Frequency Control Strategy of DFIGs based on Improved Virtual Inertia Method

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Abstract. The DFIGs can participate in frequency control by virtual inertia method. After exiting the frequency control, secondary frequency drop will occur inevitably. The current study of the problem mostly focused on the rotor speed recovery strategy and PD control parameter optimization problems, which cannot eliminate the phenomenon of secondary frequency drop in essence. This paper proposes a frequency control strategy based on the improved virtual inertia control method. When the DFIG exits the frequency modulation process, the supplementary control component based on the turbine speed is added to avoid the sudden drop of output power, so as to suppress the secondary frequency drop. Finally, a simulation model is built in Matlab/Simulink, and the feasibility of the proposed strategy is verified in two case studies of power system frequency reduction and load fluctuation.

1. Introduction

As the capacity of renewable energies continues to increase, the proportion of synchronous generators in the grid is gradually decreasing. Renewable energies such as wind turbines and photovoltaics do not have the inertia response capability of synchronous machines, and cannot participate in the frequency adjustment process without additional control. The equivalent inertia of the power system gradually decreases. When a disturbance occurs, the offset and rate of change of the frequency increase significantly compared to the traditional power system.

The continuous increase in wind turbines penetration rate has brought adverse effects on the current power system, the DFIGs are currently the main types of wind turbines in commercial applications. Applying additional control links to DFIGs has a very obvious effect on improving the frequency characteristics of the power system [1]-[4]. The basic methods for DFIGs to participate in power system frequency adjustment and inertia response include virtual inertia control, overspeed method, and pitch angle control method. The virtual inertia method of DFIGs is proposed for the first time, which verifies the feasibility of using
rotor kinetic energy to make the DFIG participate in the frequency response through additional PD control in [5]. The virtual inertia method was improved by modifying and optimizing PD parameters and adding or improving control method [6]-[11]. The three basic ways of DFIG participating in frequency modulation are combined to make it more effectively support the power system frequency modulation [12]-[14].

In order to ensure the normal operation of the wind turbines, the rotor speed cannot be reduced unlimited. When the speed drops to a fixed ratio, the wind turbines need to exit the frequency modulation process. At this time, the speed is lower than that of normal operation. After exiting the frequency modulation and entering the original operating state, the active power it emits is greatly reduced. At the same time, the rotation speed needs to absorb a certain amount of energy to return to the normal state. There will be a secondary frequency drop. Considering the secondary drop when the DFIGs exit the frequency modulation, the parameters in the frequency modulation process are optimized to reduce the secondary drop phenomenon [15], [16]. According to the speed of the wind turbine, five compensation algorithms are used to balance the secondary drop of frequency and the recovery process of the turbine speed [17]. An extended state observer is introduced to estimate the captured and output mechanical power of the DFIG by the state observation quantity, and the recovery of the speed can be accelerated by considering the secondary drop of frequency [18]. The speed recovery strategy and recovery process are designed and optimized, and the effect of the speed recovery strategy on the suppression of secondary sags is verified in the simulation process [19]-[21].

Based on the analysis of existing research, this paper summarizes the combined strategy of DFIGs participating in frequency adjustment and improves the typical virtual inertia control method. The active power output of the DFIG is compensated by adding supplementary control based on the turbine speed, so as to reduce the secondary drop of frequency and improve the DFIG's frequency regulation ability and the equivalent inertia. Finally, a simulation model was built in Matlab/Simulink to simulate two situations of power system frequency reduction and load change, which verifies the effectiveness of the proposed scheme.

The remainder of this paper is organized as follows. The typical virtual inertia control and power reserve control are introduced in Section II. The frequency control strategy of DFIGs based on improved virtual inertia method is explained in Section III. In Section IV, a simulation model is established to verify the frequency modulation performance. In the end, the paper is concluded in Section V.

2. Typical inertia control measures

2.1. Virtual inertia control

The typical virtual inertia control method is that when the power system has a power shortage, the wind turbines reduces the turbine speed through an additional PD control link, and uses the kinetic energy stored in the rotor to increase the output of the wind turbines' active power. When the wind is in normal operation, the energy stored in the rotor is:

\[ E = \frac{1}{2} J \omega_e^2 \]  

(1)

where \( J \) is the moment of inertia of the DFIG, and \( \omega_e \) is the speed. When there is no additional control link, the wind turbine usually runs in the maximum power tracking maximum power point tracking (MPPT) mode. When the power system frequency changes due to power disturbance, the wind turbine cannot adjust the output power in time, and cannot participate in the inertia response and primary frequency modulation. The equivalent inertia of the wind turbine is basically zero.

