Coordinated control strategy for improving the two drops of the wind storage combined system

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Abstract. In the power system with high permeability wind power, due to wind power fluctuation, the operation of large-scale wind power grid connected to the system brings challenges to the frequency stability of the system. When the doubly fed wind power generation unit does not reserve spare capacity to participate in the system frequency regulation, the system frequency will produce two drops in different degrees when the wind power exits frequency modulation and enters the speed recovery stage. To solve this problem, based on the complementary advantages of wind turbines and energy storage systems in power transmission and frequency modulation, a wind storage combined frequency modulation strategy based on sectional control is proposed in this paper. Based on the TOP wind power frequency modulation strategy, the wind power output reference value is determined according to the linear relationship between the output and the speed of the wind turbine, and the auxiliary wind power load reduction is controlled when the wind power exits frequency modulation into the speed recovery stage, so that the wind turbine is recovered to run at the optimal speed. Then, according to the system frequency and the wind turbine operation state, set the energy storage system frequency modulation output. Energy storage output active support is triggered during wind speed recovery. And then when the system frequency to return to the normal operating frequency range, reduce energy storage output or to exit frequency modulation. The simulation results verify the effectiveness of the proposed method.

1. Introduction

With the continuous improvement of the permeability of wind power, the safe and stable operation of the traditional power system has been challenged. The inherent random fluctuation of wind power has a certain influence on the stable operation of the system, and to some extent hinders the large-scale grid connection process of the wind power system. However, the addition of large-scale energy storage system can effectively improve the wind power acceptance ability of power grid, which is also a very important and promising application direction of energy storage technology [1].

Existing wind power frequency modulation control methods, such as integrated inertial control and TOP wind power frequency modulation control [2], according to the different operation characteristics of doubly fed wind turbines in the frequency modulation of power grid, the whole process can be divided into the frequency modulation stage and the unit recovery stage. The dividing point of the two stages is the time when the active power output of the unit starts to decrease and the speed of the generator starts to recover. The sudden drop of rotor speed will occur in both the integrated inertial control frequency modulation process and the TOP control frequency modulation process of the doubly fed wind turbine. This leads to a sudden decrease of the output power of the wind turbine after the end of the frequency regulation, which will affect the active power balance of the system. It means that an equivalent amount of power is removed in the system, resulting in two drops of the system frequency [3]. So we need to study the control strategy of wind turbine recovery stage to solve or improve the problem of power sags, so as to reduce or even eliminate the two drops of micro-grid frequency caused by frequency modulation of doubly fed induction generator.

Thus, based on the complementary advantages of wind turbines and energy storage systems in power transmission and frequency modulation, a wind storage combined frequency modulation strategy based on sectional control is proposed in this paper. Under the TOP wind power frequency modulation strategy, the wind power output reference value is determined based on the linear relationship between the wind turbine output and the speed. When the wind power is out of the frequency modulation and into the speed recovery phase, the wind power drop control is assisted to make the wind turbine resume running at the optimal speed. Then, according to the system frequency and the wind turbine operation state, set the energy storage system frequency modulation output and trigger energy storage output active support in the recovery phase of wind power. And then when the system frequency returns to normal operating range, reduce energy storage or exit the frequency modulation. Finally, the validity of the method is verified by modeling and simulation.

2. Analysis of two drops mechanism of system frequency caused by wind power participation in frequency modulation

2.1. Dynamic model of wind turbine

The basic principle of wind power generation is to convert wind energy into mechanical energy through the rotation of the wind wheel, and then turn the mechanical energy into electric energy through the rotation axis. The mechanical power of the wind turbine blade by rotating the wind to capture the wind can be expressed by the following equation[4]:

$$P_m = \frac{1}{2} C_p\left(\lambda,\beta\right)\pi R^2 \rho V^3 \tag{1}$$

Where, P_m represents the mechanical power of wind turbine(W), ρ indicates air density(kg/m^3), λ shows tip speed ratio, β represents the pitch angle(deg), V represents the equivalent wind speed(m/s), C_p represents the wind energy capture coefficient of the wind turbine, and R represents the radius of the wind turbine's blower(m).

