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Research on Primary Frequency Regulation Control Strategy of Wind-thermal Power Coordination

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ABSTRACT With the increase of wind power penetration in the electric grid, the frequency regulation method that simply reply on traditional power is gradually weakened. For this reason, the participation of wind power in system frequency regulation has become an inevitable trend in the operation of large-scale grid-connected power system. Focused on the essential difference of the frequency response speed between wind turbine and thermal power unit, a primary frequency regulation control strategy for large-scale wind power cooperative thermal power units is proposed to realize frequency regulation in the full wind speed range of doubly-fed wind turbines and improve the frequency response capability of large-scale wind power access to system. Firstly, the frequency regulation response strategy of wind turbine based on rotor kinetic energy control and power reserve control and the control strategy of rotor speed recovery are studied to improve the frequency regulation capability of wind power system. Secondly, the optimal distribution of frequency regulation power of the large-scale wind farms is realized according to the establishing of the power distribution strategy based on weight factor of each turbine in the wind farm in different operating scenarios Finally, the control framework of wind-thermal power coordination frequency regulation is constructed. The system power shortage is distributed to the wind farm and the thermal power unit in real time by the dispatch center according to the wind farms' and thermal power unit's operating states and the variation of system frequency, by which the wind-thermal power coordination frequency regulation of power system can be achieved. Simulation results of the 36-node test example demonstrate that the proposed strategy can effectively improve the frequency response capability and the frequency characteristics of the power system.

INDEX TERMS Wind farm, primary frequency regulation, wind-thermal power coordination frequency regulation, speed recovery control, optimal power distribution.

I. INTRODUCTION

As a kind of renewable energy generation, wind generation technology has gradually entered the stage of large-scale development with the increasing penetration of the wind energy in electric system in last decades. Wind turbine generally runs synchronously with the power grid through the converter, but it cannot respond to the change of frequency directly as its rotor is completely decoupled from the grid frequency. As the proportion of wind power capacity in the power grid continues to rise, conventional generator units in the original power system will be continuously replaced in the future. However, the access of large-scale wind energy system will not only significantly reduce the frequency regulation capability of the whole power system, but also bringing problems and difficulties to its dispatching and operation, even affecting the system stability [1], [2].

To tackle these issues and improve the frequency response capability of power systems with high proportion of wind power and to maintain the stability of system frequency, wind turbines must undertake the auxiliary functions of conventional generators such as rotating standby, inertial

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response and frequency regulation. Researches on how the wind power participating in system frequency regulation has attracted the attention of scholars all over the world, and developed controllers mainly concentrate on exploiting the additional control of wind turbines to response to system frequency changes [3], [4], such as the rotor kinetic energy control and power reserve control [5]–[7]. The rotor kinetic energy control includes virtual inertia control [8]–[10] and droop control [11]–[13], even though the system provides frequency support by releasing the kinetic energy of the rotor, the speed recovery control of the wind turbine still needs to be considered in the frequency regulation process. As for the power reserve control, which is mainly realized by the pitch angle control, namely letting the wind turbine deviates from the maximum power operating point and de-load operation, thus reserve certain power for frequency regulation [14]–[16].

At present, researches on the control strategy of wind power participating in system frequency regulation mainly concentrate on a single generator, whereas similar investigations on control strategy for large-scale wind farms are still not mature enough. Generally speaking, a wind farm has at least dozens or even hundreds of wind turbine units, so it is necessary to explore the frequency control strategy on the wind farm level, including the frequency regulation power distribution strategy, the speed recovery control strategy, and the coordinated control strategy among multiple wind farms. In terms of different conditions of wind speed, reference [17] applies the de-load operation concepts to reserve power so that the wind turbine has sufficiently frequency regulation capability, but it neglects the economic benefit of wind farms to some extent. Literature [18] proposes to combine rotor kinetic energy control and power reserve control to support the power using rotor kinetic energy, reducing the impact of power reserve on wind farm economics while ignoring the absorption of power to the system when the rotor is restored, which will result in a second drop of the system frequency.

Focusing on the above problems, and considering the characteristics of fast frequency response and small inertia time constant of wind turbine and the long-lasting frequency regulation capability of thermal power unit, a control strategy for large-scale wind farm cooperated with thermal power plant participating in the primary frequency regulation of system is proposed. The wind-thermal power coordination frequency regulation strategy is developed on the power system level. On the wind farm level, wind turbines are grouped according to different wind speeds and the weighting factor is set to assign the reference value of the frequency-regulated power for each group of wind turbines. On the wind turbine level, the frequency strategy of kinetic energy control and pitch angle control is proposed, and the rotor protection and variable parameter speed delay recovery strategy are added to the rotor kinetic energy control to improve the frequency response capability of the wind turbine. The simulation results of the test example show that the proposed method can fully exert the frequency regulation function of the wind farm, effectively optimize the frequency regulation capability of the power system.

The remainder of this paper is organized as follows. Section II and III present the established frequency regulation control strategy of wind turbine and wind farm respectively. In section IV, a scheme of wind-thermal power coordinated frequency regulation is constructed, and the feasibility and effectiveness of the strategy are verified by a 36-node test example. Section V concludes this research.