Suppose the active power of the wind turbine in the maximum power tracking mode is \( P_{ref} \). In order to enable the output power of the wind turbine to track the frequency response, suppose \( K_1 \) is the differential control coefficient, \( K_2 \) is the proportional control coefficient, \( f_{ref} \) is the power system
measurement frequency, and $f_{\text{ref}}$ is the reference frequency, the frequency deviation is $\Delta f = f_{\text{mea}} - f_{\text{ref}}$.

Then under the frequency control method, the additional amount of active power is:

$$\Delta P_1 = -(K_1 \frac{df_{\text{mea}}}{dt} + K_2 \Delta f)$$

(2)

The actual active power output by the wind turbines can be expressed as:

$$P_e = P_{\text{ref}} + \Delta P_1$$

(3)

Therefore, the wind turbine can quickly respond to frequency changes through the additional frequency PD control link, and has a performance similar to a synchronous generator. The schematic diagram of the virtual inertia control strategy is shown in figure 1.

However, the speed of the wind turbine cannot be reduced indefinitely. Usually, when the speed drops to 0.7 pu, it is necessary to exit the frequency modulation and return to the maximum power tracking mode for speed recovery.

2.2. Power reserve control

In order to enable the wind turbine to have a certain frequency adjustment capability, and to reserve a certain reserve capacity during normal operation of the wind turbine, the pitch angle control and overspeed control are usually used to achieve load shedding operation. Pitch angle control transformation changes the angle of the wind turbine blades to change the wind energy input, so that the wind turbine runs below the maximum power point, so as to obtain the reserve capacity. The schematic diagram of the power reserve control strategy is shown in figure 2. Since the adjustment range of the wind turbine operating speed is usually within ±0.3 pu, the overspeed control is not suitable for the situation where the wind speed is too high. In the actual situation, considering that the pitch angle control will shorten the operating life of the wind turbine, the overspeed control is usually used at low wind speeds, and the pitch angle control is used at high wind speeds. In the case of medium customs, the two load shedding methods are used in combination.

For power reserve control, there are generally three methods: fixed load shedding coefficient, fixed load shedding amount, and variable load shedding coefficient. Suppose the output power after power reserve is $P_{\text{de}}$, the output power of the wind turbine maximum power tracking state is $P_{\text{opt}}$, and the fixed load shedding coefficient $d\%$ is to keep the load shedding coefficient constant, so that

$$P_{\text{de}} = d\% P_{\text{opt}}$$

(4)

The fixed load shedding guarantees that the standby power remains unchanged and it can be expressed as:

$$P_{\text{res}} = P_{\text{opt}} - P_{\text{de}}$$

(5)

The variable load shedding factor is to adjust $d\%$ according to different wind speed conditions, so that the wind turbine has better frequency support performance. The feasibility of the above three methods has been confirmed in existing studies.
3. Frequency control strategy of DFIG based on improved virtual inertia control

3.1. Determination of compensation time
In the typical virtual inertia control, the additional control link only includes the frequency response. When the wind turbine exits the frequency modulation for speed recovery, the additional power is zero at this time, and there is no control link, and the power system frequency will include an obvious secondary frequency drop. In order to suppress the secondary frequency drop, a speed recovery link can be added to the typical virtual inertia control to avoid the secondary frequency drop and restore the rotor speed to the original operating state as soon as possible.

When the wind turbine is running normally, it runs at point 1 in figure 3. When there is a shortage of disturbance to participate in the frequency modulation process, the wind turbine speed $\omega_{w}$ decreases, at this time $d\omega_{w}/dt < 0$, and the output power $P_{out}$ of the wind turbine increases, namely $dP_{out}/dt > 0$. The wind turbine runs from point 1 to point 2. If there is no additional control link after the end of frequency modulation, it will fall from point 2 to point 3. At this time, the output power $P_{out}$ of the wind turbine drops sharply, $dP_{out}/dt < 0$, after that, the speed of the wind turbine will gradually increase and recover, $d\omega_{w}/dt > 0$. When exiting the frequency modulation and directly returning to point 3 on the MPPT curve, the secondary frequency drop will occur. That is, when $dP_{out}/dt < 0$ and $d\omega_{w}/dt > 0$ are satisfied, PI control based on the speed of the wind generator is added to increase the power $\Delta P_{2}$ of the wind generator.

