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Coordinated Frequency Modulation Control Strategy of Wind Power and Energy Storage Considering Mechanical Load Optimization

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Abstract: When a doubly fed induction generator (DFIG) participates in primary frequency modulation by rotor kinetic energy control, the torque of the generator is changed sharply and the mechanical load pressure of the shaft increases rapidly, which aggravates the fatigue damage of shafting. In order to alleviate the fatigue load of shafting, energy storage was added in the primary frequency modulation of a wind turbine, and a coordinated frequency modulation control strategy of wind power and energy storage based on fuzzy control was proposed. The wind-storage frequency modulation power command was allocated to reduce the response speed of the wind turbine to alleviate the load pressure on the shafting by the fuzzy controller considering the rotor speed range and the state of energy storage charge, and the remaining demand power was supplemented by energy storage. Finally, the joint simulation model based on GH Bladed–Matlab was used to verify the effectiveness of the proposed control strategy. Compared with the traditional integrated control of virtual inertia, the proposed method can reduce the load pressure and fatigue damage of the shafting while satisfying the requirement of frequency modulation.

Keywords: DFIG; rotor kinetic energy; energy storage; mechanical load; fuzzy control

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Citation: Zhang, C.; Li, J.; Liu, S.; Hu, P.; Feng, J.; Ren, H.; Zhang, R.; Jia, J. Coordinated Frequency Modulation Control Strategy of Wind Power and Energy Storage Considering Mechanical Load Optimization. *Energies* **2024**, *17*, 3198. https://doi.org/10.3390/en17133198

Academic Editors: Sherif Zaid and Ahmed Kassem

Received: 27 May 2024
Revised: 16 June 2024
Accepted: 24 June 2024
Published: 28 June 2024

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1. Introduction

With the widespread application of new energy sources, the penetration rate of wind power continues to increase, leading to the replacement of a large number of synchronous generators. Wind turbines lack inertia response and frequency modulation capability due to the decoupling of speed and system frequency caused by the power electronic converter [1]. This results in a significant reduction in the power system's frequency modulation and disturbance rejection capability. In order to ensure the safe and stable operation of power systems with a large amount of wind power, power system dispatch departments in many countries and regions have made explicit requirements for grid-connected wind turbines to participate in system frequency modulation and provide reserve capacity [2], to address the issues brought about by the large-scale integration of wind power into the grid.

Currently, scholars in relevant fields at home and abroad have conducted a large amount of research on the participation of wind turbines in frequency modulation, including the virtual inertia synthesis control strategy [3–6]. Although the use of virtual inertia synthesis control enables wind turbines to actively participate in system frequency modulation, the sudden increase in wind turbine load pressure during frequency modulation cannot be ignored. The literature [7] studies the impact mechanism and law of

virtual inertia control on the torsional vibration of transmission systems, showing that the introduction of virtual inertia control increases the risk of wind turbine torsional vibration, leading to mechanical component damage. The literature [8] reveals that inertia control reduces the damping of the wind turbine shaft system torsional vibration and proposes an inertia control method for wind farms with active shaft system torsional damping. The literature [9] proposes an approach based on exponential function asymptotic convergence to reduce mechanical loads during the frequency modulation process of wind turbines.

However, the rotor kinetic energy of wind turbines has certain limitations, making it difficult to provide long-term kinetic energy support independently. Therefore, many domestic and foreign scholars have proposed ways to coordinate wind turbines and energy storage to solve this problem. The literature [10] uses rotor kinetic energy and supercapacitors to achieve inertia and droop characteristics similar to synchronous units. The literature [11] considers a single disturbance of load increase and decrease, and proposes a dual-fed wind turbine primary frequency control strategy based on variable power point tracking and coordinated control with supercapacitor energy storage. The literature [12] proposes an analytical model for determining the allocation ratio coefficients of comprehensive virtual inertia and virtual droop, which are key factors in frequency modulation. Building upon this model, an adaptive control strategy is proposed for battery energy storage to participate in primary frequency modulation. The literature [13] considers the rotor speed operating range and the state of charge of energy storage, and proposes a primary frequency control strategy for wind-storage coordination based on the (DFIG) participation degree in frequency control. The literature [14] proposes a parameter adjustment method based on wind speed zoning, and determines the wind turbine curtailment ratio and energy storage output limit based on the state of charge of the energy storage system. The literature [15] discusses the equilibrium of energy storage charging and discharging. When there is a significant deviation in the balance of energy storage, the wind turbine compensates for the insufficient energy storage power through rotor kinetic energy frequency control, thereby achieving wind-storage joint primary frequency control. The literature [16] has established a virtual synchronous machine model for wind energy storage and proposes an energy storage control strategy considering the state of charge. The analysis focuses on the time scale of wind power inertia release and the energy storage steady-state output, aiming to reduce energy storage capacity requirements while enabling wind turbines to provide short-term power support. The literature [17] proposes a frequency support control scheme for wind power generation systems based on grid frequency deviation, which can adapt to maximum power point tracking under different wind speeds. A dual-layer coordinated control strategy was concurrently developed, enabling the energy storage system to collaborate with the wind power generation system.

In summary, the above literature analyzes the inertia support and frequency modulation capability of grid-connected wind turbines, studies the mechanical load issues caused by wind turbines participating in frequency modulation, and proposes various control strategies for wind-storage joint coordination in system frequency modulation. However, it does not consider the normal operating range of rotor speed during frequency modulation, the reduction in energy storage device life caused by overcharging or discharging states, and the impact on and mitigation measures for the shaft load of wind turbines in the process of frequency modulation while using wind-storage joint frequency modulation strategies to meet the system's frequency modulation requirements.

This paper proposes a wind-storage coordinated frequency control strategy based on fuzzy control to address the above issues. A fuzzy controller considering the rotor speed and state of charge (SOC) of energy storage is designed to flexibly adjust the wind-storage output by allocating frequency control power commands, reducing the response rate of the wind turbine. The proposed control strategy can reduce fatigue loads on the drive train and alleviate drive train load pressure while meeting primary frequency modulation requirements. The effectiveness of the proposed control strategy is verified through a joint

simulation model based on GH Bladed–Matlab(The GH Bladed version number is 4.1. The Matlab version number is Matlab R2023a).

