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# Primary frequency regulation strategy for doubly-fed induction generators based on virtual inertia

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**Abstract.** With the continuous increase of wind power generation capacity, the necessity of wind power generation participating in primary frequency regulation is also increasing. Most traditional doubly-fed induction generators do not have the capability of frequency regulation control. To solve this problem, the primary frequency regulation strategy for doubly-fed induction generators is designed based by using the inertia of wind turbines. The power control principle and frequency response process of doubly-fed induction generators are studied. On this basis, a strategy of primary frequency regulation based on virtual inertia is proposed. The method enhances the ability of the doubly-fed induction generator to adjust transient and steady-state power when the frequency of the power network changes, and realizes the doubly-fed generators to take part in the primary frequency regulation of the power system. The 3-generator 9-bus model is built using MATLAB/ Simulink, in which wind power capacity accounted for 20%. Using this model, it is verified that the virtual inertia strategy can make the output power of doubly-fed generator change with the frequency of the power grid, can effectively participate in the primary frequency regulation of the power grid.

**Keywords:** Frequency regulation / doubly-fed induction generator / virtual inertia

## 1 Introduction

In recent years, the installed capacity of wind power has been increasing quickly. By the end of 2023, China's grid-connected wind power installed capacity has reached 440 million kilowatts, accounting for 15.1% of the total installed power system generation capacity [1]. Wind power generation has high randomness and volatility, it is difficult to control. The characteristics of wind power bring many challenges to the safe and stable operation of power system. The increase in the proportion of wind power has reduced the operating capacity and regulation space of thermal power units, and increased the difficulty of system frequency adjustment. This poses significant risks to the frequency and power control of the power system [2]. The requirement for wind generations to participate in the frequency regulation is also increasing. The United Kingdom stipulates that wind farms with a rated capacity of more than 100 MW should have a primary frequency modulation capability with an adjustment factor of 3~5% [3]. California power grid of the United States stipulates that wind farms with a rated capacity of more than 20 MW should provide frequency modulation power of 10% of rated power within 8 s after the frequency is lower than 59.92 Hz (normal frequency 60 Hz) [4]. The Texas Power Grid stipulates that wind farms with a rated capacity of more than 10 MW should have a primary frequency regulation capability with an adjustment factor of 5% [5]. According to China's 2021 regulations, if the output of the new energy station is greater than 20% of the rated output, it should participate in the system's primary frequency regulation [6]. In the field of wind power generation, doubly-fed induction generators (DFIGs) have become the most common models. As an asynchronous generator, a DFIG cannot respond to the frequency of the power system quickly, which makes it more difficult to participate in frequency regulation control. In addition, with the increase of the proportion of wind power generation, the overall inertia of the system is reduced, and the frequency stability of the system will be seriously affected when there is a large disturbance in the power system.

At present, the frequency regulation control strategies for wind farms are mainly divided into three types: rotor inertia control, droop control, and load shedding control [7]. Reference [8] added the inertial control link. When the system frequency changes, the wind turbine increases or decreases the active power output by releasing or absorbing part of the kinetic energy in the rotor. This realizes the frequency control of the wind turbine. The process is called

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"inertial response". The response time is short and it is a transient process. In this kind of method, because the rotor speed cannot be changed in the state of decreasing or increasing speed for a long time, the system frequency may be twice dropped or increased with the stability of the rotor speed. And when the system reaches stability, it will not be able to provide active power support for frequency deviation [9]. References [10,11] use energy storage technology to compensate for virtual inertia in wind farms. This type of method can effectively compensate for the virtual inertia of wind farms, coordinate energy exchange between wind energy storage systems and conventional power system, and enable wind farms to quickly respond to system frequency changes. However, due to the high cost of energy storage systems at present, their overall economic benefits need to be improved. References [12,13] adopt load shedding control, reserving a portion of active power as frequency regulation backup for the system to provide frequency support. However, this method reduces wind energy utilization and wastes energy. References [14,15] adopt a droop control method to enable wind turbines to have the same frequency droop characteristics as synchronous generators, which is beneficial for maintaining system frequency stability. This process simulates the differential regulation process of synchronous generator primary frequency regulation, which is a steady-state process, and the system frequency will reach a new steady-state point. How to achieve an organic combination of these methods, fully utilize wind energy, and consider the combination control of the transient process of virtual simulation inertia control of wind turbines and the steady-state process of droop control, further research is needed.

