.

In terms of the research on the capacity configuration method of energy storage assisted traditional power unit participating in the secondary frequency modulation of power system, [19] established a cost model for energy storage systems participating in frequency modulation by considering the life decay of the battery in energy storage systems, and calculated the frequency modulation costs under different dead zones and SOC to better participate in auxiliary services of the grid. Reference [20] comprehensively considered the timing and depth of the action and proposed the relevant procedures processes for optimizing the capacity configuration of the energy storage system. Reference [21] proposed to use Fourier transform to synthesize the frequency signal, and compared it with the conventional control strategy to configure the capacity of the energy storage system, However, there are few literature in which the feasibility of energy storage participating in frequency modulation of power system is evaluated by comprehensively considering ACE and SOC of the battery in the energy storage system.

On this basis, this paper proposed a control strategy of using energy storage system to assist frequency modulation based on fuzzy control considering ACE and SOC. Firstly, this paper introduced the control method based on the signal of ACE, which is the basic way of secondary frequency modulation, analyzed the features of the basic control mode. and partitioned the ACE and the SOC of the battery energy storage system, giving priority to the ACE in the normal control area. Secondly, considering the SOC state of the battery of the energy storage system, fuzzy control was used to smooth the output of the energy storage system in the normal charging and discharging area. Finally, the simulation system of a two-region interconnection was established to verify the feasibility of the control strategy proposed in this paper.

II. BASIC CONTROL MODE OF FREQUENCY MODULATION OF THERMAL POWER UNIT ASSISTED BY ENERGY STORAGE

In power system, automatic generation control system is used to ensure the stability of power system frequency. By collecting the relevant parameters of the power network, the regional control deviation signal can be obtained through calculation.

The model diagram of thermal power unit assisted by energy storage system participating in the secondary frequency modulation of power system based on ACE signal is shown in Figure 1.

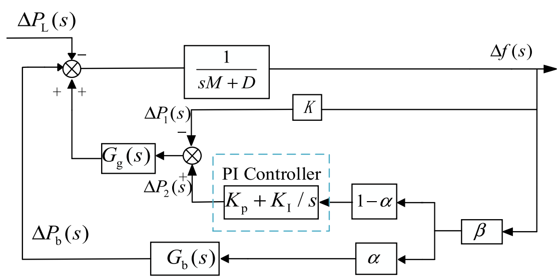


FIGURE 1. Block diagram of control mode based on ACE signal.

As shown in Figure 1, K is the regulation coefficient of unit power when the traditional power supply participates in the primary frequency modulation of the power system; K_p and K_I are the proportional parameters and integral parameters of PI controller; $G_\mathrm{b}(s)$ and $G_\mathrm{g}(s)$ are the transfer function expressions of the practical models of energy storage system and thermal power unit; α and $1-\alpha$ are the secondary frequency modulation participation of energy storage system and thermal power unit. Respectively; β is the frequency deviation parameter; M and D are rotational inertia and damping coefficient of the system; $\Delta P_\mathrm{L}(s)$, $\Delta P_1(s)$ and $\Delta P_2(s)$ are respectively the disturbance of load, the frequency modulation output on the thermal power unit and the secondary frequency modulation output on the thermal power unit. $\Delta P_\mathrm{b}(s)$ is the depth of energy storage system participating in the frequency modulation of the power grid.

The transfer function expressions G_b(s) and G_g(s) of the model of energy storage system and thermal power unit are obtained as:

$$\begin{cases} G_b(s) = \dfrac{1}{1+sT_e} \\ G_g(s) = \dfrac{1+F_{HP}T_{RH}s}{(1+T_{CH}s)(1+T_{RH}s)(1+T_g s)} \end{cases} \tag{1}$$

In (1), T_e is the delay time constant of the governor of the energy storage system; F_HP, T_RH, T_CH and T_g are respectively the delay time constant of reheater gain, reheater, turbine and governor of traditional thermal power units.

By analyzing the control diagram in Figure 1, ΔP_b, ΔP_1 and ΔP_2 are respectively the output of energy storage system and the traditional thermal power unit to participate in the primary and secondary frequency modulation.

$$\begin{cases} \Delta P_b = \beta \cdot \alpha \cdot G_b(s) \cdot \Delta f(s) \\ \Delta P_1 = -K \cdot G_g(s) \cdot \Delta f(s) \\ \Delta P_2 = \beta \cdot (1-\alpha) \cdot (K_p + K_I) \cdot G_g(s) \cdot \Delta f(s) \end{cases} \tag{2}$$