The algebraic relationship based on the nonlinear fitting of the C_p curve of the wind energy capture coefficient of a multi-group wind turbine can be used to characterize the aerodynamic characteristics of the wind turbine. The wind energy capture coefficient is the function of the tip speed ratio (λ), the pitch angle (β).According to the wind energy capture coefficient curve of the wind turbine, the general formula can be used to fit the wind turbine [5]:

$$C_p\left(\lambda,\beta\right) = 0.22\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{\frac{-12.5}{\lambda_i}} \tag{2}$$

$$\lambda_i = \left(\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}\right)^{-1} \tag{3}$$

2.2. Wind power participation in frequency modulation TOP control strategy

The frequency modulation control of TOP wind power is a common frequency modulation control method for wind turbines without FM standby. This method uses the rotor kinetic energy of the wind turbine. It releases the rotor kinetic energy and provides the frequency adjustment of the active support system by reducing the speed of the wind turbine.The dynamic running curve of frequency modulation is shown in Figure 1 [6].

The frequency modulation control strategy of TOP wind turbine is made up of three parts: TOP frequency modulation control (1-2-3) and rotor speed recovery (3-4-5-1).

When the frequency of the system falls (increasing) over a certain threshold, the wind motor immediately increases the active output, running from point 1 to 2. At this time the power reference value of the wind turbine is:

$$P_{w\_ref\,1} = 1.2w_{MPPT} \tag{4}$$

Where, w_{MPPT} shows the optimal speed before wind turbine is involved in the frequency modulation action. At the TOP frequency modulation phase (1-2-3), the rotor speed continues to decrease, and a large number of rotational kinetic energy is released to provide the system frequency support. When the frequency has gone through the lowest point of frequency fall and the frequency rises:

$$P_{w\_ref\,2} = P_4 = P_5 = P_{w\_ref\,1} - \Delta P_{34} \tag{5}$$

$$\Delta P_{34} = P_3 - P_4 \tag{6}$$

The greater the difference between the mechanical power P_m and the reference value of the power, the greater the speed recovery of the wind turbine is, the faster the speed is restored. However, the greater the value of the ΔP_{34}, the greater the probability of a two fall in frequency in the recovery process of the system.

If the wind speed w is equal to w_1 and the time continues to reach 1s, the FM strategy enters the speed recovery phase from the TOP frequency modulation stage. The power reference value $P_{w\_ref\,3}$ at this stage is equal to P_{MPPT}, and the control block diagram is as Figure 2:

$$P_{w\_ref\,3} = P_{MPPT} = \frac{\frac{1}{2}\rho\pi R^5 C_{p\max}}{\lambda_{opt}^{2}}\omega^3 = K^*(w)^3 \tag{7}$$

Where, K^* is equal to 0.002.

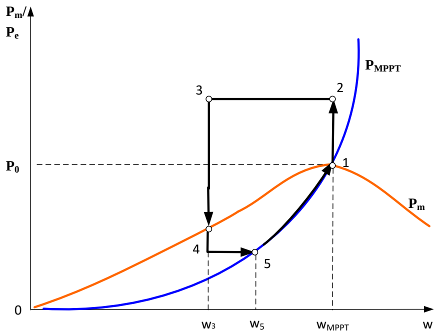

Figure 1. Frequency modulation curve under TOP control strategy

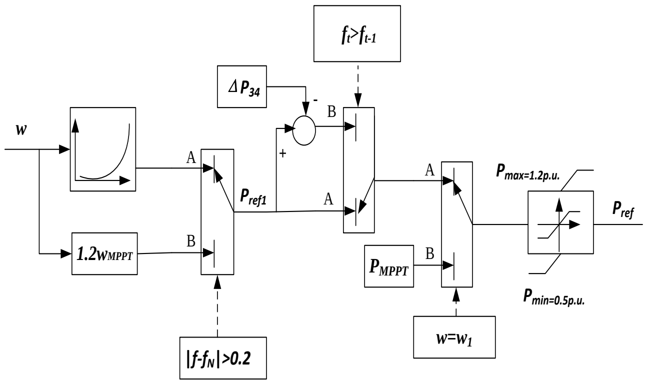

Figure 2. Improved TOP frequency modulation control chart based on improved wind turbines

2.3. Analysis of the mechanism of frequency two drops caused by wind power frequency modulation

There are two reasons for the two drops of the system frequency are as follows:

(1) When the wind turbine to participate in the process of frequency adjustment at the end, the frequency of the system has not completely recovered to the stable running state, and the system power still has the difference unbalance. If the force of the wind turbine is reduced, it will cause the loss of the system's active power again, causing the two fall of the system frequency;

(2) At the beginning of the recovery stage, the rotor speed is low and the mechanical power of the wind turbine output is small. If the wind turbine is out of the system at this time, the wind power's active value drops suddenly. The more the active power output of the wind turbine decreases, the greater the difference between the electromagnetic power and the mechanical power of the wind turbine. Correspondingly, the greater the acceleration of rotor speed is, the faster the recovery of the rotor speed is, so that the frequency of the system's two drops is more serious.