2. Comprehensive Control Strategy for Virtual Inertia of Wind Turbine Units

2.1. Operational Characteristics of Wind Turbines

Wind turbines use the mechanical energy converted from wind power to drive the generator rotor to produce electricity. The mechanical energy captured by the wind turbine can be expressed by

$$P_m = \frac{1}{2}\rho\pi R^2 v^3 C_p \tag{1}$$

where P_m is the captured mechanical energy (W); ρ is the air density (kg/m^3); v is the upstream wind speed (m/s); R is the rotor radius (m); and C_p is the wind energy utilization coefficient, which is not only related to the tip speed ratio λ, but also related to the pitch angle β. C_p can be evaluated by

$$\begin{cases} C_P(\lambda,\beta) = 0.22\left(\frac{116}{\delta} - 0.4\beta - 5\right)e^{-\frac{12.5}{\delta}} \\ \lambda = \frac{\omega_r R}{Gv} \\ \frac{1}{\delta} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \end{cases} \tag{2}$$

where ω_r is the generator speed (rad/s), and G is the transmission ratio.

When the wind speed is constant, the rotational speed corresponding to the maximum C_p value is the optimal rotational speed. At this point, the power output of the wind turbine is the power obtained in the Maximum Power Point Tracking (MPPT) mode. In the MPPT mode, the output of the wind turbine can be expressed by

$$K_{opt} = \frac{1}{2}\rho\pi R^5 \frac{C_p}{\lambda^3 G^3} \tag{3}$$

$$P_{MPPT} = K_{opt}\omega_r^3 \tag{4}$$

The operating curve of the wind turbine is shown in Figure 1.

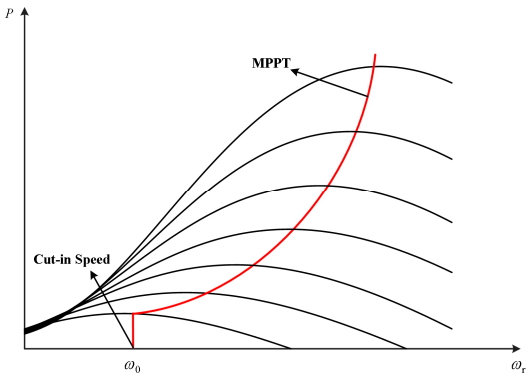


Figure 1. Operating curve of wind turbine.

2.2. Comprehensive Control Principle of Virtual Inertia

2.2.1. Virtual Inertia Control

In traditional maximum power tracking control, the converter of the wind turbine adjusts the active power output of the unit based on the generator speed. Therefore, when there is an active disturbance in the power grid, the wind turbine is unable to provide inertia support to the system. Consequently, a power control loop such as that depicted in the following Formula (5) must be appended to the wind turbine to impart it with inertial response capabilities:

$$\Delta P_1 = -K_d \frac{d\Delta f}{dt} \tag{5}$$

where K_d is the virtual inertia control coefficient, and ΔP_1 is the active power issued by the virtual inertia control (W).

2.2.2. Droop Control

When the system frequency changes, the traditional synchronous generator units gradually restore the new balance by adjusting the speed and output power, a characteristic known as frequency droop. Therefore, by introducing frequency deviation into wind turbines for additional control, a frequency droop characteristic similar to that of traditional synchronous machines can be achieved to respond to system frequency changes. The droop control characteristic can be expressed by

$$\Delta P_2 = -K_p \Delta f \tag{6}$$

where K_p is the droop control coefficient, and ΔP_2 is the active power issued by the droop control.

2.2.3. Virtual Inertia Comprehensive Control

Virtual inertia comprehensive control combines virtual inertia control with droop control, while introducing additional control of the frequency rate of change and frequency deviation. The additional active power injected by virtual inertia comprehensive control can be expressed by

$$\Delta P = -K_d \frac{d\Delta f}{dt} - K_p \Delta f \tag{7}$$

The diagram of virtual inertia comprehensive control is shown in Figure 2.

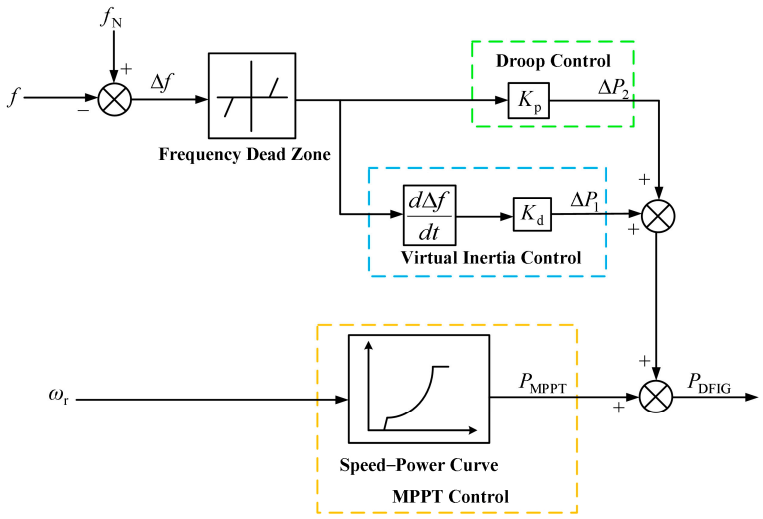


Figure 2. Diagram of integrated control block.

As shown in Figure 2, when the system frequency changes, the active power output of the wind turbine can be calculated by

$$P_{DFIG} = P_{MPPT} + \Delta P_1 + \Delta P_2 \tag{8}$$

3. Coordinated Frequency Modulation Control Strategy of Wind Power and Energy Storage Based on Fuzzy Control

3.1. Principle of Coordinated Frequency Modulation Control of Wind Power and Energy Storage

By employing rotor kinetic energy control in DFIG, the electric torque experiences a sudden change, leading to intense vibrations in the shaft system, resulting in mechanical loads being subjected to shock impacts and thereby increasing the fatigue damage to the shaft system. To alleviate the load pressure on the shaft system, this paper proposes a

frequency-shifting control strategy based on fuzzy control, whose topology structure is shown in Figure 3.

