Hindawi
Mathematical Problems in Engineering
Volume 2022, Article ID 6872799, 12 pages
https://doi.org/10.1155/2022/6872799

Research Article

Research on Combined Frequency Regulation Control Method of Wind Storage with Storage System Optimized Intervals Considered

Yulu Ma [1] **and Peng Yu** [1,2]

[1] School of Electrical and Electronic Engineering, Shandong University of Technology, Zibo 255000, China
[2] State Grid Shandong Electric Power Research Institute, Jinan 250000, China

Correspondence should be addressed to Yulu Ma; 19504010494@stumail.sdut.edu.cn

Received 28 January 2022; Accepted 22 February 2022; Published 5 April 2022

Academic Editor: Kai Wang

To solve the insufficient frequency regulation capacity and inertia of the power system caused by the increase of grid-connected wind capacity, a combined wind-storage frequency regulation control strategy considering the optimized intervals of the energy storage system is proposed. This article selects the joint frequency regulation of wind turbine overspeed control and energy storage virtual synchronous control, and virtual synchronous control is used as the upper-level control of the entire wind-storage system. In the process of frequency modulation, the output power of wind turbine and energy storage is reasonably distributed through the upper control. On this basis, to ensure the long-term and stable operation of energy storage, the state of charge (SOC) partition principle of energy storage is set up, which is divided into different areas according to the size of the SOC, and the output of the energy storage device is adjusted according to the divided regions. The results of simulation analysis and verification show that the proposed strategy provides additional frequency regulation capacity and inertia during the frequency variation and greatly improves the frequency stability. Besides, the SOC zoning principle ensures the stable operation of the energy storage.

1. Introduction

With the national "30.60" dual carbon goal, clean energy recycled, such as solar, wind, thermal, and kinetic energy, has gradually attracted attention [1]. Therefore, new energy power generation represented by wind power generation has developed rapidly. Wind power generation usually does not have inertial response and frequency regulation capabilities, and it cannot participate in frequency adjustment when the frequency of the power system changes [2]. As the penetration rate of wind power generation in the power system continues to increase, the capacity and output of conventional thermal power units in the power grid are remarkably compressed, reducing the inertia and reserve capacity of the system [3]. It is necessary to extensively increase the frequency regulation resources of the power grid and enhance the safe operation level of the power grid under the increasing penetration rate of renewable energy. According to GB/T19963-2011 "Technical Regulations for Wind Farm Access to Power System," wind farms should follow the DL/T104 criteria and have the ability to participate in power system frequency regulation, peak regulation, and backup [4].

With the rapid development of energy storage, there are many types of energy storage, including battery, supercapacitors, flywheel energy storage, and compressed air energy storage. At present, there are some new energy storage materials [5] and devices, such as integrated energy storage systems based on triboelectric nanogenerator [6–8], magnesium-decorated carbon nitride (g-C3N4) [9], and inorganic dielectric materials [10]. In summary, the current development of energy storage is rapid. The energy storage system has precise, fast, and flexible power response capabilities [11], and it is suitable for joint deployment with wind farms. On the one hand, energy storage participates in wind power peak adjustment. It can reduce wind curtailment and improve the level of wind power consumption. On the other hand, it enhances the controllability of wind farm output through real-time charge and discharges power control. It can actively contribute to power grid frequency regulation. Also, it provides a solid guarantee for the construction of safe and stable operation of a new power system with energy as the main object [12]. The joint frequency regulation of wind-storage systems requires a fast and real-time response to the power grid frequency anomalies, which poses a challenge to the real-time joint operation control method of wind farms and energy storage systems. Considering the maximum energy capture capabilities of wind turbines, associated power response capabilities, and the safe and effective operation of energy storage systems has been a prevalent concern in problem solving in recent years and is a critical issue that requires an urgent solution.

For the joint frequency regulation control of wind power generation and energy storage, Miao et al. [13] proposed the combined energy storage with the frequency regulation strategy of wind power to cater to the slow response of wind turbine pitch angle according to the fast response of energy storage. However, the combined wind and storage system cannot provide additional inertia but additional power during frequency regulation. Yan et al. [14] proposed a strategy for energy storage compensating system inertia. The energy storage is linked in parallel to the wind farm's outlet to compensate for the wind farm's inertia dynamically. The energy storage can output additional inertia and capacity during frequency regulation. However, it dramatically increases the configuration requirements for energy storage because the wind turbine does not participate in frequency regulation.

There are power and electricity limitations when energy storage participates in frequency regulation. At present, the monitoring of energy storage SOC has been very accurate [15, 16]. Therefore, it is necessary to reasonably allocate the power and set its charging and discharging strategy according to the SOC of energy storage, which ensures the safe operation of the energy storage system. Liu et al. [17] proposed a wind-storage coordinated frequency regulation control strategy, which considered the power distribution between the wind turbine and the energy storage when the wind-storage combined frequency regulation. However, they did not consider the SOC of the energy storage during frequency regulation, which may cause overcharge and overdischarge of energy storage. In order to ensure the safe operation of energy storage, Liu et al. [18] reviewed the remaining useful life prediction and state-of-charge estimation of supercapacitors. Aiming at the problem of SOC during frequency regulation of energy storage, some authors [19, 20] proposed the upper and lower limits of the energy storage SOC during frequency regulation to avoid overcharge and overdischarge of energy storage. However, it does not consider the problem of energy storage SOC recovery when the system is in a steady state. It will be unfavorable for energy storage to participate in the subsequent frequency regulation if SOC is too high or too low after frequency regulation.

