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# Study on Typical Aerodynamic Faults of Variable Pitch Wind Turbine

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**Abstract:** The variable-speed variable-pitch wind turbine is an important part of China's power and energy systems, and is also the main conversion form of wind energy utilization. Aiming at the problem that the traditional blade element-momentum theory cannot achieve the modeling and simulation of wind turbine plane wind unbalance caused by wind shear and tower shadow effect, the modeling and simulation numerical calculation method of aerodynamic load of wind turbine actuation disk with different blade wind unbalance pitch angles is proposed, This method can derive the analytical expressions for solving the key variables of load calculation, axial induction factor and tangential induction factor, and realize the aerodynamic load solution. At the same time, it is also verified that the characteristic vibration component of 3 times the low speed shaft rotation frequency (3P) is a typical dynamic load feature of tower shadow effect, and is also the most important aerodynamic load fluctuation feature of variable-speed variable-pitch wind turbine, However, under normal conditions, the wind shear effect has little effect on the wind turbine load fluctuation.

**Keywords:** Wind turbine; System vibration faults; Aerodynamic characteristics.

## 1. Review

The tower shadow effect and wind shear phenomenon are the most common aerodynamic characteristics during the operation of MW level horizontal axis variable speed variable pitch wind turbines [1-2]. Both the tower shadow effect and the wind shear phenomenon will lead to the unbalanced wind on the swept plane of the wind rotor [3], so that the rotor of the wind rotor will form the characteristic load fluctuation of the characteristic multiplier of the rotation frequency of the rotor. When the characteristic load fluctuation and the resonance frequency of the key structural components of the wind turbine are close to coincident, a resonance phenomenon will be formed with the relevant structural components, resulting in a significant reduction in system safety and the occurrence of potential failures [4-6].

## 2. Modeling method of typical aerodynamic characteristics

The key point of analyzing the typical aerodynamic characteristics of wind turbines is to determine whether the fluctuation of aerodynamic characteristics will cause resonance phenomenon. Campbell diagrams are often used as design analysis aids [7].

As shown in Figure 1, when the wind turbine is connected to the grid for power generation, the operating range of the spindle speed is 7.0rpm to 12.0rpm. When the unit runs stably at 7.2rpm, the 3P vibration excitation of the unit is very close to the resonant frequency of the tower. At 8.8rpm, the 3P vibration excitation of the unit is very close to the first-order galloping frequency of the blade. When the unit operates stably at 9.2rpm, the 6P vibration excitation of the unit is very close to the first-order shimmy frequency of the blade [8-10]. If the control system parameters are not set properly, it will cause Blade resonance. In order to reduce the overall load level of wind turbines and reduce the damage to the quality and life of the mechanical links caused by resonance phenomena, the control design of wind turbines usually designs specific load reduction control strategies for the resonance points [11-14].

Due to the large sweep area of the wind turbine, the wind speed of the MW variable speed variable pitch wind turbine is often uneven in the plane of the wind turbine due to the natural characteristics of the wind and the inherent operating characteristics of the wind turbine. This part is mainly aimed at modeling the influence of the periodic load generated by the wind shear characteristics and tower shadow effect characteristics on the vibration characteristics of the engine room. Wind shear modeling: wind shear refers to the gradual change of wind speed with the height from the ground. The higher the height from the ground, the higher the average wind speed. Therefore, the wind shear model can be expressed as a function of the average wind speed changing with the height above the ground. According to the literature, the wind speed changes exponentially with the height above the ground. In general, the following mathematical models can be used for estimation:

$$V(z) = V_{hub}(z / z_{hub})^{\alpha} \tag{1}$$

Where: z is the height from the ground, hub is the height from the ground, V (z) is the wind speed at height z, Vhub is the wind speed at height Zhub, α Indicates the wind shear index (or power). According to the power index of literature α what can select equal to 1/7.

Tower shadow effect modeling: tower shadow effect refers to that when the blade passes through the tower and coincides with the tower during the blade rotation, the wind resistance of the blade will be reduced due to the tower's blocking effect on the wind.