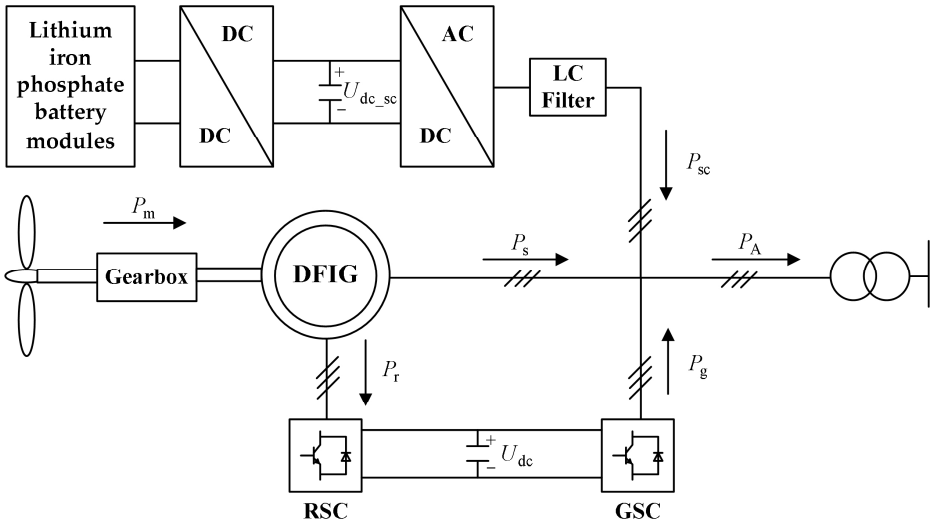


Figure 3. The topology of wind turbine-energy storage joint frequency modulation.

In Figure 3, P_m is the captured mechanical power, P_r is the active power of the rotor, P_g is the active power on the grid side, P_s is the active power of the stator, P_{sc} is the active power input to the energy storage system, P_A is the total power flowing into the grid, U_{dc} is the wind turbine unit's DC bus voltage, and U_{dc_sc} is the energy storage system's DC bus voltage.

The energy storage device depicted in the figure primarily consists of lithium iron phosphate battery modules, DC–DC converters, DC–AC converters, and filter circuits. The output end of the device is connected to the grid connection point of the wind turbine. In the event of load disturbances that cause power imbalance, coordinated control of the wind turbine's output and the energy storage device is employed to participate in system frequency modulation. A diagram of coordinated frequency modulation control of wind power and energy storage is shown in Figure 4.

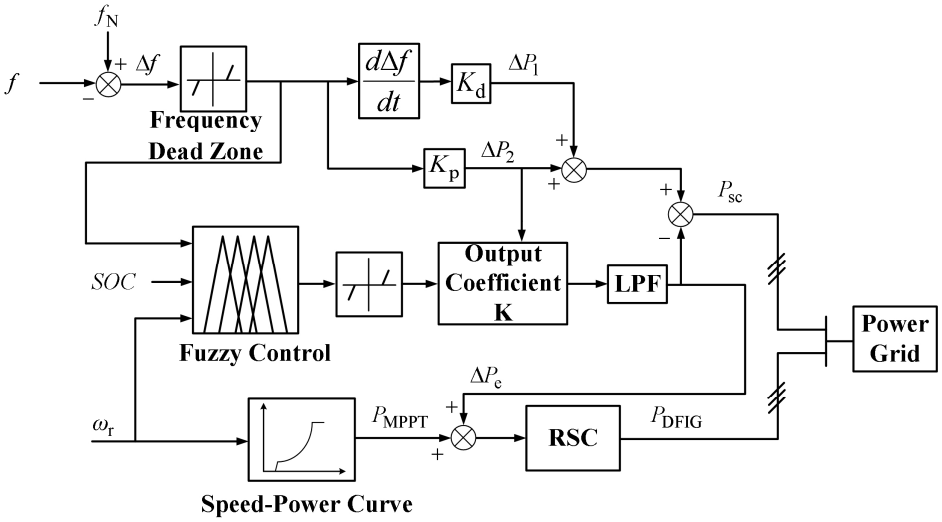


Figure 4. Control block diagram of wind turbine-energy storage joint frequency modulation.

This paper optimizes the mechanical load of wind turbines participating in frequency modulation from two aspects: the response of virtual inertia integrated control power instructions and the coordination of the output between wind turbines and energy storage.

In response to the virtual inertia comprehensive control power command, a method for coordinating the response between wind turbines and energy storage is adopted to reduce the rate of change of the power command of the wind turbine unit, thereby achieving the purpose of alleviating the load pressure on the shaft system. As shown in Figure 4, the response of the wind turbine is the power increment calculated by the droop control, while the response of the energy storage is the power increment calculated by the virtual inertia control. In addition, in order to delay the power response of the wind turbine, a low-pass filtering element is added after the droop control so that the wind turbine only responds to the low-frequency component in the power increment, while the rest of the frequency components will be responded by the energy storage together.

In the coordination of wind turbines and the energy storage output, this paper adopts a fuzzy control algorithm to optimize the allocation of the output for wind turbines and energy storage, thereby reducing the output of wind turbines, decreasing the variation range of the generator electromagnetic torque, and alleviating the load pressure on the shaft system.

Due to the use of virtual inertia comprehensive control in wind turbines, the rotor of the generator will release or absorb energy with the change in frequency, leading to a decrease or increase in rotor speed. However, the kinetic energy of the rotor is limited, and the rotor speed typically operates in the range of 0.7 pu–1.2 pu. At different wind speeds, the ability of wind turbines to participate in frequency modulation using rotor kinetic energy varies. Therefore, if the utilization of rotor kinetic energy is not restricted, it will lead to a decrease in the utilization rate of wind energy and even the possibility of machine tripping, causing power imbalance in the grid.

At the same time, when using energy storage for frequency modulation, the state of charge (SOC) of the energy storage is undoubtedly an important indicator to consider. On one hand, with coordinated frequency modulation between rotor kinetic energy and energy storage, a moderate SOC allows the energy storage to take on more frequency modulation demands, reducing the frequency modulation commands borne by the wind turbine. On the other hand, an excessively high or low SOC is not conducive to the service life of the energy storage, so whether abandoning the current frequency modulation task should be considered when the SOC of the energy storage is poor. Therefore, in the design of fuzzy controllers, not only should the goal be to reduce mechanical loads, but also the operating range of rotor speed and the SOC of the energy storage system should be considered as important factors.

Based on the above content, this paper takes frequency deviation, rotor speed, and the SOC of energy storage as the evaluation indicators, setting them as the inputs of the fuzzy controller. By using the fuzzy controller to obtain the power coefficient K of the wind turbine, multiplying it by the power increment of the droop link, and then passing it through a low-pass filtering link, the power increment of the response of the wind turbine is obtained. The remaining power commands will be taken over by the energy storage. In order to ensure that when the rotor speed of the wind turbine is 0.7 pu or 1.2 pu, the power coefficient K output by the fuzzy controller is 0, and all frequency modulation tasks are taken over by the energy storage, thus ensuring that the rotor speed of the wind turbine is within the normal operating range, a dead zone limiting link is added after the output of the fuzzy controller.

