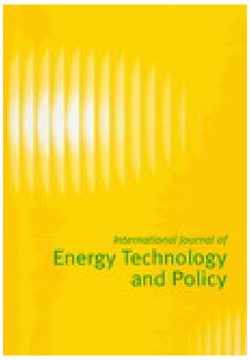

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Frequency modulation control of electric energy storage system based on abundance index

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Abstract: In order to overcome the problems of high time consumption and low accuracy of frequency regulation control in power energy storage systems, this paper proposes a frequency regulation control method for power energy storage systems based on adequacy indicators. Firstly, the control principle of energy storage charging and discharging are analysed, and a frequency characteristic model of the power energy storage system is constructed. Then, considering the adequacy index of power generation capacity, a bundle condition for capacity balance of the power energy storage system is constructed. Finally, the frequency modulation of the power energy storage system is controlled through the equivalent frequency modulation coefficient. The experimental results show that the frequency modulation control takes only 8.2 seconds, and the accuracy of frequency modulation control can reach 99.90%, indicating that the method proposed in this paper can effectively improve the effectiveness of power energy storage systems.

Keywords: electric energy storage system; frequency modulation control; abundance index; equivalent frequency modulation coefficient; capacity balancing.

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1 Introduction

The reliability and stability of the power system are crucial for ensuring power supply quality and meeting user needs. However, with the large-scale integration of renewable energy and the rapid growth of power load, the power system is facing more complex and severe regulatory challenges. In this case, the electric energy storage system plays an important role as a flexible regulation method (Liu et al., 2022; Safiullah et al., 2021; Qiu et al., 2022). Frequency modulation control is a key task in the power system, which aims to maintain frequency stability by adjusting the generator output or load when the load changes or the generator output fluctuates. The traditional frequency modulation control method mainly relies on the response speed of the generator and load, but this method has limitations when facing large-scale renewable energy integration.

Liu and Wang (2021) proposed a frequency modulation control method for power energy storage system based on source network load storage optimisation, and modelled the source, network and load of power energy storage system. Considering the transfer delay, dynamic characteristics and mutual relationship in the process of frequency modulation control, combined with the optimisation algorithm, the frequency modulation control strategy of power energy storage system is designed. A simulation experiment platform for frequency modulation control of electric energy storage system is built by using Simulink. In the actual power system, energy storage equipment is used for frequency modulation control, and real-time data is collected for verification. This method can effectively improve the frequency modulation control effect of electric energy storage system, but the frequency modulation control of electric energy storage system takes too long. Zeng et al. (2022) proposes a frequency modulation control method of power energy storage system based on the change of load shedding coefficient, and carries out theoretical analysis and related research on the relationship between the change of load shedding coefficient and frequency modulation control of power energy storage system. The frequency characteristic model of electric energy storage system is established, and the influence of load shedding coefficient on frequency response is considered. According to the magnitude and change rate of load shedding coefficient, a suitable mathematical model is designed to describe the dynamic characteristics of energy storage system in the process of frequency modulation. Based on the established frequency characteristic model, the corresponding frequency modulation control strategy is designed. Considering the change of load shedding coefficient, the power output of energy storage system is adjusted to adapt to the change of system frequency and minimise the frequency deviation. This method can effectively improve the accuracy of frequency modulation control of electric energy storage system, but the control time is too long. Song et al. (2022) proposes a frequency modulation control method for power energy storage system based on the principle of error distribution, establishes the mathematical model of frequency modulation control for power energy storage system, and considers the dynamic characteristics, time delay, nonlinearity and other factors of energy storage system to ensure that the model can accurately describe the actual situation. Based on the principle of error allocation, a strategy suitable for power system frequency modulation control is designed. According to the size and change rate of system frequency deviation, the control error is allocated to different energy storage equipment to achieve better frequency stability and minimise frequency deviation. Genetic algorithm is selected to solve the parameters in the error allocation strategy. Through the analysis of control error and parameter optimisation, the control effect and system performance are improved. The designed error allocation strategy is embedded in the model, and its performance is evaluated through simulation experiments. Considering the frequency modulation control under different load changes and different fault conditions. This method can effectively improve the efficiency of FM control, but the accuracy of FM control is not high.

