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Kaigui Xie
Jianlin Hu
Qingxin Yang
Jian Li *Editors*

The Proceedings of the 17th Annual Conference of China Electrotechnical Society

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Contents

Research on the Influence of Wind Power Grid Connected to Power System Damping Characteristics

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Abstract. With the development of wind power and large-scale grid connection, more and more new challenges are brought to the safe operation of power system. It is of great significance to analyze the damping characteristics and stability of low-frequency oscillation of wind power grid connected system, so as to improve the permeability of wind power and new energy generation. This paper based on the main physical structure and linearization model of DFIG, building the grid connected system and its linear model, analyzes the influence of the damping characteristics of power system after the wind power grid connected by using the damping torque method, and verifies the change of the damping characteristics of the system after the wind power grid connected by using the power factory simulation software. It can be seen that the influence of the permeability and control parameters of wind power on the low-frequency oscillation of power system under different operating conditions, has a more clear guiding significance for the safe and stable operation of power system.

Keywords: Doubly Fed Induction Generator · Damping torque analysis · Low frequency oscillation · Damping characteristic

1 Introduction

The growing environmental problems and the depletion of traditional fossil fuels have made the development of new energy an inevitable trend in the power industry. Wind energy has developed rapidly around the world due to its clean, renewable and good economic development prospects [1]. According to data released by the Global Wind Energy Council [2], in 2021, the global installed capacity of wind power will exceed 93.6 GW, and the global cumulative capacity will reach 837 GW. However, due to the volatility and randomness of wind, large-scale wind power grid integration has brought great challenges to the stability of power system operation [3–6].

When the generators are paralleled in the power system, the rotor will sway relatively under the disturbance, and will continue to sway without damping. The oscillation

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frequency in this case is very low, generally in the range of 0.2–2.5 Hz, so it is also low frequency oscillation [7]. With the increase in the penetration rate of wind power grid-connected, the resulting low-frequency oscillation will restrict the transmission power of the transmission line and affect the power system's ability to absorb wind power. Therefore, the increase of wind power grid-connected access points and capacity will adversely affect the damping characteristics of the system. In China, wind farms are large in scale and have a large total installed capacity. Most of the wind farms are built in relatively remote areas. The grid connection with the power system requires a long transmission line. Low-frequency oscillation has a more serious impact on the security and stability of the power grid [8–10]. It can be seen that it is very necessary to conduct a comprehensive research and analysis to analyze the influence of the wind power generation system on the system stability after it is connected to the power grid.

In this paper, a power system model connected to a doubly-fed wind turbine is established, and the damping torque method is used to analyze the influence of the damping characteristics of the system. It is verified by the DIgSILEN simulation software. The influence of the damping characteristics of the system is analyzed, and the influence of the doubly-fed wind turbine on the low-frequency oscillation of the system under different working conditions is analyzed, and the final research conclusion is obtained.

2 Linearization Model of Power System for Wind Power Grid-Connected

The common types of wind turbines in wind farms are Doubly Fed Induction Generator (DFIG) and DC permanent magnet wind turbines [11]. This paper takes the doubly-fed fan as an example to establish its mathematical model. Figure 1 is the structure diagram of the wind farm access system. In the figure, the double-fed fan adopts the motor convention, and the positive direction of the current is shown in Fig. 1.

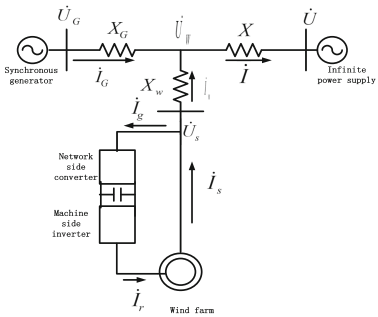

Fig. 1. Grid connection structure diagram of DFIG

From Fig. 1, the voltage and current equations are obtained as follows:

$$\begin{aligned} \dot{U}_G &= \dot{U}_W + jX_G\dot{I}_G \\ \dot{U}_W &= \dot{U} + jX\left(\dot{I}_G + \dot{I}_w\right) \\ \dot{U}_W &= \dot{U}_s - jX_w\dot{I}_w \\ \dot{I}_w &= \dot{I}_s - \dot{I}_g \end{aligned} \tag{1}$$

The synchronous generator adopts the second-order small-signal model ($E_q^{'} = const$), and its linearization equation is

$$\begin{cases} \Delta\dot{\delta} = \Delta\omega \\ \Delta\dot{\omega} = \frac{1}{M}(-\Delta P_e - D\Delta\omega) \end{cases} \tag{2}$$

where, $\Delta P_e = \frac{E_q^{'}U_W}{X_G} cos(\delta_0 - \delta_{W0})(\Delta\delta - \Delta\delta_W)$.