In conclusion, the working process of the coordinated frequency modulation control strategy of wind power and energy storage based on fuzzy control is as follows: when the system frequency deviation crosses the frequency deadband, the coordinated frequency modulation of wind power and energy storage starts to operate. First, the total power increment is obtained through virtual inertia synthesis control. At the same time, the system frequency deviation, the SOC of the energy storage, and the rotor speed of the wind turbine are used as inputs to the fuzzy controller, and the output coefficient K is obtained through predefined fuzzy logic rules. Then, the power increment obtained from droop control is multiplied by the output coefficient K, and after passing through a low-pass filtering stage,

it becomes the power increment borne by the wind turbine. The power increment borne by the energy storage, i.e., the active power output of the energy storage, is obtained by taking the difference between the total power increment and the power increment borne by the wind turbine. Next, the power increment of the wind turbine is added to its power output under the MPPT operation mode to obtain the power command of the wind turbine, and the output power of the wind turbine is adjusted by the rotor-side converter. Finally, the output power of the wind turbine and the active power output of the energy storage are fed into the grid through the grid connection busbar.

3.2. Design of Fuzzy Controllers

The relationships of frequency deviation, rotor speed, state of charge (SOC), and power coefficient are shown in Figure 5. The frequency deviation has a domain of [−1, 1], the rotor speed has a domain of [0.7, 1.2], the state of charge (SOC) has a domain of [0, 1], and the output coefficient also has a domain of [0, 1]. Each of the frequency deviation, rotor speed, and output coefficient has five fuzzy subsets. The fuzzy subset for frequency deviation includes NB (negative large), NS (negative small), ZO (zero), PS (positive small), and PB (positive large), which respectively represent negative large, negative small, zero, positive small, and positive large. The fuzzy sets for rotor speed and the output coefficient are VS, S, M, L, and VL, which represent very small, small, medium, large, and very large. SOC has three fuzzy subsets, L, M, and H, which respectively represent low, medium, and high.

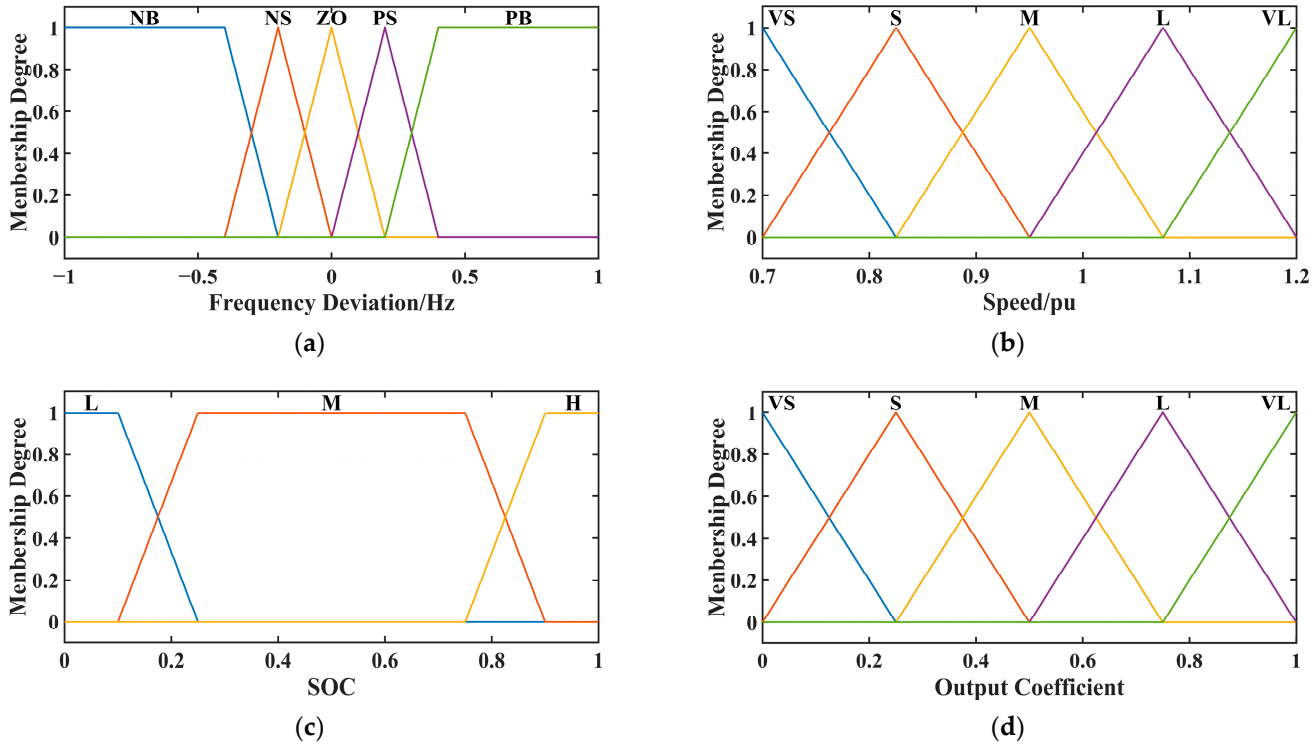


Figure 5. Membership relation between input and output of fuzzy controller: (**a**) membership relationship of frequency deviation, (**b**) membership relationship of rotor speed, (**c**) membership relationship of SOC, and (**d**) membership relationship of output coefficient.

Fuzzy logic rules were established for different SOC levels, as shown in Tables 1–3. The fuzzy controller determines the fuzzy logic rule to be executed based on the current SOC. The output of the fuzzy controller is the power coefficient of the wind turbine unit. When SOC = M, the energy storage SOC is moderate. Based on the magnitude and polarity of frequency deviation and the rotor speed, the current charging and discharging status and output of the energy storage are determined. With a good SOC of the energy storage, in order to reduce the variation of the generator electromagnetic torque and the mechanical

load impact and minimize fatigue damage, the output of rotor kinetic energy should be minimized, with the energy storage output as the main focus; thus, a smaller power coefficient should be output. When SOC = L or SOC = H, the energy storage SOC is low or high. Continuing to use the SOC = M rule in these cases would result in excessive charging and discharging of the energy storage, severely affecting its lifespan. Therefore, when the energy storage SOC is L, the energy storage system will mainly be used for power absorption, and when the energy storage SOC is H, the energy storage system will mainly be used for power release.