In order to solve this problem, this paper proposes a frequency modulation control strategy for power energy storage system based on adequacy index. The specific research ideas are as follows:

First, build the energy storage model. Determine the composition of the electric energy storage control system, analyse the control principle of energy storage charge and discharge, and build the frequency characteristic model of the electric energy storage system,

Secondly, the frequency characteristic transfer function of energy storage is designed. The first-order lag transfer function of wind turbine is constructed, and the transfer function of power system frequency characteristics under different frequency modulation units is established.

Then, the frequency regulation changes of new units and existing units are analysed under the generation capacity adequacy index, and the constraints of frequency regulation control of power energy storage system are constructed;

Then, the constraint conditions are constructed and the equivalent frequency modulation coefficient is considered to realise the frequency modulation control of power energy storage system. The effectiveness and feasibility of the frequency modulation control strategy are verified by simulation experiments.

Finally, the frequency control effect of power energy storage system is verified by the time-consuming and accuracy of frequency control, and the conclusion is drawn.

2 Research on frequency modulation control of electric energy storage system based on abundance index

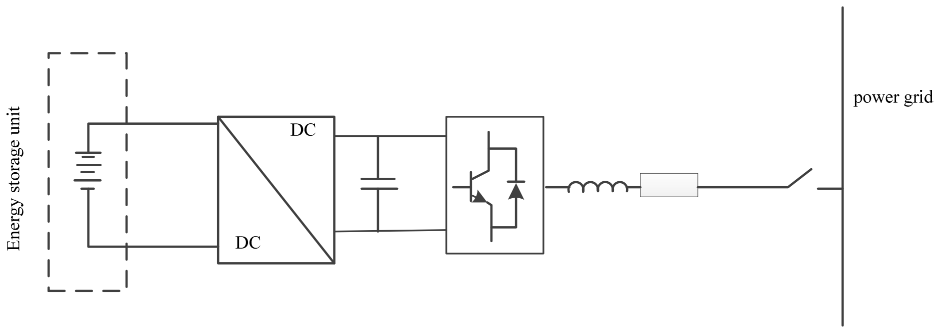
2.1 *Structure analysis of energy storage system*

2.1.1 *Composition of electric energy storage control system*

As shown in Figure 1, the energy storage system is composed of energy storage unit, battery management system (BMS), bidirectional DC-DC, voltage source converter (VSC), filter and control system.

The most important and fundamental component of the power energy storage control system is the energy storage unit, which can be used to store and release energy; BMS is mainly used for real-time monitoring and control of the output voltage, current value, and SOC of the energy storage system, to ensure the safe and efficient operation of the energy storage system. The energy storage unit is controlled by bidirectional DC-DC for voltage rise and fall, and then connected to the power grid through the energy storage inverter. The inverter is controlled to output and absorb the power of the energy storage system, allowing it to participate in system frequency regulation (Liu et al., 2021).

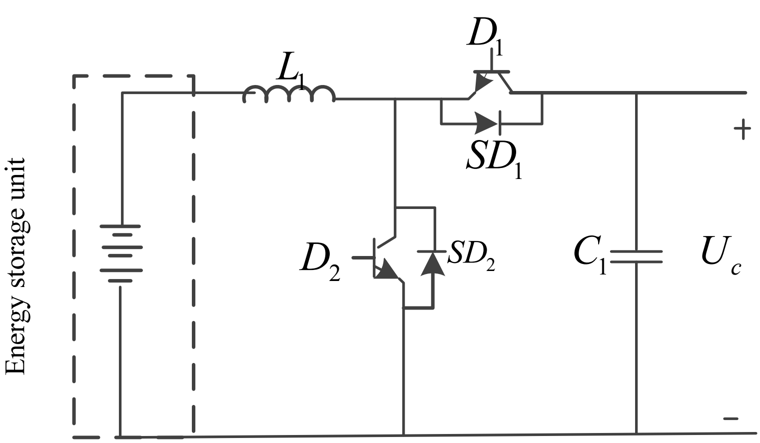
Figure 1 Energy storage system structure



2.1.2 Energy storage charging and discharging control

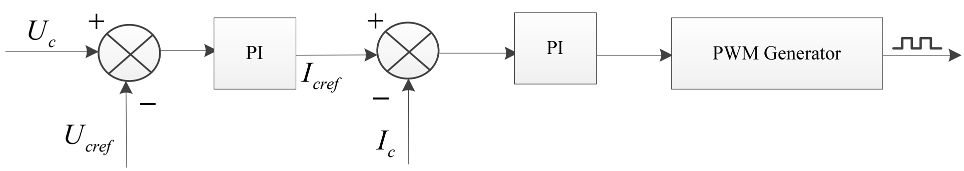
Energy storage is first controlled through bidirectional DC-DC for voltage rise and fall. Bidirectional DC-DC mainly controls the opening and closing of the fully controlled power electronic device IGBT, thereby changing the direction of input and output currents without changing the polarity of output voltage, and thus achieving bidirectional flow of energy in the energy storage system (Feng et al., 2022). The topology structure is shown in Figure 2.