II. FREQUENCY REGULATION STRATEGY OF THE WIND TURBINE

As mentioned before, the particularly vector control technology of the wind turbine makes it unable to respond quickly and effectively to the system frequency variation. Therefore, an additional frequency control system is required for the wind turbine to respond to system frequency variation. When the wind speed is 13.5m/s, the active output of the 1.5MW doubly-fed wind turbine can reach to a nominal value. For this reason, the wind speed of 13.5m/s is taken as the critical point so that the rotor kinetic energy control and the pitch angle control are combined to take part in the system frequency regulation. When the wind speed is $v < 13.5$m/s, the rotor kinetic energy control is adopted and the rotor kinetic energy is released to make it successfully participate in the system frequency regulation by converting the rotational kinetic energy stored in the rotor of the turbines into electromagnetic power; when the wind speed is $v \geq 13.5$m/s, the pitch angle control is utilized by the wind turbine to reduce the active output by changing the pitch angle β, so that the wind turbine output power is maintained in the constant range and leaves certain stored power. Fig. 1 describes the frequency control strategy of the wind turbine.

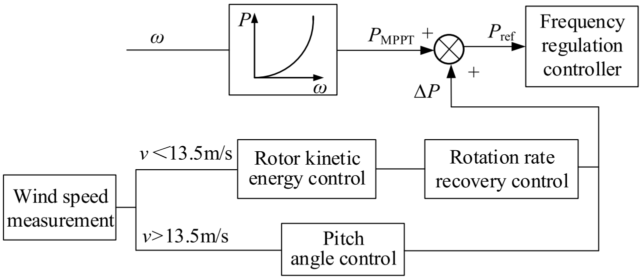


FIGURE 1. Frequency regulation strategy of the wind turbine.

The wind turbine frequency regulation strategy of Fig. 1 includes rotor kinetic energy control, rotor speed recovery control and pitch angle control.

A. ROTOR KINETIC ENERGY CONTROL

Rotor kinetic energy control mainly involves additional virtual inertia control and droop control. The function of virtual inertia control is to make the wind turbine possess the same natural frequency regulation capability as the conventional generator, by which way to enable the wind turbine to adjust the system frequency by simulating the characteristics of moment of inertia of the synchronous machine. In addition, the principle of the droop control is to simulate the static frequency characteristic curve of the active power of the synchronous machine and appropriately adjust the active output of the wind turbine. From the above analysis, an integrated frequency regulation strategy that combines the characteristics of virtual inertial control and droop control effectively is developed to form the rotor kinetic energy control, namely the integrated control. The block diagram of the integrated control is shown in Fig. 2:

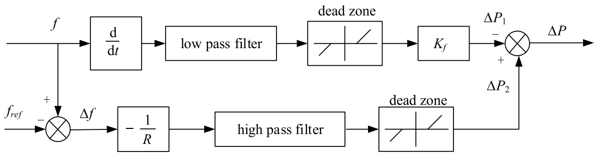


FIGURE 2. Integrated control simplified lay out.

It can be seen from Fig. 2 that the frequency regulation control of the wind turbine is realized by adding a reference value of the additional active power to the turbine, wherein ΔP_1 is the active power reference value of the virtual inertia loop, and ΔP_2 is the active power reference value of the droop control. Among them, ΔP_1 is proportional to the system frequency change rate, whose specific expression is as follows [2]:

$$\Delta P_1 = -K_f \frac{\mathrm{d}f}{\mathrm{d}t} \tag{1}$$

where K_f represents the virtual inertia control coefficient, whose value is 2; f denotes the frequency; t is the time.

A low-pass filter is added to the control loop to eliminate noise interference during frequency measurement and eliminate the individual excessive signal among the control signals.

The droop control active power reference value ΔP_2 is proportional to the frequency deviation. The specific equation [2] is expressed as:

$$\Delta P_2 = -\frac{1}{R}\Delta f \tag{2}$$

where R denotes the regulation coefficient and is taken as 0.03 here.

A high-pass filter is added to filter out the steady-state input signal and enable the droop control only respond to the dynamic frequency deviation signal.

The adoption of the frequency regulation power reference value ΔP_1 and ΔP_2 can improve the response of the wind turbine to the system frequency and prevent the frequency from changing too fast and reduce the system frequency deviation. By controlling ΔP_1 and ΔP_2, wind turbine can respond to system frequency changes and adjust frequency rapidly.

B. SPEED RECOVERY CONTEOL

Based on the law of conservation of energy, after the wind turbine releasing the kinetic energy of the rotor and providing short-term active supplement for the system, the rotor speed cannot be maintained in deceleration stage for a long time. The maintenance time of rotor speed varies from several seconds to tens of seconds according to the operation conditions of the wind turbine. After that the rotor speed of the rotor will be restored to the initial operating state. At this time, the rotor of the wind turbine will absorb the active power of system and even give rise to the system frequency drop again if controlling improper. Consequently, it is necessary to study the frequency regulation-exit control strategy for wind turbine [19], [20]. The time needed for the wind turbines exiting the frequency regulation and recovery of the rotor speed relates to the change of wind speed. When the wind speed increases, the time for the rotor of the wind turbine to obtain kinetic energy will be effectively accelerated. For this reason, the recovery time is also short, and recovery can be completed in a several seconds, even without recovery control; when the wind speed decreases, the wind turbine should immediately exit the frequency regulation. Considering the short time for frequency regulation and the wind speed fluctuate slightly during the frequency regulation period, this paper proposes to carry out the recover control of frequency regulation for wind turbines with the wind speed being constant, the specific control method is shown in Fig. 3:

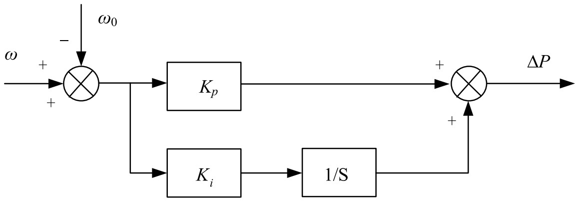


FIGURE 3. Rotor speed recovery control during frequency regulation.

