Research on variable pitch control strategy of wind turbine for tower vibration reduction

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Abstract: With the increase of wind turbine power, the vibration problem of tower has become much prominent. Tower vibration is one of the key problems that must be solved. Aimed at the problem of tower vibration caused by turbulent wind, based on analysing the causes of tower vibration, the optimisation control strategy is proposed by increasing tiny pitch angle in the pitch control system, which is equivalent to increasing the aerodynamic damping of tower to reduce the vibration. Taking the 1.577 MW wind turbine as an example to simulate and verify the control strategy, the results show that the control strategy can effectively reduce the fore-aft vibration and torque of tower with little impact on power.

1 Introduction

The large scale of single turbine capacity is the manufacturing trend of the modern wind turbines [1]. With the increase of wind turbine capacity, the tower height of modern large wind turbines can reach 100 m, the quality is more than 100 tons (accounts for about half the weight of the wind turbine), and the cost of tower is about 15–20% of the total cost of wind turbine. In order to reduce the quality and cost of tower and avoid the generation of system resonance effectively, the flexible tower structure usually is used in large wind turbines. The first-order natural frequency of tower is generally between 1 and 3 times of the wind turbine rotation frequency, and with the increase of tower height, its stiffness and frequency will be further reduced [2].

As the first-order modal damping of the flexible tower is small, the nacelle and tower will produce more severe vibrations under the strong winds and strong earthquakes, especially the fore-aft vibration, the height and weight of tower increase, and the vibration response will be further intensified [3]. Tower is the key component to support the wind turbine. Once the tower collapses, it will cause a devastating loss of the wind turbines [4]. Therefore, in order to ensure a safe and stable operation of the wind turbine, tower vibration must be considered.

Therefore, aimed at the problem of tower vibration caused by turbulent wind, based on analysing the causes of tower vibration, the optimisation control strategy is proposed by increasing tiny pitch angle in the pitch control system, which is equivalent to increasing the aerodynamic damping of tower to reduce the vibration. Based on the Bladed software platform and the SISOTOOL toolbox of MATLAB, the control strategy was simulated by using the 1.577 MW wind turbine as the verification object.

2 Reasons of tower vibration

Tower vibration is a multi-coupling vibration. During the operation of wind turbine, tower vibration is the comprehensive reflection of all exciting forces. The causes for tower vibration are as follows:

(i) Natural wind variability: Since natural wind has variability both in time and space, the effect of wind on the wind turbine tower structure is very complicated; it is necessary to consider the change of wind speed, wind direction and wind pressure along with the tower height in spatial scale. Tower vibration can be caused by wind speed fluctuation and wind vortex at temporal scale, which may lead to ten times or even several times of normal wind force in the critical range [5].

(ii) Wind rotor rotation: The problem of manufacture and installation may make the pitch between the three blades have error, resulting in quality and aerodynamic imbalance of wind rotor, so that tower produces vibration with a double rotation frequency. Due to the influence of tower shadow, gusts and turbulence, each rotation of the blade will make tower produce vibration with three times rotation frequency. There are waving vibration, swing vibration, torsional vibration, and other forms of vibration, which will also be coupled to result in dynamic instability of aerodynamic elasticity under the coupling of aerodynamic, inertial force, and elastic force [6].

(iii) Mechanical transmission chain twist vibration: The typical main drive chain of wind turbine consists of a wind rotor spindle system, gearbox, bearing, coupling, and brake. Resonance between the drive chains can affect the dynamic load of component, resulting in severe mechanical noise and causing tower vibration [7].

(iv) Wind turbine control system operation: In the yaw and variable pitch system, a typical low-speed servo motion system consists of sliding bearing and drive mechanism, which has the characteristics of internal parameter change, external load disturbance, transmission system friction interference, and a nonlinear model. Its yaw and pitch action with the characteristics of low speed, bearing large, friction brake etc. result in aerodynamic imbalance and noise and cause tower vibration [8].

(v) Wind rotor and tower coupling vibration: The main vibration of large wind turbine is the coupling vibration of wind rotor and tower. The inherent frequency of tower is mainly related...
to its own stiffness and strength. The inherent frequency of tower is higher than the passing frequency of blade, and is called rigid tower, whereas the inherent frequency of tower between the rotating frequency of wind rotor and the passing frequency of blade is called flexible tower; if the inherent frequency of tower is lower than the rotating frequency of wind rotor, then it is called very flexible tower. In order to avoid resonance of wind turbine and reduce quality and cost of tower, the first-order inherent frequency of tower is generally designed to be between 1 and 3 times of the rotating frequency of wind rotor [9].

In summary, the temporal and spatial variability of natural wind is the main cause of tower vibration, and the rotation of wind rotor will further aggravate the vibration. Therefore, this paper mainly studies the tower vibration caused by turbulent winds.

3 Tower fore-aft damping vibration control strategy

3.1 Analysis of wind turbine Campbell diagram

The Campbell diagram is also known as the resonance diagram, which is commonly used to determine whether device work at resonance and resonance speed position. The inherent frequency and exciting frequency of the equipment in resonance can be found out by using the resonance diagram, which is the basis of troubleshooting [10].

In this paper, taking the 1.577 MW wind turbine as an example to simulate by bladed software, the Campbell diagram of wind turbine is shown in Fig. 1.

By analysing the Campbell diagram of wind turbine, the first-order modal frequency of tower is between 1P and 2P, and the side–side first-order modal frequency intersects with 2P, the second-order modal frequencies intersect 9P at about 12 rpm, and the third-order modal frequencies intersect with 12P and 15P. If wind rotor running at the intersection speed will make wind turbine resonate, then it will result in wind rotor and tower vibration. As shown in the Campbell diagram that the first-order fore-aft mode of tower is the main mode. If the aerodynamic damping of wind turbine is small, small excitation may produce a large vibration response. Adding the aerodynamic damping through the variable pitch control of wind turbine, the strong vibration of tower can be effectively avoided [11].