A combined frequency regulation control method for wind power generation and energy storage with the safe operation of an energy storage system is proposed in this article. The wind turbine adopts overspeed control, and the energy storage uses virtual synchronization control. The entire wind-storage combined system has the same frequency regulation characteristics as the conventional synchronous generator. According to the definition of energy storage virtual synchronization, it is used as the upper-level control of the wind-storage combined system as a whole. It provides extra inertia and frequency regulation reserve capacity when the frequency changes, which can effectively improve the frequency stability of the system and reasonably distribute the output of wind turbine and energy storage during frequency regulation through the upper layer control. Therefore, the energy storage SOC is divided into distinct frequency regulation areas, early warning areas, and forbidden areas. The energy storage stops working in prohibited areas. The safe operation level of the energy storage system is improved by dynamically adjusting the frequency regulation coefficient control of the energy storage system when it is in the early warning area. Moreover, the SOC recovery of the energy storage in a steady state is considered, which ensures the long-term operation of the energy storage system. Besides, the feasibility and effectiveness of the wind-storage combined frequency regulation control method considering the safe operation of energy storage is verified by simulation.

2. Wind Turbine and Energy Storage Frequency Regulation Control Strategy

2.1. Wind Turbine Overspeed Load Reduction Control. The output of the wind turbine is related to the pitch angle, rotor speed, wind speed, and other factors. The output characteristics of the wind turbine are as follows:

$$P_{\mathrm{m}} = \frac{1}{2}C_{\mathrm{p}}(\lambda, \beta)p\pi R^2 v^3, \tag{1}$$

where C_{p} is the wind energy utilization coefficient, v is the wind speed, R is the blade radius, ω is the rotational angular velocity of the blade, and β is the blade pitch angle. In order to facilitate the analysis of the characteristics, the tip speed ratio λ is defined, that is, the ratio of the tip speed to the wind speed. There is a relation between the power coefficient Cp, the pitch angle β, and the tip speed ratio λ, which is given as follows:

$$\begin{cases} C_p(\lambda, \beta) = 0.22\left(\dfrac{116}{\lambda_i} - 0.46\beta - 5\right)^{e^{-12.5/\lambda_i}}, \\ \lambda_i = \dfrac{1}{1/(\lambda + 0.08\beta) - 0.035/\left(1 + \beta^3\right)}, \\ \lambda = \dfrac{\omega R}{v}. \end{cases} \tag{2}$$

The normal operation of wind power generation usually adopts the maximum power point tracking (MPPT) control strategy, which cannot address additional spare capacity to participate in the adjustment of the power system frequency, which makes the power system stability problem more serious. Suppose the wind turbine adopts the method of tracking the suboptimal power during operation and reserves a part of the reserve capacity. In that case, the wind turbine can participate in the frequency adjustment of the power system. Reservation strategies for wind turbine spare capacity include pitch angle control and overspeed control [21]. The response speed of the pitch angle control is slow, and the frequent change of the pitch angle will seriously affect the service life of the wind turbine. Therefore, the wind turbine adopts overspeed control in this study.

The overspeed control makes the wind turbine run under suboptimal power by controlling the size of the rotational speed. It can set aside a part of the spare capacity to participate in the frequency adjustment. The principle of wind turbine overspeed control is shown in Figure 1.

In Figure 1, line A is the power curve under the MPPT operating state, and line B is the power curve under overspeed control. When the wind turbine runs in the form of A, the wind turbine produce outputs the maximum power is P_a, and the rotational speed is ω_a. The wind turbine rotates to ω_b through the overspeed and load reduction control. The wind turbine output power is P_b, which can set aside a part of the spare capacity to participate in system frequency adjustment. The power of load shedding is given as follows:

$$\Delta P_0 = d\%P = P_a - P_b, \tag{3}$$

where ΔP_0 is the power reserved by the wind turbine, and $d\%$ is the load shedding rate. Wind turbines participate in grid frequency regulation by reserving reserve capacity, which reduces the installed energy storage capacity of wind farms. The control strategy of wind turbine overspeed load reduction and frequency regulation is shown in Figure 2.

In Figure 2, K_w is the set frequency regulation coefficient of the wind turbine, and ΔP_W is the power emitted by the wind turbine during frequency regulation.

2.2. Virtual Synchronization Control Strategy of Energy Storage System. The traditional generator realizes frequency adjustment through inertial response and primary frequency regulation when the power system's frequency changes. The change of the power system frequency is related to the system inertia, and the power system inertia can be expressed as the property of changing the frequency change by the kinetic energy stored in the rotor of the synchronous generator. When the frequency changes, the equation of motion of the synchronous motor rotor is given as

$$\begin{cases} \Delta P = J\dfrac{d\omega}{dt}, \\ f = \dfrac{\omega}{2\pi}, \end{cases} \tag{4}$$

where ΔP is the difference between mechanical and electromagnetic power, J is the moment of inertia, ω is the rotor angular velocity, and f is the system frequency.

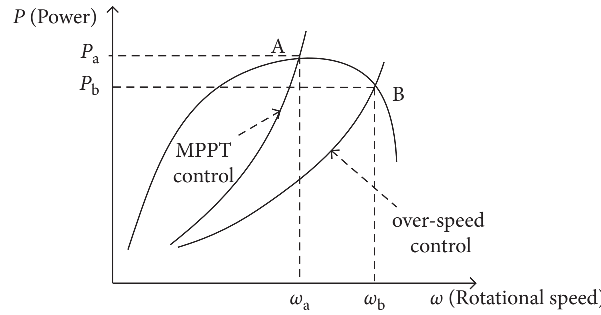

Figure 1: Overspeed load reduction control.

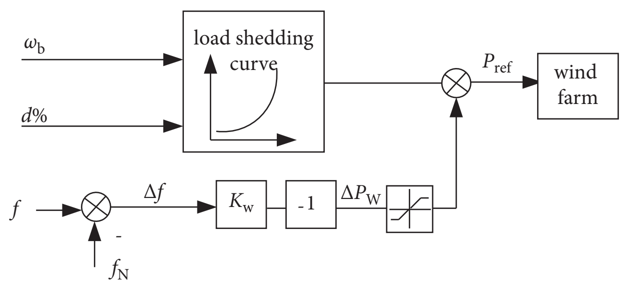

Figure 2: Wind turbine overspeed load reduction and frequency regulation strategy.