![Figure 3. Improved virtual inertia control](image)

![Figure 4. Simulation power system model](image)

However, in the actual speed recovery process of the wind turbine, the time period for the output power of the wind turbine to drop sharply is relatively short, and then as the speed recovers, the output power of wind turbines will generally increase gradually, and because the speed recovery of wind turbines usually has a certain delay, it is difficult to grasp the time period when the above two inequalities are satisfied at the same time. In addition, during the normal operation of the wind turbine, its output and wind turbine speed fluctuate, floating around 0. Based on the above two reasons, the additional control startup time can be set as:

$$dP_{out}/dt > V_{th}$$

(6)

where $V_{th}$ is the set threshold. When the speed of the wind turbine output decreases too fast, after the set threshold is exceeded, the additional control link starts to start. The selection of the threshold can be set according to the parameters of the wind turbine and the working environment. The purpose of the selection is to identify the time period during which the wind turbine output suddenly drops. In this paper, the selection range of $V_{th}$ is 6-10.

3.2. Improved virtual inertia control method
In the virtual inertia frequency modulation stage, part of the rotor kinetic energy is converted into the output of the wind turbine. Therefore, after the frequency modulation is completed, the speed of the wind turbine is significantly lower than the rated speed during normal operation. Therefore, when it is
detected that the output power change exceeds the threshold, the size of the additional control component is determined based on the current wind turbine speed and the rated wind turbine speed.

Set at a constant wind speed, the wind turbine speed corresponding to the optimal operating point is \( \omega_1 \), \( K_3 \) is the integral control coefficient, \( K_4 \) is the proportional control coefficient, \( \omega_v \) is the turbine speed, and the turbine speed deviation \( \Delta \omega = \omega - \omega_v \), then in the speed control link, the additional amount of active power can be expressed as:

\[
\Delta P_2 = -(K_3 \int (\omega - \omega_v) \, dt + K_4 \Delta \omega_v)
\]  

At this time, the actual output active power of the wind turbine can be written as follows:

\[
P_e = P_{ref} + \Delta P_2
\]

After exiting the frequency modulation process, the original frequency control link no longer functions, and the speed control link provides an additional frequency so that the output frequency of the wind turbine will not drop to the MPPT curve. As the active power output by the wind turbine increases, the deviation between the mechanical power and the electromagnetic power becomes smaller than before, so the recovery speed of the wind turbine speed becomes slower. The improved virtual inertia control is equivalent to a compromise between avoiding the secondary frequency drop and speed recovery.

4. Simulation

In order to verify the frequency modulation performance of the DFIG frequency control strategy based on the improved virtual inertia control, a simulation model is established in MATLAB/Simulink as shown in figure 4. In this model, the DFIGs are composed of six 1.5MW single units. \( T_1 \) and \( T_2 \) are two transformers. \( L_1 \) is the system load. The line represents an overhead line of 30Km, and this model is finally connected to an infinite bulk electric power system.

The initial frequency of the power system is 60Hz. In order to reduce the influence of wind speed on the simulation results, this paper uses a high wind speed with a rated wind speed of 15m/s. At this wind speed, the speed of the wind turbine is already close to the upper limit. In this scenario, the wind turbine maintains its rated power output.

4.1. The power system frequency drops

The power system frequency is reduced by 0.1Hz from 60.0Hz at 15.0s, this paper simulates three situations of wind turbine without additional control, additional virtual inertia control and additional improved virtual inertia control. The power system frequency characteristics under the above three control states are shown in figure 5.
Since the model in this paper is directly connected to the large grid, the power system frequency is highly controllable and the frequency curve fluctuation is small. In order to make the observation effect more obvious, we select the 14.5-17s time period for observation. This stage reflects the difference in frequency fluctuations under different control methods. We can see that when the wind turbine has no additional control, the frequency deviation is the largest, and the lowest point is 59.882Hz. After the additional virtual inertia adjustment control, the maximum frequency deviation is reduced from 0.118Hz to 0.112Hz, which makes the inertia response performance of the power system better, but it is inevitable that the secondary frequency drop will occur. After adding the improved virtual inertia control, the first half of its frequency characteristics is basically the same as the typical virtual inertia control. The frequency is significantly increased between 15.5s-16s, which suppresses the secondary frequency drop. This makes the DFIGs have better frequency regulation performance.

