Coordinated control of rotor kinetic energy and pitch angle for large-scale doubly fed induction generators participating in system primary frequency regulation

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Abstract
This paper presents a control strategy of large-scale wind-thermal power joint primary frequency regulation. First, an integrated control strategy is established rotor kinetic energy control and pitch angle control for wind turbine generators participation in frequency regulation within a wide range of wind velocity; Second, a fuzzy PI controller is designed for the recovery control of the wind turbine, which can avoid the occurrence of the frequency secondary drop accident during the wind generator exits the frequency regulation. Third, an optimal allocation power strategy of wind generator frequency modulation based on weighting factors is proposed in different operating conditions to make full use of the frequency modulation capability of wind turbine rotor kinetic energy control, and the strategy of orderly exiting the frequency modulation of the wind generators is established. Finally, the control framework for proposing the strategy is constructed to enhance the primary frequency regulation ability of large-scale wind generators connected to power systems. The feasibility of proposing the strategy is verified by two examples. The results show that the presented strategy is able to heighten the characteristics of the power system frequency response available and provide a reference for power system scheduling with large-scale wind power.

1 INTRODUCTION

The increasing of wind power penetration puts more stringent requirements on the safe and stable operation of the power system. To ensure the real-time balance of power in the power system, considering that the active output of wind power is difficult to predict, the standby power of the system is required to increase synchronously with the scale of wind power development and the corresponding reserve capacity is configured to guarantee the safety and stability of the power system operation [1]. Since the synchronous operation of the doubly-fed generator with power grid through the converter, the frequency of the generator rotor and the power grid is completely decoupled, so it cannot directly respond to system frequency variations like a synchronous generator [2–5]. Hence, the frequency regulation power is fully borne by the traditional synchronous generator.

According to the “13th Five-Year Plan for Wind Power Development” issued by the National Energy Administration of China in 2016, China will continue to increase the wind power generation proportion, and realize the transformation of wind power generation from supplementary energy to alternative energy. In this way, the proportion of thermal power units with frequency regulation capability is gradually decreasing, but the penetration of wind generators that cannot respond to frequency variations in system is rising. As a result, this phenomenon not only increases the frequency regulation pressure of synchronous generators, especially the peak regulation pressure, but also brings great difficulties to the dispatching and operation of power system.
To make the wind generator with primary frequency regulation capability, a large amount of research work has been carried out by international and domestic academics. The research mainly focused on the exploit of assist control of wind turbines to respond to the system frequency variations for achieving wind generator partakes in the system frequency modulation. Its main control methods contain the application of additional frequency response control for the wind turbine itself [6, 7] and the configuration of energy storage devices for the wind farms [8, 9]. Of these, the principle of peak shaving and frequency regulation is simple to configure energy storage devices for wind farms, but the cost is high, which is not suitable for large-scale promotion at present. The main strategies for additional frequency response control of the wind turbine itself are power standby control and rotor kinetic energy control [10–13]. Power standby control involves pitch angle control and rotor overspeed control, and the latter contains droop control and virtual inertia control.

Morren J et al. first proposed a virtual inertia concept that the rotary inertia characteristic of synchronous generators is simulated by the virtual control [14]; this control provides the power of frequency regulation by discharging the wind turbine rotor's kinetic energy to implement the wind generator participation in the system frequency regulation [15]. Droop control [16] is achieved by simulating the active power static frequency characteristic curve of a synchronous generator so as to adjust the active power of the wind generator appropriately. Both controls supply active power support by discharging rotor kinetic energy to the system, but the wind turbine rotor speed has a lower limit so that the time for rotor kinetic energy control to adjust frequency is transient, usually no more than 6 s [17], which also needs to consider rotor speed recovery control at the same time. Power standby control is to reserve a certain amount of power for the wind turbine through overspeed or pitch control to support system frequency regulation, and the wind generator runs in de-loading state at this time [18, 19].

At this stage, research on wind power frequency regulation is mostly concentrated on the control strategy of a single generator, and the investigation of large-scale wind generators partaking in power system frequency adjustment is still not mature. Therefore, frequency control strategies of large-scale wind power need to be explored. These strategies include the allocation of frequency-regulated power between wind generators, the exit mode control strategy of wind generators frequency regulation and the coordinated control strategy between wind farms. Ref. [20] proposes a standby control mode for frequency regulation, based on the different velocities of wind farms, but it is not conducive to the economic benefits of wind farms. Ref. [21] presented a frequency regulation method in combination with two control strategies, namely power standby control and rotor kinetic energy control but the rotor speed recovery of the wind turbine is not considered when the latter control is adopted, resulting in the secondary frequency drop in system.

According to the characteristics of small inertia time constant and fast frequency response of wind generators as well as the constant frequency regulation ability of thermal power units, this paper proposes a primary frequency regulation control strategy for large-scale wind power joint thermal power units and constructs its control framework to raise the response ability of large-scale wind generators to the frequency change of power system. The simulation results of the example show the frequency modulation strategy of wind-thermal power joint can effectively optimize the frequency regulation capability of the power system and provide certain technical support and method guidance for the dispatch and control of power system.

