Oscillation analysis of doubly-fed unit considering wind speed variation

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Abstract—Tower shadow effect and wind shear may cause power oscillation of the unit. In order to study the influence of tower shadow effect and wind shear on the output power of wind turbine, a doubly-fed turbine was taken as an example. Firstly, the influence of tower shadow effect and wind shear was considered to study the periodic power fluctuation characteristics of wind turbines. Then, according to the dynamic model of mechanical transmission mechanism, the influences of the inertia constants of generator, fan and the stiffness coefficient of the shaft system on the transient performance of the wind power generation system were considered respectively. Finally, a single machine infinite bus system model including wind speed model is built on PSCAD / EMTDC platform for simulation. The results show that the tower shadow effect and wind shear component can cause the power fluctuation of the turbine. When the power fluctuation frequency of the turbine is equal to the natural oscillation frequency of the wind turbine shafting, the resonance of the turbine occurs, and the amplitude of oscillation is the largest. Changing the transmission parameters will affect the power fluctuation amplitude and speed response speed of the unit.

1. Introduction

The low-frequency oscillation of power system is characterized by long duration and long transmission distance, causing great harm to the power system [1-3]. The fluctuation of wind turbine output power is not only related to wind speed change, but also affected by wind shear and tower shadow effect [4]. Wind turbine blades rotate through the tower, due to the effect of blocking of the tower of airflow, capture the energy from the wind blade will be significantly lower, form the shadow effect [5]. Wind shear is a phenomenon in which average wind speed changes with height in a stable state due to dynamic and thermal factors [6]. Along with the fan blade is longer, the tower is higher, the wind shear and tower shadow effect for the influence of system stability becomes increasingly visible.

For the common three-blade fans at present, wind shear and tower shadow effect will cause periodic fluctuation of 3P frequency in the output wind power, and the 3P frequency range is mainly determined by the rated rotation frequency and wind speed of the fan [7]. As can be seen from literature [8-9], the 3P frequency range of wind power fluctuations usually includes system oscillation frequency points. With the increase of the proportion of wind power generation in the power system, such periodic power fluctuations of wind farms increase. If the frequency of power fluctuation is close to the natural frequency of a certain oscillation mode of the system, the system may have resonance, and the harm to the power system can’t be ignored.

In this paper, wind speed changes are considered. Firstly, the tower shadow effect and wind shear are considered to study the periodic power fluctuation characteristics of wind turbines. Secondly, the
dynamic characteristics of wind turbines are analyzed by changing the transmission parameters of wind turbines. Finally, modeling and simulation are carried out on the PSCAD/EMTDC platform to verify the effect of equivalent wind speed and transmission parameters on the transient performance of the system.

2. Mathematical model of doubly-fed wind turbine

2.1. Two mass block shafting model

The wind turbine and gearbox are equivalent to one mass block, and the generator is equivalent to another mass block. Its mathematical model is as follows:

\[
\begin{align*}
2H_w \frac{d\delta_w}{dt} &= T_w - K_{wg}(\delta_w - \delta_g) - D_{wg}(\omega_w - \omega_g) - D_{w} \omega_w \\
2H_g \frac{d\delta_g}{dt} &= -T_r - K_{rg}(\delta_g - \delta_r) - D_{rg}(\omega_r - \omega_g) - D_{r} \omega_g \\
\frac{d\omega_w}{dt} &= \omega_w \\
\frac{d\delta_g}{dt} &= \omega_g
\end{align*}
\]

Where: \( w \) and \( g \) are the wind turbines and generators; \( \delta_w \) and \( \delta_g \) are the electrical angular displacement of shafting mass block relative to synchronous rotation reference shaft; \( \omega_w \) and \( \omega_g \) are the electrical angular velocity of the shafting mass block relative to the synchronous rotation reference shaft; \( H_w \) and \( H_g \) are the inertia time constant of the mass block; \( D_{wg} \) and \( D_{rg} \) are the self-damping coefficient of the mass block; \( D_{w} \) and \( D_{r} \) is the mutual damping coefficient between mass blocks; \( T_w \) is the primary torque acting on the wind turbine; \( T_r \) is the electromagnetic torque of generator; \( \omega_h \) is the indicates synchronous speed.