According to (1) and (2), the frequency deviation of the system can be written as:

$$\Delta f(s) = \frac{\Delta P_f + \Delta P_b + \Delta P_s - \Delta P_L(s)}{sM + D} \tag{3}$$

Then the rate of change of frequency deviation of the system to load disturbance is:

$$\frac{\Delta f(s)}{\Delta P_L(s)} = 1/\{[-K + \beta \cdot (1-\alpha) \cdot (K_p + K_I/s)] \cdot G_g(s) + \beta \cdot \alpha \cdot G_b(s) - (sM + D)\} \tag{4}$$

In (4), the partial derivative of the participation degree α of energy storage in the secondary frequency modulation can be obtained as:

$$\frac{\partial \Delta f(s)}{\partial \alpha} = \left(\frac{\Delta f(s)}{\Delta P_L(s)}\right)^2 \Delta P_L(s) \cdot [\beta \cdot G_b(s) - G_g(s)] \tag{5}$$

According to (5), the sensitivity coefficient of the secondary frequency modulation of thermal power unit assisted by energy storage system based on area control error can be written as:

$$S_{ACE} = \frac{d\Delta f(s)/\Delta f(s)}{d\alpha/\alpha} = \frac{\alpha \cdot \beta \cdot \Delta f(s)}{\Delta P_L(s)} \cdot [G_b(s) - (K_P + \frac{K_I}{s})G_g(s)] \tag{6}$$

As can be seen from (6), when the system is subjected to external step disturbance, S_{ACE} is negative at the initial stage, and then its absolute value firstly increases and then decreases to 0, and then continues to increase until the system is stable.

As the method of frequency modulation based on ACE signal that is assisted by energy storage is an open loop control, the control signal does not go through the PI controller, but directly to controls the output of energy storage power according to the ACE signal, is conducive to play the advantages of energy storage and participate in the frequency modulation of the power grid. What's more, as it is an open loop control, the control results have overshoot, which will lead to the gradual accumulation of steady-state frequency deviation and steady-state error.

III. CONTROL STRATEGY BASED ON ACE AND ENERGY STORAGE SYSTEM BATTERY SOC ZONING

A. ACE PARTITION AND CONTROL STRATEGY FOR EACH PARTITION

When the electrochemical energy storage system participates in the auxiliary frequency modulation, ACE signal is taken as the priority factor for both the conventional unit and the energy storage system. Therefore, ACE can be divided into four regulation zones according to different thresholds. The threshold values of each interval were set as ACE_1, ACE_2 and ACE_3.

As shown in Figure 2, each zone and its corresponding control strategy are as follows:

(1) When $|ACE| \leq ACE_1$, the power grid is in the dead zone of regulation, the energy storage system does not operate, and the output of the energy storage system and traditional thermal power units remains constant, so as to avoid the frequent operation of the energy storage system and shorten its service life.

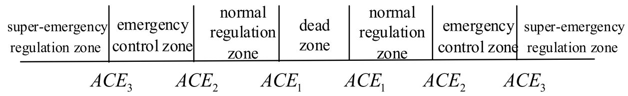


FIGURE 2. Diagram of ACE interval division.

(2) When $ACE_1 < |ACE| < ACE_2$, the power grid is in the normal regulation zone. At this time, the energy storage system provides power output to assist thermal power units to participate in the frequency modulation of the power grid. The energy storage unit gives priority to output, and gives full play to the advantages of the energy storage system with rapid output and great regulation speed to adjust the frequency of the power grid. Then the output of thermal power units gradually increases, while that of energy storage units gradually decreases. When the frequency of the power grid stabilizes, the energy storage system exits the process of frequency modulation.

(3) When $ACE_2 \leq |ACE| \leq ACE_3$, the power grid is in an emergency control zone where the restoration of power grid frequency is the highest priority, and the energy storage system adjusts the frequency of the power grid with maximum output until it is restored to stability.

(4) When $|ACE| > ACE_3$, the power grid is in the super-emergency regulation zone. At this time, the energy storage system and traditional thermal power units are not able to restore the stability of the frequency of the power grid, so the energy storage system does not operate, and the way of cutting off the load is adopted until the frequency of the power grid is restored to stability.

B. SOC PARTITION AND CONTROL STRATEGY FOR EACH PARTITION

The construction cost of energy storage system is high despite its rapid output and response. When the energy storage system participates in the frequency modulation of the system, it can effectively extend the service life of the battery in energy storage system and reduce the extra cost caused by the replacement of the battery in energy storage system by avoiding its SOC being too high or too low for a long time. Therefore, it is necessary to zone the SOC of the battery in energy storage system, and set different control strategies for each zone. The SOC zone of the energy storage system battery is shown in Figure 3.

