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Emergency frequency control method for high-proportion renewable energy power system under low inertia

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Abstract

In a new energy power system, there is a lack of sufficient inertia support when facing sudden frequency disturbances, which threatens frequency stability. To address the problem of how to control the frequency of a high-proportion new energy power system under low inertia, this paper proposes an emergency frequency control method based on the idea of control and cutting coordination to reduce the frequency deviation of the power system. With the minimization of the power system frequency offset and the minimization of the control cost as the objective function and the minimum inertia and power balance of the power system as the constraint conditions, an emergency frequency optimization control model of a high-proportion new energy power system under low inertia is established. Solving the model obtains the minimum frequency offset and the minimum control cost, and the optimal cutting and load reduction strategy is effectively determined to achieve stable control of the power system frequency. Results show that under different power shortage conditions, this method can effectively determine the inertia of the power system, thereby completing the control of the emergency frequency of the power system. Through the control of this method, the maximum frequency deviation of the power system is maintained at about 0.6 Hz, and the maximum total control cost is 16,600 CNY. Compared with the situation before the application of this method, the frequency deviation and control cost of the power system are significantly reduced, that is, the emergency frequency control effect of this method is better. The research conclusions are of great technical help in maintaining the safe and stable operation of the power system.

Keywords: low inertia; high ratio; new energy; power system; emergency frequency control; control and switching coordination

Introduction

Renewable energy, such as wind power, solar energy, and other forms of renewable energy, is gradually replacing traditional fossil energy with its clean and low-carbon characteristics and becoming the dominant energy source. However, the inherent intermittent and volatile nature of renewable energy makes the frequency stability of power systems increasingly prominent. The frequency stability of power systems is a key factor in ensuring the security of power supply and improving the quality of power [1]. With the high proportion of renewable energy access, the frequency fluctuation of power systems has become more frequent, and the fluctuation amplitude has increased, posing a serious threat to the stable operation of power systems. Therefore, studying the emergency frequency control method of power systems with a high proportion of renewable energy is of great significance for ensuring the safe and stable operation of power systems and promoting the consumption and sustainable development of renewable energy. Emergency frequency control is a rapid response measure adopted by power systems when facing frequency fluctuations. It aims to quickly compensate for frequency deviations and restore the frequency stability of power systems by adjusting power output, load demand, or charging and discharging of energy storage devices [2].

Although existing research has achieved certain results in the field of frequency control, many shortcomings remain. Traditional frequency control methods mainly rely on rotational inertia in the power grid. The high proportion of renewable energy access leads to a significant reduction in system inertia, and traditional methods are not effective enough in dealing with large-scale frequency fluctuations [3]. Existing research has mostly focused on the frequency regulation strategy of conventional power sources, and relatively little research has been conducted on the frequency control of renewable energy sources [4]. In addition, most of the current emergency frequency control methods ignore the control cost and fail to achieve an effective balance between frequency stability and economy. Therefore, it is necessary to propose a more effective frequency control method based on the particularity of a high-proportion renewable energy power system to cope with the challenges brought by frequency disturbances.

In response to the above problems, this paper proposes an emergency frequency control method based on the idea of control and switching coordination. This method aims to minimize the frequency offset and control cost of the power system, and it considers constraints such as the minimum inertia and power balance of the power system. Specifically, this paper establishes an optimization model to determine the optimal switching and load reduction strategy to achieve effective control of the power system frequency. An experiment verifies the effectiveness of this method under different power shortage conditions. The results show that this method can significantly reduce frequency deviation and control cost, and it can also improve the stability and economy of the power system. This study not only provides new ideas for frequency control of a high-proportion renewable energy power system but also contributes certain theoretical and practical value to the safe, stable operation and sustainable development of the power system.

State of the art

In power systems with a high proportion of new energy sources, more flexible, fast and accurate emergency frequency control methods need to be studied because of the uncertainty and volatility of new energy output. Navas and others first analyzed the operating characteristics of new energy power systems and clarified the necessity of frequency control. Then, a frequency control model considering optimal dispatch is constructed by combining the operating characteristics of new energy power generation equipment and the actual needs of the power system. This model uses an optimization algorithm to determine the optimal dispatch strategy to achieve rapid response and precise control of new energy power generation equipment in emergencies.

Experimental verification verified that this method can significantly reduce frequency deviation and improve the frequency stability of the power system [5]. This method effectively combines the operating characteristics of new energy sources with system requirements to achieve fast and precise control in emergencies, but it has a high dependence on optimization algorithms.