With the rapid development of energy storage, energy storage participates in the system's frequency regulation, and it provides a solid guarantee for the safe and stable operation of the system [22]. The virtual synchronous control of energy storage simulates the characteristics of traditional generators by adding virtual inertia and virtual droop coefficient to the energy storage control strategy [23]. It can provide additional capacity and inertia to slow down the rate of frequency drop when the frequency changes. The frequency regulation control strategy is shown in Figure 3.

The power generated by the energy storage system during frequency regulation is given as

$$\Delta P_{S1} = -K_d \Delta f - J_d \frac{df}{dt}, \tag{5}$$

where K_d is the virtual droop coefficient, J_d is the virtual inertia coefficient, and ΔP_{s1} is the output power.

3. Combined Frequency Regulation Control Strategy of Wind Power Generation and Energy Storage under the Optimal Operation of Energy Storage

3.1. Frequency Regulation Control Strategy of Wind-Storage Combined System. A combined frequency regulation control strategy for wind power generation and energy storage is proposed for solving the insufficient inertial capacity and frequency regulation capacity in high renewable energy penetration power grids. The structure of the wind power generation and energy storage combined system is shown in Figure 4.

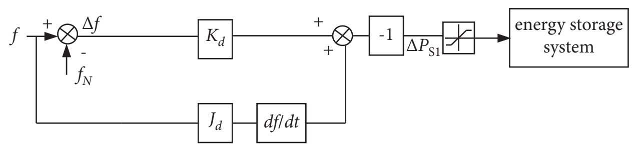

Figure 3: Virtual synchronization control strategy of energy storage system.

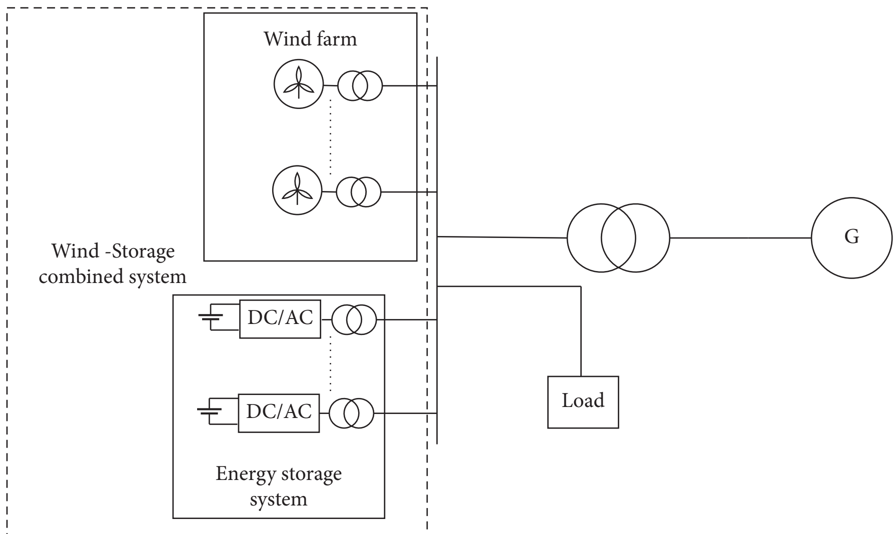

Figure 4: Combined system of wind power generation and energy storage.

It can be seen from Figure 4 that the combined wind power generation and energy storage system is mainly composed of doubly-fed wind turbines, energy storage systems, loads, and grid-equivalent frequency-modulated synchronous generators. The energy storage system is configured at the grid connection point of the wind farm. Compared with the configuration on the DC side of the turbines, the first-level energy exchange is reduced, the economy is better, and it is easy to control centrally [24]. Wind power generation and energy storage provide output power to the grid through their respective converters in a combined wind power generation and energy storage system. The wind turbine and energy storage simultaneously adjust and respond to grid frequency anomalies when the grid frequency changes.

The slow response cannot fully exert the frequency regulation capability of wind turbines, although the strategy of wind turbines improves the effectiveness of frequency regulation [25]. The energy storage system has the characteristics, such as being fast, flexible, and stable, in frequency regulation. A certain amount of energy storage is arranged in the wind farm to assist the wind turbine in participating in the frequency regulation. Only relying on energy storage to undertake the task of frequency regulation of wind farms in the process of frequency regulation will inevitably lead to large energy storage capacity, high cost, and poor economic benefits for wind farms. Therefore, combining the energy storage and the wind turbine is necessary to participate in the frequency regulation and achieve complementary advantages. Wind farms will better participate in system frequency regulation.

For a power system with n traditional synchronous motors, the equivalent inertia constant H_{sys} [26] is given as follows:

$$H_{sys} = \frac{\sum_{i=1}^{n} H_i S_i}{S_{sys}}, \tag{6}$$

where S_{sys} is the total capacity of the system and H_i and S_i are the inertia constant and capacity of the i-th traditional synchronous motor. According to formula (6), the capacity of the traditional synchronous motor decreases, the equivalent inertia of the system decreases as the installed capacity of the wind turbines in the system increases. The relationship between the equivalent inertia constant of the power system and the initial frequency change rate can be deduced as follows:

$$\frac{2H_{sys}}{f_N}\frac{df}{dt} = \frac{\Delta P}{S_{sys}}, \tag{7}$$

where f_{N} is the rated frequency.

The joint frequency regulation of wind power generation and energy storage is usually controlled separately by the wind turbine and energy storage. In this article, according to the definition of virtual synchronous control of energy storage, the virtual synchronous control as the upper-level control of the entire wind power generation and energy storage system due to the difference in response time between the wind turbine and the energy storage, it may cause frequency oscillation. It is used to calculate the power required by the entire wind power generation and energy storage combined system during frequency adjustment. It then distributes it to the wind turbine and energy storage in real time. The combined frequency regulation strategy of wind power generation and energy storage is shown in Figure 5:

According to Figure 5, the combined frequency regulation control of wind power generation and energy storage includes wind power generation and energy storage combined system layer, wind farm layer, and energy storage system layer. The upper control adopts virtual droop and virtual inertia control by taking the entire wind-storage joint frequency modulation as a system. The whole of the wind-storage combined system has the same frequency regulation characteristics as the traditional generator set. It can provide additional inertia to delay the transient frequency change and provide additional capacity to participate in the frequency regulation of the power system. The deviation coefficient of the wind turbine can simulate the primary frequency regulation ability of the synchronous generator, but it does not have the ability of the inertial response. The output power of the energy storage is the difference between the frequency regulation power output by the upper-level control and the power output by the primary frequency regulation of the wind turbine. Therefore, the energy storage can provide the inertia adjustment part and the shortage of the frequency regulation capacity of the wind turbine.