The rest of this paper is described below. Section 2 describes the control method of frequency regulation and the strategy of wind generators as well as establishes the model of the rotor kinetic energy control and pitch angle control. In section 3, frequency regulation strategy of large-scale wind generators participation in the system is investigated, including the optimal allocation of frequency regulation power of wind generators and the control strategy of orderly exit of wind generators from frequency regulation mode. Section 4 constructs a wind-thermal power joint frequency regulation control scheme. Section 5, a 36-node test example is given to verify the practicable and availability of the proposed strategy. Section 6 summarizes this paper.

## 2 WIND TURBINE FREQUENCY REGULATION STRATEGY

Wind turbines can respond to frequency variety of the system by setting additional extra system in frequency control. Because of the randomness and uncontrollability of the output power of wind generators, its frequency regulation capability is related to its own operating status, so that the frequency regulation capability of wind generator is different under different wind velocities. The generators involved in this paper are doubly-fed wind turbine generators with a rated power of 1.5 MW, and their rated wind velocity is 13.5 m/s. To ensure the economy and safety of wind generators participating in system frequency modulation, 13.5 m/s is set as the critical point of the wind velocity, the automatic switching between rotor kinetic energy control and pitch angle control is realized, and the frequency regulation performance of wind generators is enhanced. When the wind velocity is $v < 13.5$ m/s, adopting the rotor kinetic energy control to release the rotor kinetic energy, and the stored rotational kinetic energy is converted into electromagnetic power to make wind turbine participate in the system frequency adjustment [22]. When the wind velocity is $v \geq 13.5$ m/s, the pitch angle control is utilized to reduce the active power output of the wind turbine by changing the pitch angle. Therefore, the output power of the wind generator is kept in a constant region and left a certain reserve power.

### 2.1 Frequency control of wind generator at full wind speed

This paper proposes a frequency modulation strategy for wind power participating systems in the full wind speed range. Of these, rotor kinetic energy control is used at rated wind speed,
and pitch angle control is used at rated wind speed to realize real-time frequency modulation of wind turbines.

### 2.1.1 Rotor kinetic energy control

Rotor kinetic energy control is to add a frequency control link to the active power control system of the wind turbine, which provides short-term frequency modulation power by releasing the rotor kinetic energy to maintain the system frequency stability. The kinetic energy stored in the rotor of a wind turbine is:

$$ E_k = \frac{1}{2} / \omega^2 $$

Where, $f$ expresses the moment of inertia of the rotor. The rotor kinetic energy is released from the reduction of the rotor speed of a doubly fed wind turbine generators from $\omega_1$ to $\omega_2$ can be computed as follows:

$$ \Delta E_k = \frac{1}{2} f \Delta \omega^2 = \frac{1}{2} f (\omega_1^2 - \omega_2^2) $$

The rotor speed range of the doubly-fed wind turbine generators can be operated between 0.7 and 1.2 p.u. Therefore, wind generators can participate in system frequency adjustment by the virtual inertia control.

When the wind generator responds to the frequency variation of the system by virtual inertial control, its rotor motion equation is as follows:

$$ f_w \omega_s \frac{d \omega_s}{dt} = f_w \omega_r \frac{d \omega_r}{dt} = \Delta P_1 $$

Where, $\omega_s$, $f_w$ and $f_w$ are the mechanical angular velocity of rotor, pole number and moment of inertia of the rotor, respectively. $\Delta P_1$ denotes the available frequency regulation power of the virtual inertial control, $\omega_s$ is the angular frequency of the power grid.

The two sides of equation (3) are divided by the rated capacity $S_N$ of the wind generator, which can be obtained by using per unit to express $\Delta P_1$:

$$ \Delta P_1^* = \frac{f_w \omega_s^2}{S_N f_w^* \omega_s^* \frac{d \omega_s^*}{dt}} = H_w \omega_s^* \frac{d \omega_s^*}{dt} = H_w f_w^* \frac{d f_w^*}{dt} $$

Where, $H_w$ is the virtual inertial time constant of wind generator. $\omega_s^*$ denotes the rated angular frequency of power grid. $\omega_s^*$ and $f_w^*$ are per unit values of grid angular frequency and system frequency, respectively. Generally, $f_w^* = 1$ is taken when the system frequency bias is not too large then (4) can be shown as follows:

$$ \Delta P_1 = -H_w \frac{d \Delta f}{dt} $$

where $\Delta f$ is per unit of the system frequency deviation.

Equation (5) shows that the system frequency is stable and the wind turbine does not participate in the virtual inertial control when the power system is in normal operation; the wind turbine is controlled by virtual inertia when frequency deviation occurs in the power system. This moment, the output power of wind generators should be equal to the power value before disturbance plus the active power reference value provided by virtual inertia, thereby restraining the frequency deviation of the power system.

### 2.1.2 Pitch angle control

To guarantee the reliability of wind generators participation in primary frequency regulation, this paper presents a control strategy of pitch angle frequency regulation for 1.5 MW doubly fed wind generator operating above rated wind velocity. The control block diagram of pitch angle frequency regulation is shown in Figure 1.