Figure 6 shows the output characteristics of the wind turbine after the frequency drops. It can be seen that when there is no additional control link, the output of the wind turbine is basically maintained at a constant state when the power system frequency drops. When the virtual inertia control link is added, the output of the wind turbine begins to increase after 15s, and after 0.6s, the output of the DFIGs begins to decrease. At this time, the frequency will gradually shift downward along with the decrease of the torque of the wind turbine. When the improved virtual inertia control is used, DFIG adds a part of additional components in about 0.7s, so that the output of DFIG will not drop sharply, and the secondary frequency drop is suppressed by delaying its speed recovery.

4.2. The sudden load increase
Suppose the load $L_1$ in the simulation model increases suddenly at 5.0s, from 2MW to 4MW. Since the simulation model in this paper is connected to the infinite grid, when the load is disturbed, the frequency can still be restored to the original state. When the wind turbine participates in frequency regulation, figure 7 demonstrates the power system frequency characteristics in three control states.

![Figure 7. The comparison of the frequency after a sudden load increase](image)

![Figure 8. The comparison of the torque after a sudden load increase](image)

It can be seen that after the virtual inertia control is added, the minimum offset of the power system frequency and the frequency modulation speed have been significantly improved, but at 15.3s, the frequency has obvious fluctuations. After improving the virtual inertia control method, the response curve of the first half of the frequency response is basically the same as that of the typical virtual inertia control method, while the frequency fluctuation is suppressed, and the power system frequency has a better response curve.

Figure 8 shows the electromagnetic torque characteristics of DFIG output after a sudden load increase. Without additional control links, the output of the wind turbine does not change significantly. When the virtual inertia takes effect, the output of the wind generator increases. As the power system...
frequency rises rapidly, the wind generator exits the frequency modulation process, and the output of the wind generator drops sharply, causing the power system frequency to fluctuate. After the frequency drops sharply, the wind turbine generates a part of the power again under the control of the improved virtual inertia control to make the frequency modulation ability better.

5. Conclusion
In this paper, the secondary frequency drop during the frequency adjustment of DFIG is studied, and a control strategy based on the improved virtual inertia control method is proposed, and the following conclusions are obtained:

1) The typical virtual inertia control adds a control link based on the power system frequency so that the wind turbine has the ability to adjust the frequency. In the event of a power shortage, part of the rotor kinetic energy is converted into the output of the wind turbine, so that the wind turbine has a better inertia response and primary frequency modulation capability, but when exiting the frequency adjustment, the power system will have a secondary frequency drop.

2) The frequency control strategy based on the improved virtual inertia control adds a speed response link after the typical virtual inertia adjustment ends, and an control component is added based on the wind turbine speed to delay the speed of the wind turbine returning to the MPPT operation point. It can effectively avoid the secondary frequency drop.

3) The simulation results show that the frequency control strategy based on the improved virtual inertia control can effectively avoid the secondary frequency drop phenomenon, and the wind turbine has better frequency regulation characteristics.

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References
[1] M. Yin, Y. Xu, C. Shen, J. Liu, Z. Y. Dong and Y. Zou, "Turbine Stability-Constrained Available Wind Power of Variable Speed Wind Turbines for Active Power Control," IEEE Transactions on Power Systems, vol. 32, no. 3, pp. 2487-2488, May 2017.
[2] R. Azizipanah-Abarghoee, M. Malekpour, T. Dragičević, F. Blaabjerg and V. Terzija, "A Linear Inertial Response Emulation for Variable Speed Wind Turbines," IEEE Transactions on Power Systems, vol. 35, no. 2, pp. 1198-1208, March 2020.
[3] S. Wang and K. Tomsovic, "A Novel Active Power Control Framework for Wind Turbine Generators to Improve Frequency Response," IEEE Transactions on Power Systems, vol. 33, no. 6, pp. 6579-6589, Nov. 2018.
[4] M. Garmroodi, G. Verbić and D. J. Hill, "Frequency Support From Wind Turbine Generators With a Time-Variable Droop Characteristic," IEEE Transactions on Sustainable Energy, vol. 9, no. 2, pp. 676-684, April 2018.
[5] J. Morren, S. W. H. de Haan, W. L. Kling and J. A. Ferreira, "Wind turbines emulating inertia and supporting primary frequency control," IEEE Transactions on Power Systems, vol. 21, no. 1, pp. 433-434, Feb. 2006.
[6] X. Peng, W. Yao, C. Yan, J. Wen and S. Cheng, "Two-Stage Variable Proportion Coefficient Based Frequency Support of Grid-Connected DFIG-WTs," IEEE Transactions on Power Systems, vol. 35, no. 2, pp. 962-974, March 2020.
[7] A. Ashouri-Zadeh and M. Toulabi, "Adaptive Virtual Inertia Controller for DFIGs Considering Nonlinear Aerodynamic Efficiency," IEEE Transactions on Sustainable Energy, vol. 12, no. 2, pp. 1060-1067, April 2021.
[8] H. T. Nguyen, G. Yang, A. H. Nielsen and P. H. Jensen, "Combination of Synchronous Condenser and Synthetic Inertia for Frequency Stability Enhancement in Low-Inertia Systems," IEEE Transactions on Sustainable Energy, vol. 10, no. 3, pp. 997-1005, July 2019.
[9] J. Van de Vyver, J. D. M. De Kooning, B. Meersman, L. Vandevelde and T. L. Vandoorn, "Droop Control as an Alternative Inertial Response Strategy for the Synthetic Inertia on Wind Turbines," IEEE Transactions on Power Systems, vol. 31, no. 2, pp. 1129-1138, March 2016.