As shown in Figure 3, according to the state of the battery in the energy storage system, it can be divided into four working regions: normal charging and discharging area, priority area of charging, priority area of discharging and forbidden area. The corresponding control strategies for each area are as follows:

(1) When $SOC_{low} \leq SOC \leq SOC_{high}$, the energy storage system is in the normal charging and discharging

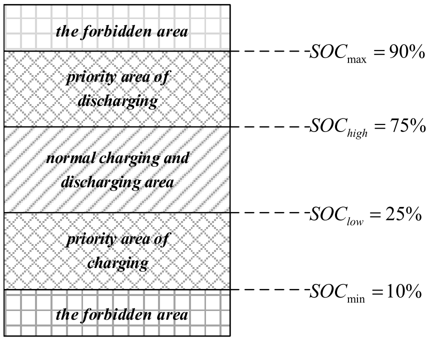


FIGURE 3. SOC partition diagram of battery in energy storage system.

area. At this time, energy storage participates in the secondary frequency modulation of the power system according to the AGC instruction and combines with the fuzzy controller to smooth the output of the energy storage system and assist the thermal power units.

(2) When $SOC_{min} \leq SOC \leq SOC_{low}$, the energy storage system is in the priority area of charging. At this time, if the battery of energy storage system continues to discharge, the SOC of the battery will be lower than SOC_{min}, which will affect the life of the energy storage system. Therefore, when the energy storage system assists the thermal power units to participate in the secondary frequency modulation of the power system, the participation of the energy storage system should be reduced.

(3) When $SOC_{high} \leq SOC \leq SOC_{\max}$, the energy storage system is in the discharge priority area. At this time, the energy storage system helps the traditional power supply to participate in the secondary frequency modulation of the power system. Therefore, the participation of the energy storage system should be appropriately increased to reduce the abrasion of the traditional thermal power unit.

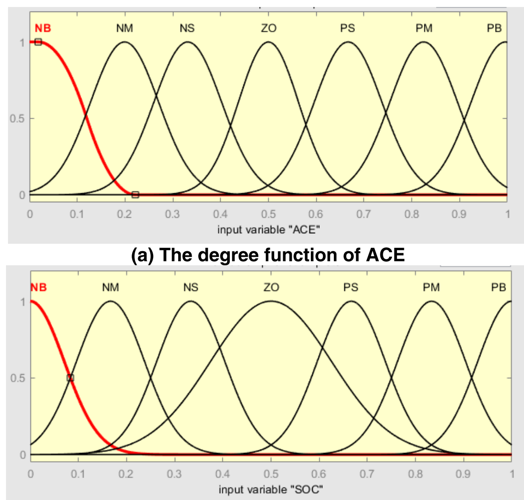
(4) When $SOC \leq SOC_{\min}$ and $SOC \geq SOC_{\max}$, the energy storage system is already in the forbidden zone. If the battery SOC of the energy storage system remains too high or too low for a long time, the service life of the energy storage system will be seriously affected. Therefore, the energy storage system should quit the process of the frequency modulation at this time.

IV. STRATEGY OF OUTPUT POWER OF ENERGY STORAGE SYSTEM

A. DESIGN OF FUZZY CONTROLLER BASED ON ACE AND SOC

When the ACE of the system is in the abnormal regulation zone, the highest priority is to restore the stability of the system frequency and increase the output of the energy storage system. If the ACE of the system is restored to the normal regulation zone, the SOC state of the battery of the energy storage system should be comprehensively considered to prevent the SOC of the battery of the energy storage system from being too high or too low, so as to improve the economical efficiency of the energy storage system participating in the frequency regulation of the power grid.

Therefore, the input of the fuzzy controller designed in this paper is the ACE of the system and the SOC of the battery of the energy storage system, and the output is the P_{out} of the energy storage system. Firstly, the signal of ACE and the SOC of the battery in the energy storage system are normalized. After normalization, the theoretical domain of both ACE and the battery SOC of the energy storage system is [0,1]. The theoretical domain of the output P_{out} is determined by the ACE and the SOC of the battery in the energy storage system, with a theoretical domain of [−1,1]. The fuzzy mean sets of ACE and SOC are {NB (negative big), NM (negative medium), NS (negative small), ZO (zero), PS (positive small), PM (positive middle), PB (positive big)} after normalization, which are consistent with the input fuzzy mean sets. The membership function settings of ACE, SOC of battery in energy storage system and P_{out} of energy storage system are shown in Figure 4 and Figure 5.



(a) The degree function of ACE

(b) The degree function of SOC

FIGURE 4. The degree function of the input.

