Rotation Speed Recovery Strategy Based On Variable Power Curve of Inertia Control from DFIG Wind Turbine

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Abstract. With the increase of wind power capacity incorporated into the grid, the permeability of wind power increases continuously, which leads to the reduction of the equivalent inertia of the system. A new strategy of recovering rotor speed that increases the output power by modifying the variable power curve is proposed in this paper, which decreases the drop of the active power. So as to reduce the secondary frequency dips caused by the sudden drop of the active power when the speed restores. The paper optimizes the secondary frequency dips by modifying the variable power curve continuously. This article simulates this strategy through setting up a system by Simulink. Compared with the traditional recovery strategy, validity of the proposed strategy is demonstrated through simulation and analysis.

1. Introduction
In recent years, the total installed capacity of wind power has increased rapidly in China, and the penetration of wind power has been increasing. The instability of wind power has had an impact on the power system security. At present, the mainstream doubly fed induction generator connects to the power grid through the power electronic converter. The output electromagnetic power decouples from the frequency of the system. It can’t respond to the frequency change of the system. The wind turbine loses the inertia response of the traditional synchronous generator, resulting in reducing a dramatic reduce in the inertia of the system. It also has a threat to the system.

Domestic and overseas scholars have made a large number of researches on frequency regulation of wind turbines in the power system. There are two ways for wind turbines to participate in the system frequency regulation, the first is standby mode and the second is non-standby mode. The purpose of the standby is to reduce the steady state output power of the wind turbine through changing the pitch angle or rotor steady speed, which makes the wind turbine run in the load-shedding state in order to obtain a part of the reserve capacity. We can increase the value of the output electromagnetic power, while the system frequency is lower than the normal value. Then we can use the spare capacity to participate in the frequency regulation. Although the standby mode has the similar frequency regulation performance as that of the thermal power unit, it can’t be popularized in the project because it is involved in the system frequency regulation to reduce the load of the wind turbine for a long time and reduce the economic benefit of the wind power generation. The non-standby mode is to change the output power of the turbine through the inertia control of the virtual rotor, and promote the turbine...
to release the kinetic energy that stores in the rotor, simulate the inertia characteristics of the synchronizer, reduce the adverse effects of the wind power grid connected to the system, and help to improve the frequency response of the system [1]. The rotor inertia control makes use of the kinetic energy stored in the rotor of the turbine. When the frequency of the system reduces, the kinetic energy released by the motor will carry out the frequency support, so the rotor speed is constantly decreasing. When the rotor speed reaches the lower speed limit, the wind turbine must withdraw from the frequency regulation. The inertial control of rotor is introduced in the paper [2]-[6]. The exit frequency regulation of the rotor caused by the inertia control of the rotor causes the sudden drop of its output power, which causes the secondary dips of the system frequency.

With regard to the optimization of the secondary frequency dips, a great number of domestic and overseas scholars have done a lot of researches. One is model the frequency regulation process of wind power, and to find variables that causes the frequency change of the system. In literature [6], the frequency regulation process of wind turbine is modelled. The relationship between frequency regulation time and frequency second frequency dips is studied. The optimal exit equation group is found. This method improves the secondary frequency dips problem well, but it is too complex for calculation to operate in engineering. The other is to avoid the frequency tumble caused by the recovery of the speed out of the frequency regulation by changing the model of the wind power frequency regulation. For this method, reference [7], [8] have changed the coefficient of the power tracking curve by constantly changing the coefficient of the power tracking curve. In order to avoid switching directly to MPPT when the wind turbine exits frequency regulation, the secondary dips of frequency is reduced. Because of revising the coefficient of power tracking curve constantly in this method, there is usually no way to apply it in engineering. According to [9], when the wind turbine exits frequency regulation, the relationship between electromagnetic power and time is linear and the frequency is reduced greatly. The reference value of literature [10] is stepped back to avoid the falling of speed recovery by controlling the reference value of speed. The rotor speed decreases continuously during the frequency regulation. In paper [11], [12], which use fixed acceleration torque and PI controller to recovery the rotor speed respectively and improve the smoothness of the mode switching. The above method can improve the secondary frequency dips problem, but it needs to change the parameters in real time, the operation is complex, and it is not easy to realize in project. In article [13], an extended state observer is used to estimate the input mechanical power of the wind turbine in real time. On this basis, a given curve of electromagnetic power is designed to improve the secondary frequency dips. However, the design criterion of the power given curve is not given, which is not easy to achieve in engineering. Based on this, a new speed recovery strategy is proposed in this paper to design a given curve of electromagnetic power in the recovery phase, thus slowing down the dips speed of the electromagnetic power of the exit of the frequency regulation moment and reducing the frequency of the secondary frequency dips caused by the sudden landing of the active power output when the speed restores.