In Figure 1, $P_{ref}$ stands for the reference value of output power of wind generator under prevailing wind velocity. The initial pitch angle $\beta_0$ of the wind generator is determined by $P_{ref}$, which leaves a certain power reserve. Therefore, the principle of pitch angle control is based on the initial pitch angle $\beta_0$, and then the variation of the pitch angle $\Delta \beta$ is given according to the grid frequency deviation, thereby further adjusting the pitch angle to make wind generators participate the frequency regulation.

When the wind generators operate at $d\%$ de-load by increasing pitch angle $\beta$, the output power is:

$$ P = \frac{1}{2} \rho C_p^* \pi R^2 v^3 $$

where, $C_p^* = (1 - d\%) C_p_{max}$, $C_p_{max}$ denotes the maximum wind energy utilization coefficient, $\rho$ is the air density, $R$ is the blade radius of wind generator, $v$ is the wind velocity.

The pitch angle $\beta = 0^\circ$ when the wind turbine is operating in the maximum power tracking zone. This moment, the wind generator runs at the optimum tip speed ratio, then linearly fits the optimum tip speed ratio curve. The relationship between the wind energy utilization coefficient and the $\beta$ is [23]:

$$ C_p = -0.014 \beta + 0.43 $$

![FIGURE 1 Variable pitch angle control block diagram](image-url)
The pitch angle should be increased by 3.1° when the wind generator operates at 10% de-load.

Generally speaking, the demarcation point between maximum power tracking area and constant rotor speed area of the output power of 1.5 MW doubly-fed wind generators is 0.75 p.u. In accordance with the 10% de-load reserve and the critical point of 0.75 p.u., the initial value of the pitch angle is 3.5°, which is combined with the actual operation of the project, and further can be obtained:

$$\beta_0 = \begin{cases} 14P_{ref} - 10, & \text{if } 75\text{p.u.} \leq P_{ref} \leq 1\text{p.u.} \\ 0, & \text{if } P_{ref} < 0.75\text{p.u.} \end{cases}$$  \hspace{1cm} (8)

After determining the initial value pitch angle of wind generator, it can respond to the frequency variation of the system, establishing the linear relationship between the system frequency and pitch angle, the specific equation is expressed as:

$$\Delta\beta = k_\beta (f_N - f) = k_\beta \Delta f$$  \hspace{1cm} (9)

Where, $k_\beta$ is the frequency response coefficient of pitch angle control.

The allowable fluctuation range of power grid frequency in China is ±0.2 Hz, the pitch angle is not adjusted when the $\Delta f$ is in the range of $[-0.2, 0.2]$ Hz. Wind generator will output maximum power at the system frequency is less than 49.2 Hz. To this end, the value of $k_\beta$ can be derived:

$$k_\beta = \begin{cases} 4 |\Delta f| > 0.2\text{Hz} \\ 0, \text{if } |\Delta f| \leq 0.2\text{Hz} \end{cases}$$  \hspace{1cm} (10)

The reference value of pitch angle $\beta_{ref}$ in Figure 1 can be obtained according to Equations (8) and (9). The pitch angle of the wind generator is adjusted by the controller until a reference value $\beta_{ref}$ is reached, where $T$ is the pitch angle adjustment mechanism time constant.

2.1.3 Integrated control

The integrated control strategy takes full account of the frequency modulation capability of wind turbines which combines the rotor kinetic energy control and pitch angle control in the light of their respective characteristics. Figure 2 shows the concrete control block diagram.

The frequency modulation power $\Delta P_1$ provided by the rotor kinetic energy control and the frequency modulation power $\Delta P_2$ provided by the pitch angle control can improve the response of the wind turbine to the system frequency, prevent the frequency from changing too fast and reduce the system frequency deviation. The reference power is controlled to enable the wind generators respond to frequency variations of system and modulate frequency fleetly.

2.2 Rotor speed recovery strategy

Available according to the law of conservation of energy, rotor kinetic energy control can provide a transient active support for the system by releasing rotor rotating kinetic energy of the rotor to meet primary frequency regulation of the power system. However, the speed of rotor cannot be kept at a reduced speed for a long time so that the rotor speed of wind turbine will return to the previous operation when it is diminished to a certain extent, namely, the wind turbine enters into the recovery stage of rotor speed when the additional power of single turbine is zero. Because the frequency regulation time of rotor kinetic energy control is short, for this reason, it is considered that the wind velocity of wind generator is constant during frequency regulation, which requires the traditional units to provide active support at the rotor speed recovery stage of wind turbine.

To ensure the rotor speed of wind turbines recovers quickly and smoothly without causing secondary frequency drop in power system, this paper designs a fuzzy PI controller to complete the wind generators exit from frequency modulation mode. The control block diagram is shown in Figure 3.