## 2 Frequency response model of power system

The traditional power system mainly relies on synchronous generators. When active power disturbance occurs in the power system, its frequency will also change accordingly. The process of its change can be described using P M. Anderson's low order system frequency response (SFR) model is employed to calculation. The basic idea of this model is to assume that the frequency variation of the power system can be equivalent to the speed variation of an equivalent synchronous generator containing a reheating turbine and a speed control system [16,17]. This model ignores the inertial and nonlinear components in steam turbines, boilers, and speed control systems that are under a relatively small impact on frequency dynamics. The model is simplified as a second-order system (as shown in Fig. 1), and the frequency response expression of the system after disturbance can be easily derived using this model.

As in Figure 1, the forward channel represents the rotor motion equation of the equivalent generator, and the feedback channel represents the turbine speed control system of the generator. $H$ is the inertia time constant of the equivalent generator, reflecting the level of inertia of the system. Its typical value is 4~6 s. $D$ is the damping coefficient of an equivalent generator, which is related to the damping of each generator in the power system and the frequency characteristics of the load in the system. Its typical value is 1. $K_m$ is the mechanical power gain coefficient of the equivalent generator governor. $R_p$ is the adjustment coefficient of the equivalent generator governor. $F_H$ and $T_R$ are the proportion of work done by the high-pressure cylinder of the steam turbine and the time constant of the reheated of the equivalent generator, respectively. The value of these parameters is related to the turbine and governor parameters of each synchronous generator in the power system. During the operation of the power system, the switching of the generator or significant load input can cause active power disturbance, leading to changes in the system frequency. Under the feedback control of the speed regulation system, the valve opening of the steam turbine increases, the mechanical power input from the generator prime mover increases, the imbalance between the electromagnetic power and mechanical power of the generator gradually decreases, and the final frequency tends to stabilize. After the system reaches a new balance, its frequency changes as follows:

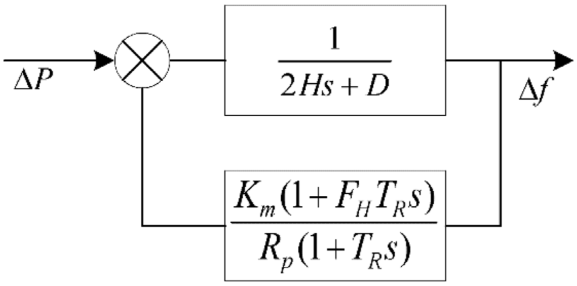

**Fig. 1.** System frequency response mode.

$$\Delta f = \frac{R_p \Delta P}{DR_p + K_m} * f_N \tag{1}$$

where: $\Delta f$ is the frequency variation; $\Delta P$ is the active power variation; $f_{\mathrm{N}}$ is the normal value of the power system frequency, 50 Hz in China.

For power systems containing wind power, the analysis method of system frequency response is related to whether wind power participates in frequency regulation:

- If all wind turbines in the system operate in maximum power point mode and do not take part in frequency regulation, the frequency response characteristics of the system are still determined by the synchronous generator in the system. After wind power is connected to the power system and partially replaces synchronous generators, the equivalent parameters in the SFR model are correspondingly reduced as the wind turbine does not exhibit the inertia, damping, and primary frequency regulation characteristics of synchronous generators, while the total installed capacity of the system remains unchanged. The frequency response characteristics of the system will also change accordingly.
- If the wind turbines in the system have frequency regulation capability, the active power output changes generated by wind power participating in frequency regulation can be equal to changes in the SFR model structure. Necessary extensions can be made to the SFR model based on the wind power model.