2. The Inertia Control

2.1. The models of wind turbine and drive train

The variable speed wind turbine consists of wind turbine, drive train, double fed induction generator (DFIG), back to back converter and control system, and its structure is shown in Figure 1.

Figure 1. The structure of the variable speed wind turbine.

The models of wind turbine and drive train

Figure 2. Principle diagram of wind turbine rotor inertia control.
The wind turbine plays the great role of converting wind energy into mechanical energy. The expression of the mechanical power captured by the wind turbine is then given by:

\[ P_m = \frac{1}{2} C_p \rho \delta v^3 s \]  

(1)

Where \( P_m \) is the mechanical power captured by wind turbine, \( V \) is the wind speed in m/s, \( \delta \) is the area swept by the rotor blades in m\(^2\), \( \rho \) is the air density in kg/m\(^3\), \( \beta \) is pitch angle and \( \lambda = \frac{R \rho \beta}{v} \) stands for the tip speed ratio and \( C_p \) stands for coefficient of utilization of wind energy. Different wind speeds have different optimal tip speed ratios. In order to capture the maximum wind energy and realize the control of MPPT, it is important to maintain the optimal tip speed ratio through adjusting the speed of the wind turbine.

2.2. The method and process of the rotor inertial control

The method of the rotor inertial control. Rotor inertial control is a common frequency-modulation technique engineering, which is usually used at present. Rotor inertial control is the ability to simulate the inertia response and primary frequency regulation of traditional wind turbine. The active power reference value \( P_{ref} \) is transmitted to the converter control system by superimposing the frequency regulation power increment \( \Delta P \) on the power reference value \( P_{MPPT} \) given by the original MPPT curve of the wind turbine. The rotor inertial control schematic diagram is shown in Figure 2. Where \( \Delta P \) is expressed by formula (3), in which \( f \) is the system frequency, \( K_f \) is the primary frequency regulation coefficient, and in the second term, the inertial frequency regulation factor \( T_j \) is the inertial response coefficient of the synchronous generator.

\[ \Delta P = K_f (f_0 - f) + T_j \frac{\Delta f}{\Delta f} \]  

(2)

The process of the rotor inertial control. There are two stages of the frequency regulation process of DFIG during the speed recovery in the rotor inertia control strategy, which are inertia support and the speed recovery. As shown in Figure 3, the frequency-modulation process begins to frequency-modulation when the frequency reduces, and enters the inertial support stage. The wind turbine releases part of the rotor kinetic energy in order to increases the electromagnetic power output for the power support, and the speed continues declining at this time. When the speed of the wind turbine is reduced to the lower speed limit, the wind turbine exits frequency regulation, the wind turbine enters the speed recovery stage, the traditional speed recovery way is MPPT curve, and the electromagnetic power falls to the current speed corresponding to the current speed on the MPPT curve, and the subsequent speed and the electromagnetic power are gradually restored.

As shown in Figure 4, compared wind power participating in frequency regulation by MPPT curve recover with that are not involved in frequency regulation, the former reduces the depth of the first dips, but causes the secondary dips of power grid frequency seriously, so it is necessary to adopt an appropriate speed recovery strategy of the wind turbine.

According to the wind speed, the working status of wind turbine can be divided into three typical phases: MPPT phase, constant speed interval and constant power phase. In condition of participating in the system frequency regulation while the wind turbine works in constant power status, it does not need to release rotor kinetic energy so that it will not cause the second frequency dip. Therefore, this article will focus on the analysis of the other two operating phases. The principle of the speed recovering method when the wind turbine runs in the MPPT phase is shown in Figure 5.

In Figure 5, the solid line shows the MPPT power curve of wind turbine while the dashed line is the mechanical power curve at some wind speed. Assuming the wind turbine operates at point A at the first time, as power grid frequency drops, the electromagnetic power will rise to point B while the rotor speed will decrease to point C gradually during the frequency regulation. Once the rotor speed reaches the low speed limit (point C), the wind turbine will withdraw from the frequency regulation. If
the traditional MPPT curve recovery method is adopted, the output electromagnetic power of the wind turbine will drop to point E instantly, then resume gradually along the MPPT power curve. It can be seen that the output power of the wind turbine is moving along the path as the A-B-C-E-A using the traditional MPPT curve. And at the moment of exiting frequency regulation, the drop of electromagnetic power with the amplitude $\Delta P_{e1} + \Delta P_{e2}$ occurred, causing serious second frequency dropping. In order to reduce the drop depth of the electromagnetic power, a new method has been designed which makes the electromagnetic power slowly drops along the red curve until it intersects the MPPT power curve (point G) before the electromagnetic power gradually recovered along the path of G-A. It can be seen that the output power of the wind turbine is moving along the path of A-B-C-G-A using new recovering method. And the drop amplitude of the electromagnetic power is $P_{e1} + P_{e3}$, which could reduce second frequency dropping greatly.