In Figure 3, $\omega_0$ denotes the initial value of wind turbine rotor speed before regulating frequency. When the wind turbine exits frequency regulation mode, the rotor speed deviation $\Delta \omega$ and the deviation change rate $d\omega/dt$ are utilized as input variables of the fuzzy PI regulator, and the fuzzy rules are utilized for fuzzy reasoning to realize the real-time adjustment of control parameters and ensure the wind generators exit frequency regulation mode smoothly. The range of the input variable universe of the regulator fuzzy PI is [-2,2], and its fuzzy subset are divided into $\Delta \omega = \{N, Z, P\}$, $d\omega/dt = \{N, Z, P\}$. To make the rotor speed recover smoothly and the output variable does not change drastically due to the input variable, so that the normal distribution type membership function is adopted to make the system have
better stability. The membership functions of \text{trimf}, \text{trimf} and \text{trimf} are selected for \( N, Z \) and \( P \) to ensure smooth transition and system stable operation [24].

The modified parameters \( \Delta K_p \) and \( \Delta K_i \) of the PI controller are inferred through fuzzy rules, and the modified parameters are superimposed on the initial parameters to obtain the real-time parameters of the PI controller. The selection of the initial parameters \( K_{p0} \) and \( K_{i0} \) of the PI controller is based on the field experiments of the wind farm. The experiment is used to obtain the actual measured values of the rotor speed and output power, and the PI controller parameters are obtained based on engineering experience, and then combined with the 1.5 MW wind turbine rotor speed to restore PI. The calculated values of the control model are synthesized to obtain the initial values of the parameters of the PI controller. In order to adapt to the safety of wind turbine rotor kinetic energy frequency modulation under different operating conditions, it is also necessary to limit the correction parameters \( \Delta K_p \) and \( \Delta K_i \). According to multiple rotor kinetic energy and recovery control experimental tests under different wind speeds of 1.5 MW wind turbines, this article sets the range of \( \Delta K_p \) as \([-2, 2]\) and the range of \( \Delta K_i \) as \([-0.2, 0.2]\).

The PI controller parameters are calculated as follows:

\[
K_p = K_{p0} + \Delta K_p \tag{11}
\]

\[
K_i = K_{i0} + \Delta K_i \tag{12}
\]

In the process of on-line operation, the input signals \( \Delta \omega \) and \( \omega / dt \) are fuzzified, and \( \Delta K_p \) and \( \Delta K_i \) are obtained by fuzzy tuning. The values of \( K_p \) and \( K_i \) are calculated by the above equation. Finally, the on-line self-tuning of PI controller parameters is completed. The initial values of \( K_{p0} \) and \( K_{i0} \) are 1.2 and 0.15, respectively.

### Table 1: Wind for turbine component group

| Wind velocity segment | Wind velocity (m/s) | Weighting factors |
|-----------------------|---------------------|-------------------|
| 1                     | (7–9)               | 3                 |
| 2                     | (9–10)              | 5                 |
| 3                     | (10–11)             | 9                 |
| 4                     | (11–13.5)           | 10                |

**3 | WIND FARM FREQUENCY REGULATION STRATEGY**

#### 3.1 | Coordination control strategy of wind generator

The random fluctuation and uncertainty of wind velocity make it possible for wind generators in wind farms to operate under different wind velocity conditions. When the wind velocity is greater than the rated wind velocity, this paper proposes a unified control method of pitch angle to make the wind generator run in the de-load mode and leave the standby frequency regulation power, the standby power of all wind generators in the wind farm is reserved at 10% de-load. When the wind velocity does not exceed the rated velocity, this paper adopts the rotor kinetic energy control to regulate frequency. Because of the different wind velocity conditions of wind generators, the capacity to control frequency regulation through rotor kinetic energy is also different. The higher the wind velocity, the longer the duration and the better the frequency modulation ability. To ensure the reliability of frequency regulation of wind generators, the lower limit of wind velocity should be set for wind generators through rotor kinetic energy control to participate in frequency regulation of the system.

The rotor speed of wind generator participating in system frequency regulation should be higher than that of sub-synchronous operation 0.7 p.u. [25]. Wind generators investigated in this paper are all taken as 1.5 MW doubly-fed wind generators. When the speed of the generator rotor is 0.7 p.u., the corresponding wind velocity is 6.7 m/s. To enhance the security of wind power participation, setting the lower limit wind velocity of the wind generator to participate in the system frequency regulation is 7 m/s. To this end, the wind velocity range of the wind generator is 7–13.5 m/s by employing rotor kinetic energy control to participating system frequency regulation. To speed up the frequency response speed of wind farms, according to the actual running wind conditions of generators, the wind generators are first divided into several groups on the basis of the wind velocity. Then the frequency control of each group of wind generators is performed.

A wind generator coordination control strategy based on the weighting factor is proposed in this paper, further calculates the frequency regulation power reference of each group of wind generators. The wind velocity segment grouping and weighting factor setting values are depicted in Table 1:

The wind velocity segment controlled by rotor kinetic energy of the wind farm is divided into four groups. This allocation method can ensure that different power reference values are allocated in different wind velocity segments and that the power reference values in higher wind velocity segments are higher than those in lower wind velocity segments. The calculation formula of the distributed power of each group of generators can be obtained from the number and weight factor of generators in each wind velocity section, as follows:

\[
\Delta P_{Wx} = \Delta P_{W} \sum \lambda_k N_k k = 1, 2, 3, 4 \tag{13}
\]

Where, \( \Delta P_{W} \) denotes the frequency regulation power reference value of wind farm participating in system, \( \lambda_k \) is the weight factor of the wind velocity in section \( k \). \( N_k \) is the number of wind generators of \( k \)-th wind velocity.