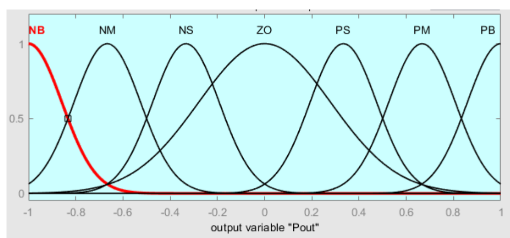


FIGURE 5. The degree function of the output.

The table of fuzzy rule designed in this paper is shown in TABLE 1.

The method of area gravity center is used to clarify the fuzzy set of P_{out}, and the modified real-time power is expressed as;

$$P_{out} = \frac{\int_{c_2}\int_{c_1} A_{c_1} \cdot c_1 \cdot A_{c_2} \cdot c_2 dc_1 dc_2}{\int_{c_2}\int_{c_1} A_{c_1} \cdot A_{c_2} dc_1 dc_2} \tag{7}$$

where C_1 and C_2 are the quantized domain of ACE and SOC respectively, and A_{C1} and A_{C2} are the degree functions of

TABLE 1. Table of control rules for fuzzy controllers.

SOC \ ACE	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NM	NS	ZO	ZO	ZO	ZO
NM	NB	NM	NS	ZO	ZO	ZO	ZO
NS	NM	NM	NS	ZO	PS	PS	PB
ZO	NM	NM	NS	ZO	PS	PM	PM
PS	NS	NS	NS	ZO	PS	PM	PM
PM	ZO	ZO	ZO	ZO	PS	PM	PB
PB	ZO	ZO	ZO	ZO	PS	PM	PB

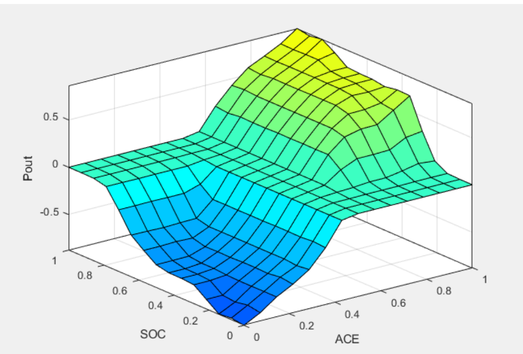


FIGURE 6. Real time output power of P_{out}.

ACE and SOC respectively. The modified real-time output power P_{out} is shown in Figure 6.

B. THE CONTROL STRATEGY OF ENERGY STORAGE SYSTEM ASSISTED FREQUENCY MODULATION CONSIDERING ACE AND SOC

In this paper, the specific frequency modulation control strategy is designed as follows by comprehensively considering ACE and SOC of battery in energy storage system.

(1) First of all, the ACE is partitioned. The energy storage system does not operate when in the emergency regulation zone and the regulation dead zone; When in the emergency regulation area, the highest priority is to restore the stability of system frequency, and the energy storage system helps the thermal power unit to adjust the system frequency with the maximum output. When it is in the normal regulation zone, the SOC state of the energy storage system is considered.

(2) When the SOC of battery in the energy storage system is in the forbidden area, the battery of the energy storage system should be not placed in this area for a long time, and the energy storage system should quit the process of frequency modulation. When the SOC of the battery in energy storage system is in the charging priority area or discharging priority area, the participation of energy storage in the frequency modulation process should be appropriately reduced or increased. When the battery of the energy storage system is charged and discharged normally, the fuzzy controller is integrated to smooth the output.

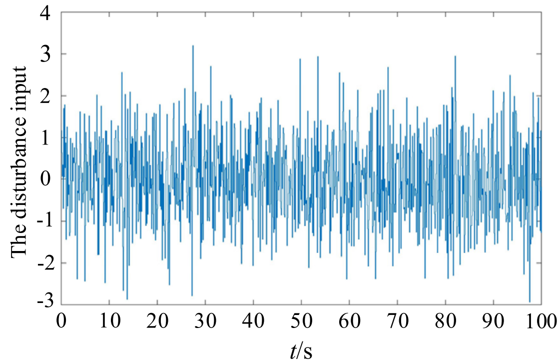


FIGURE 7. The input of the random disturbance.

V. SIMULATION ANALYSIS

A. PARAMETERS OF SIMULATION

In order to verify the frequency modulation control strategy assisted by energy storage system proposed in this paper, considering the ACE and SOC of the battery in energy storage system, the simulation model of a regional grid assisted by the electrochemical energy storage system with secondary frequency modulation was established, and the simulation was carried out on the Matlab. The selected parameters are shown in TABLE 2.

TABLE 2. Selection of simulation parameter.