The expression of the output power required for the frequency regulation of the combined wind power generation and energy storage system is as follows:

$$\Delta P_{W+S} = -K \cdot \Delta f + \left(-K_J \frac{df}{dt}\right), \tag{8}$$

$$\Delta P_W = -K_w \Delta f, \tag{9}$$

$$\Delta P_S = K_2 \left(\Delta P_{W+S} - \Delta P_W\right), \tag{10}$$

where ΔP_{W+S} is the power generated by wind power generation and energy storage during frequency regulation; K and K_J are the virtual droop coefficient and virtual inertia coefficient of the entire wind power generation and energy storage system; K_2 is the energy storage constraints frequency regulation factor.

The upper-level control of the wind power generation and energy storage system adopts virtual synchronous control. The inertia constant H_{W+S} of the joint system as a whole can be deduced as

$$H_{W+S} = \frac{f_N}{2} * K_J. \tag{11}$$

By adding virtual inertia, the total equivalent inertia constant H_{sys} of the system can be expressed as

$$H_{sys} = \frac{\sum_{i=1}^{n} H_i S_i + \sum H_{W+S} S_{W+S}}{S_{sys}}, \tag{12}$$

where S_{W+S} is the rated capacity of the combined wind power generation and energy storage system. According to the above equation, it can be seen that the equivalent inertia of the entire power system can be provided by adding virtual inertia to the whole wind power generation and energy storage system.

In order to ensure the superiority of the frequency regulation of the wind-storage combined system in the process of frequency regulation, the wind-storage integrated approach needs to generate additional power when the system frequency decreases. At this time, the frequency regulation coefficient of the wind farm is increased so that the wind turbine can provide more power and improve the utilization rate of wind energy. The combined system of wind power generation and energy storage needs to reduce the output power when the frequency increases. At this time, the adjustment coefficient of the wind farm is reduced, and the energy storage system absorbs extra power as much as possible to avoid the low utilization rate of wind energy. The power allocation flow chart of the wind-storage combined system is as follow:

According to Figure 6, the wind power generation and energy storage combined system layer respond first when the frequency fluctuation of the system crosses the dead zone. When the frequency changes, it calculates the power required by the wind power generation and energy storage combined system. If the load shedding power of the wind turbine is greater than the power required for droop control in the wind-storage combined system when the frequency decreases, in that case, the output power of the wind turbine is the same as the power required for the droop control of the wind-storage combined system. The energy storage provides the power needed for inertia response. Assuming that the output power required for the wind-storage combined system is greater than that provided by the wind turbine, the energy storage provides additional power at this time. When the frequency rises, if the power required to be reduced by the wind-storage combined system is greater than the power that the energy storage can absorb, the excess power will be absorbed by the wind turbine. If the power required to be reduced by the wind-storage combined system is less than the power that the energy storage can absorb, the wind turbine will not work at this time.

3.2. The Principle of Energy Storage Optimization Operation Interval Partition. The combined system of wind power generation and energy storage needs to consider the SOC constraint of energy storage in the actual operation [27]. The output power is related to the frequency change because the energy storage uses virtual synchronous control when it participates in frequency regulation. The SOC may exceed the limit during the frequency regulation process if the energy storage is always in the state of charging and discharging. The service life of the energy storage will be affected when the SOC is too large or too small. Simultaneously, the energy storage causes the SOC to be too high or too low after frequency regulation, which is not conducive to the energy storage for the following frequency

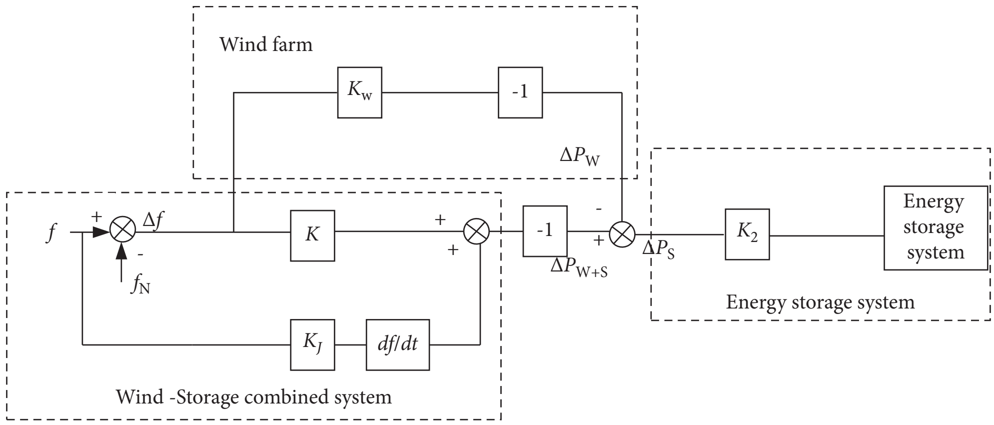

Figure 5: Combined frequency regulation strategy of wind power generation and energy storage.