In term of the total frequency regulation power of each group of wind generators, the frequency modulation power of any
wind generator in the wind farm is computed as:

$$\Delta P_i = \begin{cases} 
\Delta P_{\text{FK}} & v < v_N \\
0.1 P_N & v \geq v_N 
\end{cases}$$

(14)

where, $P_N$ is the rated power of the wind turbine, and $v_N$ is the rated wind speed of the wind turbine.

### 3.2 Orderly exit of frequency regulation strategy for wind generators

When the wind turbine adopts pitch angle control, under the condition that the wind velocity is unchanged, the reserve power of de-load is used to supply a lasting frequency support for the system. The additional power is added to the system at the expense of rotor speed in the wind turbine with kinetic energy control. Providing transient frequency regulation power for the system; then the wind turbine needs to restore the rotor speed and exit the mode of frequency regulation. When the wind turbine exits, in the constant wind velocity, it needs to absorb the active power from the system to restore the rotor speed. If the turbine is not controlled, the frequency of the system may drop again, which may threaten the safe operation of the power system [26].

To avoid the occurrence of secondary frequency drop, this paper proposes a control strategy for the wind generator to exit the mode of frequency regulation in order. The sequentially exit mode is based on the wind velocity segment $k$ in Table 1 and the number of wind generators $N_k$ in each wind velocity segment. Due to the wind conditions of wind generators are complex, the number of generators in four groups of a wind farm cannot be evenly distributed, and even there will be less than four groups of generators. Hence, it is unreasonable to exit from frequency regulation mode only in the light of wind velocity segment, the strategy is also necessary to combine the number of wind generators in each group. The specific strategies are as follows:

First, the amount of wind generators in each group is determined. If the amount of wind generators in any group exceeds 1/2 of the total number of wind generators in the wind farm, the wind generators in this group are divided into two groups on average. Then, the wind velocity segment is divided according to Table 1, considering the above situation; the number of wind generator component groups that exit the frequency regulation mode is obtained from the low wind velocity to the high wind velocity. In terms of the new number of groups, the wind generators in each group are divided into two groups on average. Then, the wind velocity segment is divided according to Table 1, considering the above situation; the number of wind generator component groups that exit the frequency regulation mode is obtained from the low wind velocity to the high wind velocity. In terms of the new number of groups, the wind generators in each group are divided into two groups on average.

When the wind velocity in the lower segment, the wind generator needs to exit the frequency regulation, it is determined that the recovery start time $t_0$, and the rest groups in turn increased the delay $\Delta t_i$, which are based on the former group of recovery time. Thus, generators at different wind velocity can successively exit the mode of frequency regulation, so as to ensure normal operation of the generators and realize stable and rapid recovery of system frequency. If the number of generators in a group exceeds 1/2 of the total number of generators, the wind generators in the group also need to be ordered to exit. Two groups of wind generators exit the mode of frequency regulation sequentially, and the time interval is taken as $\Delta t_0$. In consideration of the problem of rotor speed recovery of wind turbine about safety and reliability, wind generators in each wind velocity segments need to exit the mode of frequency regulation in an orderly manner quickly. According to the measured data of the wind farm experiment, $\Delta t = 1.3 \, \text{s}$ and $\Delta t_0 = 1 \, \text{s}$ are obtained.

### 3.3 Verification of wind power frequency regulation performance

To verify the feasibility and effectiveness of wind power participation in system frequency regulation, this paper connects a wind farm into a typical two-zone four-machine system for simulation calculation. The wiring diagram is shown in Figure 4. The total active load of the system is 2734 MW.

The effect of power shortage on system frequency as well as the influence of wind power integration on system frequency regulation capability is explored by adding a wind farm at bus 5. The wind farm consists of 1.5 MW doubly-fed wind generators with a total of 100 units, namely the total installed capacity is 150 MW. In the simulation calculation, the upper limit of the active output of the G2 synchronous generator is reduced by 150 MW.

The disturbance mode of power system frequency response is the increase of load suddenly in system, namely 200 MW is added to bus 7, comparing the fluctuation of system frequency before and after wind power incorporation. Since the system frequency adjustment can usually be completed in a few seconds to tens of seconds, the wind velocity can be considered constant and the wind power does not participate in the system frequency regulation. Figure 5(a) shows the simulation comparison results.

In Figure 5(a), the frequency is shown with and without wind power access to the system in the same load disturbance. When there is wind power into the system, the dynamic stability of the frequency decreases, the frequency drop speed is obviously
accelerated and the amplitude is increased, which is larger than the frequency drop of wind power not integrated into the grid. Taking into account doubly fed wind generators cannot participate in system frequency regulation, the task of traditional synchronous generator frequency regulation is aggravated, resulting in the ability of system frequency regulation weakly, and this situation will become more evident with the increasing proportion of wind power in the power grid.