The influence range of tower shadow effect is generally considered that the blade azimuth angle is greater than 90°and less than 270°(0°vertically and positive clockwise). The wind speed considering tower shadow effect can be modeled according to the following formula:

$$V_{tower} = V_H + mb^2 \frac{y^2 - x^2}{(y^2 + x^2)^2} \tag{2}$$

$$m = 1 + \frac{\alpha(\alpha - 1)R^2}{8H^2} \quad (3)$$

$$y = r\sin\theta \ (90° \le \theta \le 270°) \quad (4)$$

In the formula, Vtower is the inter-blade wind speed considering the tower shadow effect, m/s; VH is the wind speed at the hub, m/s; b is the radius of the tower tube at the height corresponding to the blade element, m; x is the distance from the plane of the wind rotor to the center line of the tower distance, m; y is the horizontal distance between the blade element and the center line of the tower, m;α is the wind shear index; H is the hub height, m; θ is the azimuth angle of the blade.Assuming that the tower is a cylinder whose section radius increases uniformly from top to bottom, it can be obtained by simple geometric calculation.

$$b = -r\cos\theta / H \times (b_2 - b_1)/2 + b_1/2 \quad (5)$$

In the formula, b1 is the radius of the top section of the tower, m; b2 is the radius of the bottom section of the tower, m.

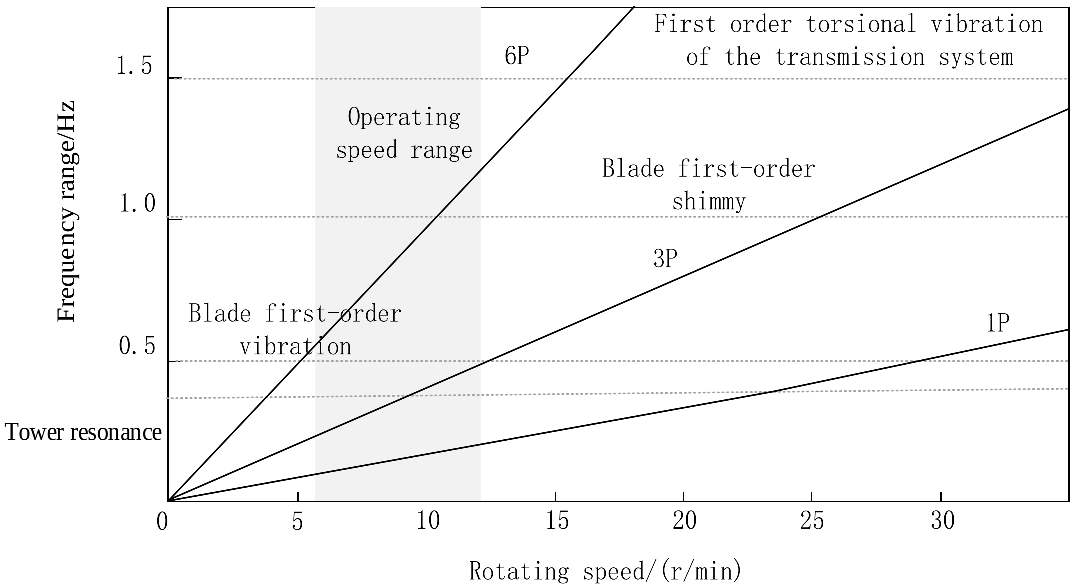


**Figure 1.** The Campbell chart of wind turbine operation

Design of simulation conditions: In order to explain the related inherent load characteristics, the following idealized assumptions are made in the aerodynamic load simulation: 1. It is assumed that the pitch angle of blades is the same and fixed during the simulation; 2. The wind turbine runs stably at a constant speed; 3. The instantaneous wind speed in the sweeping plane of the wind wheel satisfies the wind shear model, and the turbulence intensity is zero during the simulation operation; 4. The wind wheel rotates clockwise. When the initial angle of the wind wheel is zero, blade 1 corresponds to 12 o'clock direction, blade 2 corresponds to 4 o'clock direction and blade 3 corresponds to 8 o'clock direction. Based on the above assumptions, the relevant simulation parameters of a wind turbine generator unit are shown in Table 1 and Table 2:

**Tab 1.** List of the simulation parameters

| Parameters | Value |
|---|---|
| Rotational angular speed of wind wheel Ω/(rad/s) | $2\pi/3$ |
| Air density ρ/(kg/m3) | 1.225 |
| Blade radius R/m | 37.5 |
| Blade 1 pitch angle β1/(°) | 0 |
| Blade 2 pitch angle β2/(°) | 0 |
| Blade 3 pitch angle β3/(°) | 0 |
| Wind speed at hub VN/(m/s) | 13 |
| Wind shearing index α/ | 1/7 |
| Hub height H/m | 100 |
| Distance from the plane of the wind wheel to the center line of the tower x/m | 3 |
| Section radius of tower top b1/m | 2.65 |
| Section radius of tower bottom b2/m | 6 |