So we need to study the control strategy of wind turbine recovery stage and solve or improve the problem of power sags, so as to reduce or even eliminate the two drops of micro-grid frequency caused by frequency modulation of doubly fed induction generator.

3. A coordinated frequency modulation strategy for wind storage system with TOP control

3.1. Frequency modulation control strategy for wind storage combined system based on piece wise control

In order to improve the two drops of system frequency that the wind turbines participate in the frequency modulation during the stage of load reduction and wind turbine speed recovery, a new frequency support control strategy based on battery energy storage system is proposed in this section. The energy storage model uses the first order inertial link model, as shown in the following figure:

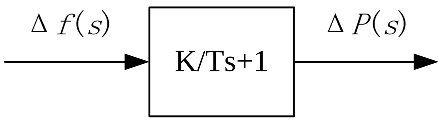

Figure 3. The first order equivalent model of energy storage system

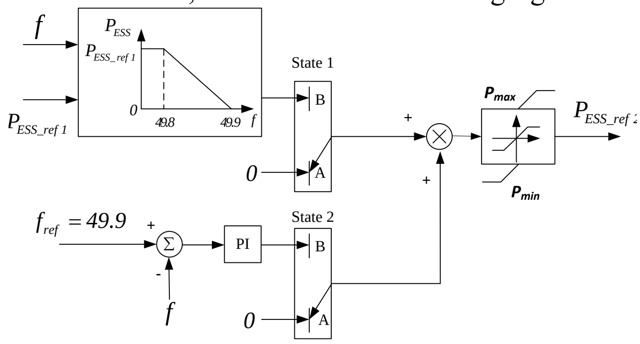

Figure 4. Energy storage system participation system frequency regulation control strategy

As shown in Figure 4, the energy storage system participates in the system frequency modulation control strategy, consisting of state 1 and state 2 in two parts.

(1) State 1: frequency modulation in the auxiliary system of energy storage system

State 1 works normally under mode A. The wind turbine exit participates in the frequency adjustment to the load reducing operation stage, the state 1 is transferred from the mode A to the mode B, that is, the energy storage system output reference value $P_{ESS\_ref\,1}$ is as follows:

The power reference value $P_{ESS\_ref\,1}$ of the energy storage system is used to compensate the speed recovery stage of the wind turbine after the wind power stop frequency support. $P_{ESS\_ref\,1}$ is the difference between P_4 and $P_{w\_ref\,2}$ when wind power is running in stage of load reduction; $P_{ESS\_ref\,1}$ is the difference between P_3 and $P_{w\_ref\,3}$,when wind power is running in the stage of speed recovery.

(2) State 2: the droop control of additional energy storage system

If the support power injected by the energy storage system is too much more than the actual system needs, it may lead to excessive frequency recovery. It is necessary to control the output power of the energy storage system so that it is gradually reduced to a suitable range, and the system frequency is maintained within an acceptable range. In view of the above situation, whether the additional energy storage system droop control method is adopted, it is judged by the system frequency value according to the real-time measurement. If the system frequency value exceeds the frequency threshold (set as

49.8Hz), the energy storage additional droop control is applied. The reference value P_{ESS_droop} of the droop controlled energy storage system can be expressed as:

$$P_{ESS\_droop} = -P_{ESS\_49.8} \times \frac{f - 49.8}{50 - 49.8} + P_{ESS\_49.8} \tag{8}$$

Where, $P_{ESS\_49.8}$ shows the output power of the energy storage system when the system frequency is at 49.8Hz, and the f is the real time system frequency value. In order to reduce the influence of the decrease of the reference value $P_{ESS\_ref\,2}$ of energy storage system in the second stage of energy storage system on the system, the auxiliary PI control link is adopted to maintain the system frequency in the normal operation of 50Hz. As shown in Figure 4, the energy storage system control strategy, the state 2 is converted from the mode A to the mode B to ensure that the system frequency is smoothly restored to the normal range. The output power reference value under the integrated energy storage control strategy is expressed as the following:

$$P_{ESS\_ref} = \begin{cases} P_{ESS\_ref\,1} = P_3 - P_{w\_ref\,2} or P_{w\_ref\,3}, f < 49.8Hz \\ P_{ESS\_ref\,2} = P_{ESS\_droop} + \Delta P', f \geq 49.8\,Hz \end{cases} \tag{9}$$

Where, $\Delta P'$ represents the power reference value generated by the PI controller.