Next, the availability of the proposed strategy of generators participation in system frequency modulation is analysed. Rotor kinetic energy control includes virtual inertia control and droop control, Figure 5(b,c) analyses the changes in system frequency and the rotor speed variation of wind generator when wind turbines adopt traditional control, virtual inertia control, droop control and integrated control. The operation data of wind farm comes from the actual measurement data of a wind farm in an area of Inner Mongolia. Taking the wind farm wind velocity conditions at below rated wind velocity, which is the same loading event as the previous case.

From Figure 5(b,c) that the wind generator adopts different frequency regulation strategies, the frequency response ability of the system is also different. In Figure 5(b) that the frequency regulation effect of the integrated control strategy is the best and the frequency drop value is the smallest, which is consistent with the rotor speed change in Figure 5(c). Under the integrated control, the wind turbine rotor speed decreases most and the frequency regulation duration is the longest. It can also be seen from Figure 5(b) that in addition to the frequency drop of the virtual inertial control exceeding the traditional system, the other two control strategies are smaller than that of the traditional system. Hence, taking frequency regulation control strategy for wind turbines can improve the frequency response characteristics of the system, and further proves the feasibility of wind power participating in frequency regulation of the system.

4 | WIND-THERMAL POWER JOINT FREQUENCY REGULATION

According to the research results of the wind generator participating in the system frequency regulation, the frequency regulation power output of the wind generator is basically controlled by the rotor kinetic energy within 5 s, while conventional thermal units have a large inertia and a slow frequency response speed. After the grid break out, resulting in a power shortage and frequency fluctuations, the thermal unit is usually to increase the power smoothly after 5—10 s to compensate the power shortage of the grid and effectively restrict the frequency fluctuation until stability. As a result, combining the durability of the thermal unit and the rapidity of the wind generator in frequency regulation, this paper constructs a wind-thermal power joint frequency regulation scheme, as shown in Figure 6. The
grid frequency can be quickly stabilized through this scheme, which can not only improve the response capability of the system frequency, but also effectively avoid wind abandoning phenomenon of wind power.

In Figure 6, the wind-thermal power joint frequency modulation scheme utilizes dispatching centre to distribute the power shortage for wind farms and thermal power plants timely, and then they quickly adjust the frequency to supplement the power shortage for the power system. In the process of joint frequency regulation, it is necessary to coordinate the frequency regulation power between thermal power plants and wind farms as well as between wind turbines in wind farms. When the system frequency drops, assuming the active power shortage of the system is \(\Delta P\), the power shortage will be sent to the wind farm and the thermal power plant according to their real-time operation conditions. Their control centre adjusts the frequency according to the active power shortage issued by the dispatching centre, among them, the wind generators will be divided into groups by the wind farm control centre in accordance with their current wind velocity, and then achieves the optimal distribution of frequency modulation power according to the weight factor, so as to quickly respond to the frequency variations of the system.

Since wind power has the ability to respond quickly in frequency variations, and the driven mechanism of the variable-pitch system has a certain time lag compared to the rotor kinetic energy control. Therefore, receiving the power shortage \(\Delta P\), generators with wind velocity lower than 13.5 m/s can provide an active support first by the discharging the rotor kinetic energy control. Therefore, receiving the power shortage \(\Delta P\) pitch system has a certain time lag compared to the rotor kinetic energy control, so as to quickly respond to the frequency variations of the system.

As the lag of output power of a thermal unit, when it provides stable active output, the wind turbine with a rotor kinetic energy rapidly, and the generators with wind velocity higher than 13.5 m/s through the pitch angle control to release spare power for system. If the wind farm additional total power can generate is denoted by \(\Delta P_{WF}\), the formula can be represented as:

\[
\Delta P_{WF} = \begin{cases} 
\Delta P, & \Delta P_{WF} \geq \Delta P \\
\sum_{WF} \Delta P_{WF} < \Delta P 
\end{cases}
\]  \hspace{1cm} (15)

where, \(\Delta P_{WF}\) is the sum of the frequency regulation power provided by rotor kinetic energy control and the reserve frequency modulation power of pitch angle control.

As the lag of output power of a thermal unit, when it provides stable active output, the wind turbine with a rotor kinetic energy control begins to enter the rotor speed recovery stage. Frequency regulation power that the thermal unit needs to provide is:

\[
\Delta P_G = \sum_{i=1}^{l} \Delta P_G = \Delta P - \Delta P_{WC} \hspace{1cm} (16)
\]

where, \(\Delta P_{WC}\) is the reserve power of pitch angle control in wind farm, \(l\) is the number of thermal power units. The active power that can be added by the \(i\)-th thermal power unit in the thermal power plant is denoted by \(P_G\).

### 5 | EXAMPLE ANALYSIS

#### 5.1 | Introduction of simulation system

To testing the availability and feasibility of the presented wind-thermal power joint frequency regulation strategy, a typical 36-node test example is adopted to analyse the proposed strategy whose simulation model is established in the Matlab/Simulink simulation software as shown in Figure 7.

