Research on frequency modulation of DFIG wind turbines auxiliary power grid based on improved frequency control

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Abstract. With a large number of DFIG wind turbines connected to the power grid, in order to improve the frequency fluctuation caused by its decoupling, this paper first analyses the current situation of DFIG wind turbines participating in the primary frequency modulation of power grid, and establishes the corresponding model based on the above analysis. According to the commonly used inertial control methods, a frequency modulation method for auxiliary power grid of DFIG wind turbines based on improved frequency control strategy is proposed. Through the simulation of actual power grid model, the grid frequency fluctuation has been effectively alleviated after adding frequency control link to DFIG wind turbines, and it is concluded that the higher the wind power penetration, the more significant the frequency improvement effect.

1. Introduction

In order to solve the frequency shock caused by wind power connected to the grid, most of the research focuses on improving the frequency response control of DFIG wind turbines[1-2]. Based on the rotor kinetic energy control method, the frequency control link is added in the reference [3-5], which can release the kinetic energy in the rotor and realize the frequency modulation control of DFIG wind turbines. Based on the standby power control method, the reference [6-8] uses the pitch angle or rotor speed as control to make the DFIG wind turbines run in the effective frequency regulation section. There is a similar conclusion in reference [9].

Aiming at the control strategy of DFIG wind turbines participating in grid frequency regulation, this paper proposes a control strategy based on improved frequency control for DFIG wind turbines auxiliary grid frequency regulation. Different from the previous electromagnetic transient small system simulation model, this paper builds a hybrid power supply network model of wind turbine in the electromechanical transient software PSASP. The frequency modulation capability of DFIG is analysed and simulated based on the actual regional power grid. It is concluded that the auxiliary frequency modulation of DFIG wind turbines based on the improved frequency control can effectively improve the frequency of the grid, and provide a theoretical basis for the safe and stable grid connected operation of DFIG wind turbines.
2. The principle and control strategy of DFIG wind turbines participating in the primary frequency modulation of the power grid

2.1. The basic principle of DFIG wind turbines participating in the primary frequency modulation of the power grid

When the rotor speed is $\omega$, the rotational kinetic energy of the wind turbine can be expressed as:

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

(1)

In the formula, $J$ is the moment of inertia of the wind turbine.

When the frequency of the power grid changes, the speed of the wind turbine will change from $\omega_0$ to $\omega_1$ accordingly. The rotational kinetic energy absorbed or released by the wind turbines is:

$$\Delta E = \frac{1}{2} J \times (\omega_1^2 - \omega_0^2)$$

(2)

Because DFIG wind turbine realizes variable speed operation, its rotor speed has a large operating space, from super-synchronous operation to sub-synchronous operation. From equation (2), it can be seen that by changing the rotor speed of the wind turbine, 66% of the rotor kinetic energy can be provided. Therefore, when the proportion of wind power in the power grid is large, its contribution to the moment of inertia of the entire system cannot be ignored [10].

Equation (2) is the hidden kinetic energy of the variable speed wind turbine. When the hidden kinetic energy of the DFIG wind turbine is reflected by this part of the kinetic energy, the variable-speed wind turbine will have the inertial response capability similar to that of a synchronous generator. When the grid frequency changes, the rotor speed of the wind turbine is controlled to release this part of the kinetic energy. The electromagnetic power of the variable speed wind turbine can be obtained as:

$$P = \frac{dE}{dt} = J \omega \frac{d\omega}{dt}$$

(3)

The time that a generator set can use its rotational kinetic energy to provide power output is the inertia time constant, which can be defined as $T_j$:

$$T_j = \frac{E}{S} = \frac{J \omega_0^2}{2S}$$

(4)

Among them, $\omega_0$ is the rated angular velocity and $S$ is the apparent power. $J$ in formula (4) is substituted into formula (3) and expressed by unit value:

$$\bar{P} = 2T_j \bar{\omega} \frac{d\bar{\omega}}{dt}$$

(5)

Adding an auxiliary frequency control loop to the DFIG wind turbine power control link, and revising the original power control link, so that the DFIG wind turbine generator can adjust the active power output in a short time. DFIG has an inertial response characteristic similar to a synchronous generator. When the grid frequency does not change, the frequency control link does not have any effect. On the contrary, the frequency control link starts to work. When the grid frequency drops, the DFIG reduces the rotor speed through the frequency control link and releases part of the rotational kinetic energy into the active power input system. When the grid frequency increases, the DFIG wind turbine unit absorbs part of the electromagnetic power by increasing the rotor speed and increases the rotor speed. Part of the kinetic energy stored in the rotor of the wind turbine to reduce the output of active power, thereby achieving the purpose of participating in the frequency adjustment of the power grid.