Based on fuzzy logic rules, fuzzy logic inference results under different SOC conditions are obtained, as shown in Figure 6.

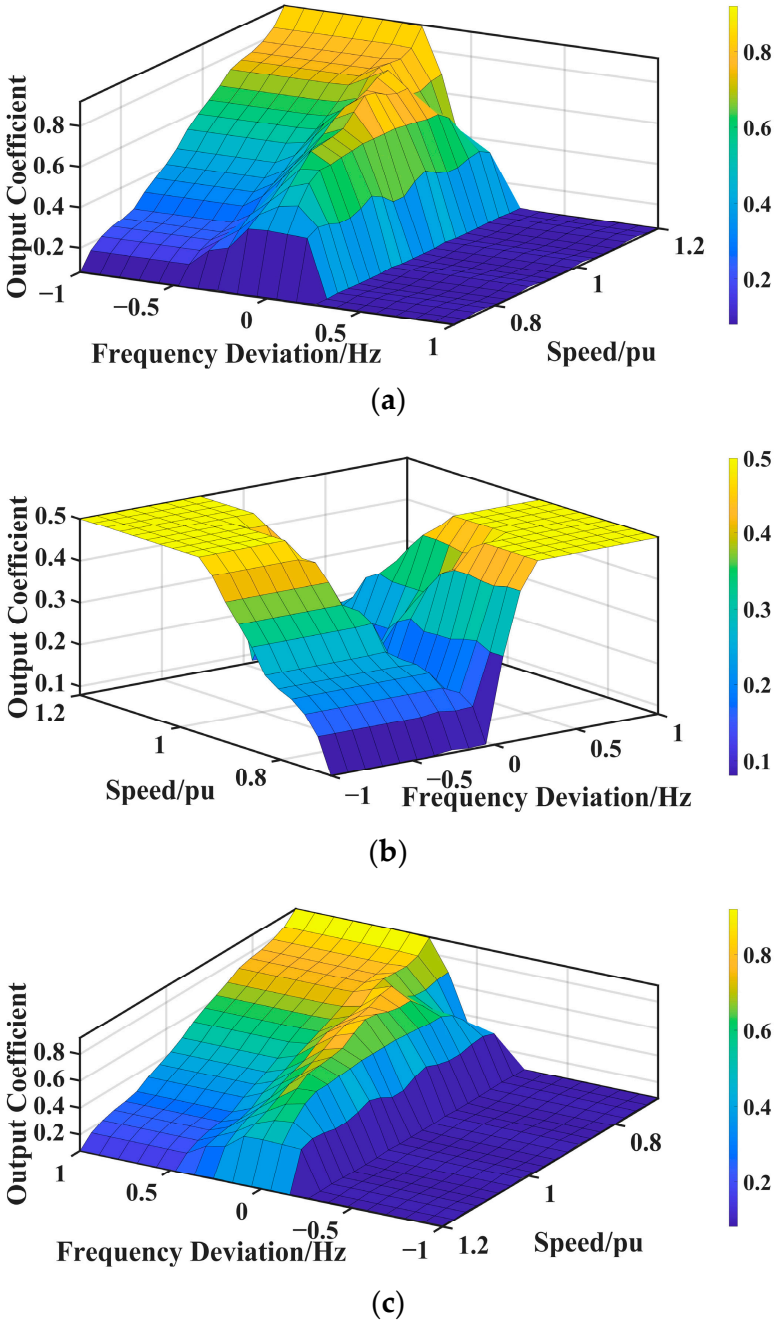


Figure 6. Results of fuzzy logic inference under different SOCs: (**a**) SOC = L, (**b**) SOC = M, and (**c**) SOC = H.

Table 1. Fuzzy control rule with SOC = L.

Output Coefficient (SOC = L)		Rotor Speed				
		VS	**S**	**M**	**L**	**VL**
Frequency Deviation	NB	VS	S	M	L	VL
	NS	VS	M	L	VL	VL
	ZO	VS	L	VL	VL	VS
	PS	VS	VS	VS	VS	VS
	PB	VS	VS	VS	VS	VS

Table 2. Fuzzy control rule with SOC = M.

Output Coefficient (SOC = M)		Rotor Speed				
		VS	**S**	**M**	**L**	**VL**
Frequency Deviation	NB	VS	S	M	M	M
	NS	VS	S	S	M	M
	ZO	VS	VS	VS	VS	VS
	PS	M	M	S	S	VS
	PB	M	M	M	S	VS

Table 3. Fuzzy control rule with SOC = H.

Output Coefficient (SOC = H)		Rotor Speed				
		VS	**S**	**M**	**L**	**VL**
Frequency Deviation	NB	VS	VS	VS	VS	VS
	NS	VS	VS	VS	VS	VS
	ZO	VS	L	VL	L	VS
	PS	VL	VL	L	M	VS
	PB	VL	L	M	S	VS

4. Simulation Example

To verify the effectiveness of the control strategy proposed in this paper, a joint simulation was conducted using GH Bladed and Matlab to build a simulation model. In GH Bladed, the wind model, rotor model, tower model, nacelle model, drive train model, and control model were established. The electrical model and control model were built in Matlab.

The main parameters of the coordinated simulation are as follows: the rated power of the wind turbines is 2 MW, the frequency deadband is set to ± 0.05 Hz, the generator rated speed is 1800 r/min, the virtual inertia coefficient is 0.1, the droop coefficient is 0.4, and the initial SOC of the energy storage system is 0.7.

Due to the minimal support of a single wind turbine for system frequency changes, this paper uses the frequency curve with droop characteristics of synchronous generators during frequency modulation as the frequency variation curve for wind turbine frequency modulation simulation. Co-simulation is conducted in three scenarios, as shown in Table 4.

Table 4. Simulation cases.

Scenario	Frequency Modulation Strategy
Scenario 1	None
Scenario 2	Virtual Inertia Comprehensive Control
Scenario 3	Virtual Inertia Comprehensive Control + Energy Storage

4.1. Constant Wind Speed

This paper conducts a joint simulation of the three scenarios mentioned above at a constant wind speed of 8 m/s, and the simulation results are shown in Figure 7.