Figure 2 Bidirectional DC-DC topology structure



According to Figure 2, when the system requires energy storage to provide electrical energy, the energy storage operates in a discharge state, similar to the operation principle of a boost circuit. The DC control system controls the opening and closing of power electronic switch D_2, while switch D_1 is always in the open state. When D_2 is turned on, the energy storage unit charges inductor L_1 and provides electrical energy to the grid through capacitor C_1. When D_2 is turned off, The energy storage unit and inductor provide electrical energy to the power grid through a diode SD_1 connected in parallel with switch D_1; when the system provides electrical energy to the energy storage system, the energy storage operates in a charging state, similar to the working principle of a buck circuit. At this time, switch D_2 is always in the open state, and the DC control system controls the opening and closing of switch D_1. When D_1 is in the on state, the power grid provides electrical energy to the energy storage system through inductor L_1 and capacitor C_1. When D_1 is turned off, The electrical energy stored in inductor L_1 is charged to the energy storage system through diode SD2 in parallel with switch D_2. By setting a reasonable DC control method, the energy storage system can ensure the transmission/absorption of electrical energy to the power system. So, in order to ensure the stability of the DC bus voltage in the energy storage system, the control method used is shown in Figure 3.

Figure 3 Bidirectional DC-DC control strategy

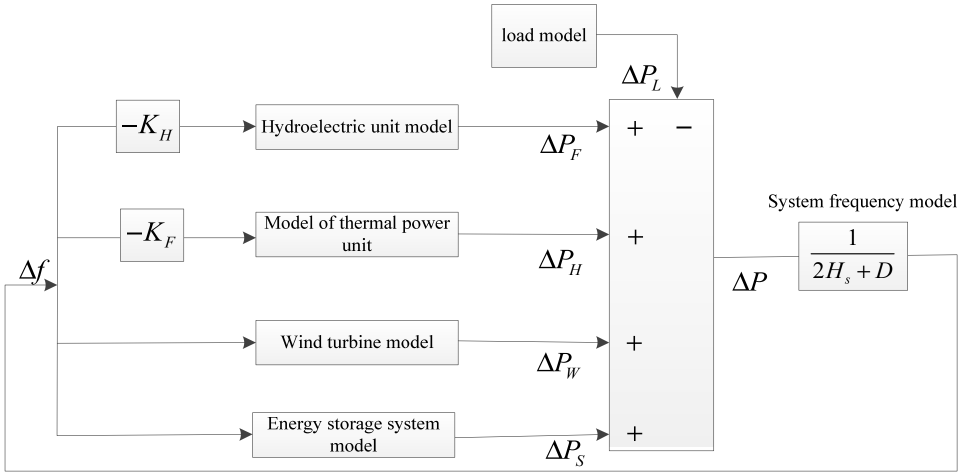


In Figure 3, U_c and I_c represent the output voltage and current on the DC side of the energy storage system, while U_{cref} and I_{cref} represent the reference values for DC voltage and current. Based on the above analysis, the bidirectional DC-DC structure of energy storage is simple and easy to control. Therefore, using a voltage and current dual closed-loop control strategy for bidirectional DC-DC control can ensure the constant DC side voltage of the energy storage system and ensure the bidirectional flow of energy in the energy storage system (Xie et al., 2022).

2.2 Design of frequency characteristic transfer function of electric energy storage system

In order to further analyse the impact of wind storage combined frequency modulation on system frequency, a frequency characteristic model of wind turbine and energy storage frequency modulation unit was established. Analyse the frequency characteristics of the system under non frequency regulation of wind turbines, separate frequency regulation of wind turbines or energy storage, and combined frequency regulation of wind storage (Sheng et al., 2022; Luo et al., 2022; Wang, 2023). According to Figure 4, it can be seen that the wind storage joint frequency regulation system includes wind farms and energy storage systems, as well as traditional synchronous generators. The frequency characteristic model of traditional synchronous generators includes thermal power units and hydropower units. The specific frequency characteristic model of the power system is shown in Figure 4.