Frequency changes in power systems are often very rapid, especially when faced with sudden frequency disturbances. However, the HVAC load cluster may not be able to respond to these changes in real time and quickly because of its own operating characteristics and control mechanism, resulting in unsatisfactory control effects. Kumar, V et al. aimed to utilize the flexibility and large-scale access potential of electric vehicles to optimize the charging and discharging behavior of electric vehicles through an integrated model predictive control (MPC) scheme, thereby achieving effective control of the power system frequency. In this scheme, first, the interaction characteristics between electric vehicles and the power system are analyzed, an electric vehicle charging and discharging model is established, and its impact mechanism on the frequency of the power system is studied. Then, combined with MPC theory, a frequency control strategy for electric vehicle integrated MPC is designed. This strategy can predict the frequency changes of the power system in real time and optimize the charging and discharging strategy of electric vehicles based on the prediction results to achieve stable frequency control [6]. MPC solutions rely on accurate predictive models and real-time data. In the case of sudden frequency perturbations, the dynamic characteristics of the system may change rapidly, thus affecting the accuracy of the prediction model. If the prediction model cannot accurately capture the real-time status of the system, then the frequency control strategy based on MPC cannot respond to frequency disturbances in a timely and effective manner and cannot effectively reduce the amplitude of frequency changes. By monitoring the operating status and frequency changes of the power system in real time, this method can adjust the operating status of large-scale air conditioning loads in real time to achieve precise control of the frequency of the power system. This strategy demonstrates a new way to exploit the flexibility of electric vehicles for frequency control, although its successful execution relies on high-precision prediction capabilities and data processing.

Although the model-free adaptive control algorithm does not require precise model parameters, its control effect relies on a large amount of real-time data and computing resources. When faced with sudden frequency disturbances, the system is required to respond quickly and accurately. However, the collection, transmission, and processing of data may experience a certain delay, resulting in the control strategy not being able to take effect in a timely manner and thus being unable to effectively suppress drastic changes in frequency. Rajamand, aims to achieve stable control of power system frequency by optimizing the coefficients of the PID controller. As an intelligent optimization algorithm, the metaheuristic algorithm can search for optimal solutions globally and adapt to different system environments and parameter changes. This method uses a metaheuristic algorithm to optimize the PID coefficients to cope with real-time changes in power system frequency [7]. Although this method has rapid adaptability, it may be limited by data latency and processing power in practical applications.

In power systems, frequency stability is crucial to maintaining the balance between active power supply and demand. Applying multi-scale morphological filtering methods ensures that the frequency changes of power systems can be monitored in real time, and the power generation and load management can be quickly adjusted to reduce frequency deviation. This method can not only improve the frequency stability of power systems but also enhance the anti-interference ability of the system [8]. Duan, et al. achieved precise regulation and stable control of the power system frequently by constructing a multi-level power flow control structure. Under the hierarchical power flow control framework, the system is divided into different control levels. Each level is responsible for different control tasks, and coordinated management of the entire power system is achieved. By optimizing the power flow distribution and power transmission at each level, this method can reduce frequency fluctuations and improve the stability of the power system [9]. The hierarchical power flow control method involves coordination between multiple control levels and control objectives. Ding, et al. collected the operating data of the power system in real time, including frequency, power, and load, through sensors and measuring equipment; constructed load models and speed regulator models; and predicted future load change trends and the speed regulator adjustment range. On the basis of the load prediction results and the speed regulator adjustment range, the frequency control objectives were clarified, and the frequency control strategy was formulated to achieve precise control of the frequency [10]. The multi-level control strategy effectively improves the overall coordination and response speed of the system, making the frequency control more accurate and stable.

As a robust control method, the sliding mode observer can effectively deal with the uncertainty and interference brought by the access of new energy sources and provide a stable frequency control effect. By designing a suitable sliding surface and switching control strategy, this method can respond quickly when the system state changes and suppress drastic frequency fluctuations [11]. Nguyen, et al. introduced a full predictive control strategy and combined it with a two-level distributed control structure [12] to solve the frequency fluctuation problem in the new energy power system, especially when considering communication delay. The application of the full predictive control strategy enables the system to predict and respond to possible frequency changes in advance and effectively suppress frequency fluctuations. At the same time, the adverse effects of delay on system performance are reduced by optimizing the communication protocol [13].