In Fig. 3, ω_0 stands for the initial value of the rotor speed before modifying frequency. The rotor speed ω is compared with the initial value ω_0 timely, and then the wind turbine is controlled by the PI regulator to sequentially exit the frequency regulation mode. In order to make the rotor speed of the wind turbine units recover smoothly, this paper adopts the PI controller to eliminate the rotor speed deviation by stepwise in case the output power of the rotor speed recovery change suddenly, so that the system frequency is prevented from falling twice. The proportional coefficient K_p and the integral coefficient K_i are bounded by the control of variable parameters, the specific value range are as follows:

$$K_p = \begin{cases} 0 & t < t_b \\ \dfrac{t - t_b}{\delta} & t_b \le t \le t_b + \delta \\ K_1 & t > t_b + \delta \end{cases} \tag{3}$$

$$K_i = \begin{cases} 0 & t < t_b \\ \dfrac{t - t_b}{\delta} & t_b \le t \le t_b + \delta \\ K_2 & t > t_b + \delta \end{cases} \tag{4}$$

In equations (3) and (4), t_b is the time at which the rotor speed starts to recover, and δ is the time constant of the PI controller, where the values of K_p and K_i gradually change with time until the stable values K_1 and K_2 are reached.

In the initial stage, K_p and K_i gradually increase along the curve from zero, which effectively avoid the matter of active power drop caused by the fixed parameter choice, which can not only control the jumping phenomenon of power value caused by recovery of the rotor speed but also shorten the recovery time. The specific values of the above parameters are divided into three segments according to wind speed as follows:

When the wind speed varies in [8,10), $t_b = 0.8$s, $\delta = 0.6$; in [10,12), $t_b = 2.7$s, $\delta = 0.7$; in [12,13.5), $t_b = 4.4$s, $\delta = 0.8$; besides, $K_1 = 1.1$, $K_2 = 0.15$.

In order to ensure the safe operation of the wind turbine and avoid over-regulation, the rotor speed protection module is added in the Speed recovery control. When the rotor speed $\omega < 0.7$p.u., the rotor protection module is activated and the wind generator immediately exits the frequency regulation mode.

C. PITCH ANGLE CONTEOL

The pitch angle control can be applied to the whole wind speed segment in principle and participates in the adjustment of the system frequency by leaving a certain reserve power. While in actual engineering, to pursuit the maximizing profit, the wind power enterprise usually tracks the maximum power point in the low wind speed segment and not supplies active power reserve to the system. Hence the pitch angle control strategy of wind turbines is extensively used in high wind speed conditions.

The wind turbines maintain a certain power reserve for ensuring that the turbines operate in a constant power stage. The pitch angle control chart is depicted in Fig. 4:

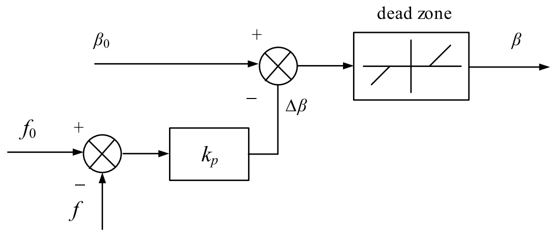


FIGURE 4. **Pitch angle control.**

In Fig. 4, β_0 is the initial pitch angle of the wind turbine, f_0 is the initial frequency of the system, k_p is the proportional coefficient, and $\Delta\beta$ is the variation of the pitch angle. The specific control process is shown in Fig. 5.

III. WIND FARM FREQUENCY REGULATION STRATEGY

Since the geographical location of the wind farm generator units are different, the wind speeds received by each turbine are different. In the power characteristic curve of the wind turbine in Fig. 6, the active power that wind generators export differently when they operate in the maximum power tracking state under different wind speeds can be seen. The kinetic energy of the rotor under normal operation of the wind turbine is as follows:

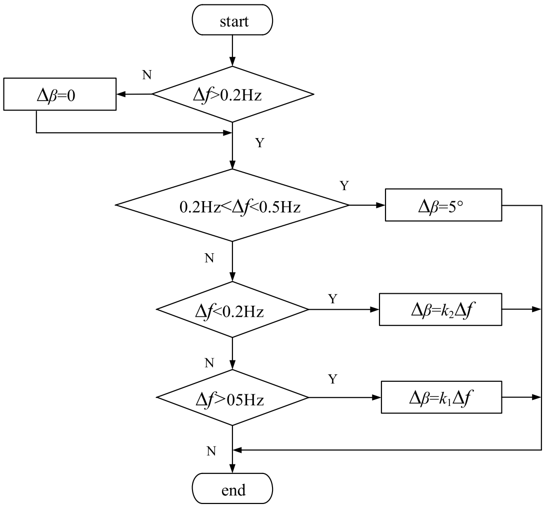


FIGURE 5. **The flow chart of frequency regulation under the pitch angle control.**

$$E = \frac{1}{2} J \omega^2 \tag{5}$$

In formula (5), J is the rotor inertia of the wind turbine.

The function of kinetic energy control of the wind turbine rotor is to participate in the primary frequency regulation and temporarily provide power supplement by releasing the kinetic energy of the rotor. However, different operating conditions of the unit result in different ability to regulate frequency through the kinetic energy of the rotor. Taking the two operating points a and b in Fig. 6 as example, they are restricted by the lower limit of the rotor speed during rated operation period of the wind turbine, and the maximum kinetic energy that can be released when the wind turbine operating at the points a and b are as follows:

$$\Delta E_a = \frac{1}{2} J (\omega_a^2 - \omega_{\min}^2) \tag{6}$$

$$\Delta E_b = \frac{1}{2} J (\omega_b^2 - \omega_{\min}^2) \tag{7}$$

Equations (6) and (7) show that the energy released by the wind turbine is changing with wind speeds, and the energy released by the wind turbine at point b is greater than point a.