Figure 4 Power system frequency characteristic model



The deviation between the actual frequency and the rated frequency can be obtained by using the frequency characteristic model of power system, and the accuracy of frequency modulation control can be evaluated through the deviation. The frequency deviation should generally remain stable within a certain range. If the frequency deviation is too large, it indicates that the frequency modulation control is not accurate enough. By establishing the frequency response model and measuring the actual data, the frequency modulation control can be quantitatively evaluated. This can help determine the performance level of the control system and the need for improvement measures. In Figure 4, K_H and K_F respectively represent the frequency modulation coefficients of water and thermal power units. The transfer functions G_F(s) and $G_D(s)$ of the thermal power unit and hydroelectric unit models are based on the given model. When the generator speed control system is not considered, the transfer function G(s) of the system frequency model can be expressed as:

$$G(s) = \frac{1}{2H_s + D} \tag{1}$$

In the equation, D is the damping coefficient. According to the analysis, as the wind power penetration rate continues to increase, the equivalent inertia of the system decreases. When the wind power penetration rate is n, the transfer function of the system frequency can be expressed as

$$G'(s) = \frac{1}{2H(1-n)_s + D} \tag{2}$$

Based on the analysis of the wind turbine frequency regulation strategy, this article selects overspeed control as the wind turbine frequency regulation strategy, and uses a simplified first-order lag transfer function (Jia et al., 2022) for the wind turbine's transfer function. Therefore, after the wind turbine adopts overspeed control, the transfer function G_W(s) of the wind turbine frequency characteristic model is:

$$G_W(s) = -\frac{K_{df}}{1 + T_w s} \tag{3}$$

In the formula, K_{df} is the frequency modulation coefficient of the fan, and T_w is the response time constant of the fan overspeed control [15].

For the energy storage system, virtual synchronous control is adopted to enable the energy storage to have inertial response and primary frequency modulation capability during the frequency modulation process. The frequency characteristic transfer function G_S(s) of the energy storage is:

$$G_S(s) = -\frac{K_{cf}s + K_{df}}{1 + T_S s} \tag{4}$$

In the formula, K_{cf} is the inertia coefficient of energy storage, the primary frequency modulation coefficient of energy storage is K_{df}, which is the same as that of the fan, and T_S is the response time constant of energy storage.

According to equations (3) and (4), the frequency characteristic transfer function of the wind storage joint system can be obtained as:

$$G_W S(s) = G_W(s) + G_S(s) = \frac{K_c f T_w s + \left(K_c f + ?\, K_d f T\, ?_S + K_d f T_w\right)s + 2K_d f}{\left(1 + \left(T_w + T_S\right)s + T_w T_S S^2\right)} \tag{5}$$

Based on the above transfer functions for each frequency modulation unit, establish the transfer functions for the frequency characteristics of the power system under different frequency modulation units. Assuming the wind power penetration rate in the power system is n, the proportion of thermal power units is p, and the proportion of hydroelectric units is $1–p$.

When the wind turbine and energy storage are not involved in system frequency regulation, the frequency modulation unit in the power system is only traditional thermal power and hydropower units, and the system frequency characteristic transfer function is:

$$G_{FD}(s) = \frac{\Delta f}{\Delta P_L} - \frac{G'(s)}{1 - G'(s)(1-n)\left[pK_F G_F(s) + (1-p)K_H G_D(s)\right]} \tag{6}$$

When the fan participates in system frequency regulation alone, the transfer function of system frequency characteristics is:

$$G_{FDW}(s) = -\frac{G'(s)}{1 - G'(s)(1-n)\left[pK_F G_F(s) + (1-p)K_H G_D(s)\right] + nG_W(s)} \tag{7}$$

When the fan is not involved in frequency regulation and the energy storage is separately involved in system frequency regulation, the system frequency characteristic transfer function is:

$$G_{FDS}(s) = -\frac{G'(s)}{1 - G'(s)(1-n)\left[pK_F G_F(s) + (1-p)K_H G_D(s)\right] + nG_S(s)} \tag{8}$$

When wind storage joint frequency modulation is used, the system frequency characteristic transfer function is:

$$G_{FDWS}(s) = -\frac{G'(s)}{1 - G'(s)(1-n)\left[pK_F G_F(s) + (1 - pK_H G_D(s)\right] + nG_{WS}(s)} \tag{9}$$

Thus, the frequency characteristic transfer function of the power energy storage system is obtained.