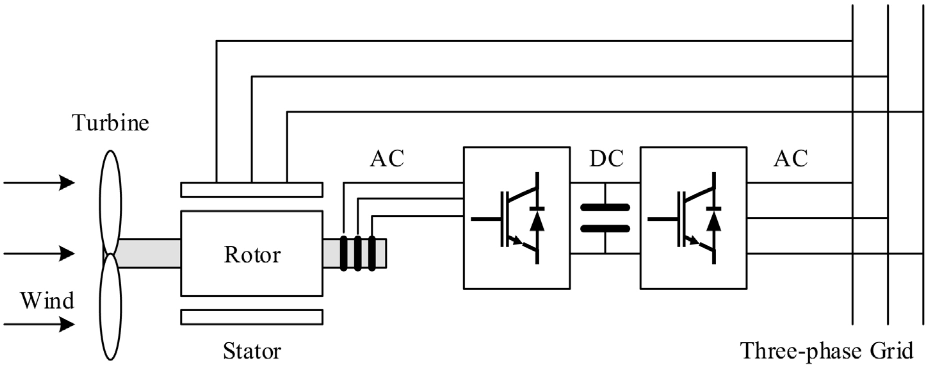

**Fig. 2.** Wind turbine and doubly-fed induction generators power control system.

## 3 Frequency response of DFIG

### 3.1 Active power control of DFIG

DFIG is a kind of wound induction generator. The generator body consists of a stator, rotor, and bearing system. The stator winding is directly connected to the power grid. The rotor winding is connected to the power grid through an inverter. The frequency, voltage, amplitude, and phase of the rotor winding power supply are automatically adjusted by the frequency converter according to operating requirements. The unit can achieve constant frequency power generation at different speeds, complying with the requirements of electrical load and grid connection. The system topology of DFIG is shown in Figure 2.

The rotor of the DFIG converts the kinetic energy of the flowing air into mechanical energy, which is input into a doubly fed asynchronous generator to generate electrical energy. The mechanical power $P_m$ captured by the paddle is related to the air density $\rho'$ wind speed $v_w$, sweep radius $r$ of wind turbine blades, rotor speed $\omega'$ pitch angle $\beta'$ and the wind energy utilization coefficient $C_p$:

$$\begin{cases} P_m = \dfrac{1}{2}\rho {v_w}^3 \pi r^2 C_p(\lambda, \beta) \\ C_p(\lambda, \beta) = 0.22\left(\dfrac{116}{\lambda} - 0.4\beta - 5\right) e^{\left(\dfrac{-12.5}{\lambda}\right)} \\ \lambda = {}^{\omega r}/_{v_w} \end{cases}. \tag{2}$$

If the wind speed is low, the turbine captures the maximum wind power and operates on the maximum power curve. With the increase of the wind speed, until it reaches the upper limit of the rotor speed, the rotor speed is maintained at the upper limit and operated at a constant speed. The corresponding wind speed range is called the medium wind speed zone. When the wind speed continues to increase until the power of the turbine reaches the rated power, the pitch angle control is used to limit the power of the fan to the rated power and operate at constant power, corresponding to the high wind speed range. The pitch angle control and generator control of wind turbines are the main contents of the doubly fed unit control system. Wind turbines only perform speed control in low and medium wind speed zones to avoid the action of the pitch adjustment control system. During the start-up stage and high wind speed zones, pitch angle control is mainly carried out.

### 3.2 Frequency response of DFIG

Frequency regulation of the power system is the process of rapidly increasing or decreasing the active power output by the generator, and rebalancing it with the active power of the load. The frequency stability of the power system is closely related to the safety and efficiency of power generation, transmission and consumption equipment. And it is an important indicator for power quality. Usually, the frequency deviation is required to be less than ± 0.2 Hz. When the generator suddenly malfunctions or a heavy load trips, the system frequency begins to drop or rise, and its rate of change depends on the system's rotational inertia, with a duration of 0~10 s. At this point, the power plant needs to provide additional frequency response, namely primary frequency regulation and secondary frequency regulation. Primary frequency regulation is differential regulation, which is provided with additional output power by the automatic differential regulation link of the generator, with a duration of 10–30 s. The secondary frequency regulation uses a slow auxiliary control loop to restore the frequency to its rated value, with a duration of 30 s to 30 min. Primary frequency regulation requires as many generators as possible to participate, while secondary frequency regulation is mainly completed by frequency regulation power plants.