3.2. Control process of wind storage joint system participates in frequency modulation

The wind power and energy storage coordination control strategy block diagram is shown in Figure 5.

The coordinated control strategy proposed in this paper includes the following two parts:

(1) Frequency modulation control based on TOP wind power.

The system frequency monitoring system is adopted. Once the system frequency is lower than 49.9Hz for more than 50 milliseconds while the wind turbine speed is still higher than 0.6 p.u., the wind turbine adopts the improved TOP frequency modulation method to enter the frequency control.

(2) Frequency regulation of energy storage auxiliary system.

When the system frequency has dropped through the frequency of the lowest point and is in the frequency of recovery, the wind turbine's entry into the load reduction operation will bring the influence of the frequency falling again. In order to compensate for the two drops of frequency caused by the lack of power caused by wind power reduction, the energy storage system will provide additional active power compensation. In this state, when the frequency of the system is higher than 49.8Hz, the system frequency is stabilized at about 50Hz by gradually reducing the output of the energy storage system.

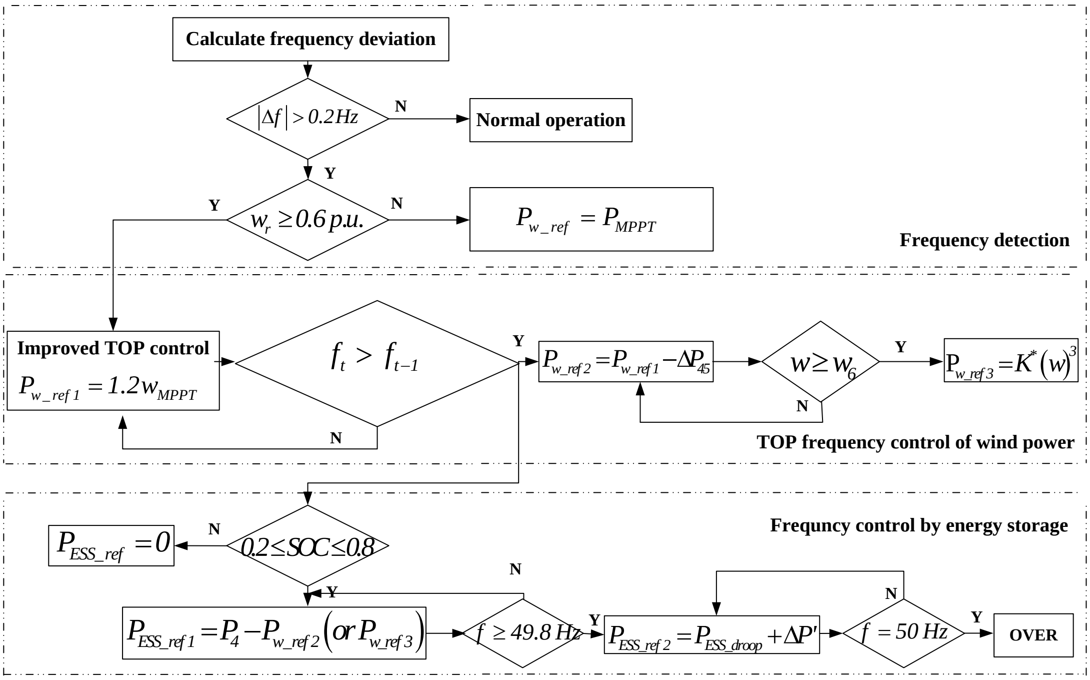

Figure 5. The coordinated control flow chart of wind storage joint participation in the system frequency adjustment

4. Simulation Experiment

4.1. Simulation conditions

In the Matlab/Simulink simulation environment, a small power system containing wind farms is set up. The structure diagram of the system is shown in Figure 6 below. It mainly includes conventional unit, wind turbine, energy storage system and load.