Parameter	Value	Parameter	Value
F_{HP}	0.5	T_B	0.1
T_{CH}、T_{RH}	0.3、10	K_P	-0.822
T_g	0.08	K_I	-0.16
M	10	K	-20
D	1	B	21

B. ANALYSIS OF SIMULATION RESULTS

The random function in Simulink is selected as the disturbance input of the system, and the disturbance input is shown in Figure 7. Output of energy storage combined thermal power unit without and with fuzzy controller is shown in Figure 8 and Figure 9 respectively. Figure 10 shows the comparison of frequency deviations between the system without energy storage, with the conventional PID controller and the control strategy proposed in this paper.

By comparing Figure 8 and Figure 9, it can be found that the energy storage system and traditional thermal power unit fail to timely and accurately track the random disturbance input without adding the fuzzy controller, and that there is a certain time lag and deviation. Combined with the traditional thermal power unit, the energy storage system can quickly respond to random load disturbance by adding fuzzy controller. As can be seen from Figure 10, the frequency deviation between regional power grids is large when the AGC control mode of traditional thermal power units are adopted. The energy storage system can assist the traditional thermal power unit control mode and effectively reduce the frequency deviation. The control method based on fuzzy controller proposed in this paper can obviously reduce the frequency deviation of the system, and the frequency modulation using such method is more efficient than using the traditional PID control method.

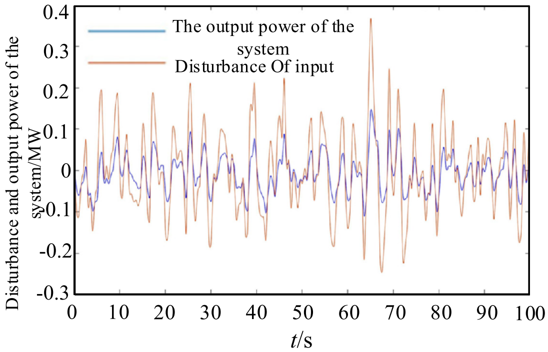


FIGURE 8. The output of a system following the disturbance without the addition of a fuzzy controller.

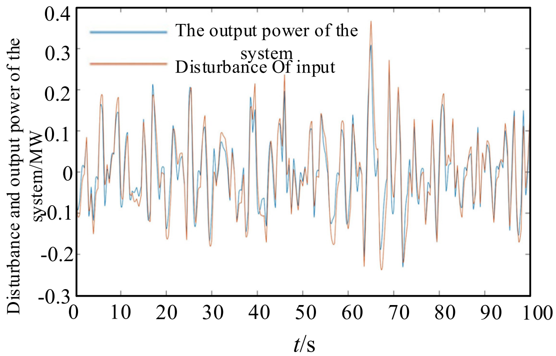


FIGURE 9. The output of the system following the disturbance when a fuzzy controller is added.

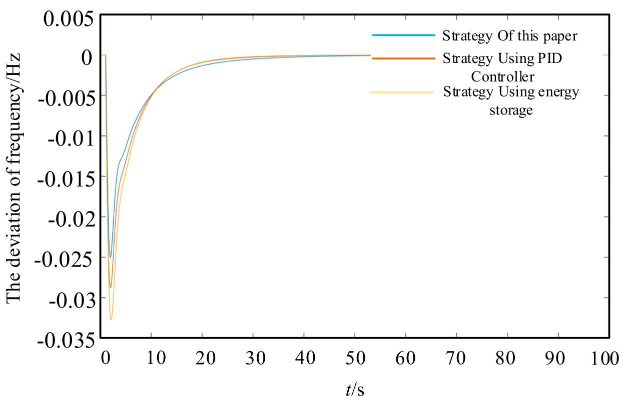


FIGURE 10. Comparison of system frequency deviations.

VI. CONCLUSION

In this paper, ACE and SOC of the battery in energy storage system are considered comprehensively, and a secondary frequency modulation control strategy of traditional thermal power unit assisted by energy storage based on fuzzy controller is proposed. The SOC of the battery in energy storage system and ACE signal are taken as fuzzy controller inputs to smooth the output power of the system. The simulation results indicate that:

(1) Using fuzzy controller, the combined unit of the energy storage system can quickly and accurately track the load disturbance of the system.

(2) After the addition of the energy storage system, the recovery time of frequency deviation of the system is shortened, which reflects the advantage of high response speed of energy storage when it participates in the auxiliary frequency modulation of traditional power supply.

(3) Compared with the traditional control strategy using PID controller, the proposed frequency modulation control strategy based on fuzzy controller can effectively reduce the frequency deviation of the regional power grid and improve the efficiency of frequency modulation.

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