The frequency response performance of the power system is a common reflection of all generator units and loads in the power system. The total frequency regulation capacity of all generator units in the system basically determines the amplitude of frequency fluctuations caused by generator units and load disturbances in the power grid. When the system is connected to a large number of variable speed wind turbines such as DFIG, the decoupling control between the rotor speed of the doubly-fed unit and the grid frequency is equivalent to the moment of inertia of the doubly-fed unit being "hidden" by the power electronic converter. Therefore, replacing conventional units with a large number of doubly-fed induction wind turbines will

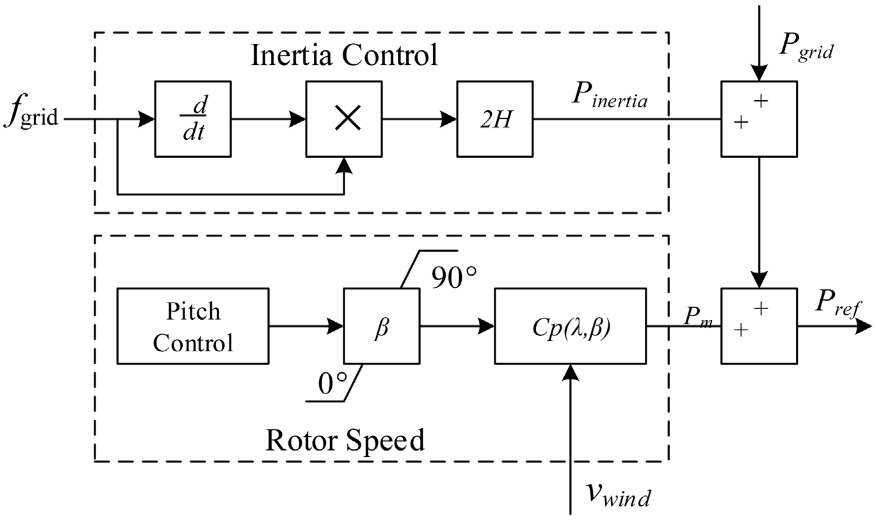

**Fig. 3.** DFIG frequency regulation strategy based on virtual inertia.

lead to a decrease in the inertia of the entire power system, which is not conducive to the safe and stable operation of the entire network. Doubly-fed units usually operate in maximum power tracking mode, where the mechanical power output from the prime mover (wind turbine) to the generator can only be reduced and cannot be increased. They cannot be quickly adjusted through speed controllers like synchronous generators, meaning they do not have spare capacity and cannot participate in the primary frequency regulation process of the system.

Due to the high control flexibility of DFIG, the inertia time is about 2–6 s. The rotational kinetic energy stored in the rotor is quite considerable. By adjusting the control objectives and strategies, the generator can actively respond to changes in system frequency, making it have inertia response characteristics similar to traditional units. DFIG participates in the primary frequency modulation of the system, providing frequency support for the system frequency. This paper proposes a method to obtain the reference value of compensating active power by adding a frequency response control link. The frequency response control consists of virtual inertia control and droop control. Through this method, DFIG can have good power frequency response, and the output active power follows the changes with the power system frequency.

## 4 Combination frequency regulation strategy

### 4.1 Virtual inertia

The wind turbine is connected to the generator rotor through a gearbox, and its weight is relatively large. During normal operation of the unit, the wind turbine stores rotational energy. When the frequency of the power system experiences a sudden change, the response of wind turbines is similar to that of synchronous generators. When the system frequency drops, the generator slows down and the rotor reduces its rotational speed, converting some of the kinetic energy of the unit into electrical energy to supplement the active power deficit of the system. When the system frequency increases, the rotational speed of the unit increases, increasing the rotational kinetic energy and reducing the output of electrical energy. The rotational kinetic energy $E_k$ possessed by a fan can be expressed as:

$$E_k = \frac{1}{2} J {\omega_r}^2 \tag{3}$$

where: $J$ is the moment of inertia of the generator ($\mathrm{kg \cdot m^2}$), which is the total moment of inertia of the generator and prime mover. $\omega_r$ is rotor speed (rad/s).