2.2. Third order simplified model of doubly-fed induction generator

Ignoring the stator flux transient and using the transient voltage source to represent the induction generator, the third-order simplified model of the doubly-fed induction generator can be obtained as follows:

\[
\begin{align*}
\frac{d\epsilon'_d}{dt} &= -\frac{\alpha R_i}{X'_d + X_n} \epsilon'_d + \left[ \frac{X'_d}{X'_d + X_n} \right] i_{d} - \frac{X_n}{R_i} u_{d} + \text{soa} \epsilon'_q \\
\frac{d\epsilon'_q}{dt} &= -\frac{\alpha R_i}{X'_q + X_n} \epsilon'_q - \left[ \frac{X'_q}{X'_q + X_n} \right] i_{q} + \frac{X_n}{R_i} u_{q} - \text{soa} \epsilon'_d \\
i_{ad} &= R i_{ad} - X'_d i_{d} + \epsilon'_d \\
i_{aq} &= R i_{aq} + X'_q i_{q} + \epsilon'_q
\end{align*}
\]

Where: \( X' = X_s + X_r \parallel X_m \); \( X' \) is the transient reactance; \( X_s \) is the stator synchronous reactance(\( X_s = \omega_s L_s \)); \( X_r \) is the rotor loop reactance(\( X_r = \omega_r L_r \)); \( X_m \) is the excitation reactance(\( X_m = \omega_e L_e \)); \( \epsilon'_d \) and \( \epsilon'_q \) are dq axis components of the transient voltage source respectively.

3. Equivalent wind speed model considering tower shadow effect and wind shear

The equivalent wind speed expression considering tower shadow effect and wind shear is:

\[
V_{eq} = V_H' + V_{eqs} + V_{epo}
\]

Where:

\[
V_{epo} = V_{sd} \left[ \frac{a(\alpha-1)}{8} \left( \frac{R}{H} \right)^2 + \frac{a(\alpha-1)(\alpha-2)}{60} \left( \frac{R}{H} \right)^3 \cos 3\beta \right]
\]

\[
V_{eqs} = \frac{m V_H'}{3R^2} \sum_{\lambda=0}^{3} \frac{a^2}{\sin^2 \beta_{\lambda}} \ln \left( \frac{R^2 \sin \beta_{\lambda}}{x \sin \beta_{\lambda}} + 1 \right) - \frac{2a^2 R^2}{R^2 \sin^2 \beta_{\lambda} + x^2}
\]

\[
V_H' = \frac{\alpha R_i}{X_d + X_n} \epsilon'_d + \left[ \frac{X_d}{X_d + X_n} \right] i_d - \frac{X_n}{R_i} u_d
\]
\[ m = 1 + \frac{a(a-1)}{8} \left( \frac{R}{H} \right)^2 \]; \( V_h \) is the wind speed at the hub; \( V_{eqw} \) is the wind shear component; \( V_{eqt} \) is the component of tower shadow effect; \( H \) is the height of the hub; \( R \) is the impeller radius; \( \alpha \) is wind shear index; \( \beta \) and \( \beta_b \) are the blade direction Angle; \( a \) is the tower radius; \( x \) is the distance from blade to tower; \( m \) is the wind speed conversion coefficient.

4. Simulation verification

The model is modeled in PSCAD, and the system parameters are shown in Table 1. The rated wind speed of the doubly-fed unit is 11 m/s. According to the parameters of the shafting model in Table 1, the natural oscillation frequency \( f_r \) of the wind turbine shafting can be written:

\[ f_r = \frac{1}{2\pi} \sqrt{K_{e0} \left( \frac{1}{2H_1} + \frac{1}{2H_e} \right)} \approx 1.01 \text{Hz} \]  

(5)

Firstly, the influence of tower shadow effect and wind shear on output power fluctuation of doubly-fed turbine is analyzed to illustrate the necessity of using equivalent wind speed model when studying low-frequency oscillation of wind turbine. Finally, the transient performance of the doubly-fed unit system is studied when each parameter changes.

Table 1 Grid-connected system parameters of doubly-fed wind turbines

| Parameter                  | Numerical value |
|----------------------------|-----------------|
| DFIG                       |                 |
| Rated capacity /MW         | 1.5             |
| Rated line voltage /kV     | 0.69            |
| Shafting                   |                 |
| Inertia time constant /s   | 4.3/2.1         |
| Stiffness coefficient /pu  | 0.37            |
| Wind shear coefficient     | 0.2             |
| Blade radius /m            | 40              |
| Wind turbine               |                 |
| Wheel hub height /m        | 60              |
| Tower radius /m            | 2               |
| Hanging distance /m        | 2.9             |