**Figure 3.** Diagram of frequency regulation with rotor inertia control.

**Figure 4.** The contrast diagram of the frequency variation.

**Figure 5.** The contrast diagram of the principle of speed recovery.

**Figure 6.** The image of the variable power function $f(t)$.

3. **Speed recovery strategy based on variable power curve for rotor inertia control of DFIG**

3.1. **The working principle of the proposed speed recovery strategy**

Using MPPT strategy to recovery the rotor speed, the sudden drop of the active power of the wind turbine will cause the second frequency dropping. For this consequence, a new speed recovery strategy based on the variable power curve has been proposed in this paper. This strategy aims at reducing the
active power output gradually by changing the parameters of the variable power curve, so as to optimize the secondary dips of frequency. The structure of the proposed strategy is shown in Figure 6.

\[
P_{ac} = f(t) \cdot \frac{\omega_{ref} - \omega}{\omega_{ref} - \omega_{rmin}}
\]

Figure 7. The structure of the proposed speed recovery strategy.

In Figure 7, \(\omega_{ref}\) presents the reference value of the rotor speed, and \(\omega_{rmin}\) is the lower limit of the speed drop of the DFIG when it participates in frequency-modulation. \(f(t)\) is a variable power function, it is a human set function, and the expression of the variable power curve \(P_{ac}\) of the strategy is:

The wind turbine would withdraw from the frequency regulation once the rotor speed \(\omega_r\) drops to the lower speed limit \(\omega_{rmin}\). Set the coefficient of the variable power curve \(\frac{\omega_{ref} - \omega}{\omega_{ref} - \omega_{rmin}}\) to avoid the output electromagnetic power of wind turbine dropping too much at the beginning of the exiting of frequency regulation during which the rotor speed \(\omega_r\) restores to \(\omega_{ref}\) and the variable power curve coefficient reduces from 1 to 0 gradually.

3.2. The design of variable power curve

The image of the variable power function \(f(t)\) is shown in the figure 7, where \(t_1\) is the time of exiting the frequency regulation, and \(t_2\) is the time when the variable power function reaches the maximum value. After \(t_2\), \(f(t)\) remains unchanged.

4. Simulation analysis

4.1. Construction of simulation system

A wind power system simulation model has been built which includes both of virtual and conventional synchronous units to simulate the secondary dips of wind power virtual synchronous machine based on rotor inertial control strategy. The proposed variable power curve recovery method has been studied and verified comparing with the classic MPPT recovery method.

Firstly, building a wind power system simulation model first which includes both of virtual synchronous generator (2MW/690V x 31) and conventional synchronous generator (250MVA/13.8kV). The structure of the system is shown in Figure 8 of which main parameters are given in Tables 1 and 2.

Figure 8. Topology diagram of simulation system.
Table 1. Main parameters of normal synchronous generator

| Parameter                                    | Value  |
|----------------------------------------------|--------|
| Inertia constant /s                          | 5      |
| Frequency regulation coefficient             | 15     |
| Load frequency modulation coefficient        | 2      |
| One frequency regulation limited amplitude   | 3.5%   |
| Main steam pressure pipe flow coefficient    | 3      |

| Parameter                                    | Value  |
|----------------------------------------------|--------|
| drum heat storage volume time constant /s    | 300  |
| Super heater volume time constant /s         | 10    |
| boiler fuel release time constant /s         | 10    |
| combustion release delay /s                  | 20    |
| drum heat storage volume time constant /s    | 300  |

Table 2. Main parameters of wind turbine VSG

| Parameter                                    | Value  |
|----------------------------------------------|--------|
| Inertia constant /s                          | 5.005  |
| Primary frequency regulation coefficient     | 20     |

| Parameter                                    | Value  |
|----------------------------------------------|--------|
| inertial frequency regulation coefficient    | 5      |
| frequency regulation speed lower limit /pu  | 0.83   |

By the end of 2016, the proportion of new energy machine assembly capacity in the regional power grids such as the Northwest Power Grid and North China Power Grid has reached about 20% [14]. In the event of grid frequency disturbances that have occurred in recent years, the maximum power shortage is about 4% [15]-[16]. Therefore, in the simulation, wind power accounts for about 20% of the installed capacity of the system and power shortage of 4% of the system capacity occurs in the power grid.