When the DC voltage is stable, the dynamics of the grid-side converter is not considered, and the mechanical power of the wind turbine is constant, the linearization model of the DFIG system is:

$$\begin{cases} \Delta\dot{\psi}_{rd} = \omega_{slip0}\Delta\psi_{rq} - \psi_{rq0}\Delta\omega_r + \Delta U_{rd} = K_1\Delta\psi_{rq} + K_2\Delta\omega_r + K_3\Delta U_{rd} \\ \Delta\dot{\psi}_{rq} = -\omega_{slip0}\Delta\psi_{rd} - \psi_{rq0}\Delta\omega_r + \Delta U_{rq} = K_4\Delta\psi_{rd} + K_5\Delta\omega_r + K_6\Delta U_{rq} \\ \Delta\dot{\omega}_r = \Delta T_e = \frac{p_n L_m U_{s0}}{L_s\delta}\Delta\psi_{rq} + \frac{p_n L_m I_{rq0}}{L_s}\Delta U_s = K_7\Delta\psi_{rq} + K_8\Delta U_s \end{cases} \tag{3}$$

According to the linearization Eq. (3) of the doubly-fed wind power generation system and the classical second-order model Eq. (2) of the synchronous generator, the linearization model of the grid-connected doubly-fed wind farm is obtained as

$$\begin{aligned} \dot{\mathbf{X}} &= \mathbf{AX} + \mathbf{Bu} \\ \mathbf{Y} &= \mathbf{CX} + \mathbf{Du} \end{aligned} \tag{4}$$

where, $X = \left[\, \Delta\psi_{rd} \ \Delta\psi_{rd} \ \Delta\omega_r \ \Delta X_1 \ \Delta X_2 \ \Delta X_3 \ \Delta X_4 \,\right]^T$, $u = \Delta\delta$, $y = \Delta P_{we}$,

$$A = \begin{bmatrix} K_3(K_{34}+K_{39}K_{45}) & K_1+K_3(K_{37}+K_{39}K_{46}) & K_2+K_3(K_{33}+K_{39}K_{47}) & 0 & 0 & K_3K_{35} & K_3K_{36} \\ K_4+K_6(K_{29}+K_{33}K_{45}) & K_6(K_{28}+K_{33}K_{46}) & K_5+K_6(K_{30}+K_{33}K_{47}) & K_6K_{31} & K_6K_{32} & 0 & 0 \\ K_8K_{45} & K_7+K_8K_{46} & K_8K_{47} & 0 & 0 & 0 & 0 \\ K_{20}K_{45} & K_{19}+K_{20}K_{46} & K_{20}K_{47} & 0 & 0 & 0 & 0 \\ 0 & K_{21} & 0 & K_{22} & 0 & 0 & 0 \\ K_{23}+K_{24}K_{45} & K_{24}K_{46} & K_{24}K_{47} & 0 & 0 & 0 & 0 \\ K_{25}+K_{27}K_{45} & K_{27}K_{46} & K_{27}K_{47} & 0 & 0 & K_{26} & 0 \end{bmatrix}$$

$$B = [K_3K_{39}K_{44} \quad K_6K_{33}K_{44} \quad K_8K_{44} \quad K_{20}K_{44} \quad 0 \quad K_{24}K_{44} \quad K_{27}K_{44}]^T$$

$$C = [K_{18}K_{45} \quad K_{16} + K_{18}K_{46} \quad K_{17} + K_{18}K_{47} \quad 0 \quad 0 \quad 0 \quad 0]$$

3 Damping Torque Analysis of Influence of Fan Grid-Connected on Low-Frequency Oscillation of System

After the DFIG is connected to the power system, the damping torque of the synchronous generator oscillation circuit will be provided by two parts: one part comes from the synchronous generator excitation winding and automatic voltage controller (AVR), and the other part comes from the DFIG fan. Based on the damping torque analysis method and principle, this paper obtains the damping torque provided by the doubly-fed wind turbine to the system in the low frequency oscillation, and gives the change of the damping torque of the system when the wind power output changes through an actual example, and analyzes the wind power The influence of grid connection on the low frequency oscillation of the system.