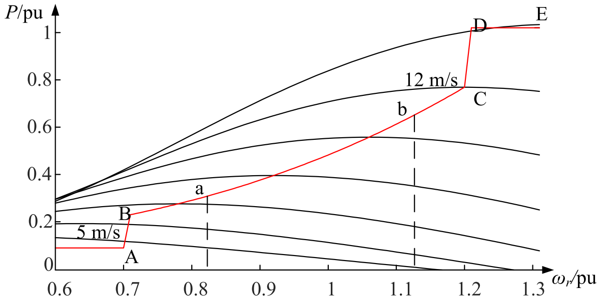


FIGURE 6. **The curve of $P - \omega_r$.**

Above analysis indicates that the frequency regulation capability of wind turbine is influenced by different wind conditions. The higher the wind speed, the stronger frequency regulation capability and the longer it lasts.

Notice that the wind turbine located in different position acquires different wind speed and in turn affects the frequency regulation capability of wind turbines, if each turbine is controlled one by one, workload will be enlarged and time consuming, hence this paper groups the wind turbines and determines their active power reference values according to the wind speed, the specific grouping rules are as follows:

(1) Set the minimum wind speed cut-in value to participate in the frequency regulation. The rotor speed of wind turbine should be higher than the synchronous operation speed of 0.7p.u. for ensuring wind turbines enter the system primary frequency regulation [21]. All the wind generator units involved in this paper are 1.5MW double-fed units, and the corresponding wind speed is about 6.7m/s according to the minimum speed of 0.7p.u..In order to improve the safety of wind power participating in frequency regulation, the value of the minimum wind speed for frequency regulation should be as conservative as possible, which is taken as 8m/s in this paper.

(2) Regulate the frequency according to the wind speed segment. Due to the large number of units in large-scale wind farms, it is difficult to control the frequency and orderly recover the rotor speed according to the measured wind speed. To this end, the wind turbines are grouped into different wind speed segments, and the same frequency regulation control strategy and rotor speed recovery strategy are applied in each group. When the wind speed exceeds 13.5m/s, the wind turbine enters the constant power zone where the variation of wind speed does not affect the output power, and it does not participate in the wind speed grouping. Since the wind speed value of the wind turbine at a certain moment is not completely an integer, the wind speed is rounded down to an integer, and the wind speed value of 13.5m/s is retained, namely, taking 8m/s, …, 12m/s, 13m/s and 13.5m/s for grouping.

(3) Calculate the active power reference value. In order to give full play to the frequency regulation capability of wind turbines under different wind conditions, a method using the weighting factor and setting the weighting factor for the turbines within different wind speed segments to distributing the frequency regulation power is proposed. The wind speed segments groups and the corresponding weighting factor settings are listed in Table 1:

TABLE 1. **Weighting factors of each wind speed segment.**

Wind speed(m/s)	Weighting factors
[8-10)	2
[10-12)	4
[12-13.5)	10

The distribution factor of wind turbines within each wind speed segment can be calculated by the weighting factor and the number of turbines in each wind speed segment. The calculation formula is as follows:

$$DF_{WT}(v_g) = \frac{W(v_g) \times N(v_g)}{\sum W(v_g) \times N(v_g)} \times \frac{1}{N(v_g)} \tag{8}$$

where $DF_{WT}(v_g)$ denotes the distribution factor for each wind speed segment; $W(v_g)$ is the weighting factor for each wind speed segment; $N(v_g)$ is the number of wind turbines within each wind speed segment.

Next, the active power setting value of each group of wind turbines is calculated according to the active power demand and distribution factor of the wind farm, whose calculation formula is:

$$P_{ref}(v_g) = P_{WF} \times DF_{WT}(v_g) \tag{9}$$

where $P_{ref}(v_g)$ is the active power setting value of each group; P_{WF} stands for the required additional active power for wind farms. The distribution of active power to the wind turbines based on the distribution factor enables the units with higher wind speed to obtain a higher power setting value and give full play to the frequency regulation capability of each unit.

Strategy for wind turbines exits the frequency regulation mode. The wind turbine with rotor kinetic energy control provides the additional active power to system by sacrificing the rotor speed. In order to avoid the wind turbines from exiting the frequency regulation due to the low speed and triggering the action of rotor speed protection module, the wind speed segment that the wind turbines belong to and the power increments they generate are taken as the judgment basis for how they exit frequency regulation mode in sequence. To be specific, the power increment generated from wind turbines within the low-speed segment is lower than that within the high-speed segment, so the former ones exits the system frequency regulation mode prior to the latter ones. According to the wind speed segment divided by Table I, when the wind turbine within the lower wind speed segment exits the frequency regulation mode, t_{b0} is determined as the recovery initial time, and the remaining groups sequentially add a delay time Δt based on the recovery time of the previous group. Therefore, the turbines within different wind speed segments can be orderly removed from the frequency regulation mode, and the system frequency can be stably and quickly recovered on the basis of ensuring the normal operation of turbines. Taking into account of the safety and reliability of the rotor speed recovery control as well as the frequency regulation characteristics of the thermal power unit, wind turbines within all the wind speed sections should exit the frequency regulation mode as soon as possible. For this reason, $\Delta t = 1.7$s is determined.