4.1. Influence of tower shadow effect and wind shear on wind turbine

The equivalent wind speed is set to 6 m/s – 12 m/s, and the equivalent wind speed is used as the input wind speed of the wind turbine for simulation. The power output of the doubly-fed unit is shown in Figure 1. Power oscillation frequency and fluctuation are shown in Table 2.
Table 2 Power oscillation frequency and fluctuation of wind turbine under two wind speeds

| The wind speed/(m/s) | Power oscillation frequency /Hz | Power fluctuations /MW |
|---------------------|--------------------------------|------------------------|
| 6                   | 0.667/1.133/1.833              | 0.022                  |
| 7                   | 0.750/1.500/2.250              | 0.003                  |
| 8                   | 0.833/1.667/2.500              | 0.070                  |
| 9                   | 0.909/1.818/2.727              | 0.092                  |
| 10                  | 1.000/2.000/3.000              | 0.121                  |
| 11                  | 1.091/2.182/3.273              | 0.100                  |
| 12                  | 1.091/2.182/3.273              | 0.062                  |

As can be seen from FIG. 1 and Table 2, the unit oscillates after considering tower shadow effect and wind shear. When the wind speed is 10m/s, the power fluctuation of the unit reaches the maximum of 0.1216MW, because the power oscillation frequency of 1.0Hz is close to the natural oscillation frequency of the unit shafting of 1.02Hz, and the unit resonates. Therefore, it is necessary to consider the equivalent wind speed of tower shadow effect and wind shear as the input wind speed when studying wind turbine oscillation.

4.2. Dynamic characteristics of unit after changing transmission parameters

According to Equation (5), the natural oscillation frequency of wind turbine shafting is related to the generator inertia time constant \(H_g\), wind turbine inertia time constant \(H_w\), and shafting stiffness coefficient \(K_{eg}\). By 9 m/s wind speed in 10 s mutation for 10 m/s, analysis the parameters change after 10 s influence on the transient characteristic.

4.2.1 Change the generator inertia time constant

The time constants of generator inertia were changed to 0.5s, 1.0s, 1.5s, and other parameters remained unchanged. The natural oscillation frequencies of the unit are 1.81Hz, 1.34Hz and 1.13Hz respectively. Through simulation available generator speed, active power spectrum is shown in figure 2. Power fluctuations are shown in Table 3.

Table 3 Power fluctuation of generator unit when generator inertia time constant changes

| \(H_g/s\) | Power fluctuations /MW |
|-----------|------------------------|
| 0.5       | 0.023                  |
| 1.0       | 0.059                  |
| 1.5       | 0.092                  |

(a) Generator speed (b) Unit output active power spectrum

FIG. 2 generator inertial time constant speed change unit and active power spectrum
It can be seen from the simulation results that with the increase of the generator inertia constant, the slower the speed response of the generator, the closer the shafting natural oscillation frequency is to the power oscillation frequency of the generator set, and the power fluctuation increases.

4.2.2 Change the inertia time constant of wind turbine

The inertia time constants of the wind turbine were changed to 35s, 15s and 5s respectively, and other parameters remained unchanged. The natural oscillation frequencies of the unit are 0.86Hz, 0.89Hz and 0.98Hz respectively. Through simulation available generator speed, active power spectrum is shown in figure 3. Power fluctuations are shown in Table 4.

4.2.3 Change the shafting stiffness coefficient

The stiffness coefficients of shafting were changed to 0.4pu, 0.8pu and 1.2pu, and other parameters remained unchanged. The natural oscillation frequencies of the unit are 1.06Hz, 1.47Hz and 1.80Hz respectively. Through simulation available generator speed, active power spectrum is shown in figure 4. Power fluctuations are shown in Table 5.
### Table 5 Power fluctuation of unit when shafting stiffness coefficient changes

| $K_{wg}/pu$ | Power fluctuations /MW |
|-------------|-------------------------|
| 0.4         | 0.110                   |
| 0.8         | 0.046                   |
| 1.2         | 0.020                   |

It can be seen from the simulation results that with the increase of shafting stiffness coefficient, the natural oscillation frequency of shafting is far away from the power oscillation frequency of the unit, and the power fluctuation increases.

### 5. Conclusion
In this paper, the variation of wind speed, tower shadow effect and wind shear are taken into account to study the characteristics of unit power fluctuation. Finally, the influence of transmission parameters on the dynamic performance of the unit is analyzed by simulation. Simulation and calculation results show that:

1. When the equivalent wind speed considering tower shadow effect and wind shear is taken as the input wind speed, the frequency of output power oscillation of wind turbine increases with the increase of wind speed, and the amplitude of power fluctuation of wind turbine also increases; when the frequency of the output mechanical power of the wind turbine is equal to the natural oscillation frequency of the wind turbine at a certain wind speed, the resonance of the wind turbine occurs, and the amplitude of oscillation is the maximum.

2. In the wind power generation system, the rotational inertia of the fan and the generator and the stiffness coefficient of the shafting have a great influence on the transient response of the wind power generation system. Proper system parameters can make the system have good transient performance.

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