[10] M. Hwang, E. Muljadi, J. Park, P. Sorensen and Y. C. Kang, "Dynamic Droop–Based Inertial Control of a Doubly-Fed Induction Generator," IEEE Transactions on Sustainable Energy, vol. 7, no. 3, pp. 924-933, July 2016.

[11] J. Ying, X. Yuan, J. Hu and W. He, "Impact of Inertia Control of DFIG-Based WT on Electromechanical Oscillation Damping of SG," IEEE Transactions on Power Systems, vol. 33, no. 3, pp. 3450-3459, May 2018.

[12] J. Zhao, X. Lyu, Y. Fu, X. Hu and F. Li, "Coordinated Microgrid Frequency Regulation Based on DFIG Variable Coefficient Using Virtual Inertia and Primary Frequency Control," IEEE Transactions on Energy Conversion, vol. 31, no. 3, pp. 833-845, Sept. 2016.

[13] X. Tang, M. Yin, C. Shen, Y. Xu, Z. Y. Dong and Y. Zou, "Active Power Control of Wind Turbine Generators via Coordinated Rotor Speed and Pitch Angle Regulation," IEEE Transactions on Sustainable Energy, vol. 10, no. 2, pp. 822-832, April 2019.

[14] R. Prasad and N. P. Padhy, "Synergistic Frequency Regulation Control Mechanism for DFIG Wind Turbines With Optimal Pitch Dynamics," IEEE Transactions on Power Systems, vol. 35, no. 4, pp. 3181-3191, July 2020.

[15] H. Shao et al., "Stability Enhancement and Direct Speed Control of DFIG Inertia Emulation Control Strategy," IEEE Access, vol. 7, pp. 120089-120105, 2019.

[16] Z. Chu, U. Markovic, G. Hug and F. Teng, "Towards Optimal System Scheduling With Synthetic Inertia Provision From Wind Turbines," IEEE Transactions on Power Systems, vol. 35, no. 5, pp. 4056-4066, Sept. 2020.

[17] K. Liu, Y. Qu, H. Kim and H. Song, "Avoiding Frequency Second Dip in Power Unreserved Control During Wind Power Rotational Speed Recovery," IEEE Transactions on Power Systems, vol. 33, no. 3, pp. 3097-3106, May 2018.

[18] F. Liu, Z. Liu, S. Mei, W. Wei and Y. Yao, "ESO-Based Inertia Emulation and Rotor Speed Recovery Control for DFIGs," IEEE Transactions on Energy Conversion, vol. 32, no. 3, pp. 1209-1219, Sept. 2017.

[19] M. Toulabi, S. Bahrami and A. M. Ranjbar, "An Input-to-State Stability Approach to Inertial Frequency Response Analysis of Doubly-Fed Induction Generator-Based Wind Turbines," IEEE Transactions on Energy Conversion, vol. 32, no. 4, pp. 1418-1431, Dec. 2017.

[20] M. Kheshti, L. Ding, W. Bao, M. Yin, Q. Wu and V. Terzija, "Toward Intelligent Inertial Frequency Participation of Wind Farms for the Grid Frequency Control," IEEE Transactions on Industrial Informatics, vol. 16, no. 11, pp. 6772-6786, Nov. 2020.

[21] A. Ashouri-Zadeh, M. Toulabi, S. Bahrami and A. M. Ranjbar, "Modification of DFIG's Active Power Control Loop for Speed Control Enhancement and Inertial Frequency Response," IEEE Transactions on Sustainable Energy, vol. 8, no. 4, pp. 1772-1782, Oct. 2017.