2.3 Frequency modulation control constraints of electric energy storage system based on abundance index

Considering the mechanism of generating capacity adequacy, the constraints for frequency regulation control of the power storage system are constructed based on the reporting of new and existing units:

For the existing units, it is considered that the investment cost has been recovered. Therefore, in the centralised auction of the two-way option contract for the *n*th year, the electric energy part of the existing units is quoted as the marginal coast of electricity by source, and the capacity quotation $B_{i,n}^{RO}$ is the annual fixed operating cost:

$$B_{i,n}^{RO} = C_{i,n}^{GO} \tag{10}$$

For new units, additional consideration should be given to investment costs. Therefore, in the centralised auction of two-way option contracts for revenue in the nth year, the electric energy part of new units is quoted as marginal cost of electricity by source, and the capacity quotation $B_{i,n}^{RO}$ is the sum of annual fixed operating cost and annual capital cost:

$$B_{i,n}^{RO} = C_{i,n}^{RO} + IC_{i,n} \tag{11}$$

The system capacity requirement objectives are:

$$P_n^t arget = \frac{(1+R_m)D_n^{max}}{P_{FOR}} \tag{12}$$

Among them, P_n^{target} is the system capacity demand for the target year, R_m is the reserve margin, D_n^{max} is the annual peak load for the target year, and $\overline{P}_{FOR}$ is the equivalent availability of all units, which is related to the equivalent shutdown rate of each unit.

The price cap P^{cap} in the reliability option auction is:

$$P^{cap} = C_{j,n}^{Pre} - R_{j,n}^{E} - R_{j,n}^{A} \tag{13}$$

Among them, $C_{j,n}^{Pre}$ represents the expected cost of peak power generation type in the target year, $R_{j,n}^{E}$ and $R_{j,n}^{A}$ represent the expected revenue of peak power generation type in the energy market and auxiliary service market in the target year, respectively. In this article, the auxiliary service market is ignored.

In the *n*th year capacity market auction, the clearance function is the minimum total capacity cost:

$$min \sum\nolimits_{i \in G\{G^{EX}, G^{NE}\}} x_{i,n} \cdot B_{i,n}^{CM} \cdot P_i^{max} \tag{14}$$

In the formula, G^{EX} and G^{NE} respectively represent the set of existing units and the set of new units. $B_{i,n}^{CM}$ is the auction price for Unit i in the capacity market.

The constraint condition is capacity balance constraint:

$$\sum_{i\in\{G^{EX},G^{NE}\}} x_i \cdot P_i^{max} = R_n \tag{15}$$

In the equation, R_n represents the capacity demand of the system in the nnd year.

2.4 Research on frequency modulation control of electric energy storage system

The frequency modulation capability of an electric energy storage system depends on the equivalent frequency modulation coefficient of the system, and the magnitude of the frequency modulation coefficient is related to the total regulated power in the electric energy storage system. The total regulated power of n traditional synchronous generator units in the electric energy storage system can be expressed as:

$$\Delta P_{GN} = \sum_{i=1}^{n} \Delta P_{Gi} = \Delta P_{G1} + \Delta P_{G2} + \ldots + \Delta P_{Gn} \tag{16}$$

In the formula, ΔP_{GN} represents the total adjustable power, and ΔP_{Gi} represents the adjustable power of the ird synchronous generator.

In order to ensure the stable operation of the unit, it is generally not required that the adjustable power of the synchronous generator be too large. From equation (16), it can be seen that the more units in the system that can participate in frequency regulation, the larger the frequency modulation coefficient and the more stable the frequency variation characteristics. With the increasing penetration rate of wind power generation, wind turbines are unable to provide backup capacity for frequency regulation. Therefore, the total equivalent regulated power in the electric energy storage system decreases, the frequency regulation coefficient decreases, and the frequency stability of the electric energy storage system deteriorates, which is not conducive to the stable operation of the system.