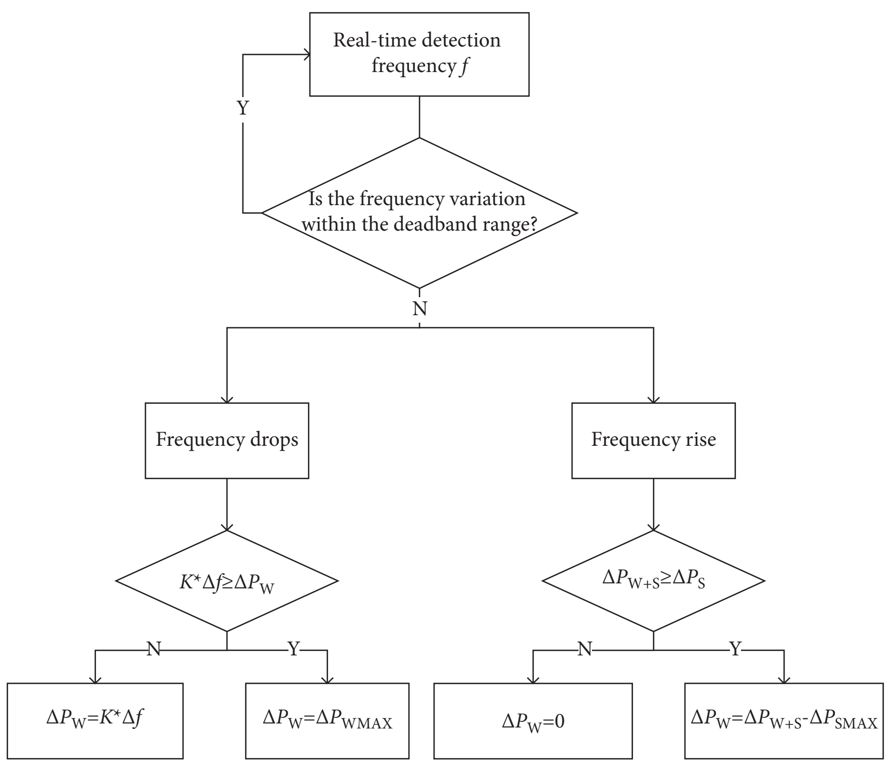

Figure 6: Power distribution flow chart.

regulation. To cope with this problem, we set the SOC partition principle according to the state of the energy storage SOC and the system's operating condition. In the frequency regulation state, the dead zone of the energy storage charge and discharge is set. The energy storage SOC is restored to the set range in the nonfrequency regulation state to ensure the safe operation of the energy storage. The specific SOC partition principle is shown in Figure 7.

The battery management system (BMS) is used to measure the size of the SOC of the energy storage system online. To prevent the overcharge or over-discharge of the energy storage, the normal area, early warning area, and forbidden area are set during the frequency regulation period. Energy storage provides an early warning of insufficient capacity during discharging when SOC ≤20%, and it does not discharge when SOC ≤10%. Energy storage raises a capacity overshoot warning during charging when SOC ≥80%. Charging is prohibited when SOC >90%. Normal charging and discharging of energy storage and wind power will participate in grid frequency regulation when 20% <SOC <80%. It is easy to cause insufficient absorption or output power during frequency regulation to avoid the SOC of energy storage being too large or too small before frequency adjustment. Therefore, 30% ≤SOC ≤70% is set as the

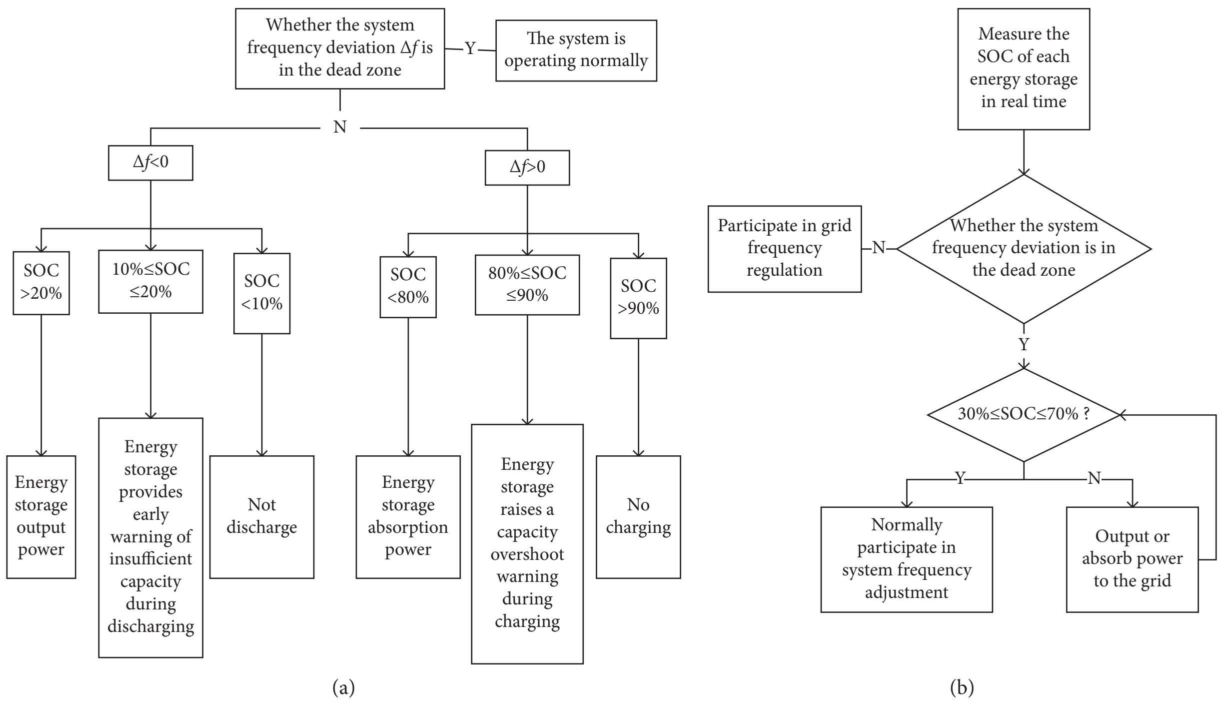

Figure 7: Energy storage participates in frequency regulation SOC partition. (a) Frequency adjustment period. (b) Nonfrequency regulation period.

safety range of the nonfrequency regulation period of energy storage. During the nonfrequency regulation period, the energy storage will send power to the grid at this time until the SOC drops to 70% if the SOC is too large. The power will be absorbed from the grid until the SOC reaches 30% when the SOC is too small. The energy storage absorbs/outputs 1 MW of power to the grid when the energy storage is set in the nonfrequency regulation period and not within the specified interval. The energy storage SOC can always be within the set range, thereby ensuring energy storage's safe and efficient operation.