Define the inertial constant $H$ as the ratio of kinetic energy of rated speed $\omega_N$ divided by apparent power $S_B$:

$$H = \frac{J {\omega_N}^2}{2 S_B} \tag{4}$$

when $\omega_r$ changes, the rate of change of kinetic energy $E_k$ is:

$$P_{interia} = \frac{dE_k}{dt} = J\omega_r \frac{d\omega_r}{dt} = 2HS_B \frac{\omega_r}{{\omega_N}^2} \frac{d\omega_r}{dt}. \tag{5}$$

Using per unit value, it can be expressed as:

$$\begin{aligned} \overline{P}_{interia} &= \frac{P_{interia}}{S_B} = 2H \frac{\omega_r}{\omega_N} \frac{d\,{\omega_r}/{\omega_N}}{dt} \\ &= 2H\overline{\omega}_r \frac{d\overline{\omega}_r}{dt} = 2H\overline{f}_{grid} \frac{d\overline{f}_{grid}}{dt} \end{aligned} \tag{6}$$

After adding a virtual inertia control loop, DFIG can simulate the inertia characteristics of conventional synchronous generators, as shown in Figure 3. The $f_{grid}$ in the figure represents the measured frequency value of the power grid; $P_{grid}$ is the active power output from the wind turbine to the grid; $P_{inertia}$ is the power compensated by virtual inertia control; $P_{ref}$ is the reference value of active power output from the wind turbine to the grid. Considering that $P_{inertia}$ is directly proportional to the

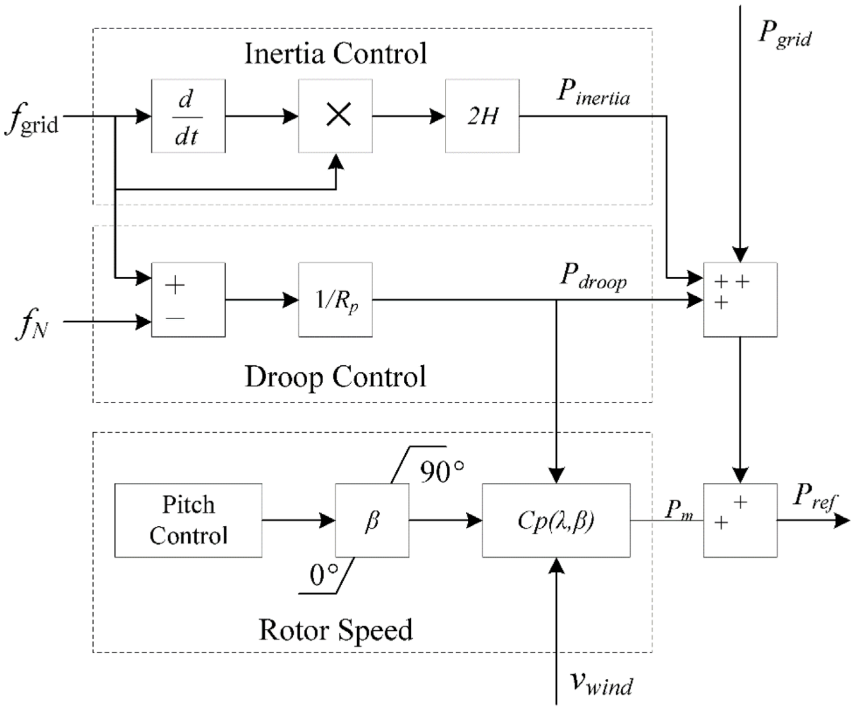

**Fig. 4.** DFIG frequency regulation strategy based on virtual inertia and droop control.

frequency change rate, it can only provide transient power support during the transient change process of frequency mutation.

Virtual inertia control is a transient process that provides active power support when the frequency of the power system changes, in order to slow down the speed of system frequency change. When the system frequency rises to the highest or drops to the lowest, it stops working, with $P_{inertia} = 0$.

### 4.2 Droop control

When the frequency of the power system deviates from the normal frequency, generators are required to provide active power support for frequency regulation, which requires droop control. Droop control is a steady-state process that simulates the differential regulation process of synchronous generator primary frequency regulation, which is beneficial for maintaining frequency stability in the power system. When the active power output of the system power supply is less than that of the load, it will lead to a decrease in system frequency. On the contrary, it will cause an increase in system frequency. Traditional synchronous generators can respond to changes in system frequency by controlling the speed controller to reduce or increase, changing the output power of the synchronous machine, and gradually reaching a new balance state of power in the system. This process is called droop control, as shown in Figure 4. Referring to the droop control of synchronous generators, a frequency deviation control link is added to the wind turbine control strategy to respond to frequency changes in the power system. The active power-frequency characteristics of wind turbines can be expressed as:

$$\frac{P_{droop}}{P_N} = -\frac{1}{R_p}\frac{(f_{grid} - f_N)}{f_N}. \tag{7}$$

Using per unit values, it can be expressed as:

$$\frac{P-_{droop}}{P_N} = -\frac{1}{R_p}(f_{grid} - 1) \tag{8}$$

However, wind turbines cannot maintain power balance by adjusting the mechanical power of the prime mover like conventional generators. Directly introducing droop control does not enable wind turbines to have the same primary frequency regulation control capability as conventional generators. Sag control needs to be combined with wind turbine load reduction operation control. The wind turbine needs to reserve a portion of standby power through overspeed control or pitch angle control, so that the wind turbine has the ability to support up and down frequency, thereby achieving the purpose of changing and continuously providing additional output power.

## 5 Case study

To demonstrate the effectiveness of the coordinated frequency control strategy mentioned above, a simulation model was constructed using MATLAB/Simulink for simulation analysis. The model is based on WSCC's 3-machine 9-bus model [18] and requires necessary modifications:

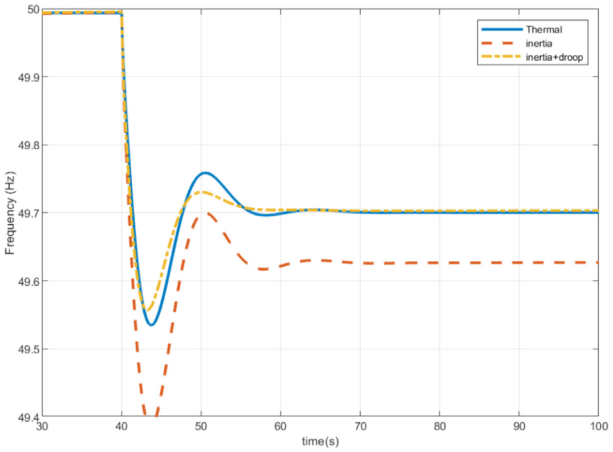

**Fig. 5.** Response frequency change with different control strategies.

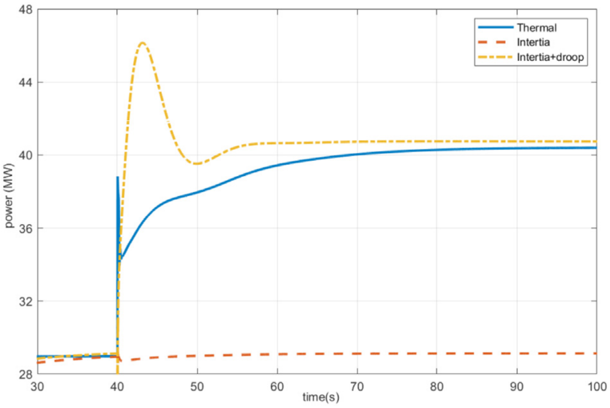

**Fig. 6.** Power output of G3 to response frequency change with different control strategies.

- According to the characteristics of China's power grid, the power system frequency is adjusted to 50 Hz.
- Simplify the system model and adjust all three generators to be thermal generators, using the parameters of generator G2 uniformly.
- The installed capacity of the system is 500 MW, with generator G1 200 MW, generator G2 200 MW, and generator G3 (wind power generation) 100 MW. The installed capacity of wind power accounts for 20%. The adjustment coefficient $Rp = 0.05$, G1 is the swing node, and G2 and G3 are the PV nodes.

After 10 s of stable operation of the power system, an additional load of 60 MW is added at bus 5. The load power of the entire system is 315 MW to 365 MW, and the increased load accounts for 19% of the total load. For a typical thermal power system, an increase in load will lead to a decrease in frequency. Taking 200 MW as the base capacity, there are:

$$\Delta f=\frac{\frac{\Delta P}{P_N}}{\frac{1}{R_{p1}}+\frac{1}{R_{p2}}+\frac{1}{R_{p3}}}*f_N=\frac{-\frac{60}{200}}{\frac{1}{0.05}+\frac{1}{0.05}+\frac{1}{0.05/2}}*50=-0.3Hz \tag{9}$$

So, it can be determined that the final frequency of the system is 49.7 Hz. It can be seen form Figure 5. The G3 is a thermal power unit, and the frequency of the entire system eventually stabilizes at 49.7 Hz.