In electric energy storage systems, the inertia constant of a single traditional synchronous generator is usually defined as:

$$H = \frac{E_{KN}}{S_N} = \frac{J\omega_N^2}{2S_N} \tag{17}$$

In the formula, H is the inertia constant of a single synchronous generator, and E_{KN} is the kinetic energy of the rotor at rated speed; S_N is nameplate capacity; ω_N is the rated speed. For a power system containing n traditional synchronous motors, the equivalent inertia constant H_{sys} is:

$$H_{sys} = \frac{\sum_{i=1}^{n} H_i S_i}{S_{sys}} \tag{18}$$

In the equation, S_{sys} represents the total installed capacity of the system, H_i and S_i represent the inertia constant and capacity of the i^{th} traditional synchronous motor. According to the above equation, as the installed capacity of the wind turbine unit in the power energy storage system increases, it means that the capacity of the traditional synchronous motor decreases, leading to a decrease in the equivalent inertia of the system. According to the Equations of motion of the generator rotor, the relationship between the equivalent inertia constant of the electric energy storage system and the initial frequency change rate can be deduced as follows:

$$\frac{2H_{sys}}{f_N}\frac{df}{dt}=\frac{\Delta P_0}{S_{sys}} \tag{19}$$

In the formula, ΔP_0 represents the difference in active power of the electric energy storage system. According to the above equation, as the inertia of the power energy storage system decreases, the frequency of the power energy storage system changes faster.

In summary, with the continuous increase of wind power grid connection capacity, the equivalent inertia and frequency regulation capacity of the power energy storage system decrease, which is not conducive to the stable operation of the power energy storage system. Therefore, it is necessary for the wind turbine itself or to configure corresponding energy storage to participate in system frequency regulation to ensure the stability of the power energy storage system frequency. Based on this strategy, frequency regulation control of the power energy storage system based on adequacy indicators is achieved.

3 Experiment

3.1 Experimental design

All experiments in this article were completed on the platform shown in Table 1.

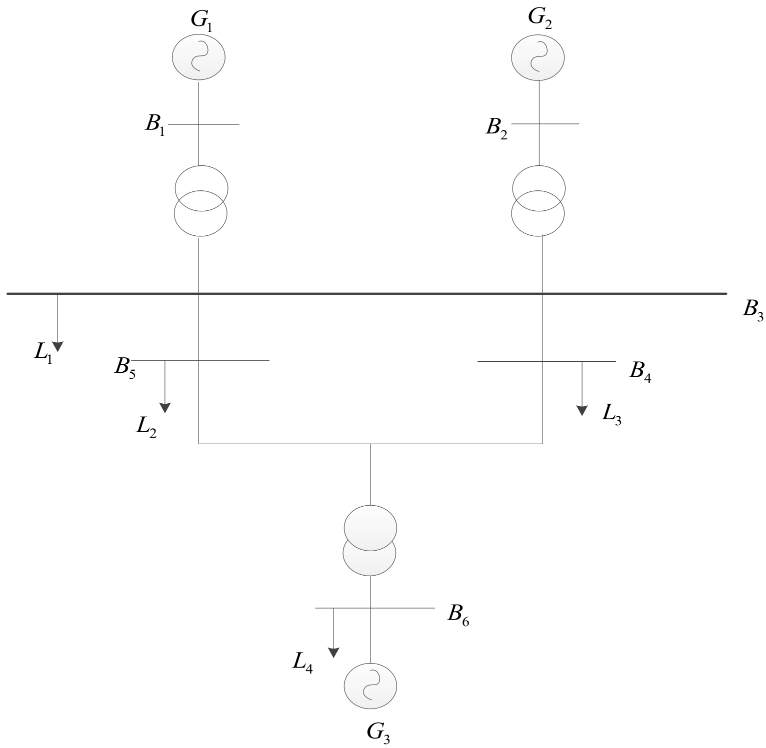
Table 1 Software and hardware environment parameters

Software and hardware environment name	*Parameter description*
Processor	Intel I7-10700
Graphics card	Nvidia GTX2080TI
Memory	32G
operating system	Ubuntu 18.04
Experimental platform	Pytorch deep learning framework
Programming language	Python3.6

Based on the above analysis, a simulation model for the grid connection of a doubly fed fan was built in MATLAB/Simulink software, as shown in Figure 5. Among them, G_3 are wind farms composed of doubly fed wind turbine generators, G_1 and G_2 are synchronous generators, which both include prime mover and governor models, but do not include AGC adjustment systems. L_1, L_2, L_3, and L_4 are loads in the system.