Guzman, et al. used the fast response and energy regulation capabilities of the energy storage system to adjust the frequency of the power system in real time. The energy storage system can quickly release or absorb energy when the frequency is disturbed according to the needs of the power system to balance the difference between the system load and the generated power, thereby maintaining the voltage and frequency stability of the power grid. At the same time, accurate frequency control can be achieved by optimizing the control strategy and dispatching algorithm of the energy storage system. This method can not only improve the frequency stability of the power system but also improve the power quality and promote the consumption of new energy and the smooth operation of the power system [14]. Although the response speed of the energy storage system is relatively fast, its regulation ability may still be limited when facing extremely sudden and large frequency disturbances. The capacity and charging and discharging rate of the energy storage system are subject to physical and technical limitations, which is why when the frequency disturbance exceeds its regulation range, the energy storage system cannot provide sufficient energy support in time, resulting in relatively drastic frequency changes. Low inertia may cause the system to lack sufficient inertial support when facing sudden frequency disturbances, making the frequency change more drastic [15]. Considering the low inertia characteristics of the power system can allow the formulated emergency frequency control strategy to respond to these disturbances more accurately, reduce the amplitude and duration of frequency deviation, and ensure the stability of the system.

This paper reviews a variety of emergency frequency control strategies for power systems with a high proportion of new energy and analyzes in detail the effects and challenges of various methods in theory and practical applications. Although the optimization dispatch model proposed by Navas, et al. has been verified experimentally to be effective in reducing frequency deviation, this method may be limited in practical applications due to the complexity of the algorithm and the high demand for real-time data processing. Kumar, et al. used an integrated model predictive control strategy for electric vehicles. This method showed innovation but relied on accurate prediction models and fast data updates, which may be difficult to achieve in actual power systems. Rajamand, provided a frequency control method that does not rely on accurate model parameters through a model-free adaptive control algorithm. This strategy has strong adaptability, but the actual effect is limited by data real-time and computing resources. The multi-level power flow control structure method proposed by Duan, et al. can effectively reduce frequency fluctuations and improve system stability. However, it requires fine inter-layer coordination and synchronous operation, which may encounter implementation difficulties in large-scale cross-regional power systems. Finally, the full predictive control strategy and sliding mode observer introduced by Nguyen, et al. effectively deal with the uncertainty and communication delay problems brought about by the access of new energy and demonstrate superiority in dynamic and uncertain environments. However, the application of these technologies still faces the challenges of high cost and technical integration. In summary, although the current research has certain advantages in theory, such as the optimization scheduling method, the electric vehicle integrated MPC scheme, and the model-free adaptive control algorithm, each method has shown different degrees of limitations in actual implementation, mainly limited by computing resources, data accuracy, response speed, and technical implementation. Therefore, future research needs to conduct more in-depth discussions on improving the accuracy of the prediction model, optimizing the data processing speed, and reducing the implementation cost to achieve fast and effective control and ensure the stable operation of the power system under the condition of a high proportion of new energy access. These studies provide not only valuable technical support for solving the frequency stability problem of new energy power systems but also important theoretical and practical guidance for the modern management of power systems.

Methods

Control and cutting coordination ideas for high-proportion renewable energy power systems under low inertia

Under low inertia conditions, the frequency deviation of renewable energy power systems will increase significantly. Therefore, emergency frequency control methods for high-proportion renewable energy power systems need to be studied to improve the frequency stability of the power system. When only the load shedding control strategy is adopted, although the system power can be balanced by reducing some non-critical loads and thus stabilizing the frequency [16], this strategy may have a certain impact on users during implementation. Especially when the load shedding amount is large, it may cause insufficient power supply or power outage to users, affecting the normal power demand of users. When only the generator cutting control strategy is adopted, although the system power can be quickly balanced by cutting off some renewable energy generators and restoring frequency stability [17], this strategy may cause a loss of system power generation capacity. Particularly when the proportion of renewable energy access is high, cutting off renewable energy generators may have a negative impact on the renewable energy utilization rate and economic benefits of the system. The simultaneous use of load shedding control and generator cutting control strategies can complement each other and jointly cope with the frequency disturbance of the power system. Load shedding control reduces the overall load demand of the system by reducing the power supply of some non-critical loads, thereby balancing the relationship between power generation and load, which helps stabilize the system frequency [18]. Generator shedding control quickly reduces the unbalanced power of the system by cutting off some renewable energy generators and can provide additional support when the system faces severe disturbances. This coordinated strategy can more comprehensively respond to frequency disturbances in different situations and improve the stability and reliability of the system. Therefore, based on the control and shedding coordination method, the emergency frequency control idea of a high-proportion renewable energy power system under low inertia is designed.

$P_{\max}$ is the maximum load reduction power of the new energy power system, and the formula is as follows:

$$P_{\max} = \sum_{j=1}^{N} \varphi_w \Delta P_{w,j} \tag{1}$$

where $\Delta P_{w,j}$ is the power change of the j renewable energy generator set; N is the number of renewable energy generator sets in the power system; and φ_w is the response coefficient of the power system frequency to the power change of high-proportion renewable energy generator sets.

