Functional orientation analysis of primary frequency regulation and inertia control of DFIG

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Abstract. With the penetration of wind power increasing continuously, the inertia and the capability of primary frequency regulation of grid are declining. To deal with this problem effectively, additional primary frequency regulation control and inertia control adopted in wind turbines are necessary. However, at present, the functional orientation of primary frequency regulation control and inertia control is still unclear. It is urgent to clarify the difference between the two kinds of control methods and to make clear the demand of power grid for them. In this paper, based on analysis of main methods of primary frequency regulation and inertia control of doubly-fed induction generators (DFIG), the functional orientation distinction between inertia support function and primary frequency regulation function is studied from perspective of control principles and control results. The different effectiveness of different control functions on the frequency regulation process in different scenarios are analyzed by simulations.

1. Introduction
In order to meet the demand of sustainable development of resources and environment, the installed capacity of wind power has been increasing rapidly in recent years, and doubly-fed induction generators (DFIG) have been widely used. To maximize the use of energy, DFIGs usually adopt maximum power point tracking (MPPT) control, which cannot participate in the frequency regulation of the system. With the continuous improvement of wind power penetration, the inertia and the ability of primary frequency regulation of the power grid are declining, which makes the frequency deviation and the frequency change rate of the system increase under the disturbances of unit off-grid, line fault, load mutation and so on. Therefore, it brings risks to the frequency stability and recovery ability of the system [1-3].

In order to improve the response performance of wind turbines to the frequency changes of power system and maintain system frequency stability, some newly issued guidelines for power grid at home and abroad have clearly proposed that grid-connected wind farms need to be able to participate in system frequency modulation [4,5]. By adding frequency control, DFIGs have the ability of primary frequency regulation and inertia support, so as to improve the stability of the grid with high wind power penetration under the impact of power shortage. Nowadays, there are a lot of researches on primary frequency regulation and inertia support, but the main focus is on its control strategy and response characteristics, and attention is paid to the study of control methods on the wind unit side.
From the perspective of power grid, the study on the effect of primary frequency regulation and inertia support on power grid frequency is insufficient. In addition, there are some deficiencies in understanding of the function orientation of primary frequency regulation and inertia support and their application in large power grid.

Based on this, the primary frequency regulation and the inertial control methods are studied in this paper. On this basis, the differences between the two kinds of control are analyzed from the control law and energy viewpoint, and the positioning distinction between primary frequency regulation and inertia control is analyzed in detail. Moreover, the quantitative analysis is discussed for the two kinds of control for power systems with different wind power penetration levels from the perspective of grid side demand.

2. Power control of DFIG

DFIG wind turbines are the main type wind turbines used in large-scale wind farms. Figure 1 shows a typical DFIG configuration. DFIGs adopt a back-to-back PWM converter topology composed of fully controlled devices to reduce the harmonic pollution of the converter and improve the fault traversal performance, thus improving performance of wind power in power grid. With the MPPT as the control target, the vector control technology is adopted to realize active power and reactive power decoupling of the wind turbines. The MPPT control is realized by a rotor-side converter.

![Figure 1. Typical configuration of the DFIG wind turbine system.](image-url)

Through the aerodynamic model of wind turbines, it can be seen that for a given pitch angle, variable speed wind turbines can keep the optimal tip speed ratio by controlling the rotational speed of wind turbines to follow the change of wind speed, and then obtain the maximum wind energy utilization coefficient to achieve MPPT. The reference instruction of generated active power \( P_{opt} \) can be given by angular velocity feedback \( \omega_r \) as shown in equation (1),

\[
P_{opt}^* = \begin{cases} 
0 & 0 < \omega_r < \omega_b \\
 k_{gpe} \omega_r^3 & \omega_b \leq \omega_r < \omega_c \\
 \frac{P_{max} - k_{gpe} \omega_r^3}{\omega_{max} - \omega_a} (\omega_r - \omega_{max}) + P_{max} & \omega_c \leq \omega_r < \omega_{max} \\
P_{max} & \omega_r \geq \omega_{max}
\end{cases}
\]  

(1)
where, $k_{opt}$ is ratio coefficient of MPPT curve; $\omega_0$ is cut-in electric angular velocity; $\omega_i$ is initial angular velocity when entering constant speed zone; $\omega_{max}$ is limiting amplitude of electric angular velocity; $P_{max}$ is limiting amplitude of output active power. The MPPT curve is shown in figure 2 [6].

![Figure 2. Maximum power point tracking curve.](image)

Due to the mechanical and electrical limitation of wind turbines, the power output curves of wind turbines can be divided into four areas according to wind conditions: starting area, maximum power tracking area, constant speed area and constant power area.

Under the MPPT control strategy, wind turbines follow the MPPT control command to transfer power to the power grid. There is no direct coupling relationship between wind turbine speed and grid frequency, and the inertial response which can restrain the system frequency variation is lost. Moreover, if the system frequency drop occurs, the wind turbine cannot provide continuous power support due to the lack of active power reserve, and cannot share the unbalanced power of the system for a long time.