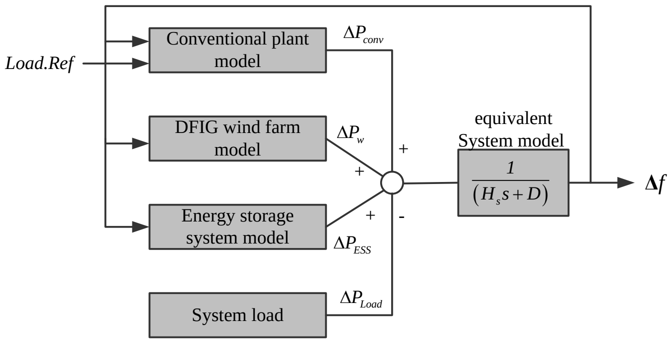

Figure 6. Structure block diagram of the combined system of wind and storage

Where, ΔP_{conv} represents the total power generated by conventional generating set, ΔP_w indicates the total power generated by the wind power system, ΔP_{Load} represents the change of the load power, ΔP_{ESS} represents the power emitted by the energy storage system, and Δf represents the change value of the system frequency. H_s represents the equivalent inertia constant of the system, D represents equivalent damping coefficient of the system. The parameters of the simulation model of the wind turbine and the conventional synchronous unit of the system are shown in Table 1.

Table 1. System parameters of wind power

parameter	value	unit

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System capacity	100	MVA
System frequency modulation coefficient R	5	%
The equivalent inertial constant Hs of the system	4	s
The equivalent damping coefficient D of the system	1	
Rated power of wind farm	20	MW
Battery power storage system power	2	MW
System first type of load	70	MW
System second type of load	10	MW

4.2. Simulation verification

4.2.1 Analysis of frequency modulation characteristics of wind storage system under different wind conditions

(1) Analysis of frequency modulation characteristics of wind storage combined under stroke speed The wind speed is 8m/s, and the load increases 4MW when the load is 10s.

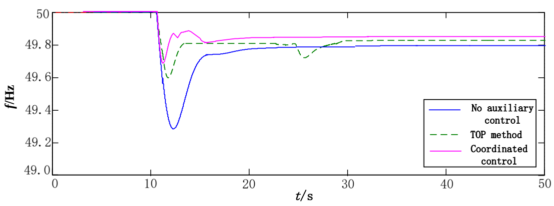

Figure 7. Frequency characteristics

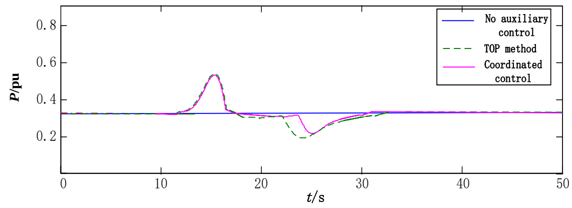

Figure 8. Wind power's output

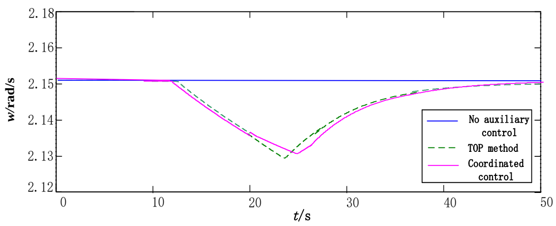

Figure 9. Wind turbine rotor speed

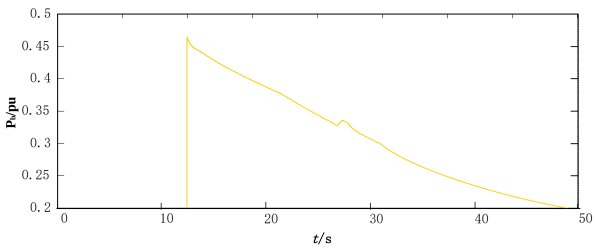

Figure 10. Energy storage system output

As shown in Figure 10, the frequency response of the wind turbine is faster. However, when the wind turbine exits the frequency modulation system and enters the speed recovery phase, no additional power is supplied to the rotor kinetic energy that is missing from the wind turbine. This results in a system power shortage and two drops in the system frequency. When the energy storage system participates in frequency modulation, the system frequency falls at a smaller amplitude, the frequency response speed is faster, and the speed of the speed recovery slows down, and the system frequency two drops is improved.

(2)Analysis of frequency modulation characteristics of wind storage combined under high speed

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The wind speed is set to 11m/s, and the load increases by 4MW when the load is 10s.