The 36-node system consists of eight synchronous generators. The total power of the load is 4200 MW and the total installed capacity of G1–G8 is 5765 MW. To demonstrate the frequency regulation effect of wind farm, generators G7 and G8 connected to bus 7 and bus 8 in 36-node system is replaced by two wind farms, namely WF1 and WF2. Meanwhile, in order to further approach the actual operation of the wind farm merge to power system, another wind farm, namely WF3 is connected to the bus 16 and integrated into the system. The positions of the three wind farms connected to the 36-node system are shown in Figure 7.

The 36-node system forms a power system composing of three wind farms and six synchronous generators after being merged into three wind farms WF1, WF2 and WF3. The wind farms WF1∼WF3 with a total installed capacity of 742.5 MW have 495 doubly-fed wind generators, and the proportion of wind power grid-connected has reached nearly 18%. WF1 and WF2 are composed of 150 wind generators and WF3 consists of 195 wind generators. The three wind farms operational data are based on the measured values in Baotou, Inner Mongolia. In the initial condition to the wind farm is not connected to the power grid, the system operates normally with a frequency of 49.97 Hz.

The traditional synchronous generator adopts the unified speed control system model in the 36-node system. Since the frequency regulation technology of the synchronous generator is very mature, it will not be described in detail here.
5.2 Analysis of simulation calculation

The performance of wind-thermal power joint frequency regulation is verified by adding a sudden load as a disturbance to the power system, namely the total load of 400 MW is divided into 100, 100 and 200 MW and added to Bus29, Bus23 and Bus20 respectively. Due to the different positions of three wind farms, the wind conditions of each wind farm and each generator in each wind farm are different at the same time. By analysing the two-year measured data of three wind farms in Baotou area, this paper divides the operation of wind farm participation system frequency regulation into low wind velocity \((v < 13.5 \text{ m/s})\) operation and high wind velocity \((v > 13.5 \text{ m/s})\) operation, which is more reasonable with the actual operation.

As mentioned above, the rotor kinetic energy control is applied to have a hand in system frequency modulation in low wind velocity, while the pitch angle control is employed to partake in system frequency modulation in high wind velocity. According to the two wind velocity segments, this paper divides the frequency regulation mode of the wind farm participating system into two types. Scenario 1 is that all the three wind farms are operating in the low wind velocity segment; Scenario 2 is that only WF\(_3\) runs in the low wind velocity section, while WF\(_1\) and WF\(_2\) operate at high wind velocity section, that is, there are wind turbines running in both high and low wind velocity. Here, wind generators can provide long-term power shortage by controlling the pitch angle to de-loading and storing the frequency regulation power when the wind velocity does not change suddenly, and this control technology is mature. For this reason, this paper does not separately analyse the wind frequency regulation characteristics of the pitch angle control, but coordinate with the rotor kinetic energy control to analyse the frequency response of the system.

Next, the frequency response characteristics of the wind-thermal power joint frequency regulation scheme are investigated according to the two operational scenarios of the wind farm.

5.2.1 Scenario 1

As the previous analysis, when the wind generator is operating at low wind velocity section, the rotor kinetic energy control is exploited to participate in the system frequency regulation, and the rotor kinetic energy integrated control strategy has the optimal frequency regulation performance. The following is a simulation calculation of the frequency regulation strategy of large-scale wind power by rotor kinetic energy control joint with thermal power unit. Before the simulation calculation, the wind generators are grouped according to the wind velocity segment, taking WF\(_1\) as an example, the specific grouping is shown in Table 2.

In the simulation, the system is suddenly loaded with 400 MW at \(t = 1 \text{ s}\), and the results are shown in Figure 8. Besides, adding the low-pass filter to wind turbine with virtual inertia control to eliminate the noise interference in frequency measurement.

| Wind velocity segment | Number of wind generator | Wind velocity segment | Number of wind generator |
|-----------------------|--------------------------|-----------------------|--------------------------|
| 1                     | 23                       | 3                     | 28                       |
| 2                     | 38                       | 4                     | 11                       |

Figure 8 shows that the system frequency response performance of the wind-thermal power joint frequency regulation is significantly improved, and the bottom value of the system frequency drop is upper than that of the conventional thermal unit alone, which further indicates that the frequency response speed of the wind generator is rapidly, and effectively compensates for the hysteresis characteristics of the thermal unit frequency regulation power output caused by its large inertia. Figure 8 also shows that the system frequency drops to the minimum and then rises rapidly when wind-thermal power joint frequency regulation and its rising speed are faster than that of traditional thermal units. When the frequency maximum value is reached, beginning to decline until it is stable. This is mainly because the rotor kinetic energy control can discharge the rotor kinetic energy quickly, but the duration is transient, so wind turbine is necessary to restore the rotor speed and exit the frequency regulation mode when the rotor speed is reduced to a certain extent. At this time, restoring the rotor speed is also necessary to absorb active power from the power system, so the frequency begins to fall, and then the thermal unit begins to provide stable power, after which the frequency gradually stabilizes and reached a new equilibrium point. Consequently, wind-thermal power joint frequency regulation is beneficial to improve the frequency response characteristics of the power system and enhance the frequency regulation capability of the power system.

To further investigate the frequency regulation working principle of wind power participation system, Figure 9(a) shows the output power of WF\(_1\) and Figure 9(b) shows any wind turbine rotor speed in wind velocity segment 4.