P_d is the excess power of the renewable energy power system under low inertia. In case $P_d \le P_{\max}$, the load shedding control strategy can be adopted to achieve emergency frequency control, that is, $P_d \le P_{\max}$ is the condition for adopting the load shedding control strategy. In case $P_d > P_{\max}$, the machine cutting control strategy is adopted to cut off the renewable energy generator set and increase the maximum controllable power of the renewable energy generator set to achieve emergency frequency control [19]. Let $P'_{\max}$ be the maximum controllable power, and the formula is as follows:

$$P'_{\max} = \sum_{i=1}^{M} \sum_{j=1}^{N-M} \varphi_w (P'_{w,i} + \Delta P_{w,i}) \qquad (2)$$

where $P'_{w,i}$ is the active power of the i renewable energy generator set to be removed, and M is the number of renewable energy generator sets that need to be removed. Under condition $P_{\max} \le P_d \le P'_{\max}$, the purpose of emergency frequency control of a renewable energy power system can be achieved by adopting only the generator cutting control strategy or load shedding control strategy [20].

If all new energy generator sets participate in frequency control and the power fluctuation problem of the power system cannot be solved, then appropriately cutting off traditional generating sets is necessary to ensure that the power of the power system remains balanced. This approach is adopted to allow the power system to meet condition $\sum_{i=1}^{M} P'_{w,i} + \sum_{l=1}^{\eta} \Delta P_{S,l} \le P_d + \varphi_w \Delta f_{\max}$, where $\sum_{i=1}^{M} P'_{w,i}$ is the total power of the cut-off new energy generator sets; $\sum_{l=1}^{\eta} \Delta P_{S,l}$ is the total regulated power of the traditional generating sets; η and l are the number and serial number of traditional generating sets participating in emergency frequency control in the power system, respectively; and $\Delta f_{\max}$ is the maximum frequency deviation of the power system.

Emergency frequency optimization model for high-proportion new energy power system under low inertia

Objective function of emergency frequency optimization control for high-proportion new energy power system under low inertia

According to the control and cutting coordination idea in Section 2.1, an emergency frequency optimization control model for high-proportion new energy power system under low inertia is constructed. The power instructions of each new energy generator set, and the traditional generator set are obtained by optimizing and solving the model, strategies for the new energy generator set and the traditional generator set to be in normal operation, and cutting and load reduction control states are formulated. According to the formulated control strategy, the new energy generator set, and the traditional generator set coordinate the control of the active power output by the new energy generator set and the traditional generator set to complete the emergency frequency control of the high-proportion new energy power system.

Load reduction control and cutting control each have different action mechanisms and effects. A key issue is how to coordinate these two control strategies so that they can complement each other and work together. To this end, with the goal of minimizing frequency offset and minimizing control cost, an emergency frequency optimization control model for a high-proportion renewable energy power system under low inertia is established. The frequency offset and control cost of the power system are comprehensively considered to determine the optimal load reduction and machine cutting amount, achieve the coordination of the two control strategies, and improve the emergency frequency control effect of a high-proportion renewable energy power system under low inertia.

If the purpose of emergency frequency control can be achieved by controlling renewable energy generators only by cutting and reducing load, then the objective function of minimizing frequency offset is as follows:

$$F_1 = \min\left[\sum_{i=1}^{M}\sum_{j=1}^{N-M}\varphi_w(P'_{w,i}+\Delta P_{w,j})+\sum_{l=1}^{\eta}\varphi_{S,l}\Delta P_{S,l}+\varphi_L\Delta P_L\right] \tag{3}$$

Where $\varphi_{S,l}$ is the frequency response coefficient of the traditional generator set; $\Delta P_{S,l}$ is the load reduction power of the l traditional generator set; φ_L is the load frequency characteristic coefficient; and ΔP is the load change of the power system.

When all new energy generator sets participate in frequency control and cannot reduce the power fluctuation amplitude of the power system, the objective function of minimizing the frequency offset is as follows:

$$F_1 = \min\left[\sum_{i=1}^{M}\varphi_w P'_{w,i}+\sum_{l=1}^{\eta}\varphi_{S,l}P_{S,l}+\sum_{l=1}^{\eta-\eta s}\varphi_{S,l}\Delta P_{S,l}+\varphi_L\Delta P_L\right] \tag{4}$$

where η_s is the number of traditional generators to be removed, and $P_{S,l}$ is the active power of the l traditional generator.