IV. PRIMARY FREQUENCY REGULATION STRATEGY FOR THE WIND-THERMAL POWER COORDINATION SYSTEM

The conventional generator can only respond to the power deficiency and frequency fluctuation after the power grid fault 5s, and the active power can be increased steadily 10-15s after the frequency dropping. The wind turbine responds quickly but only provides short-term active power output. In order to solve the problem that the synchronous generator cannot quickly compensate for the system frequency drop before 5s, a wind turbine is needed to take part in the grid frequency regulation.

Therefore, this paper proposes to take use of the rapid responsiveness of wind power to make up for the power vacancy of traditional generators in 0-5s, by combining the stability of frequency regulation of thermal power unit with the good response characteristic of wind farm, and the fast and stable return of power grid frequency is ensured, which can improve the frequency response capability of the system on one hand, and actively eliminate the wind-off phenomenon of wind power on the other hand. Fig. 7 is a flow chart for the coordinated dispatching of wind farms and thermal power plants:

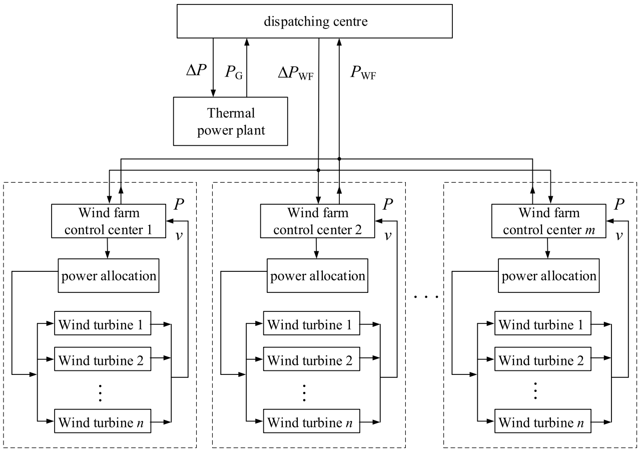


FIGURE 7. **Wind-thermal coordinated frequency regulation scheme.**

As seen in Fig. 7, the wind-thermal coordinated frequency regulation relies on the dispatching center to allocate power shortage, therein the collaborative process includes the coordination of thermal power units with wind farms and the coordination of wind turbines within the wind farm. According to the power reserve that the thermal power plant and wind farm upload in real time after the system frequency dropping, and the dispatch center sends the power shortage to thermal power plant and wind farm dynamically, in this way the thermal power plant and the wind farm control center performs frequency adjustment, of which the wind farm control center groups the wind turbines according to the real-time wind speed and realizes the optimal allocation of the frequency regulation power based on the weighting factor, thus to respond to system frequency variation quickly.

Once the system power frequency drops, the active power shortage ΔP occurs and then the shortage signal is issued to the wind farm and the thermal power plant timely. Thanks to the fast respond ability of wind farm to the frequency variation and due to the time lag of mechanical actuator of the pitch angle control system compared to the kinetic energy control of the rotor, if v <13.5m/s, the wind turbine will release the rotor kinetic energy rapidly after receiving the vacancy signal ΔP and provided the system with short-term active support firstly. Then, the turbines with v ≥13.5m/s release reserve power to the system by the pitch angle control. The total active power that the wind farm can increasingly provide is expressed as P_{WF}, and the active power that the wind farm needs to increasingly provide is denoted by ΔP_{WF}, which can be expressed as:

$$\Delta P_{WF} = \begin{cases} \Delta P & P_{WF} \geq \Delta P \\ P_{WF} & P_{WF} < \Delta P \end{cases} \tag{10}$$

After providing additional short-term active power to the system, the thermal power plant has gradually achieved stable and active power increasing state due to the short-term supplement of the wind farm. At this time, the wind turbine enters the speed recovery state and exits the system frequency regulation mode. The additional active power that the thermal power units generate can be expressed as:

$$P_G = \sum_{i=1}^{m} P_{Gi} \tag{11}$$

where m is the number of thermal power units in the thermal power plant; P_{Gi} denotes ith power thermal power unit to generate additional active power in the thermal power plant.

V. SIMULATION AND ANALYSIS

A. OVERVIEW OF THE TEST EXAMPLE

In this paper, the feasibility and effectiveness of the proposed wind-thermal power coordination frequency regulation control strategy are verified by the 36-node test example whose wiring diagram is shown in Fig. 8. The test example includes 8 synchronous generators G1∼G8 with a total installed capacity of 5765 MW and a total load of 4200 MW. In order to verify the feasibility of the above control strategy, this paper replaces the two synchronous generators No. 7 and

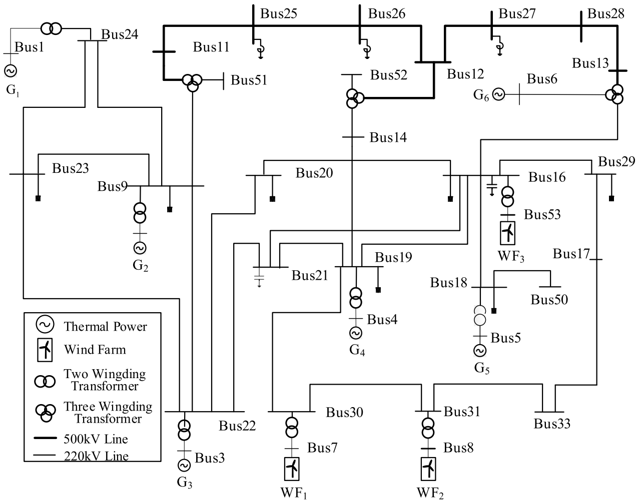


FIGURE 8. **36-node network wiring diagram.**

No. 8 with wind farms WF1 and WF2, and merges the wind farm WF3 into the Bus16 node, thus forming a power system that consisting of six synchronous generators and three wind farms. There are 495 doubly-fed wind turbines with the rated capacity of 1.5MW in the three wind farms in total, and the total installed capacity is 742.5MW with a wind power grid connection ratio of 17.7%. Under the initial conditions the system operates normally with a frequency of 49.97 Hz without the access of wind farm.