2.2. The control model of DFIG wind turbines participating in primary frequency modulation of power grid

Due to the special structure of the doubly-fed wind turbine, the rotor speed of the wind turbine is decoupled from the grid frequency and cannot participate in the frequency adjustment of the grid itself.
In order to enable the wind turbine to have the ability of frequency modulation like a traditional synchronous generator, an auxiliary frequency control link needs to be added. Adjust active power output in order to participate in grid frequency modulation.

Considering the economics of wind power generation, wind turbines are not suitable and need not always participate in grid frequency regulation. Therefore, this paper improves the frequency control link so that the wind turbine only participates in the primary frequency modulation of the grid within a certain frequency range, which makes the doubly-fed wind turbine operate in different control intervals according to the grid frequency status. The frequency response curve is shown in Figure 1.

![Frequency response curve](image)

**Figure 1.** The frequency response curve.

Each quantity in Figure 1 adopts the standard unit value, where $f_b$ and $f_c$ are the upper and lower limits of the frequency of the set wind turbines that do not participate in the primary frequency modulation of the grid. Where $f_a$ and $f_d$ are the upper and lower values of the set frequency of wind turbines. $P_{bc}$ is the wind power. That unit does not participate in the active power output of grid frequency modulation. Therefore, when the frequency is in the BC section, the wind turbine runs at a certain value below the maximum power and does not participate in the frequency modulation of the power grid. When in the AB and CD sections, the wind turbine participates in the power grid frequency modulation. If the frequency is too low, when $f < f_a$, the wind turbine runs at the maximum power tracking. If the frequency is too high, when $f > f_d$, the wind turbine can exit operation.

![Active power-frequency control model](image)

**Figure 2.** Active power-frequency control model.

Figure 2 is a block diagram of the system's active power-frequency control principle. It takes the frequency control module as the core, including the speed protection module, the speed recovery module and the power coordination control module. This paper only analyses the frequency control module. The maximum available power is obtained from the wind speed-power model, and the first-order inertia link acts on the frequency response curve link. The grid bus frequency directly affects the frequency response curve. If the grid frequency is less than $f_b$ or the frequency is greater than $f_c$, it will enter the FM control section. Then put $f_{lg} = 1$ and set. According to the power value on the frequency response curve corresponding to the grid frequency, the power correction coefficient $C$ and $P_{set}$ are obtained:

$$P_{set} = C \times P_{wind}$$  \hspace{1cm} (6)

Among them, $P_{wind}$ is the active power of the wind turbine. $P_{set}$ directly outputs $P_{ref}$ through the limiting link. Under normal circumstances, the grid frequency is between $f_b$ and $f_c$, and the active power correction coefficient obtained is constant. When the system is disturbed and the frequency increases, and in the interval greater than $f_c$, the smaller the frequency, the smaller the correction coefficient obtained. The smaller the $P_{set}$ value, the smaller the output $P_{ref}$, resulting in a smaller active control signal and a smaller system output active power. Try to reduce the grid frequency to achieve wind turbine frequency modulation control.

3. **Simulation analysis of small examples**

3.1. **Simulation model**
This text uses the power system simulation software PSASP to carry on the simulation analysis, the simulation system adopts the power supply network model of the wind and thermal power unit hybrid, the wiring diagram is shown in Figure 3.

Figure 3. Small examples of primary supply power system diagram.

The thermal power unit shown in Figure 3 is a synchronous generator with a rated capacity of 600MW and connected to a 220kV line via a step-up transformer. The wind generator has a capacity of 100MW and a terminal voltage of 0.69kV, which is boosted to a 220kV line by a two-stage transformer. And jointly supply 200MW of load. In the simulation process, each parameter adopts the standard unit value, assuming that the wind speed remains at the rated wind speed value and does not consider the influence of wind turbine power fluctuations on the grid frequency.