Firstly, set the wind turbine to work at the rated wind speed, regardless of the wind speed change, where G_1 and G_2 are synchronous generators with a Nameplate capacity of 100 MW, and the total active load of the electric energy storage system is 170 MW. Verify the frequency regulation control effect of the power energy storage system.

Figure 5 Grid connected model of doubly fed fan



3.2 Experimental result

3.2.1 Accuracy of frequency modulation control for power energy storage systems

In order to verify the frequency modulation control effect of the power energy storage system proposed in this paper, the methods of Liu and Wang (2021), Zeng et al. (2022), and this paper were used to verify the accuracy of frequency modulation control in the power energy storage system. The results are shown in Table 2.

According to Table 2, when the number of iterations increases from 1,000 to 6,000, the accuracy of frequency regulation control for the power storage system using Liu and Wang (2021) method varies between 61.82% and 76.18%, while the accuracy of frequency regulation control for the power storage system using Zeng et al. (2022) method varies between 63.18% and 76.60%. The accuracy of frequency regulation control for the power storage system using this method varies between 98.62% and 99.90%; The above results indicate that the method proposed in this paper can effectively improve the accuracy of frequency modulation control in power energy storage systems, and the frequency modulation control effect of power energy storage systems is good.

Table 2 Accuracy of frequency modulation control in electric energy storage system

Iterations/time	*Accuracy of frequency modulation control for power energy storage systems/%*		
	Liu and Wang (2021) method	*Liu and Wang (2021) method*	*Proposed method*
1,000	61.82	69.29	99.18
2,000	65.90	63.18	98.62
3,000	76.18	64.51	99.29
4,000	73.68	69.18	99.52
5,000	70.52	70.32	98.72
6,000	72.18	76.60	99.90

3.2.2 *Time consumption of frequency modulation control in power energy storage system*

In order to verify the frequency control efficiency of the method proposed in this paper, the methods of Liu and Wang (2021), Zeng et al. (2022), and this paper were used to verify the frequency control time consumption of the power energy storage system. The results are shown in Table 3.

Table 3 Time consumption for frequency modulation control of power energy storage system

Iterations/time	*Time consumption of frequency modulation control in power energy storage system/s*		
	Liu and Wang (2021) method	*Liu and Wang (2021) method*	*Proposed method*
1,000	32.8	18.9	0.6
2,000	65.9	46.8	1.9
3,000	78.2	58.9	2.8
4,000	98.8	87.3	5.2
5,000	128.6	122.6	6.6
6,000	159.3	186.1	8.2

From Table 3, it can be seen that when the number of iterations increases from 1,000 to 6,000, the frequency control time of the power storage system using Liu and Wang (2021) method increases from 32.8 seconds to 159.3 seconds, and the frequency control time of the power storage system using Zeng et al. (2022) method increases from 18.9 seconds to 186.1 seconds. The frequency control time of the power storage system using this method only increases from 0.6 seconds to 8.2 seconds; The frequency regulation control time of the power storage system proposed in this paper is lower than that of the other two traditional methods. This is because this method considers the generation capacity adequacy index, constructs the constraint conditions for the capacity balance of the power storage system, and controls the frequency regulation of the power storage system through the equivalent frequency regulation coefficient, effectively improving the efficiency of the frequency regulation control of the power storage system.

4 Conclusions

The paper proposes a frequency modulation control strategy based on the adequacy index, analyses the principle of energy storage charging and discharging control, constructs a frequency characteristic model of the power storage system, considers the generation capacity adequacy index, and constructs a constraint condition for the capacity balance of the power storage system: the frequency modulation of the power storage system is controlled through an equivalent frequency modulation coefficient. The experimental results indicate that:

1 When the number of iterations increases from 1,000 to 6,000, the accuracy of frequency regulation control for the power energy storage system proposed in this paper varies between 98.62% and 99.90%, indicating that this method can effectively improve the accuracy of frequency regulation control for the power energy storage system.

2 When the number of iterations increases from 1,000 to 6,000, the frequency modulation control time of the power energy storage system proposed in this paper is only 8.2 seconds, indicating that this method can effectively improve the frequency modulation control efficiency of the power energy storage system.

Considering the integration of frequency modulation control and power market demand, the unified optimisation of economic dispatch and frequency stability is realised. By optimising the mode and mechanism of FM control participating in market transactions, the economy and feasibility of electric energy storage system are improved.

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