3. Frequency control strategies of DFIG

3.1. Primary frequency regulation strategy of DFIG

According to the power-frequency static modulation characteristic of primary frequency regulation, the active power change value proportional to frequency deviation is increased to the original active power reference value, so as to adjust the output of DFIG. For the system frequency regulation (above 20 s), DFIG wind turbines should continuously adjust the mechanical power captured by wind turbines and complete primary frequency regulation according to the static frequency characteristics required by the grid. Therefore, in order to realize the primary frequency regulation of the DFIG, reserve power is needed if without configuration of energy storage. However, since the wind turbine usually operates in the MPPT mode, with low or medium wind speed, the wind turbine operates in the maximum power tracking area or constant speed area with no reserve considered, only in high wind speed situation, where in order to prevent the wind turbine speed from breaking through the maximum speed limit, the wind turbine operates in the constant power operation area with power reserve.

Primary frequency regulation is essentially referred to as power-frequency droop control. Set the grid rated frequency as $f_N$, the measured grid frequency as $f$, and the active power reference signal for wind turbine can be expressed as:
\[ P_p = K_p (f - f_N) \]  \hspace{1cm} (2)

where, \( K_p \) is power regulation factor of primary frequency regulation.

Thus, the active power \( P_{\text{ref}} \) generated by the wind turbine can be calculated as

\[ P_{\text{ref}} = P_{\text{Deload}} + P_p \]  \hspace{1cm} (3)

where, \( P_{\text{Deload}} \) is the power adjustment signal for wind turbine under the load reduction control of DFIG.

According to equations (2) and (3), the primary frequency control block diagram of wind turbines can be obtained as shown in figure 3.

\[ \omega_s \]
\[ f \]
\[ \frac{1}{T_s + 1} \]
\[ \Delta f \]
\[ K_p \]
\[ f_N \]
\[ P_{\text{Deload}} \]
\[ P_{\text{ref}} \]

Figure 3. The primary frequency control block diagram of wind turbines.

When the power grid runs stably, the frequency variation of the system \( \Delta f \) is zero, and the wind turbines do not participate in the primary frequency regulation. But when the system frequency changes, there is a difference between the rated frequency and the measured value. An additional active power reference value \( \Delta P \) can be obtained according to the relationship between the frequency and the active power. Then active power reference value \( P_{\text{ref}} \) in the active power control system can be adjusted to participate in the primary frequency regulation of the system.

3.2. Inertia control strategy of DFIG

The inertia of the power system reflects the ability to prevent frequency mutation, so that the synchronous generator in the system has enough time to adjust the output power and reconstruct the power balance. When the frequency changes, the inertial control of the DFIG needs to adjust the electromagnetic power rapidly and release or store rotational kinetic energy to realize the inertial support for the system. The wind turbine controlled by power electronic converters cannot automatically provide inertial support, but the virtual inertia which is larger than the inherent inertia can be simulated by its rapid active regulation characteristics. The control method of wind turbine inertia response based on differential control link is commonly used in variable speed wind turbine inertia control scheme [7], that is, the variation of system frequency is added to the maximum power controller of wind turbine through differential link. DFIGs can absorb or release rotor kinetic energy rapidly by adjusting rotor speed, providing short-term power support for the system frequency change via making use of wind turbines’ rotating reserve. With inertial control, the load reduction control is unnecessary.

Under the inertial control, the supplementary active power \( P_{\text{r}} \) of the rotor-side converter can be calculated as shown in equation (4)
where, $K_D$ is the power regulation coefficient of inertia control.

Then, attach $P_D$ to the target value of power control $P_{MPPT}$ for maximum power tracking to get the reference active power $P_{ref}$ of wind turbine, which can be expressed as:

$$P_{ref} = P_{MPPT} + P_D$$

Thus, when frequency changes, the output power of the wind turbine will increase or decrease accordingly to achieve the goal of inertia control. The inertia control block diagram of wind turbines is shown in figure 4.

3.3. Discrimination between functional orientation of primary frequency regulation and inertia control

The primary frequency regulation function of wind turbines is essentially similar to the active power-frequency droop control of synchronous generators, so as to realize the adaptive regulation of the active power output of wind turbines with the frequency variation of the grid system, and make corresponding contributions to make the power grid reach a new power balance point. Inertia control is to restrain the rate of frequency drop, and to gain time for primary frequency regulation. An example of system frequency change process is shown in figure 5 [8].

$$P_D = K_D \frac{df}{dt}$$

\[(4)\]
First, from the characteristics of the control law, we can find that inertia support is a differential feedback control of system frequency, and primary frequency regulation is a proportional feedback control of system frequency. As can be seen from figure 5, compared with the primary frequency regulation control, the inertial support control has advanced characteristics because of its differential control law and can respond quickly. However, at the beginning of the system frequency change, the frequency deviation is small, so the primary frequency regulation control is relatively slow due to its proportional control law.