The wind farm operation data is derived from the measured values of three wind farms in Baotou area which are assumed to participate in the system frequency regulation according to the cooperative frequency regulation strategy proposed in this paper. Among them, the governor of the synchronous generator adopts a unified speed controller to achieve no-deviating adjustment, and the control block diagram is shown in Fig. 9.

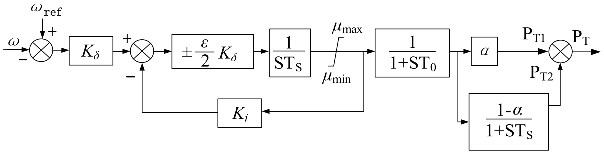


FIGURE 9. Synchronous generator speed controller.

In Fig. 9, K_δ is the magnification factor for measurement link, ε is the governor dead time, T_S is the time constant of the servo mechanism, $\mu_{\max}$, $\mu_{\min}$ denotes the upper and lower limits of the valve opening respectively. T_0 is the steam volume time constant (s), α is the overheat coefficient of the turbine and K_i is the feedback amplification factor.

B. SIMULATION AND CALCULATION

To verify the property of wind-thermal power coordination frequency regulation, a load is added to the power system suddenly as disturbance, namely 200MW is added to Bus20, Bus23 and Bus29 respectively, for a total load of 600MW. Wind speeds of the three wind farms are different due to the positional difference. Combining with the measured data, the way that wind farm participating in the system frequency regulation is organized into three scenarios in this paper. Firstly, the three wind farms are all running below the rated wind speed, which is the low wind speed segment. Secondly, the three wind farms are all running above the rated wind speed, which is the high wind speed segment. Thirdly, among the three wind farms, WF1 and WF2 operates in the low wind speed segment, while WF3 operates in the high wind speed segment, that is, the full wind speed segment. Next, the performance of the wind-thermal power coordination frequency regulation technique is analyzed under the three operating scenarios of the wind farm.

The system frequency response process of the wind power when it connects to the grid but not participate in frequency regulation is firstly calculated. When t=1s, the system suddenly increases a power load of 600MW and the simulation results are shown in Fig. 10.

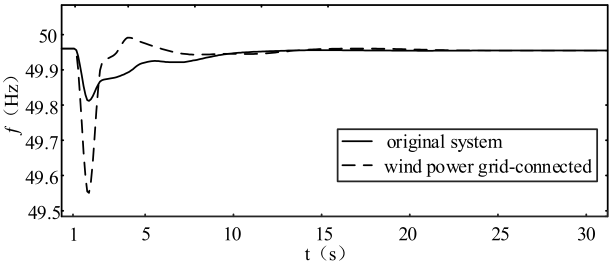


FIGURE 10. Wind power into system frequency.

As can be seen in Fig. 10, the access of wind power is significantly increased in the frequency drop of the system. The maximum drop reached 0.43Hz, which has exceeded the allowable range of China's power grid frequency and may cause grid frequency instability problems. For this reason, wind farms are decided to participate in the system frequency regulation to ensuring the safe and stable operation of the power grid.

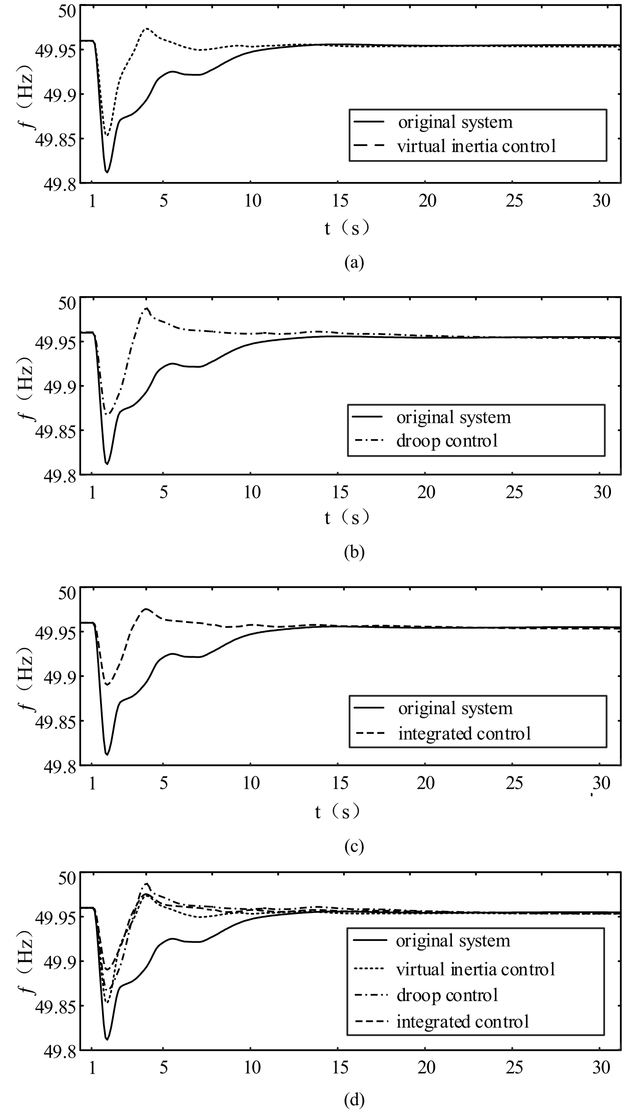
The wind-thermal power coordination frequency regulation strategy under the three operation scenarios of the wind farm are analyzed separately. To be specific, all the three wind farms operate in the low wind speed segment are defined as scenario 1; all the three wind farms operate in the high wind speed segment are defined as the scenario 2; two wind farms operate in the low wind speed segment and the other one wind farm in the low wind speed segment is defined as scenario 3.