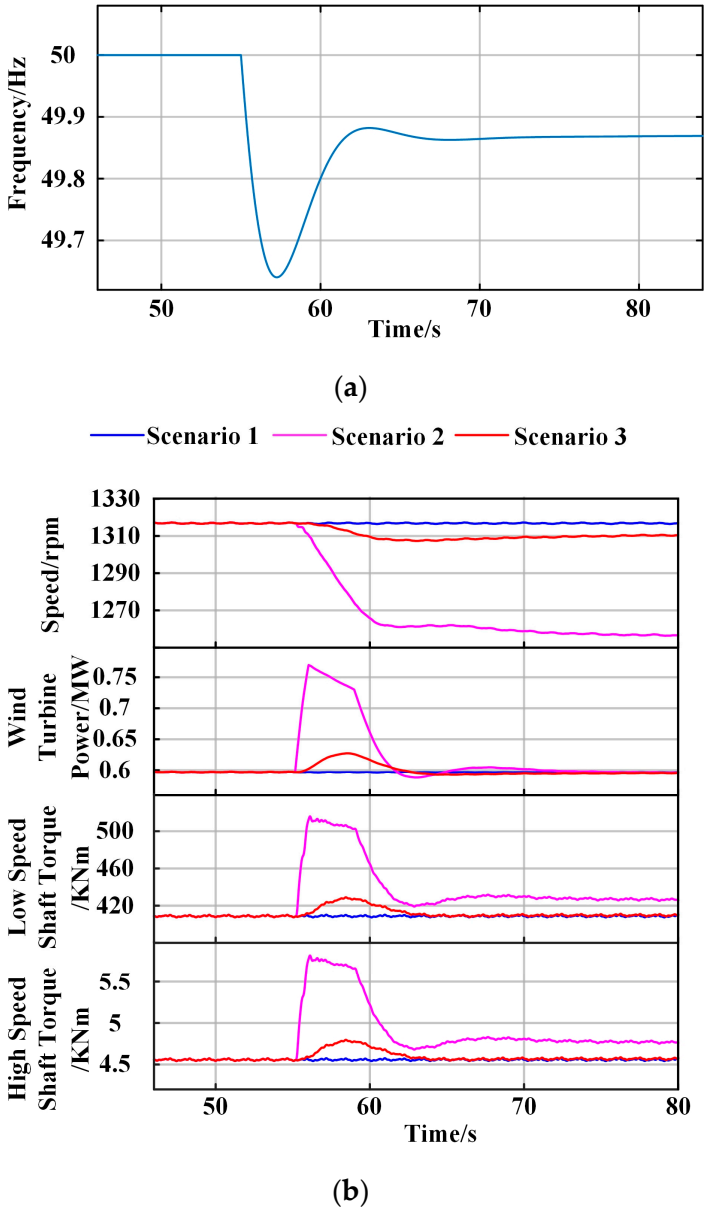


Figure 7. Simulation results of constant wind speed: (**a**) curve of frequency variation and (**b**) curve of simulation variation.

As shown in Figure 7a, under a constant wind speed of 8 m/s, the system frequency starts to change at a time of 55 s, with the lowest point of frequency dropping to 49.64 Hz and eventually stabilizing at 49.87 Hz. During the normal operation of the wind turbine, the rotor speed is 1317 rpm, the power output is 0.597 MW, and the loads on the low-speed and high-speed shafts are 409 kNm and 4.56 kNm, respectively. Following the transition, when the frequency variation exceeds the deadband, the wind turbine and energy storage start to participate in frequency modulation. In scenario 2, the wind turbine releases rotor kinetic energy, causing the rotor speed to rapidly decrease to 1261 rpm, the power output of the wind turbine to quickly rise to 0.767 MW, and the loads on the low-speed and high-speed shafts to increase sharply to 516 kNm and 5.82 kNm. As the rotor kinetic energy is consumed and the rotor speed decreases, the power output of the wind turbine in MPPT

mode also decreases, leading to a decline in power output. Subsequently, as the system frequency rises and gradually stabilizes, the rotor speed, wind turbine power, low-speed shaft load, and high-speed shaft load all gradually stabilize. In scenario 3, the response of the rotor speed is slow, with a small decrease to 1307 rpm. The response rate and magnitude of the wind turbine power output are also reduced, with the maximum power output of the wind turbine reaching 0.627 MW. It can be seen from the output power curve of the energy storage equipment in Figure 8 that the output power of the energy storage equipment rises to 0.175 MW in a relatively short time because of the control strategy proposed in this paper, which assumes the task of rapid power support and reduces the speed and amplitude of the output power of the wind turbine. Additionally, in this simulation scenario, the wind turbine system effectively alleviates the shaft loads. The maximum values of the loads on the low-speed and high-speed shafts are 429 kNm and 4.8 kNm, respectively. Compared with scenario 2, the maximum values of the loads on the low-speed and high-speed shafts have decreased by 87 kNm and 1.02 kNm, respectively. Scenario 3 effectively mitigates the load pressure on the wind turbine system shafts in terms of the rate and magnitude of load changes.

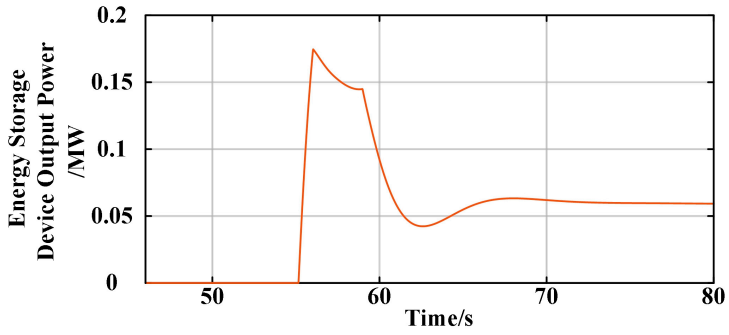


Figure 8. Curve of energy storage device output power under constant wind speed.

Based on the load data presented in Figure 7, the high-speed shaft damage equivalent load (HSS-DEL) and the low-speed shaft damage equivalent load (LSS-DEL) are computed using the rainflow counting method with a slope of m = 4 for the S–N curve, for various simulation scenarios. The computation results are tabulated in Table 5.

Table 5. Calculation results of fatigue load of shafting with constant wind speed.

DEL (/kNm)	Scenario 1	Scenario 2	Scenario 3
LSS-DEL	3.172	51.992	10.205
HSS-DEL	0.037	0.613	0.121

Based on the calculation results of scenario 1, the fatigue loads on the low-speed shaft and high-speed shaft in scenario 2 increased by 48.82 kNm and 0.576 kNm, respectively. In scenario 3, the increases were 7.033 kNm and 0.084 kNm, respectively. The above results indicate that, under the current simulation conditions, the control strategy proposed in this paper significantly reduces the fatigue loads on the wind turbine drivetrain compared with traditional rotor kinetic energy control, alleviating the load pressure.