To ensure the safety of energy storage during frequency regulation, combined with the set energy storage SOC division principle, when the energy storage provides an early warning of insufficient capacity or capacity overshoot, the frequency regulation coefficient is dynamically adjusted, thereby controlling the output power of the energy storage.

The logistic function combined with the partition principle is used in this article to control the frequency regulation coefficient of the energy storage system due to the value of the logistic function increasing exponentially in the initial stage with reasonable continuity. It gives full play to the frequency regulation capability of the energy storage system and maintains the stability of the SOC. The adaptive adjustment frequency regulation coefficient is shown in Figure 8.

The self-adaptive frequency regulation coefficient of the energy storage running in the discharge state is given as

$$K_2 = \begin{cases} 0, SOC(t) < 10\%, \\ \dfrac{0.02e^{10\left(SOC(t)-SOC_{\min}\right)/\left(20\%-SOC_{\min}\right)/2}}{1+0.02\left(e^{10\left(SOC(t)-SOC_{\min}\right)/\left(20\%-SOC_{\min}\right)/2}-1\right)}, 10\% \le SOC(t) \le 20\%, \\ 1, SOC(t) > 20\%. \end{cases} \quad (13)$$

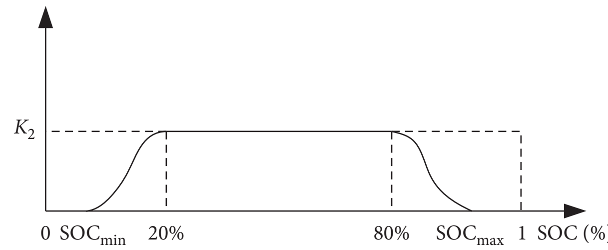

FIGURE 8: Energy storage adaptive frequency regulation coefficient.

The self-adaptive frequency regulation coefficient of the energy storage running in the charging state is given as

$$K_2 = \begin{cases} 1, SOC(t) < 80\%, \\ \dfrac{0.02e^{10\left(SOC_{max} - SOC(t)\right)/\left(SOC_{max} - 80\%\right)/2}}{1 + 0.02\left(e^{10\left(SOC_{max} - SOC(t)\right)/\left(SOC_{max} - 80\%\right)/2} - 1\right)}, 80\% \leq SOC(t) \leq 90\%, \\ 0, SOC(t) > 90\%, \end{cases} \quad (14)$$

where $SOC_{min} = 10\%$, $SOC_{max} = 90\%$. When SOC <10% or SOC >90%, the energy storage exits frequency regulation. The safe operation of the energy storage is ensured by dynamically modifying the frequency regulation coefficient of the energy storage.

4. Simulation Experiment Analysis

Aiming at the joint frequency regulation strategy of wind power generation and energy storage proposed in this article, we consider the optimal operating range of the energy storage system and a simulation model of the wind-storage combined system shown in Figure 5, which is built in Matlab/Simulink software to verify the feasibility of its control technology. The equivalent simulated grid capacity is 200 MVA, the initial load power is 120 MW, and the rated power of the wind farm is 50 MW and consists of 25 double-fed wind turbines with the power of 2 MW. The wind farm operates at a fixed wind speed, regardless of wind speed fluctuations. The wind farm reserves a capacity of 5 MW, and the adjustment coefficient K_w of the wind farm is 20 MW/Hz during normal operation. The rated power of the energy storage system is 5 MW, the rated frequency f of the system is 50 Hz, the frequency regulation coefficient K_d of the combined wind power generation and energy storage system is 20 MW/Hz, and the equivalent inertia time constant is 5 s.

4.1. Simulation Analysis on the Effectiveness of Combined Frequency Regulation Strategy for Wind Power Generation and Energy Storage. We increased the load by 20 MW at 6 S to verify the effectiveness of the wind-storage joint frequency regulation strategy presented in this study. Figures 9 and 10 show the frequency change, wind power generation, and energy storage output power, respectively.

According to Figures 9 and 10, the lowest frequency is 49.66 Hz when wind power and energy storage do not participate in frequency regulation. The lowest frequency of wind turbines alone is 49.75 Hz, which decreases the frequency drop compared with wind power and energy storage without frequency regulation. The lowest frequency is 49.76 Hz under the combined frequency regulation strategy of wind power generation and energy storage. It can provide certain inertia and delay the rate of frequency drop due to the virtual synchronous control adopted by the upper-level control of the combined frequency regulation of wind power generation and energy storage. According to the set power distribution, the power required for the combined frequency regulation of wind power and energy storage is less than the output power of the wind farm. The energy storage provides additional power needed for an inertial response during the initial phase of the frequency change to slow down the rate of frequency drop while the wind farm provides additional power.

We set that the load is reduced by 20 MW at 6 S. Figures 11 and 12 show the frequency change, wind power generation, and energy storage output power, respectively.