1) SCENARIO 1

As mentioned above, when a wind turbine operates in the low wind speed segment, the rotor kinetic energy control method is applied by it to participate in the system frequency regulation which includes the virtual inertia control and the droop control, and the performance of the integrated frequency regulation control strategy proposed in this paper are compared with them. The sudden increased load of 600 MW is added to system as the disturbance at 1s, the calculation results are shown in Fig. 11.

It can be seen in Fig. 11 that by adopting the rotor kinetic energy control of wind turbine, the frequency response capability of power system is effectively improved, which effectively suppress the frequency drop and improve the frequency stability of the power system after being disturbed by the sudden addition of load. Among them, the integrated control has the optimal frequency regulation effect and the smallest frequency fluctuation. To illustrate the mechanism of wind power to participate in system frequency regulation furtherly, Fig. 12 and Fig. 13 presents the rotor speed of the wind turbine and output power of wind farm 1.

It can be seen in Fig. 12 and Fig. 13 that the variation curve of the rotor speed of wind turbine and the wind farm output power are coincide with the theoretical investigate of the rotor kinetic energy control. The output power is increased by reducing the rotor speed to support the power system and perform primary frequency regulation.



(a)

(b)

(c)

(d)

FIGURE 11. Rotor kinetic energy control (a) virtual inertia control. (b) droop control. (c) integrated control. (d) Comparison of three control strategies.

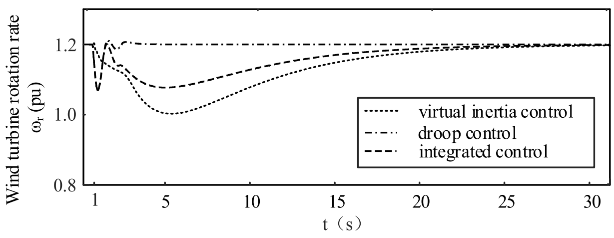


FIGURE 12. Rotor speed of the wind turbines.

After releasing the rotor kinetic energy by reducing the rotor speed and providing a short-term power support for the system, the rotor speed needs to be restored to stable state. Since the rotor speed is recovered by absorbing active power from the system and which would easily cause a secondary drop of the system frequency, the proposed strategy for wind turbines exiting the frequency regulation mode is simulated, and the results are shown in Fig. 14.

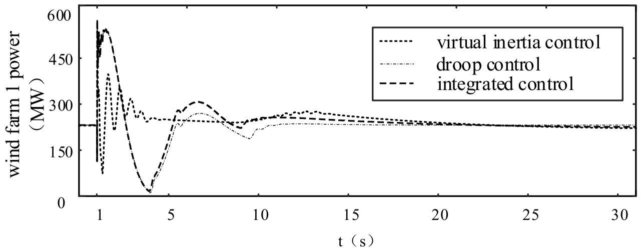


FIGURE 13. Output power of wind farm 1.

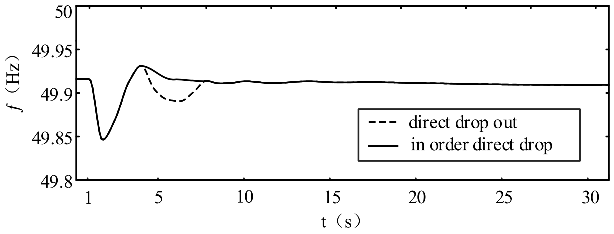


FIGURE 14. Wind farm orderly exits the frequency regulation mode of the system.

It is observed that if all wind turbines exit the frequency regulation directly at the same time, it brings out obvious frequency drop phenomenon. Fig. 14 shows that after exiting the frequency regulation mode orderly, the system frequency would not drop again and recover to stable value quickly.

Simulation results of the rotor speed of the three wind speed segments of the wind farm 1 are shown in Fig. 15.

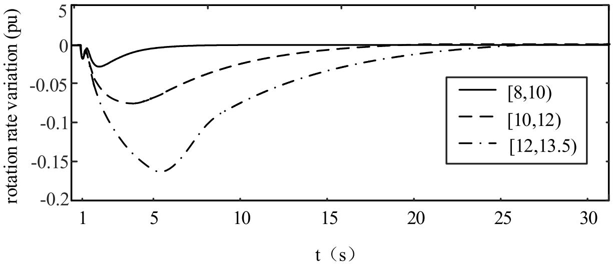


FIGURE 15. Wind farms orderly exit the frequency regulation.

Fig. 15 shows that the wind turbines exit the frequency regulation mode sequentially and orderly in the light of their different frequency regulation capabilities, then the rotor speed is restored by the variable parameter PI controller until it achieved the speed before regulating the frequency.

2) SCENARIO 2

As noted earlier, when the wind turbines operate in the high wind speed segment, the pitch angle control technique is used to control them participate in the system frequency regulation. k_1 and k_2 are taken as 60 and 93 respectively in the simulation process. The disturbance mode is same as that in Scenario 1, and the system frequency variation under the pitch angle control is shown in Fig. 16.