4.2. Turbulent Wind Speed

In this paper, joint simulations were performed for three scenarios under turbulent wind conditions with an average wind speed of 8 m/s. The simulation results are presented in Figure 9.

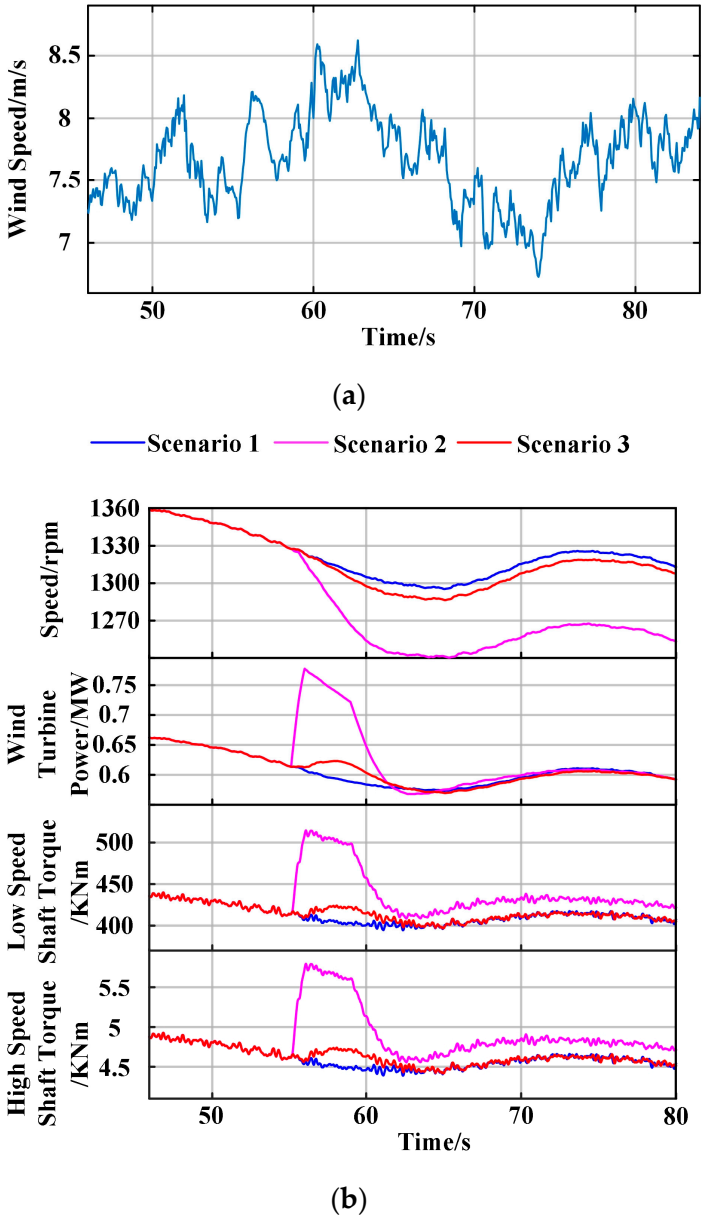


Figure 9. Simulation results of turbulent wind speed: (**a**) curve of wind speed variation and (**b**) curve of simulation variation.

Referring to the curve in scenario 1, the simulation results indicate that, in scenario 2, the rotor speed significantly decreases with a large magnitude, dropping to 1241 rpm, and the wind turbine output power experiences a sudden spike to 0.772 MW. Scenario 3, on the other hand, shows a slow and minor change in rotor speed, leading to a gradual increase in wind turbine output power, reaching a maximum of 0.622 MW. At the same time, as shown in Figure 10, the energy storage device provides rapid power support. Due to the use of the same frequency variation curve as in the constant wind speed condition and the similar range of rotor speed variation during frequency variation, the power command output by the virtual inertia comprehensive control and the output coefficient K by fuzzy control are approximately consistent between the two conditions, resulting in the energy storage device outputting roughly the same power. In scenario 2, the low-speed shaft and high-speed shaft experience a sudden increase in loads, spiking up to 514 kNm and 5.8 kNm, respectively. In scenario 3, the loads slowly change to 424 kNm and 4.74 kNm. Compared with scenario 2, the maximum loads on the low-speed shaft and high-speed shaft in scenario 3 are reduced by 90 kNm and 1.06 kNm, demonstrating the advantageous

effects of the control strategy proposed in this paper in reducing the load pressure on the shaft system.

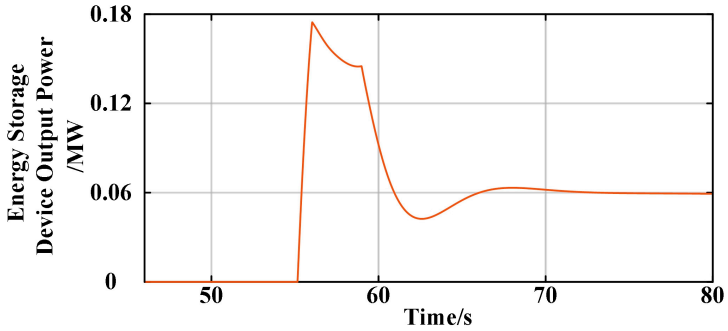


Figure 10. Curve of energy storage device output power under turbulent wind speed.

By using the load data provided in Figure 9, the equivalent fatigue loads under different simulation scenarios were calculated using the rainflow counting method with an S–N curve slope of m = 4. The calculation results are presented in Table 6.

Table 6. Calculation results of fatigue load of shafting with turbulent wind speed.

DEL (/kNm)	Scenario 1	Scenario 2	Scenario 3
LSS-DEL	15.126	60.941	16.834
HSS-DEL	0.180	0.729	0.201

Compared with the calculation results of scenario 1, the fatigue loads on the low-speed shaft and high-speed shaft in scenario 2 increased by 45.815 kNm and 0.549 kNm, respectively. In scenario 3, the fatigue loads on the low-speed shaft and high-speed shaft increased by 1.708 kNm and 0.021 kNm, respectively. In comparison, under the current simulation conditions, the control strategy proposed in this paper has a good mitigating effect on the fatigue loads of the shaft system.