From Figure 9(a,b) it is found that the curves of wind farm output power and wind turbine rotor speed are corresponding to the theoretical study on rotor kinetic energy control. The output power is increased by reducing the rotor speed to support the frequency regulation of the power system. At the end of frequency regulation, the rotor speed of wind turbine starts to recover and absorbs power from the grid until it recovers. Here, the wind farm output power is almost the same as before
regulating the frequency. In addition, Figures 8 and 9(b) show that the optimal frequency modulation effect can be achieved by adopting the integrate control strategy, not only has a slight frequency fluctuation, but also provides long-term output frequency regulation power for wind farms, which the rotor speed of the turbine decreases the most. The effect of virtual inertial control is the most unsatisfactory, especially the fluctuation of wind farm output power, which is adverse to the stable operation of the power system.

Due to the large amount of wind generators in the wind farm, and its rotor speed based on the rotor kinetic energy control needs to be restored, the orderly exit frequency modulation strategy of wind turbines has been further verified, and compared with the direct exit frequency modulation mode of the wind farm. Figure 10(a) shows the simulation results.

In Figure 10(a), the frequency regulation strategy is integration control. It will occur in an obvious frequency drop phenomenon along with adopting the direct exit frequency regulation mode. However, the frequency of the system does not have a second drop, and it can quickly recover to the stable value when the system exits the frequency regulation mode orderly.

Figure 10(b) shows the rotor speed variation in four wind velocity sections of WF1, and further illustrates the strategy of orderly exiting the frequency regulation mode.

As Figure 10(b) shows, the wind generators exit the frequency modulation mode sequentially and orderly according to their disparate frequency regulation capability, and then the fuzzy PI controller is used to restore the rotor speed until it achieved the initial speed value before regulating the frequency.

It can significantly enhance the frequency response ability of power system in the wind farm employing rotor kinetic energy control and combined with thermal unit to regulate the frequency, which can relief system frequency fluctuation, and improve the speed of frequency recovery in the frequency modulation period. By orderly exiting the frequency regulation mode and utilizing the rotor speed recovery control of the fuzzy PI controller, this way effectively avoids the frequency secondary drop of power system and improves its stability.

5.2.2 Scenario 2

In scenario 2, the WF3 adopts the rotor kinetic energy control, while WF1 and WF2 adopt the pitch angle control to have a hand in system frequency modulation in the high wind velocity segment in terms of the previous analysis.

Reserve power of WF1 and WF2 operates at 10% de-load under variable pitch control system, which disturbance mode is consistent with scenario 1. The frequency variation of the system using integrated control under scenario 2 is shown in Figure 11.

Figure 11 shows that under the frequency modulation strategy using integrated control, the minimum value of the system frequency drop is still greater than that of the frequency regulation control of traditional thermal units. It is mainly because the system frequency response speed of the pitch angle control is still faster than that of the synchronous unit, and the wind power installed capacity of WF1 and WF2 accounts for half of the total wind power. Thus, the frequency regulation power
supply is timely, which makes the frequency recovery of the system faster and has evident advantages over the original method of simply using thermal power unit, the practicability of the primary frequency regulation of the wind-thermal cooperative power system has been further verified.

Pitch angle control is included in scenario 2; it can provide long-term frequency regulation power for the system. Thereby, thermal units do not have to provide all power shortages in this mode of operation. Figure 12 shows the active output of generator G6 and compares it with the traditional system which is not connected to the wind farm.

As illustrated in Figure 12, when the integrated control is activated, the output power of synchronous generator is notable decreased, and the rising speed of frequency regulation power can be less, which can effectively alleviate the frequency-regulated pressure of synchronous generator and enhance the frequency response performance of power system.

6 | CONCLUSIONS

Taking into account the wind turbine rotor is completely decoupled from the grid frequency and cannot respond to its changes in. This paper presents a primary frequency modulation control strategy of large-scale wind-thermal power joint participation system, based on the characteristics of fast frequency response and small inertia time constant of wind generator and the lastable capability of thermal power units’ frequency regulation, the conclusions can be obtained as follows:

1. According to the different wind conditions of wind generators, the frequency regulation control strategy of rotor kinetic energy control is proposed for wind turbines at rated wind velocity and below, and adopted pitch angle control over rated wind velocity, so as to realize the frequency modulation of wind turbines participation in system within the overall wind velocity range.

2. Considering that the rotor speed of wind turbine needs to be restored after providing frequency modulation power through rotor kinetic energy control, a coordinated rotor speed recovery control strategy for wind generators orderly exiting the frequency regulation mode is proposed to prevent the occurrence of secondary system frequency drop accident.

3. According to the 36-node example, it can be known that the frequency regulation control of wind-thermal power joint is helpful for frequency modulation of the power system and the feasibility of the proposed is verified; besides the capability to adjust the frequency of the power system has been effectively improved.

The research contribution of this paper is to provide a theoretical basis for the realization of large-scale wind farm participation in power system frequency adjustment, and also provides technical guidance for dispatching operation. In addition, wind power frequency modulation under unknown wind speed has not been considered.

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