4.2. The selection of variable power function $f(t)$ and Simulation Analysis under the different variable power functions

In order to apply this method better in engineering, the variable power function $f(t)$ should be as simple as possible. By changing the four parameters $a$, $b$, $t_1$, and $t_2$, a simple primary function $f(t)$ has been constructed as a variable power function in this paper. And a variable power function with different parameters has been selected for simulation and comparison. At $172$ s, the rotor speed of the wind turbine constructed in this paper reaches the lower speed limit (0.83 p.u.) while the wind turbine exits the frequency regulation. So $t_1$ is equal to 172.

Influence of the Change of $b$ in $f(t)$ on system. Keeping $a$, $t_1$, and $t_2$ constant ($a=-0.00428$, $t_1=172$, and $t_2=200$). Take a different value for parameter $b$ in $f(t)$. $f_5(t)$ stands for speed recovery strategy based on MPPT curve. Then perform simulation analysis and compare the changes in frequency, power, and speed as shown in Figures 9(a), (b) and (c) respectively:

From the simulation results shown in Figures 9(a), (b) and (c), it can be seen that the proposed strategy for changing the power curve reduces the depth of the second drop significantly. Keep $a$, $t_1$, and $t_2$ constant. With the increase of $b$, the depth of the second drop is getting smaller and smaller, which leads to that the effect is getting better and better. But the speed of speed recovery becomes slower. In other words, the decrease of the second drop depth is at the expense of the speed of speed recovery. Therefore, when ensuring the speed of speed recovery properly, the value of $b$ cannot exceed the value of $b$ in $f_4(t)$, in that, $b$ is equal to 0.3772. In addition, the proposed strategy improves the smoothness of the output electromagnetic power significantly. At the moment of exiting the frequency regulation, the output electromagnetic power does not fall to the minimum immediately in order to reduce the
depth of the second drop. It will cause the active power to drop to the lowest value when using the classic MPPT strategy to recover the speed, which will lead to the second drop.

(a). Frequency simulation contrast diagram at different b.

(b). Power simulation contrast diagram at different b.

(c). Speed simulation contrast diagram at different b.

Figure 9. Simulation contrast diagram at different b.

Influence of the Change of a in f(t) on system. Keeping b, t1, and t2 constant (b=0.13, t1=172, and t2=200). Take a different value for parameter a in f(t). Then perform simulation analysis and compare the changes in frequency, power, and speed as shown in Figures 10(a), (b) and (c), respectively:

(a). Frequency simulation contrast diagram at different a.

(b). Power simulation contrast diagram at different a

(c). Speed simulation contrast diagram at different a.

Figure 10. Simulation contrast diagram at different a.

The simulation results shown in Figure 10(a), (b) and (c) show that the depth of the second drop will get smaller and smaller when keeps b, t1, and t2 constant and with the decrease of a. So the effect will get better. The active output drops of using the strategy mentioned in the article is shallower than using the MPPT curve strategy at the moment of exiting the frequency regulation. But the speed recovery of the former is slower than the latter. In other words, the decrease of the second drop depth is at the expense of the speed of speed recovery.

Influence of the Change of t1 in f(t) on system. Keeping b, a, and t2 constant (a=-0.00428, b=0.3772, and t2=200). Take a different value for parameter t1 in f(t). Then perform simulation analysis and compare the changes in frequency, power, and speed as shown in Figures 11(a), (b) and (c) respectively:

The simulation results show that the decrease of the second drop depth is at the expense of the speed of speed recovery. With the increase of t2 (keep a, b, and t1 constant), the depth of the second drop becomes smaller, the effect becomes better, but the speed of speed recovery becomes slower.
5. Conclusion
In recent years, the cumulative installed capacity of wind power in China has increased rapidly, and the penetration rate of wind power continues to increase. The instability of wind power has threatened the safety of power systems. DFIG cause the secondary dips of frequency when rotor inertia control is used to participate in frequency regulation. This paper proposes a new speed recovery strategy. By changing the power curve to increase the value of the output power and reduce the drop of the active output, the second drop of the frequency caused by the sudden drop of active power output reduces at the moment of the speed recover. Power changes smoothly. The secondary dips is optimized by continuously designing a modified variable power curve. The simulation verified its effectiveness. This strategy optimizes the secondary dips of the system frequency on the premise of ensuring the recovery speed of the wind turbine speed. Effectively improve the secondary dips of frequency after adopting the rotor inertial control. There are still some deficiencies in this article. It needs to continue to be optimized. For the improvement of the secondary dips problem, we can use the combination of energy storage system and wind power. We can adopt a multi-machine coordinated control strategy as well. In addition, the model predictive control theory can be applied to wind power frequency regulation. The model predictive control can achieve accurate tracking of frequency, power and speed, which achieves the purpose of reducing secondary dip.

6. References
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