5. Conclusions

A coordinated frequency modulation control strategy of wind power and energy storage based on fuzzy control is proposed to address the issue of mechanical load impact caused by rotor kinetic energy control, with the following main contributions:

(1) The control of the rotor kinetic energy of wind turbines leads to drastic changes in torque, causing sudden changes in shaft loads, resulting in mechanical load impacts and increasing the equivalent fatigue load on the shaft system.

(2) This paper introduces mechanical load analysis elements while satisfying frequency modulation requirements. It focuses on the impact of loads on the shaft system and analyzes the primary frequency modulation process of wind turbines from multiple perspectives.

(3) Compared with rotor kinetic energy frequency modulation, a coordinated frequency modulation control strategy of wind power and energy storage based on fuzzy control fully considers the impact of load fluctuations. It reduces the power increment borne by the wind turbine in a coordinated manner with energy storage, decreases the rate of change in wind turbine output power, reduces fatigue loads on the shaft system, and alleviates the load pressure on the wind turbine shaft system.

However, there are insufficient quantifications on the impact of a reduced axial load on the extended lifespan of wind turbines and economic evaluations on the benefits after lifespan extension, reduced operational costs, and energy storage configuration costs. Therefore, further research will be conducted in the future.

Author Contributions: Conceptualization, C.Z., J.L. and S.L.; methodology, C.Z., J.L. and S.L.; software, J.L. and S.L.; validation, J.L. and S.L.; formal analysis, C.Z.; writing—original draft preparation, H.R. and R.Z.; writing—review and editing, P.H., J.F., H.R., R.Z. and J.J. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by the National Natural Science Foundation of China under grant no. 52207102.

Data Availability Statement: The data presented in this study are confidential at the request of the corresponding author.

Acknowledgments: The authors gratefully thank the financial support of the National Natural Science Foundation of China under grant no. 52207102.

Conflicts of Interest: Authors Chaoyu Zhang, Jiabin Li, Shiyi Liu, Peng Hu, Jiangzhe Feng were employed by the company Longyuan (Beijing) New Energy Engineering Technology Co. Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Zhang, X.; Chen, Y.; Yue, S.; Zha, X.; Zhang, D.; Xue, L. Retrospect and prospect of research on frequency modulation technology of power system by wind power. *Power Syst. Technol.* **2018**, *42*, 1793–1803.
2. Liu, J.; Yao, W.; Wen, J.; Huang, Y.; Liu, Y.; Ma, R. Prospect of technology for large-Scale wind farm participating into power grid frequency modulation. *Power Syst. Technol.* **2014**, *38*, 638–646.
3. Li, S.; Qin, S.; Wang, R.; Chen, C.; Yang, J. Control strategy of virtual inertia frequency modulation for large capacity DFIG-based wind turbine. *Power Autom. Equip.* **2018**, *38*, 145–150+156.
4. Peng, X.; Jia, J.; Zhou, J.; Huang, S.; Wei, S. Speed Modulation Strategy Based on Variable Proportion Coefficient for Optimizing Inertial Response of Wind Generator. *Proc. CSEE* **2018**, *38*, 5625–5635+5920.
5. Hwang, M.; Muljadi, E.; Park, J.W.; Sørensen, P.; Kang, Y.C. Dynamic Droop–Based Inertial Control of a Doubly-Fed Induction Generator. *IEEE Trans. Sustain. Energy* **2016**, *7*, 924–933. [CrossRef]
6. Morren, J.; De Haan, S.W.; Kling, W.L.; Ferreira, J.A. Wind Turbines Emulating Inertia and Supporting Primary Frequency Control. *IEEE Trans. Power Syst.* **2006**, *21*, 433–434. [CrossRef]
7. Zhang, X.; He, W.; Hu, J. Impact of Inertia Control of DFIG-based WT on Torsional Vibration in Drivetrain. *IEEE Trans. Sustain. Energy* **2020**, *11*, 2525–2534. [CrossRef]
8. Xi, X.Z.; Geng, H.; Yang, G. Inertia Control of the grid connected doubly fed induction generator based wind farm with drive-train torsion active damping. *Trans. China Electrotech. Soc.* **2017**, *32*, 136–144.
9. Qin, S.; Dai, L.; Wang, R.; Bi, R.; Xu, T.; Zhao, J. Virtual inertia control method considering wind turbine power drop and mechanical load optimization. *Power Syst. Technol.* **2021**, *45*, 1665–1672.
10. Yan, X.; Sun, X.; Cui, S.; Li, X.; Li, T. Improved control strategy for inertia and primary frequency modulation of doubly fed induction generator based on rotor kinetic energy and supercapacitor Energy Storage. *Trans. China Electrotech. Soc.* **2021**, *36*, 179–190.
11. Yan, X.; Song, Z.; Cui, S.; Sun, Y.; Li, T. Primary frequency modulation strategy of doubly-fed wind turbine based on variable power point tracking and supercapacitor energy storage. *Trans. China Electrotech. Soc.* **2019**, *35*, 530–541.
12. Li, X.; Cui, X.; Huang, J.; Li, S.; Meng, Y. The self-adaption control strategy of energy storage batteries participating in the primary frequency modulation. *Trans. China Electrotech. Soc.* **2019**, *34*, 3897–3908.
13. Ma, D.; Li, W.; Wen, C.; Chai, R. Wind/Storage coordinated primary frequency modulation control strategy based on participation level of DFIG units. *Power Syst. Technol.* **2023**, *47*, 968–979.
14. Shang, Q.; Li, F.; Wang, S.; Li, Y.; Yin, C. Primary frequency modulation strategy for wind-storage combined system based on multivariable fuzzy logic control. *Power Syst. Technol.* **2023**, *47*, 2344–2360.
15. Zhang, X.; Qin, S.; Chen, C.; Zhang, Y.; Hao, S.; Wu, Q. Wind turbine storage joint frequency modulation control strategy considering the balance of energy storage charge and discharge. *Power Syst. Technol.* **2024**, *48*, 1938–1946.
16. Zhang, G.F.; Yang, J.Y.; Wang, H.X.; Xie, C.J.; Fu, Y. Coordinated Frequency Modulation Control Strategy of Wind FarmStorage System Based on Virtual Synchronous Generator Technology. *Trans. China Electrotech. Soc.* **2022**, *37*, 83–92.
17. Liang, K.; Peng, X.T.; Qin, S.; Wang, J.R.; Zhang, Z.; Chen, R.J. Study on synergetic control strategy for optimizing frequency response of wind farm augmented with energy storage system. *Proc. CSEE* **2021**, *41*, 2628–2641.

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