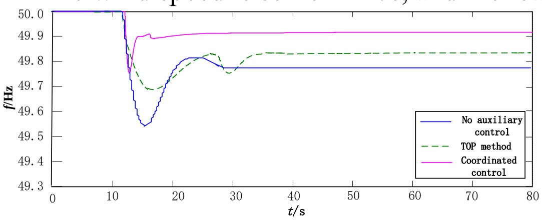

Figure 11. Frequency characteristics

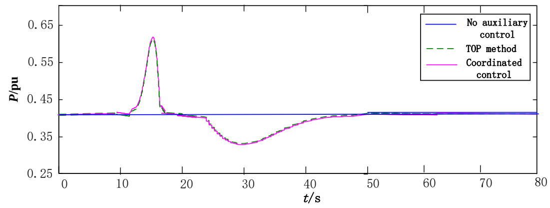

Figure 12. Wind power active power output

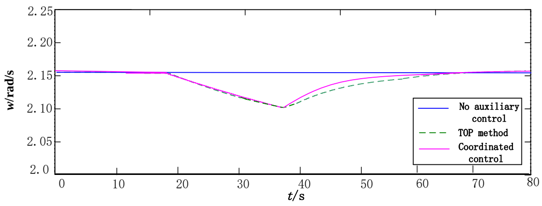

Figure 13. Wind turbine rotor speed

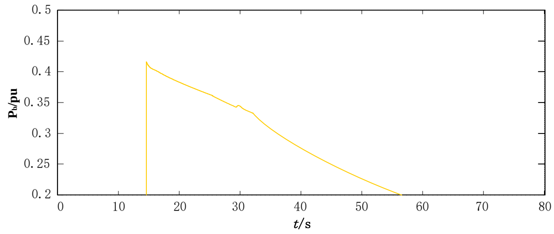

Figure 14. Energy storage system output

According to the operation state of the system by simulation results, because the rotor's kinetic energy stored in the rotor speed of the wind power system can provide the frequency support for the system, to a certain extent, the charging and discharging power and the number of storage batteries are reduced. This improves the frequency of secondary drop while reducing the frequency of frequent charge and discharge energy storage. This increases the life of the energy storage battery and further enhances the economy of wind farm coordinating and participating in frequency modulation.

4.2.2 Analysis of frequency modulation characteristics of wind storage system under different wind power permeability

In this section, the wind power permeability is set to 24.6% and 32.8% respectively, and the primary frequency modulation characteristics under different wind power permeability are analyzed.

(1) Example 1: the permeability of wind power is 24.6%

The wind speed is set to 8m/s, the wind power capacity is 30MW, the energy storage capacity is 2MW, the power generation capacity of the traditional generating unit is 90MW. The load increased by 4MW when the load was 10s. Figure 15 is the frequency variation curve of the system frequency under the load drop under three different frequency modulation control methods.

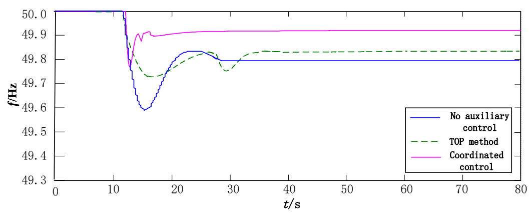

Figure 15. The system frequency response curve

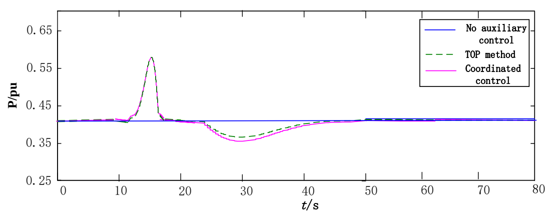

Figure 16. Wind power output curve

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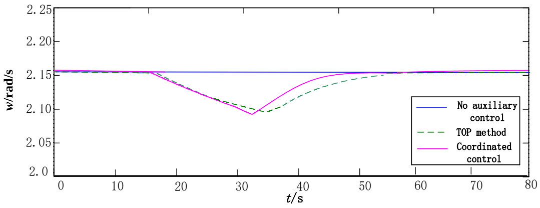

Figure 17. Wind turbine rotor speed

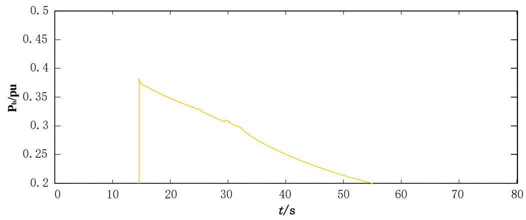

Figure 18. The output power curve

(2) Example two: the permeability of wind power is 32.8%

The wind speed is set to 8m/s, the wind power capacity is 40MW, the energy storage capacity is 2MW, the power generation capacity of the traditional generating unit is 80MW. The system load increased by 7MW at 10s.