According to Figures 11 and 12, wind power generation and energy storage do not participate in frequency regulation. When the load is reduced, the peak frequency rises 50.34 Hz. Wind turbines' peak independent frequency regulation is 50.25 Hz, and the peak of combined frequency regulation of wind power generation and energy storage is 50.24 Hz. Moreover, the rate of frequency rise is delayed. According to the set power distribution principle, the power required by the entire wind-storage combined frequency regulation system is less than the output power of the energy storage. At this time,

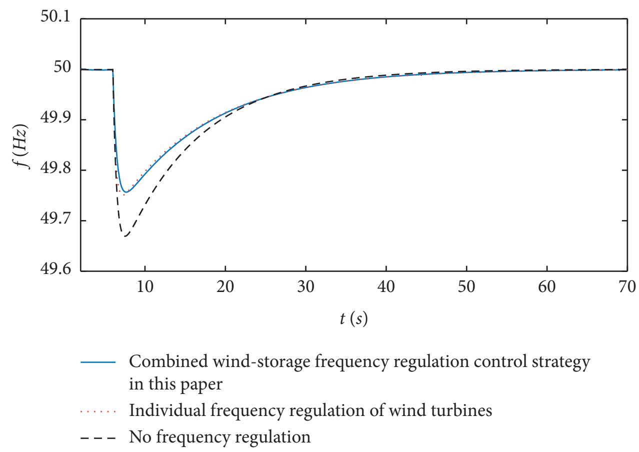

Figure 9: Comparison of frequency changes.

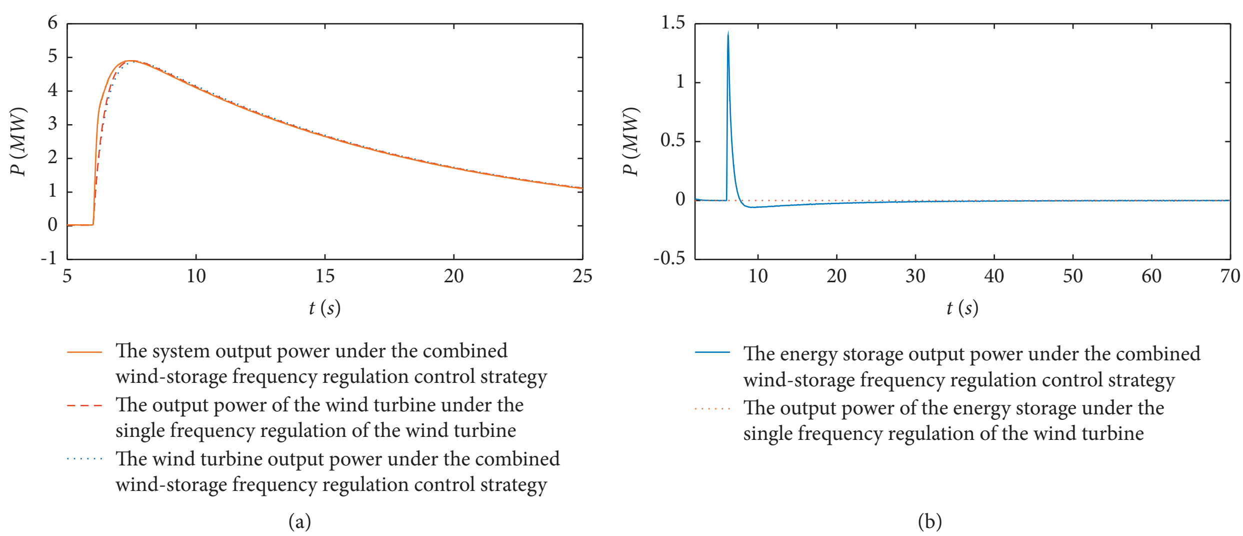

Figure 10: Output power of wind turbine and energy storage. (a) Wind turbine frequency regulation output power. (b) Energy storage frequency regulation output power.

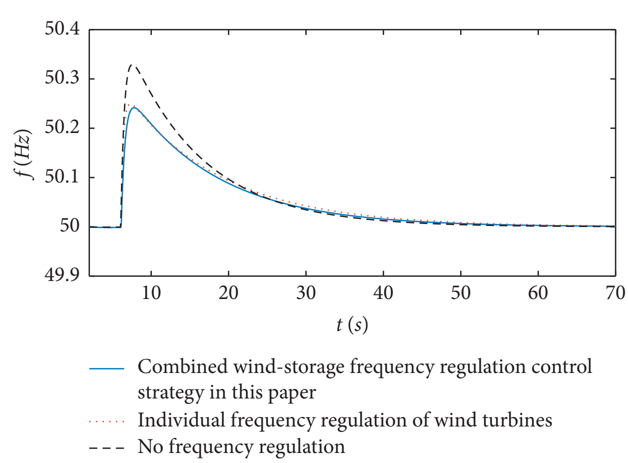

Figure 11: Comparison of frequency changes.

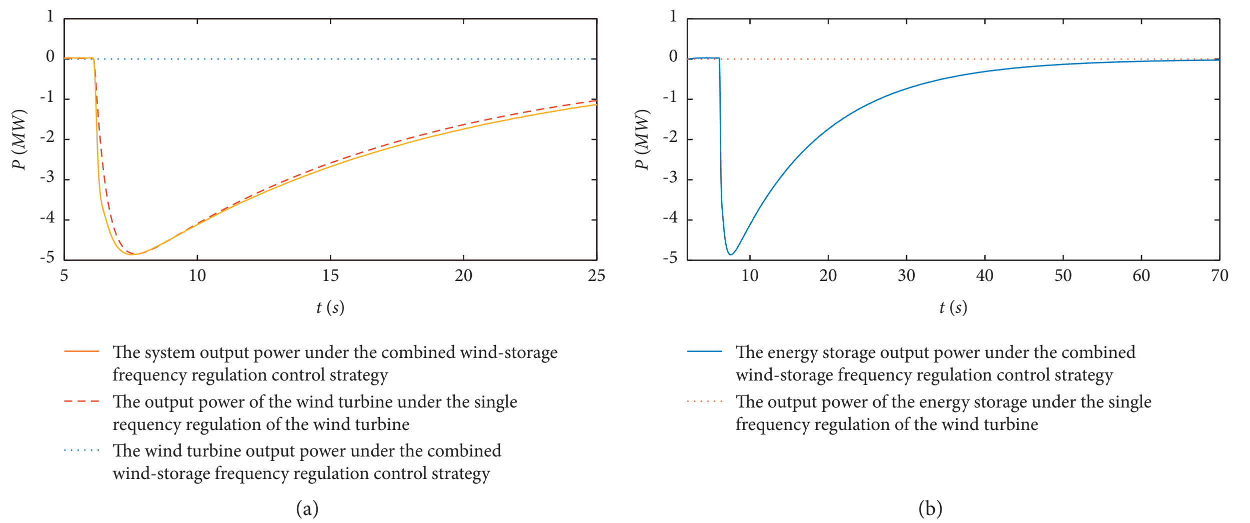

Figure 12: Wind turbine and energy storage output power. (a) Wind turbine frequency regulation output power. (b) Energy storage frequency regulation output power.

the power required for frequency regulation is all issued by the energy storage, and the wind turbine does not perform frequency regulation. The wind turbine will continue to reduce the power, and the wind energy utilization rate is too low when wind turbines participate in frequency regulation alone.