The objective function for minimizing the control cost of the power system is as follows:

$$F_2 = \min\sum_{t=1}^{M}\sum_{l=1}^{\eta}[h_l(P_{S,l}(t)k_1(t))+G_l(t)]+C_1 + C_2+\Delta R_w c_w \tag{5}$$

where h_l is the fuel cost of the l traditional generator set; $G_l(t)$ is the start-up and shutdown cost of the l traditional generator set; $k_l(t)$ is the operating status of the traditional generator set; C_1 and C_2 are the costs of wind and solar power abandonment; ΔR_w is the virtual inertia of the additional high-proportion new energy generator set; and c_w is the unit cost of virtual inertia correction.

Constraints for emergency frequency optimization control of high-proportion renewable energy power system under low inertia

For the objective function of emergency frequency optimization control of a high-proportion renewable energy power system under low inertia in Section 2.2.1, the following constraints are included:

(1) Minimum inertia constraint of power system

The inertia of the power system in each period must exceed its minimum inertia requirement to ensure the stability of the power system frequency. The formula is as follows:

$$R_w(t) \ge R_{\min}(t) \tag{6}$$

where, at time t, $R_w(t)$ is the actual inertia, and $R_{\min}(t)$ is the minimum inertia.

The calculation formula of $R_w(t)$ is as follows:

$$R_w(t)=\sum_{l=1}^{\eta}P_{S,0}\tau_{S,0}k_l(t)+\sum_{j=1}^{\eta}P_{w,0}\tau_{w,0} \tag{7}$$

Where $P_{w,0}$ and $P_{w,0}$ are the rated power of traditional generator sets and new energy generator sets, respectively, $\tau_{S,0}$ and $\tau_{w,0}$ correspond to the inertia time constant.

The calculation formula of $R_{\min}(t)$ is as follows:

$$R_{\min}(t)=\max\{R_{\min,1},R_{\min,2}\} \tag{8}$$

where $R_{\min,1}$ is the minimum inertia considering the frequency offset, and $R_{\min,2}$ is the minimum inertia considering the lowest frequency point.

The calculation formula of $R_{\min,1}$ is as follows:

$$R_{\min,1} = \frac{\Delta\hat{P}_{\max} f_0}{2V\max} \tag{9}$$

where f_0 is the rated frequency of the high-proportion renewable energy power system; $V_{\max}$ is the maximum frequency change speed; and $\Delta\hat{P}_{\max}$ is the maximum load change of the power system.

Let $f_{\min}$ be the minimum frequency of the high-proportion renewable energy power system and f_b be the lower limit of the frequency stability unit action value. The conditions that the power system needs to meet are as follows:

$$f_b \le f_{\min} \tag{10}$$

The primary frequency modulation dead zone action time is as follows:

$$t_\alpha = \frac{4\tau_\alpha f_\alpha}{2f_0\Delta P_{\max} - f_0 K_L f_\alpha} \tag{11}$$

where f_α is the primary frequency modulation control dead zone, and τ_α is the equivalent inertia time constant.

The primary frequency modulation response time is as follows:

$$t_\beta = t_\alpha + \frac{\Delta\hat{P}_{\max}}{V_\alpha} \tag{12}$$

Where V_α is the primary frequency modulation speed.

The calculation formula of $f_{\min}$ is as follows:

$$f_{\min} = f_0 - \frac{2t_\alpha f_0 V_\alpha \Delta\hat{P}_{\max} + f_0 \Delta\hat{P}^2{}_{\max}}{4\tau_\alpha V_\alpha + K_L t_\alpha f_0 V_\alpha + K_L f_0} \tag{13}$$

Formula (10) is substituted into formula (13) to obtain $R_{\min,2}$. Then, the formula is as follows:

$$R_{\min,2} = -\frac{2f_0 t_\alpha V_\alpha \Delta\hat{P}_{\max} + f_0\Delta\hat{P}^2_{\max} + f_0 K_L t_\alpha V_\alpha (f_b - f_0) + f_0 K_L \Delta\hat{P}_{\max}(f_b - f_0)}{4(\tau_\alpha f_b - V_\alpha f_0)} \tag{14}$$

(2) Adding the virtual inertia constraint

The upper limit constraint of ΔR_w is

$$0 \le \Delta R_w \le \Delta R_w^{\max} \tag{15}$$

where ΔR_w is the upper limit of ΔR_w.

(3) Power balance constraint

The large fluctuation range of energy supply and demand in the power system will directly affect its frequency stability. Therefore, when constructing the emergency frequency optimization control model of a high-proportion new energy power system under low inertia, the energy supply and demand balance constraint, that is, the power balance constraint, need to be considered. The formula is as follows:

$$P_{L,all}(t) = \sum_{l=1}^{\eta} P_{s,l}(t) + \sum_{j=1}^{N} P_{w,j}(t) \tag{16}$$

where at time t, $P_{L,all}$ is the total load of the high-proportion renewable energy power system.