3.1 Analysis of System Damping Characteristics of Fans Connected to the Grid

The damping torque method [12] first appeared in the 1960s. Based on the classical control theory and the decomposition of the torque of the generator rotor motion, it reflects the close relationship between the low frequency oscillation of the generator output power and the rotor angular displacement. According to Fig. 2, the Phillips-Heffron model of the generator electromechanical oscillation circuit can be obtained.

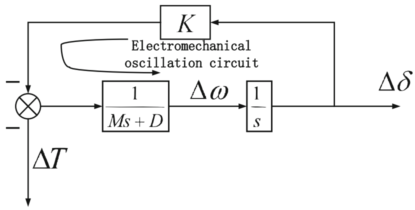

Fig. 2. Electromechanical oscillation circuit of generator

$$\Delta\ddot{\delta} + (\frac{D}{M} + \frac{T_d}{M})\Delta\dot{\delta} + (\frac{K}{M} + \frac{T_s}{M})\Delta\delta = 0 \tag{5}$$

Among them, ΔT is the input signal of the electromechanical oscillation circuit, which reflects the influence of the doubly-fed wind turbine on the movement of the synchronous generator rotor, and $\Delta T = T_d \Delta\omega + T_s \Delta\delta$.

It can be seen from Eq. (5) that part $T_d \Delta\omega$ of the electromagnetic torque ΔT affects the damping of the low-frequency oscillation of the system, and part of $T_s \Delta\delta$ it has no effect on the damping of the low-frequency oscillation of the system. Therefore, $T_d \Delta\omega$ is called damping torque, and $T_s \Delta\delta$ is called synchronous torque, so the influence of DFIG on system damping can be analyzed by analyzing the size of T_d. If $T_d > 0$, it provides positive damping for the system, otherwise it is negative damping.

According to Fig. 1, the linearization model of the system active power linearization can be obtained as follows.

$$\begin{cases} \Delta P_e = \frac{E'_{q0}U_{W0}}{X_G} cos(\delta_0 - \delta_{W0})(\Delta\delta - \Delta\delta_W) = B_1(\Delta\delta - \Delta\delta_W) \\ \Delta P_{we} = \frac{U_{s0}U_{W0}}{X_W} \cos(\theta_0 - \delta_W)(\Delta\theta - \Delta\delta_W) = B_2(\Delta\theta - \Delta\delta_W) \\ \Delta P_{e1} = \frac{U_{W0}U_0}{X} \cos(\delta_{W0})\Delta\delta_W = B_3\Delta\delta_W \end{cases} \tag{6}$$

where, $\Delta P_e + \Delta P_{we} = \Delta P_{e1}$.

According to formula (6), we can get:

$$M\Delta\ddot{\delta} + D\Delta\dot{\delta} + \frac{B_1 B_3}{B_1 + B_3}\Delta\delta - \frac{B_1}{B_1 + B_3}\Delta P_{we} = 0 \tag{7}$$

According to the above-mentioned damping torque analysis theory, when the damping torque $T_d = \left|G_{p\delta}(s)\right| sin\left(\angle G_{p\delta}(s)\right) < 0$ provided by ΔP_{we}, $sin\left(\angle G_{p\delta}(s)\right) < 0$, $180^\circ < \angle G_{p\delta}(s) < 360^\circ$, the DFIG provides positive damping torque for the system.

According to the linear control theory, we get:

$$\frac{\Delta P_{we}}{\Delta\delta} = G_{p\delta}(s) = C(sI - A)^{-1}B \tag{8}$$

where, I is the identity matrix.

The output electromagnetic power of the doubly-fed wind turbine can be decomposed into the damping torque part and the synchronous torque part as:

$$P_{we} = T_d\Delta\omega + T_s\Delta\delta \tag{9}$$

Then, when the oscillation frequency of the doubly-fed wind turbine is, the damping torque provided to the system is

$$T = -\frac{B_1}{B_1 + B_3}\left|G_{p\delta}(s)\right| \sin\left(\angle G_{p\delta}(s)\right) \tag{10}$$

It can be seen from the above analysis that the influence of the doubly-fed wind turbine on the damping of the power system is mainly manifested by its output active and reactive power. Among them, the analysis of the influence of reactive power of DFIG on system damping is the same as that of active power. The torque provided by DFIG to the system can generally be decomposed into synchronous torque and damping torque. The synchronous torque part affects the frequency of the system, the damping torque part affects the damping of the system, and the positive damping torque part helps to suppress the low-frequency oscillation of the system.