3.2 Tower fore-aft damping control principle

The motion equation of tower fore-aft vibration can be approximated as a second-order harmonic vibration with attenuation

$$\ddot{x} + B_x \dot{x} + K_x x = F_A + \Delta F_A$$

where $x$ is the tower top displacement; $M_i$ is the tower equivalent mass; $B_i$ is the tower equivalent damping, generally smaller; $K_i$ is the tower equivalent stiffness; and $F_A$ is the applied force, here it is the wind rotor thrust. The Tower frequency is $\sqrt{K_i/M_i}$ (rad × s⁻¹).

Modern large-scale wind turbine usually use flexible tower; the damping is smaller and belongs to the weak damping system. Therefore, the damping can be increased by the tower active damping control technology. The control idea is as follows: an additional axial thrust is generated on the basis of the original axial thrust by adding an additional pitch angle to increase the damping [11].

Using the tower active damping control technique, the motion equation of the tower fore-aft vibration changes to

$$\ddot{x} + B_x \dot{x} + K_x x = F_A + \Delta F_A$$

If $\Delta F_A$ is proportional to $-x'$, that is $\Delta F_A = -B_p x'$, the substitution formula (2) is obtained

$$\ddot{x} + (B_i + B_p) \dot{x} + K_x x = F_A$$

where $B_p$ is an additional damping term.

The axial thrust of wind rotor can be expressed as

$$F_d = f(v, \beta, \omega)$$

$F_d$ is linearly processed at run equilibrium point $(v_0, \beta_0, \omega_0)$:

$$F_A = F_A(v_0, \beta_0, \omega_0) + \frac{\partial F_A}{\partial v} \delta v + \frac{\partial F_A}{\partial \beta} \delta \beta + \frac{\partial F_A}{\partial \omega} \delta \omega + \text{hogs}$$

Ignoring higher order term, formula (5) can be simplified as

$$\Delta F_A = F_A - F_A(v_0, \beta_0, \omega_0) + \frac{\partial F_A}{\partial v} \delta v + \frac{\partial F_A}{\partial \beta} \delta \beta + \frac{\partial F_A}{\partial \omega} \delta \omega$$

If wind speed and wind rotor speed are constant, the additional axial thrust can be expressed as

$$\Delta F_A = \frac{\partial F_A}{\partial \beta} \delta \beta$$

Substituting $\Delta F_A = -B_p x'$ in formula (7), we have

$$\delta \beta = -\frac{B_p}{\frac{\partial F_A}{\partial \beta}} x'$$

Therefore, in the variable pitch control system of wind turbine, according to the law of formula (8) to increase additional pitch angle, the first-order modal plus resistance control can be realised. The velocity can be obtained by adding an integral link after tower top acceleration signal measured in the control system.

4 Tower fore-aft damping vibration control process

The tower fore-aft damping vibration control block diagram is shown in Fig. 2.

We establish a detailed model of 1.577 MW wind turbine in the GH Bladed software, export the state-space equation including the modal characteristics of wind turbine by the Bladed software linearisation module, and derive the transfer function of tower damping control system at different wind speeds by using the linear processing tool of MATLAB. Using the SISOTOOL toolbox in the MATLAB software to obtain the root locus, its zero pole position is changed to complete the tower damping controller gain setting. Through the external controller, the input function after adding the resistance is input into the Bladed software for simulation calculation.
5 Simulation results

Based on the Blade software platform, we take 1.577 MW wind turbine as an example to simulate the above control strategy. Taking the external turbulence wind of 15 m/s as an example, the simulation results are shown in the following figures.

As shown in Figs. 3–7, the red line is the line before adding resistance, and the black line is the line after adding resistance. Through the comparison can be found that after increasing the aerodynamic damping of tower, the fore-aft displacement, speed acceleration, and torque of tower are reduced, and have less influence on power, which indicates that the control strategy can effectively reduce the fore-aft vibration and torque of tower with little impact on power.

Nacelle fore-aft acceleration and tower fore-aft torque are analysed in frequency spectrum, as shown in Figs. 8 and 9.

Fig. 2 Tower fore-aft damping vibration control diagram

Fig. 3 Nacelle fore-aft displacement

Fig. 4 Nacelle fore-aft speed

Fig. 5 Nacelle fore-aft acceleration

Fig. 6 Tower fore-aft torque

Fig. 7 Electrical power

Fig. 8 Nacelle fore-aft acceleration spectrum

Fig. 9 Nacelle fore-aft acceleration spectrum
Figs. 8 and 9 show that the red line is the line before adding resistance, and the black line is the line after adding resistance. The amplitude decreases significantly at the frequency of 0.35, which further proves that the control strategy can effectively reduce the fore-aft vibration and torque of tower.

6 Conclusions

This study analyses the reasons of tower vibration, such as natural wind variability, wind rotor rotation, mechanical transmission chain twist vibration, wind turbine control system operation, wind rotor, and tower coupling vibration. The temporal and spatial variability of natural wind is the main cause of tower vibration; therefore, this paper mainly examined the vibration problem caused by turbulence wind.

Aimed at the tower vibration caused by turbulent wind, the optimisation control strategy is proposed by increasing tiny pitch angle in the pitch control system, which is equivalent to increasing the aerodynamic damping of tower to reduce the vibration. Taking the 1.577 MW wind turbine as an example to simulate and verify the control strategy, the results show that the control strategy can effectively reduce the fore-aft displacement, velocity, acceleration, and torque vibration amplitude of tower with little impact on power.

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