(4) Traditional generator set constraints

In the low-inertia high-proportion renewable energy power system, traditional generator sets must comply with output constraints and unit start-stop time constraints. The formula is as follows:

$$\begin{cases} P_{S,l}^{\min} \le P_{S,l}(t) \le P_{S,l}^{\max} \\ t_{S,l,on} \ge t_{S,l,on}^{\min} \\ t_{S,l,off} \ge t_{S,l,off}^{\min} \end{cases} \tag{17}$$

Where $P_{S,l}^{\max}$ and $P_{S,l}^{\min}$ are the upper and lower limits of $P_{S,l}(t)$, respectively; $t_{S,l,on}$ and $t_{S,l,off}$ are the uninterrupted operation and stop time of the traditional generator set, respectively; $t_{S,l,on}^{\min}$

and $t_{S,l,off}^{\min}$ are the minimum values of $t_{S,l,on}$ and $t_{S,l,off}$, respectively.

(5) Constraints of high-proportion new energy generator sets

The output constraints of high-proportion new energy generator sets are

$$P_{w,j}(t) \le P_{w,j}^{\max}(t) \tag{18}$$

where $P_{w,j}^{\max}(t)$ is the maximum value of $P_{w,j}(t)$.

Through the objective function of Section 2.2.1 and the constraints of Section 2.2.2, an emergency frequency control model for a high-proportion renewable energy power system under low inertia can be constructed. Solving this model can obtain the minimum frequency offset and the minimum control cost, and the corresponding normal operation, machine cutting, and load reduction control strategies of the high-proportion renewable energy power system can be obtained to achieve the reduction in the frequency deviation of the power system and ensure the stable operation of the power system.

Result Analysis

The energy transformation case of the Wuhan power grid in China with a high proportion of new energy power system under low inertia is taken as the research object. The proposed method is used to perform emergency frequency control on the system, reduce the frequency deviation, and ensure its stable operation. The topological structure of the high-proportion new energy power system is shown in Figure 1.

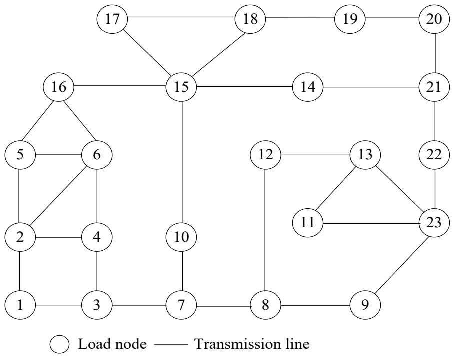

Figure 1: *Topology structure of high-proportion new energy power system*

The power system topology structure in Figure 1 contains 23 nodes in total, among which wind turbine generator sets are connected at nodes 1, 2, 3, 5, 8, and 9, which are recorded as wind turbine generator sets 1, 2, 3, 5, 8, and 9, and photovoltaic generator sets are connected at nodes 12, 17, 18, 19, and 20, which are recorded as photovoltaic generator sets 12, 17, 18, 19, and 20. The proportion of new energy access is 47.8%. Traditional generator sets are connected to nodes 4, 10, 11, and 22, which are recorded as traditional generator sets 4, 10, 11, and 22, and the remaining nodes are load nodes. The relevant parameters of this high-proportion new energy power system are shown in Table 1.

Table 1: Relevant parameters of high-proportion new energy power system

Parameter class	Numerical value
Total installed capacity	1670MW
The proportion of new energy	47.8%
Solar photovoltaic installed capacity	300 MW
Wind power installed capacity	540 MW
Annual power generation	800000000 kWh
Generation efficiency	15%
Loss ratio	5%
Average capacity of photovoltaic modules	250 kW
Average capacity of wind turbines	3 MW
Upper limit of active power of traditional generator set	389MW
Lower active power limit of traditional generator set	250MW
Voltage level of transmission line	220 kV
Line resistance	0.1 Ω/km
Average utilization hours of power generation equipment	2000 h
Equipment failure rate	2%

Power disturbances of 200 MW to 600 MW are added in the power system. The actual inertia and minimum inertia of the power system are calculated by the proposed method when different power disturbances occur, and the minimum inertia constraint of the emergency frequency optimization control model of the high-proportion renewable energy power system in this method is determined. The calculation results are shown in Figure 2.