3.2 Case Analysis

The parameters of the system shown in Fig. 1 and its initial operating point (all per unit values) are given as follows:

Unit reactance of transmission line: $x_{G0} = x_{w0} = x_0 = 0.04\,\Omega/\text{km}$

Transmission line length: $l_G = l_w = l = 10\,\text{km}$.

Generator: $X_d = 2$, $X_q = 2$, $X'_d = 0.3$.
Double-fed wind turbines: $R_s = 0$, $X_s = 0.125$, $R_r = 0$, $X_r = 0.05$, $X_m = 2.5$.
Initial operating point: $U_{G0} = 1.05$, $U_{s0} = 1.0$, $U_{w0} = 1.0$, $U_0 = 1.0$.

When the active output of the synchronous generator is 0.4 × 103 MW, the active output of the wind farm is 0.2 × 103 MW, the damping torque provided by the wind farm to the electromechanical oscillation of the synchronous machine is calculated as follows.

According to the linearization model of the wind power plant access system given in Sect. 1, and substituting the actual data of the above example into Eq. (5), we can get

$$A = \begin{bmatrix} -0.2487 & 3.1435 & -2.9736 & 0 & 0 & -0.3471 & -2.5809 \\ -0.1744 & -2.5 & -0.7455 & -1.2673 & -0.7637 & 0 & 0 \\ 0.3510 & -17.4809 & 0.2 & 0 & 0 & 0 & 0 \\ 0.1376 & -20.7396 & 0.13 & 0 & 0 & 0 & 0 \\ 0 & -0.12 & 0 & 0.1746 & 0 & 0 & 0 \\ -0.3151 & -13.5761 & -0.6759 & 0 & 0 & 0 & 0 \\ -6.1382 & -11.4753 & -0.3749 & 0 & 0 & 0.4298 & 0 \end{bmatrix} \quad (11)$$

$$B = \begin{bmatrix} -0.1251 & -0.0612 & -22.8719 & -41.7442 & 0 & 0.2617 & -0.2160 \end{bmatrix}^T$$

$$C = \begin{bmatrix} 0.2582 & 0.0875 & -0.1773 & 0 & 0 & 0 & 0 \end{bmatrix}$$

From the initial conditions of the system, it can be known that

$$B_1 = \frac{E'_{q0}U_{w0}}{X_G}\cos(\delta_0 - \delta_{w0}) = -2.45$$
$$B_3 = \frac{U_{w0}U_0}{X}\cos\delta_{w0} = -2.5$$

According to the above results, it can be obtained that the oscillation frequency of the doubly-fed wind turbine is $\omega_s = -1.2713 + j10.9003$, the damping torque provided to the system is.

$$T = -\frac{B_1}{B_1 + B_3}\left|G_{p\delta}(s)\right| sin\left(\angle G_{p\delta}(s)\right) = 0.0285$$

3.2.1 Influence of Fan Output Change on Damping Characteristics of the System

According to the above calculation process, change the output of the wind turbine to observe the change of the damping characteristic provided to the generator electromechanical oscillation circuit. Keeping the total output of the system unchanged, increasing the output of the fan and reducing the output of the synchronous generator, the calculation results of the damping ratio provided by the wind farm to the electromechanical oscillation circuit of the generator and the electromechanical oscillation mode of the system under different working conditions are shown in Fig. 3, shows the trends of the system damping ratio and the imaginary part of the oscillation mode as a function of the fan output.

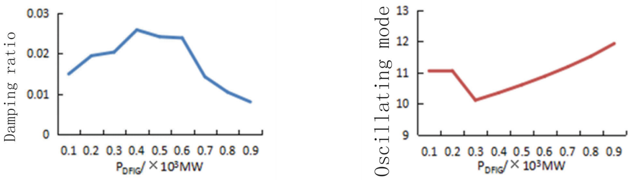

Fig. 3. Influence of wind generator output change on system damping characteristics

It can be seen from Fig. 3 that when the total output of the system remains unchanged, as the output of the synchronous generator decreases and the output of the fan increases, the damping ratio provided by the wind turbine to the system first increases and then decreases, but the overall damping is lower than the initial situation; The imaginary part of the mode first decreases and then increases. It shows that with the increase of wind power penetration rate, the low frequency oscillation of the system increases, which is not conducive to the system stability, but the optimal result of wind power grid-connected power and synchronous generator output makes the system stability better.