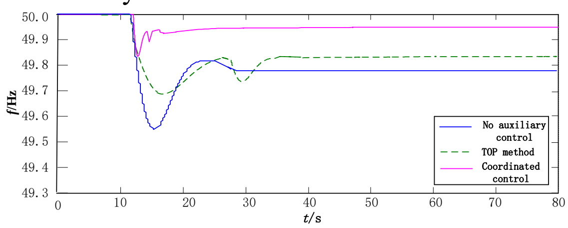

Figure 19. System's frequency response curve

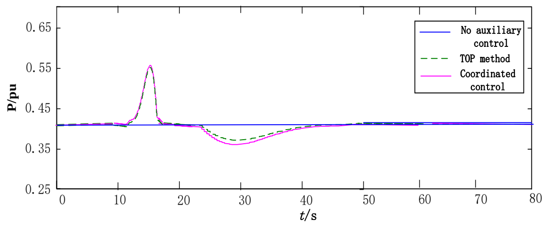

Figure 20. Wind power output curve

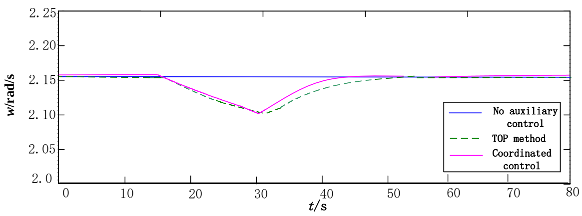

Figure 21. Wind turbine rotor speed

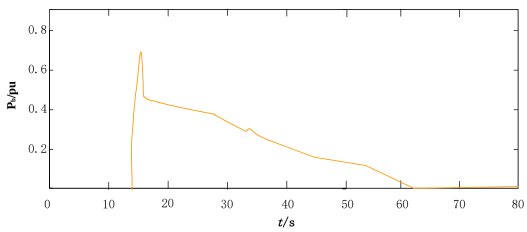

Figure 22. The output power curve of the energy storage system

As can be seen from table 2, the frequency modulation control ability of wind storage combined with frequency modulation is better than that of wind power frequency modulation control and no auxiliary frequency modulation control under different wind power permeability. Compared with other control methods, the minimum frequency of the wind storage joint system is in line with the national standard 0.2Hz deviation of wind power operation frequency, and the frequency recovery time is faster. When the wind power penetration of the system reaches a certain value, if only the conventional generating set is used, it will not provide enough primary frequency modulation support power. The addition of the energy storage system will increase the additional primary frequency regulation reserve capacity for the system. It compensates for the lack of power when the wind power is insufficient, and enhances the system's frequency modulation capability. The frequency modulation effect is optimized.

Table 2. Simulation result

FM method	Wind power permeability 24.6%			Wind power permeability 32.8%		
	Non auxiliary control	Only wind power participati on	Combinat ion of wind and reservoir	Non auxiliary control	Only wind power participati on	Combinat ion of wind and reservoir
The lowest point of frequency fall /Hz	49.59	49.73	49.78	49.55	49.7	49.82

The first drop time of frequency /s	14.5	15	11.5	15	16	12
The lowest point of frequency second drop. /Hz	—	49.75	49.87	—	49.74	49.88
Frequency of restoring stability /Hz	49.8	49.83	49.92	49.78	49.83	49.95

5. Conclusion

In this paper, the research on the relationship between wind power storage system and system frequency regulation is taken as the research background based on the increasing permeability of wind power system and the no-coupling relationship between wind turbine speed and frequency. As the wind power participates in the system frequency adjustment in its speed recovery phase, the system frequency will fall again when the power support of the system decreases. In this paper, a certain capacity of energy storage system is used to improve the frequency modulation effect of the system through the optimization control of wind storage. The simulation results show that the wind storage coordination control strategy in this paper can effectively improve the fluctuation of the system frequency due to load.

Acknowledgments

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