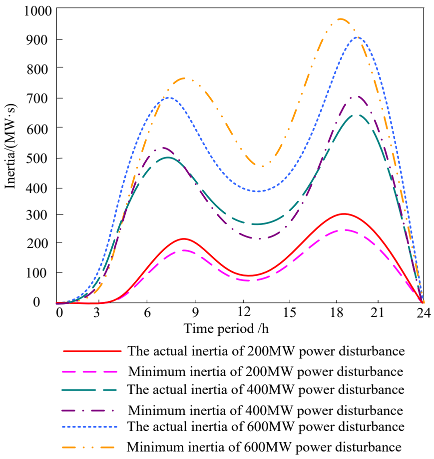

Figure 2: Calculation results of minimum inertia and actual inertia

As can be seen from Figure 2, the proposed method can effectively calculate the minimum inertia and actual inertia of the power system under different power disturbances. The calculation results indicate that under different power disturbances, the inertia change trend of the power system is basically the same. A large power disturbance corresponds to a large inertia. This condition occurred because when the power system faces a larger power disturbance, more rotating mass (such as generators) is required to provide the necessary inertia and thus maintain the stability of the system. Therefore, as the power disturbance increases, the power system needs higher inertia to maintain its stable operation. When the power disturbance is 200 MW, the actual inertia of the power system is higher than the minimum inertia requirement in different periods. When the power disturbance is 400 MW, the actual inertia of the power system is lower than the minimum inertia requirement in some periods, and a problem of insufficient inertia arises. When the power disturbance is 600 MW, the actual inertia of the power system is lower than the minimum inertia requirement in some periods, the period of time when the actual inertia is lower than the minimum inertia increases significantly, and a serious problem of insufficient inertia occurs. This finding shows that great disturbance of the power system corresponds to a high actual inertia and the minimum inertia, and the problem of insufficient inertia becomes more serious.

The proposed method is used to perform emergency frequency control on the high-proportion new energy power system under low inertia when the power disturbance is 200 and 600 MW. The emergency frequency control strategy is shown in Table 2.

Table 2: Emergency frequency control strategy of high-proportion new energy power system under low inertia

Power disturbance /MW	Set	Output form	Power variation /MW
200	Wind turbine 1	Load shedding	35
	Wind turbine 2	Load shedding	25
	Wind turbine 3	Cutting machine	89
	Wind turbine 5	Load shedding	65
	Wind turbine 8	Load shedding	54
	Wind turbine 9	Load shedding	32
	Photovoltaic unit 12	Load shedding	23
	Photovoltaic unit 17	Load shedding	24
	Photovoltaic unit 18	Load shedding	30
	Photovoltaic unit 19	Cutting machine	60
	Photovoltaic unit 20	Load shedding	15
	Conventional unit 4	Normal operation	0
	Conventional unit 10	Normal operation	0
	Conventional unit 11	Load shedding	15
	Conventional unit 22	Normal operation	0
600	Wind turbine 1	Cutting machine	68
	Wind turbine 2	Cutting machine	76.5
	Wind turbine 3	Cutting machine	89
	Wind turbine 5	Cutting machine	90.5
	Wind turbine 8	Cutting machine	95.5
	Wind turbine 9	Cutting machine	123.5
	Photovoltaic unit 12	Cutting machine	101.5
	Photovoltaic unit 17	Cutting machine	55
	Photovoltaic unit 18	Cutting machine	35
	Photovoltaic unit 19	Cutting machine	60
	Photovoltaic unit 20	Cutting machine	48.5
	Conventional unit 4	Cutting machine	110
	Conventional unit 10	Load shedding	30
	Conventional unit 11	Load shedding	20
	Conventional unit 22	Load shedding	10

As can be seen from Table 2, under different power disturbances, the proposed method can effectively formulate emergency frequency control strategies for high-proportion new energy power systems under low inertia and determine the operating status of wind turbines, photovoltaic units, and traditional units. When the power disturbance is small, most units adopt a load reduction strategy—that is, they reduce the power they emit to maintain the power balance of the power system, ensure that the power system maintains stable operation under small disturbances, and reduce the impact on the power grid. When the power disturbance is large, most units adopt a machine cutting strategy—that is, they cut off the operation of some units to reduce the total output, ensure the power balance of the power system, prevent system collapse, and improve the stability of the power system operation. Comprehensive analysis shows that in a low-inertia power system, the system's ability to respond to load changes will be weakened because of the reduction in rotating mass. When a power disturbance occurs, the system takes a longer time to restore balance. The proposed method can fully utilize the complementarity of various energy resources, improve the response speed and stability of the power system, effectively shorten the time for the power system to restore balance, and flexibly respond to various power disturbances to ensure the stable operation of the power system by intelligently adjusting the operating status of wind turbines, photovoltaic units, and traditional units.