3.2.2 Influence of Control Parameters on Damping Characteristics of the System

According to the linear model formula (5) of the doubly-fed wind turbine connected to the system, the low-frequency oscillation of the system is related to the control parameters of the wind turbine, and the involved control parameters include K_{p1}, K_{I1}, K_{p2}, K_{I2} and so on. Keep the output of synchronous generator and fan unchanged, which are 0.8 and 0.45 respectively. According to the damping torque analysis method, the control parameters of the active power are changed through the control variables, and its influence on the damping characteristics is analyzed. The calculation results are shown in Fig. 4, shows the trends of the system damping ratio and the imaginary part of the oscillation mode as a function of the fan control parameters.

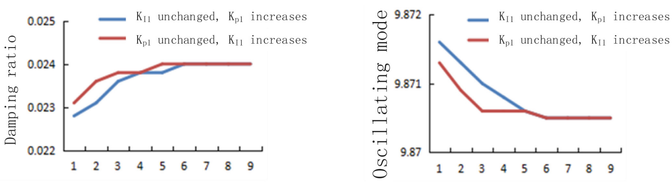

Fig. 4. Influence of wind control parameters change on system damping characteristics

The results show that with the increase of the fan control parameters K_{p1} and K_{I1}, the overall trend of the system damping ratio has increased, so if the model of the fan control system is considered perfect, the change of the control parameters may have a certain impact on the oscillation stability of the system, which is conducive to improving the System stability.

4 DIgSILEN Simulation Analysis of F Wind Turbines Connection

In this paper, DIgSILEN software is used to build a grid-connected system of DFIG, and the influence of DFIG on the system damping under different operating conditions is calculated. Accuracy.

4.1 DIgSILEN Simulation Model of Wind Turbine Connected to Power System

According to the requirements of this paper, the power system model connected with the doubly-fed wind power plant is built in the DIgSILEN simulation software, as shown in Fig. 5.

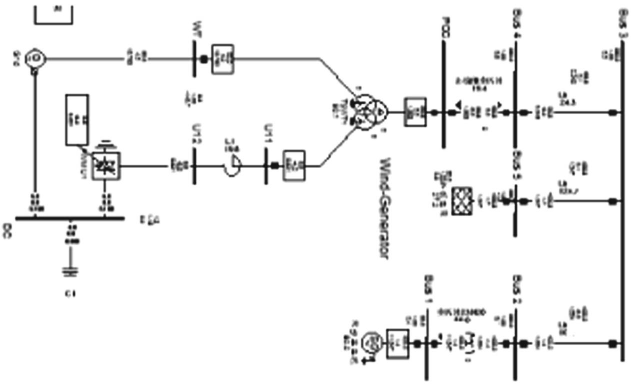

Fig. 5. Digsilen simulation model of DFIG access system

4.2 Result Analysis

4.2.1 Influence of Fan Output on Damping Characteristics of the System

In order to facilitate the comparative analysis with the theoretical analysis results, the parameters of each component in the model are consistent with the example parameters in Sect. 3.2. Under the condition that the total output of the wind farm and the synchronous generator remains unchanged, increase the output of the wind turbine and reduce the output of the synchronous generator. Using the DIgSILEN simulation software, Fig. 6 shows the waveforms of the angular velocity and rotor angle of the synchronous generator SG when the total output of the system is 1 × 103 MW and the output of the fan is 0.2, 0.6, and 0.9, respectively. A three-phase short-circuit fault occurs at the grid-connected point PCC in the system at 2 s, and the fault is removed after 2.2 s.