3.2. Analysis of simulation results
In the simple hybrid power supply network model shown in Figure 4, the synchronous motor adopts the non-speed regulation mode. When \( t = 1s \), the 10MW grid load is removed on the bus bar. When the frequency control strategy is adopted/not adopted, the double-fed wind turbine pair. The adjustment effect of the grid frequency and its active power output are shown in Figure 4.

Figure 4. a) Grid frequency change curve b) Powerful output of wind turbine.

It can be seen from Figure 4 that the grid frequency increases due to the change of system load. When the frequency control strategy is adopted, the frequency modulation function of DFIG wind turbine started, the output of wind turbine is reduced, the frequency of power grid is improved, and the frequency offset caused by load fluctuation is reduced. However, the DFIG wind turbine without frequency control strategy does not have the ability of frequency modulation, the output power of wind turbine basically unchanged, and the grid frequency cannot be recovered after the frequency exceeds the normal range. Within 3~5s after the frequency changes, the frequency value is still in BC section. At this time, the DFIG wind turbine does not participate in the power grid frequency regulation, so the curve changes of the two are consistent. After \( t = 5s \), the frequency offset increases and enters the frequency modulation section, and the DFIG wind turbine begins to participate in the frequency regulation.

The thermal power unit adopts the speed regulation mode, when \( t = 1s \), the power grid load of 15MW is cut off from the bus, and the frequency control strategy is adopted/not adopted, the simulation results of DFIG wind turbine participating in frequency regulation are shown in Fig. 5.
Figure 5. Grid frequency change curve.

It can be seen from Figure 5 that when the load is cut off, the thermal power unit participates in frequency modulation alone, and the grid frequency can reach up to 50.45 HZ, which has reached the upper limit of the normal frequency range. However, after adding the frequency control link to the DFIG wind turbines, the grid frequency can quickly stabilize and the frequency adjustment effect obviously improved when the power grid frequency modulation is jointly participated with the thermal power unit. In addition, the maximum frequency deviation reduced from 0.45 HZ to 0.3 HZ, and the DFIG wind turbines has a good frequency adjustment effect.

4. Simulation analysis of practical examples

4.1. Actual power grid model
In this example, the total installed capacity of power grid is 1166.50MW, the installed capacity of thermal power unit is 949MW, and the installed capacity of doubly fed wind turbine is 217.50MW, as shown in the figure 6.

Figure 6. Practical examples of actual power grid.

4.2. Analysis of simulation results
The simulation model of power supply network in this area is established by using PSASP software. The generator set use the synchronous speed regulation model, and the simulation time is 50s. When the time is 1s, the certain load will be cut off from 10kV bus of Jin Kuang substation. The simulation analysis realized when the wind power penetration rate is 10% and 15%. As shown in the figure.
Figure 7. a) Wind power penetration rate is 10% b) Wind power penetration rate is 15%. It can be seen from the figure that when the DFIG does not participate in the primary frequency regulation of the grid, the grid frequency offset is large with the increase of wind power penetration rate. However, when the DFIG participates in the primary frequency regulation, the maximum frequency offset decreases. With the increase of wind power penetration rate, the effect of frequency modulation control is more and more obvious, which shows that the improved frequency control method has played an optimization role in the power grid. At the same time, the overload and loss of synchronous motor are reduced, so the service life of the unit is prolonged.

5. Conclusion
In order to improve the decoupling problem of DFIG, this paper analyzes the principle of DFIG participating in primary frequency regulation. The common inertial control method is improved, and a method based on the improved frequency control strategy is obtained. After modeling and simulation, and according to the actual power grid operation verification, the conclusions are as follows:

Based on the improved frequency control strategy, the frequency regulation ability of DFIG is improved by adding frequency control link to the traditional inertial control method. With the increase of wind power penetration, the frequency modulation control ability of DFIG is enhanced and improved, which can be used as a reference for wind power plants to participate in frequency regulation in the future.

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