4.2. Simulation Analysis on the Effectiveness of Frequency Regulation Strategy considering Energy Storage Optimization Operating Range. The effectiveness of the wind-storage combined frequency regulation strategy in the energy storage optimal operating range is verified. We set the initial SOC of the energy storage to 70%. When the system reduces the load of 20 MW at 6 s, the energy storage system's output power and SOC changes are shown in Figures 13 and 14.

It can be seen from Figures 13 and 14 that when the frequency increases, the energy storage will absorb the power, and the SOC of the energy storage will increase at this time. After considering the energy storage constraint range, the frequency regulation coefficient is fixed. Also, the energy storage system automatically exits the frequency adjustment when the energy storage SOC rises to 90% during the frequency regulation process, which avoids the further decline of the energy storage SOC. Suppose the adaptive droop coefficient control is considered. In that case, the absorbed power of the energy storage is reduced when the SOC of the energy storage rises to the early warning range, thereby avoiding the withdrawal of the energy storage during frequency regulation, further ensuring the safe operation of the energy storage. The energy storage provides output power to the grid when the system frequency returns to stability. The energy storage stops absorbing power until the energy storage SOC rises to the set area. The energy storage SOC is always kept within a safe range and ensures the safe operation of the energy storage. However, the energy storage does not consider the constraint range that continues to provide output power during frequency regulation. So that the energy storage SOC rises to an excessively high state, and

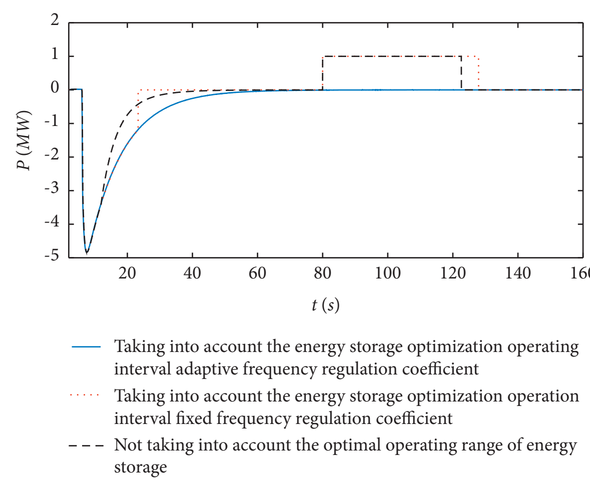

Figure 13: Comparison of energy storage output power under different strategies.

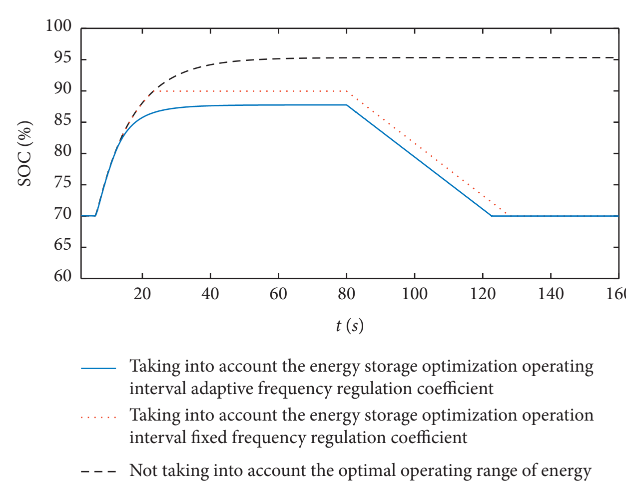

Figure 14: Comparison of SOC changes under different strategies.

the SOC will not recover in the steady state, resulting in the energy storage SOC remaining at an overly high level. In this state, it is not conducive to the stable operation of energy storage.

In general, the combined frequency regulation control strategy of wind power generation and energy storage considering the optimal operation range of energy storage can provide the required reserve capacity and inertia when the frequency fluctuates, and it effectively improves the frequency stability of the power system. At the same time, it not only avoids the overcharge and overdischarge of energy storage in the frequency regulation state but also ensures that the energy storage can always be located in a safe range after considering the constraint range of energy storage. Thus, the safe operation of the energy storage system in the wind-storage combined system is guaranteed.

5. Conclusion

The thesis sentence proposes a unique combined frequency regulation control method for wind power generation and energy storage that considers the optimal operating range of energy storage. The wind-storage combination is achieved using the overspeed control of the fan itself and the virtual synchronous control of the energy storage. The control has the advantages of overspeed control and virtual synchronous control. It can provide additional inertia and reserve capacity for the system during frequency adjustment and effectively improve the system frequency variation characteristics by setting the upper-level control of the wind-storage combined system to reasonably distribute the frequency regulation power. At the same time, the optimal operating range and partition principle of the energy storage SOC is considered in the energy storage control. The energy storage is regulated according to the divided intervals, which avoids the phenomenon that the SOC of the energy storage exceeds the limit during frequency regulation and controls the energy storage. It ensures the safe operation of the energy storage system due to the energy storage SOC always being within a safe range. Thereby, the sustainability and effectiveness of the wind-storage combined frequency regulation system have been improved.

Data Availability

The (all data) data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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