Convert generator G3 to a DFIG with an installed capacity of 100 MW, consisting of 66 generators with a capacity of 1.5 MW. The system operates according to the principle that the wind turbine does not participate in frequency regulation, inertial frequency regulation, and inertial+droop control frequency regulation. The frequency variation of the system is shown in the Figures 5 and 6.

If DFIG is not involved in frequency modulation:

$$\Delta f=\frac{\frac{\Delta P}{P_N}}{\frac{1}{R_{p1}}+\frac{1}{R_{p2}}+\frac{1}{R_{p3}}}*f_N=\frac{-\frac{60}{200}}{\frac{1}{0.05}+\frac{1}{0.05}}*50=-0.375Hz \tag{10}$$

The final frequency of the system is 49.625 Hz. It is lower than all three generators participating in frequency modulation.

The output power and speed variation of doubly fed wind turbines are shown in Figures 5 and 6. When the frequency of the power grid suddenly drops, if there is no frequency auxiliary control link, the support effect of a 100 MW wind turbine on the system frequency is relatively small. It generates an inertial response power of 0.7 MW, with a response time of about 3 s. Moreover, the inertia part only provides active power support to the system during frequency changes, slowing down the frequency changes and accelerating the speed of frequency stability. Due to the lack of active power support based on frequency difference, it has no impact on the final frequency difference of the system. The final frequency difference of the system is consistent with wind power not participating in frequency regulation. When the DFIG uses inertia + droop control, the DFIG can participate well in frequency regulation. Due to the continuous existence of grid frequency deviation, frequency droop control can enable wind turbines to continuously compensate for additional active power, with a compensation power of up to 11.6 MW. The DFIG primary frequency regulation strategy based on virtual inertia and frequency droop control can continuously provide frequency support for the power grid during the transient process of frequency drop to a new steady state, improving the stability of wind turbine output power. Compared with thermal power units, wind turbines have greater inertia and can slow down the transient frequency changes of the system, accelerating its stability.

When the frequency of the power grid suddenly drops, without a frequency auxiliary control link, a 100 MW wind turbine will generate an inertia response power about 0.7 MW, with a response time of about 3 s, which has a relatively small supporting effect on the system frequency. Moreover, the inertia part only provides active support to the system during frequency changes, slowing down the frequency changes and accelerating the speed of frequency stability. Due to the lack of active power support based on frequency difference, it has no impact on the final frequency difference of the system. The final frequency difference of the system is consistent with wind power not participating in frequency regulation. The power system eventually reached 49.625 Hz. When the fan adopts inertia+droop control, the fan can participate well in frequency regulation. Due to the continuous existence of grid frequency deviation, frequency droop control can enable wind turbines to continuously compensate for additional active power, with a compensation power of up to 11.6 MW. The DFIG primary frequency regulation strategy based on virtual inertia and frequency droop control can continuously provide frequency support for the power grid during the transient process of frequency drop to a new steady state, improving the stability of wind turbine output power. Compared with thermal power units, wind turbines have greater inertia and can slow down the transient frequency changes of the system, accelerating its stability. The final mediation effect of wind power can be similar to that of thermal power, and the final frequency of the system can reach 49.7 Hz.

## 6 Conclusions

With the increasing installed capacity and scale of wind power generation, the proportion of wind power generation in the installed capacity of the entire power system continues to increase. If wind power generation does not participate in the primary frequency modulation of the power system, the frequency change of the power system will be aggravated when the system power float. It is urgent for wind power generation to participate in the primary frequency regulation of the power system. The combination frequency modulation of inertia and droop control can not only speed up the stable speed of the system but also reduce the frequency change of the system, which is a better method for the DFIG to participate in frequency modulation.

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### Conflicts of interest

All authors declare that they have no known competing financial interests.

### Data availability statement

This article has not generated or analyzed more data than already shown in the manuscript.

### Author contribution statement

Jingwei Zhao: Writing, review & editing. Zhenhai Dou: Review, methodology, Investigation.

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