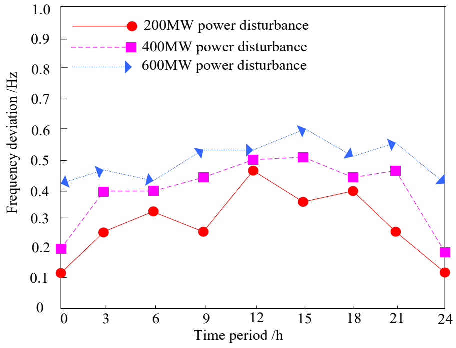

Figure 3: Variation of frequency deviation under different power disturbances

After the proposed method is applied, the frequency deviation of the high-proportion new energy power system under low inertia is analyzed. Before the proposed method is applied, the maximum frequency deviation of the power system is 0.8 Hz. The analysis results are shown in Figure 3.

Figure 3 shows that a great power disturbance corresponds to a great frequency deviation of the high-proportion renewable energy power system under low inertia. When the power disturbance is 200 MW, the maximum frequency deviation is about 0.45 Hz. When the power disturbance is 400 MW, the maximum frequency deviation is about 0.5 Hz. When the power disturbance is 600 MW, the maximum frequency deviation is about 0.6 Hz. The values are significantly lower than the maximum frequency deviation of the power system before the application of the proposed method. This finding shows that after the application of the proposed method, the frequency deviation of the power system can be effectively reduced and the stability of the power system operation can be improved.

The changes in the control costs of each unit before and after the application of the method in this paper are analyzed, and the analysis results are shown in Table 3.

Table 3: Control costs before and after the application of this method

Set	Before applying this method			After applying this method		
	200MW power disturbance	400MW power disturbance	600MW power disturbance	200MW power disturbance	400MW power disturbance	600MW power disturbance
Wind turbine 1	840	1594	1594	610	1374	1374
Wind turbine 2	820	1198	1198	590	978	978
Wind turbine 3	1155	1115	1115	925	925	925
Wind turbine 5	840	1904.5	1904.5	610	1684.5	1684.5

Wind turbine 8	1796.5	1796.5	1796.5	590	1576.5	1576.5
Wind turbine 9	1020	1010	2026.5	790	790	1806.5
Photovoltaic unit 12	2018.5	2018.5	2018.5	760	760	1798.5
Photovoltaic unit 17	760	1040	1040	530	820	820
Photovoltaic unit 18	640	920	920	410	700	700
Photovoltaic unit 19	1177	1177	1177	947	947	947
Photovoltaic unit 20	940	1110	1110	710	890	890
Conventional unit 4	0	3600	3600	0	0	3100
Conventional unit 10	0	0	0	0	0	0
Conventional unit 11	0	0	3600	0	0	0
Conventional unit 22	0	0	0	0	0	0

Table 3 shows that under different power disturbances, the control costs of each unit before the application of the proposed method are significantly higher than after the application of the proposed method. When the power disturbance is 200 MW, the total control costs before and after the application of the proposed method are 12,007 and 7,472 CNY, respectively. When the power disturbance is 400 MW, the total control costs before and after the application of the proposed method are 18,483.5 and 11,445 CNY, respectively. When the power disturbance is 600 MW, the total control costs before and after the application of the proposed method are 23,100 and 16,600 CNY, respectively. Before and after the application of the proposed method, a great power disturbance corresponds to a high emergency frequency control cost of the high-proportion new energy power system under low inertia.

Conclusion

This paper studies the emergency frequency control method for frequency fluctuation problems in low-inertia high-proportion new energy power systems. 1. This method effectively responds to sudden frequency disturbances through precise load shedding control and rapid shutdown control, ensuring the stable operation of the power system. 2. By constructing a mathematical model to find optimal load shedding control and machine shearing control strategies, this study reduces economic losses during operation and significantly improves the frequency stability of the system. 3. A specific case analysis verifies that this control strategy can significantly reduce the amplitude of frequency changes and improve the frequency stability of the system in practical applications.

As the proportion of new energy access continues to increase and the inertia of the power system decreases, the issue of emergency frequency control will continue to receive attention. Future research can further examine the following aspects: First, more intelligent decision support systems can be explored. Real-time monitoring and prediction of the operating status of new energy power systems can be achieved by integrating big data, artificial intelligence, and other technologies, thus providing more accurate and timely decision support for emergency frequency control. Second, emergency frequency control methods for multi-source coordination can be studied. The complementarity and synergy between different energy systems should be considered comprehensively, and a multi-source coordinated control strategy should be designed to improve the stability and reliability of the entire energy system. Finally, attention needs to be paid to the interaction between new energy power systems and other infrastructure. Comprehensively considering the operating status and needs of other infrastructure such as transportation and communications can achieve collaborative optimization and emergency response in multiple fields, providing strong support for building a more intelligent and resilient energy infrastructure.

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