Then, we can find discrimination between functional orientation of primary frequency regulation and inertia control from the perspective of energy change. The inertia support is only a very short-term impulse power support. When the system frequency is no longer changing (frequency deviation still existing), the available support power of DFIG under inertial control is 0, and the accumulated energy generated by the inertia support is very limited. However, the power support of primary frequency regulation is continuous. As long as the system frequency deviation exists, the primary frequency regulation power always exists, and accumulated energy generated is very considerable, so that the system frequency can stop falling (rising) and keep running at a lower (higher) balance point.

4. Simulation and analysis

In order to distinguish the function of primary frequency regulation control and inertia control in the process of system frequency change, a classical two-area four-machine system model is built in PSASP. The system parameters are detailed in [9]. The system model is shown in figure 6.

![Figure 6. Two-area four-machine system model.](image)

On the basis of this system model, DFIG wind farms are connected to the system to replace part of the synchronous generators. Two cases are set where the rated wind power output is set 300 MW and 1200 MW, respectively, with the penetration of wind power in the whole system is 11% and 42.5%, respectively. By adding disturbances to cause system frequency changes, the supporting effects of primary frequency regulation control and inertia control on system frequency are analyzed in these two cases.

4.1. Case 1: A 300 MW wind farm is connected to bus 6

In this case, the 300 MW wind farm includes 20 wind power units with capacity of each unit as 15 MW. These wind power units are arranged in 5 rows and 4 columns, connected to the public connection point (PCC) by individual transformer for one unit. The whole wind farm is connected to the external power grid through an outlet transformer. The wind farm model is shown in figure 7.

A sudden 200 MW load increase at bus 7 happens at time 2.5 s. Primary frequency control and inertia control are adapted, respectively. The simulation results of wind power output and system frequency under two kinds of control strategies are shown in figures 8 and 9.
Figure 7. The 300 MW wind farm.

Figure 8. Wind power output response under different control strategies.

Figure 9. Frequency response under different control strategies.
From figures 8 and 9, it can be seen that the increased active power output generated by the wind farm is continuous under primary frequency regulation control, and the amount of increased power is proportional to the change of system frequency. But under inertia control, the increased active power generated by the wind farm is instantaneous, and the change of wind power output is proportional to the change rate of system frequency. In the process of system frequency change, the drop rate of system frequency is not significantly slowed down under inertia control. In other words, the inertia supporting function of wind farm is not obvious. However, the function of primary frequency regulation is more obvious. The final frequency regulation deviation under primary frequency control is less compared with that under inertial control. This is because the main purpose of inertial support is to gain time for primary frequency regulation, while in systems with low wind power penetration, due to the large number of synchronous machines in the network, considerable inertia already exists, making effects of inertial support from wind turbines less obvious. Therefore, the system with a large proportion of synchronous generators needs wind turbines to provide primary frequency regulation support rather than inertia support.

4.2. Case 2: A 600 MW wind farm is connected to bus 6, and G1 is replaced with another 600 MW wind farm

In this case, each wind farm includes 40 wind generation units with a unit capacity of 15 MW. Wind power units in each wind farm are arranged in 5 rows and 8 columns, connected to the public connection point (PCC) by means of one transformer for one unit, and wind farms are connected to the external power grid through the outlet transformers.

A sudden 200 MW load increases at bus 7 happened at time 2.5. Primary frequency control and inertia control are adapted, respectively. The simulation results of wind power output and system frequency under these two kinds of control strategies are shown in figures 10-12.

In this case, the inertia of synchronous generators in this system is reduced by replacing the G1 with a wind farm. Therefore, the inertia control of wind generation plays a significant role in the system frequency dropping period, effectively slowing down the system frequency dropping speed. Although the additional power generated by wind turbines under inertia control is short-term, the amount is still considerable in high wind power penetration scenarios lacking inertial generated by synchronous generators. In small and medium-sized power grids and microgrids with relatively low inertia and high proportion of new energy sources, the system frequency drops rapidly when power shortage occurs, and if there is no additional inertia support, frequency collapse may occur before the primary frequency regulation can be applied. In this case, the need for both inertia support function and primary frequency regulation function will be more urgent.

![Figure 10. Wind power output response of wind farm 1 under different control strategies.](image-url)
5. Conclusions
Distinguishing functional orientation of primary frequency control and inertial control in wind turbines plays a significant part in effective control of wind generation in frequency regulation. From theoretic analysis and simulation results comparison, we can come to the conclusions that the main function of the inertia support is to provide short-term power support which can respond to the frequency change rate of the system to prevent the system frequency from dropping rapidly, while primary frequency regulation can provide continuous active power support which can prevent the system frequency from dropping continuously and to work with the frequency effect of load to achieve a new balance. The effects of inertial control are much more obvious in power system with higher penetration of renewable energy.

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