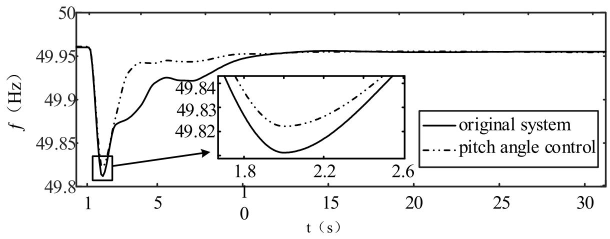


FIGURE 16. **The system frequency variation under the pitch angle control.**

It can be seen in Fig. 16 that the minimum system frequency drop is similarly to that of original system under the pitch angle control strategy. This phenomenon can be explained by that the output power under the pitch angle control has a certain hysteresis so it fails to timely supply the power vacancy. However, by taking the pitch angle strategy the system frequency recoveries much faster than that of the original control method for all thermal power units, which verifies the feasibility of the wind-thermal power coordination regulation of the primary system frequency furtherly.

The rotor speed and wind farm output power curve under the pitch angle control are drawn in Fig. 17 and Fig. 18.

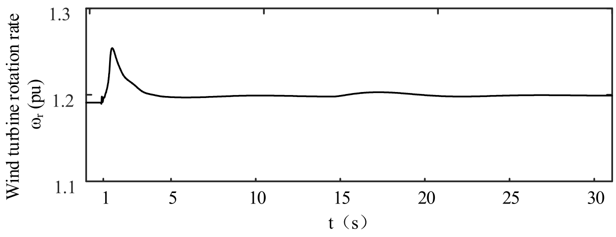


FIGURE 17. **The rotor speed of the wind turbine under the pitch angle control.**

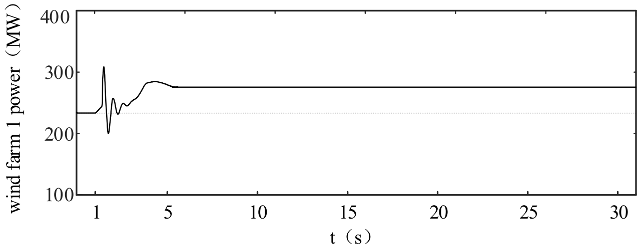


FIGURE 18. **Output power of wind farm under the pitch angel control.**

As shown in Fig. 17, the rotor speed of the wind turbine rises visible under the pitch angle control at first, and it gradually decreases and tends to steady along with the increasing of output power. The increasing process of the wind farm active power can be clearly seen in Fig. 18. In this period the wind turbine provides a certain amount of power supporting to the system.

3) SCENARIO 3

Scenario 3 introduced the frequency regulation strategy of the simultaneously action of rotor kinetic energy control and pitch angle control. Because the rotor kinetic energy control and the pitch angle control have been simulated in detail before, and both the two control strategies improve the primary frequency regulation capability of the power system, for scenario 3, the frequency variation of the test example is chiefly simulated and the simulation result is shown in Fig. 19.

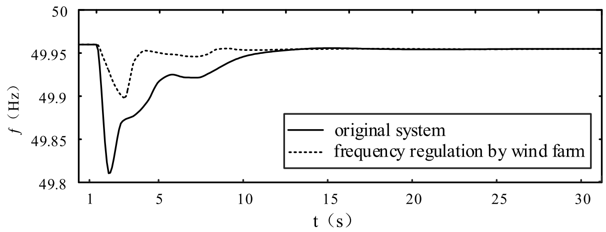


FIGURE 19. **System frequency under the simultaneously action of rotor kinetic energy control and pitch angle control.**

It can be seen in Fig. 19 that the frequency response capability of the power system is desirably enhanced after launching the rotor kinetic energy control and the pitch angle control simultaneously, and the frequency fluctuation is quickly adjusted, which improves a lot than the original system. Therefore, the participation of wind power in system frequency regulation is testified being beneficial to the primary frequency regulation.

VI. CONCLUSION

The rotor of wind turbines is complete decoupled with the grid frequency which makes it fails to respond to the change of the system frequency and participate in power system frequency regulation. To solve this problem, the wind-thermal power coordination regulation strategy of the primary frequency of power system is investigated in this paper, the main conclusions can be reached as follows:

1) The participation of power system frequency regulation in the full wind speed range of doubly-fed wind turbines is achieved through the establishing of the frequency regulation control scheme of large-scale wind power cooperative thermal power unit and the mathematical model of wind-thermal coordination frequency regulation.

2) The simulation model of wind-thermal cooperative frequency regulation control is established through 36-node test example. The simulation results show that the frequency regulation performance of integrated frequency regulation control strategy of wind turbine is better than that of virtual inertia control and droop control strategy, and the exit mode can be recovered orderly, which ensures the reliability of wind power participation system frequency regulation.

3) The frequency response capability of large-scale wind power access to system is significantly improved through wind-thermal power coordination frequency regulation and

the feasibility and effectiveness of the participation of wind power in system frequency regulation are verified.

The research results in this paper can provide a theoretical basis for the implementation of large-scale wind farm participation in primary frequency regulation of power system. It is suggested that relevant departments formulate guidelines for wind farm participation in primary frequency regulation of power system as soon as possible to improve the dominant position of wind power frequency regulation and lay a technical support for the development of large-scale wind power.

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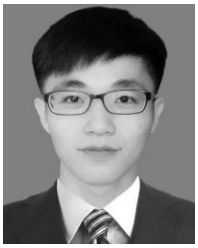

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