It can be seen from Fig. 6 that as the output of the synchronous generator decreases and the output of the fan increases, the SG angular velocity and the amplitude of the rotor angular oscillation decrease slightly, but the decay speed becomes slower with the increase of the fan output. The simulation results show that the output of the synchronous generator decreases, and the increase of the output of the fan is not conducive to the

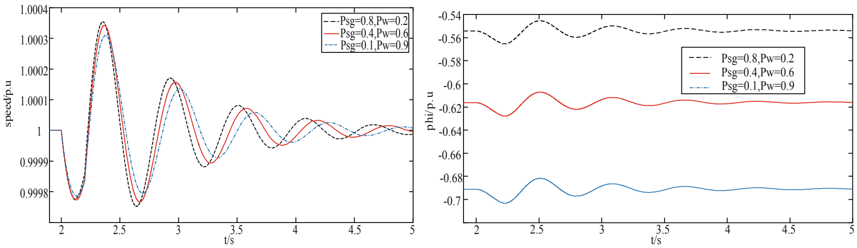

Fig. 6. The SG angular speed and rotor angle change curve when the total output remains unchanged and the wind generator output changes

oscillation stability of the electromechanical oscillation circuit of the system, which is consistent with the theoretical analysis results.

4.2.2 Influence of Control Parameters on Damping Characteristics of the System

In addition to the influence of the fan output on the low frequency oscillation of the system, the change of the control parameters of the wind turbine may also have different effects on the damping characteristics of the system. The same as the example analysis, keep the output of the synchronous generator at 0.8 and the output of the fan at 0.45, and use the control variable method to simulate the influence of the control parameters of the active power on the damping characteristics.

Figure 7 remains K_{I1} unchanged shows the waveforms of the angular velocity and rotor angle of the synchronous generator SG when Kp1 is 1, 5, and 10, respectively. Figure 8 shows the waveform curves of the angular velocity and the rotor angle of the synchronous generator SG when Kp1 remains unchanged and is 1, 5, and 10, respectively. A three-phase short-circuit fault occurs at the grid-connected point PCC in the system at 2 s, and the fault is removed after 2.2 s.

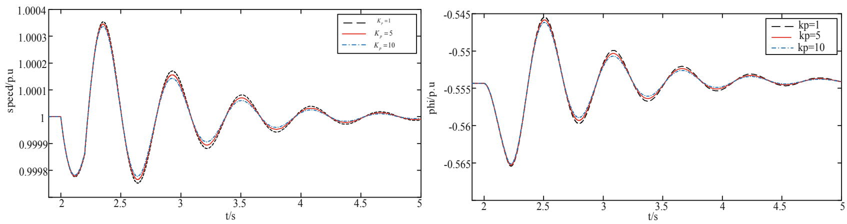

Fig. 7. The SG angular speed and rotor angle change curve when the K_{I1} remains unchanged, K_{p1} increase

Observing Fig. 7 and 8, it can be seen that with the increase of the PI control parameters of the active power, the SG angular velocity and the rotor angular oscillation amplitude gradually decrease, and the attenuation speed also accelerates with the increase of the fan output. The results show that the increase of fan control parameters is beneficial

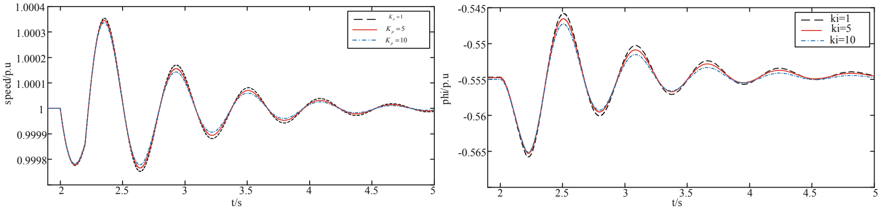

Fig. 8. The SG angular speed and rotor angle change curve when the K_{p1} remains unchanged, K_{I1} increase

to the stability of low-frequency oscillation of the system, which verifies the accuracy of the theoretical results of damping torque analysis.

5 Conclusion

In this paper, a linear model of grid-connected DFIGs is established, and the effect of grid-connected DFIGs on the low-frequency oscillation stability of the system is studied by means of damping torque analysis. The analysis results were verified. It can be seen from the results of the example analysis that the influence of wind power on the low-frequency oscillation of the power system is related to factors such as generator output and system control parameters. When the total output of the system remains unchanged, as the output of the synchronous generator decreases and the output of the fan increases, the overall damping ratio of the system shows a downward trend; when the control parameters of the system are increased, the damping ratio of the system increases. Therefore, by optimizing the output of the fan and the synchronous generator and the system control parameters, the low frequency oscillation of the system can be reduced and the system stability can be improved. In this paper, the damping torque analysis and DIgSILEN simulation analysis are used to double verify the influence of wind turbine grid connection on the damping characteristics of the system.

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