**Tab.2** Parameters of the blade aerofoil

| r/R | Thickness ratio/% | Chord length/m | Torsional angle/(°) |
|---|---|---|---|
| 0.05 | 100 | 1.934 | / |
| 0.15 | 21 | 2.001 | 12.500 |
| 0.25 | 21 | 3.033 | 12.500 |
| 0.35 | 21 | 2.523 | 10.167 |
| 0.45 | 21 | 1.935 | 7.422 |
| 0.55 | 21 | 1.683 | 4.687 |
| 0.65 | 21 | 1.340 | 2.466 |
| 0.75 | 21 | 1.140 | 1.322 |
| 0.85 | 21 | 0.871 | 0.908 |
| 0.95 | 17 | 0.556 | 0.364 |

## 3. Analysis of simulation results

Figure 2 A) shows that the axial thrust fluctuation of the blade due to wind shear is not obvious during the rotation of the blade, and only the thrust fluctuation of 1P frequency with very small amplitude is generated. B) shows that the axial thrust of the blade fluctuates obviously due to the tower shadow effect during the rotation of the blade, and its axial thrust can be decomposed into a stable thrust component and the superposition of harmonic components such as 1P, 2P, 3P and 4P in frequency domain. C) shows that the Fourier transform results of the axial thrust of a single blade under the simultaneous action of wind trimming and tower shadow effect show that the tower shadow effect leads to the rapid change of the blade thrust in a short time, which is the main reason for the fluctuation of the blade thrust, and the frequency domain of the thrust fluctuation is integer times of the rotor rotation frequency such as 1P, 2P, 3P and 4P.

Figure 3 A) shows that the axial thrust fluctuation of the wind turbine wheel caused by wind shear is not obvious during the rotation process of the wind turbine wheel, but only the thrust fluctuation of 1P frequency with very small amplitude. B) is shown that the axial thrust of the wind wheel fluctuates obviously due to the tower shadow effect during the rotation of the wind wheel, and its axial thrust can be decomposed into a stable thrust component in the frequency domain and the superposition of higher harmonic components such as 3P, 6P, 9P and 12P.C) shows that the tower shadow effect causes the rapid change of wind turbine thrust in a short time, which is the main reason for the wind turbine thrust fluctuation. The frequency domain of the thrust fluctuation is 3N (N is an integer) times the wind turbine rotation frequency, such as 3P, 6P, 9P, 12P.

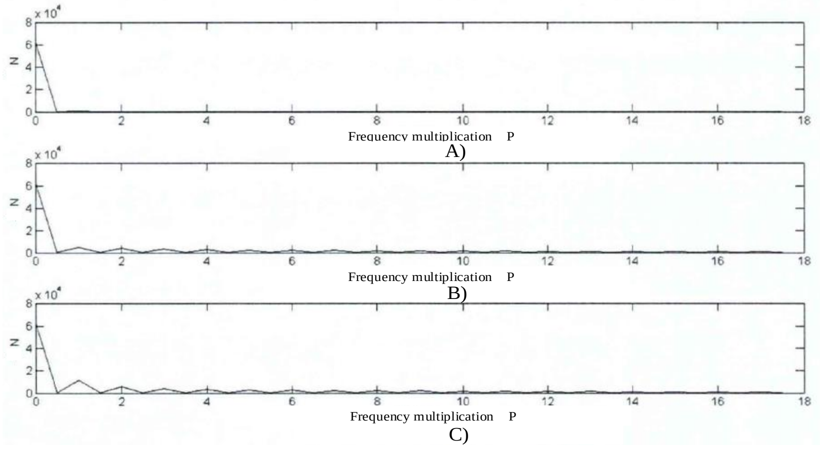


**Figure 2.** FFT wave-forms of blade thrust force. A) The FFT waveform of blade thrust force under wind shear condition; B) The FFT waveform of blade thrust force under tower shadow condition; C) The FFT waveform of blade thrust force under wind shear and tower shadow condition.

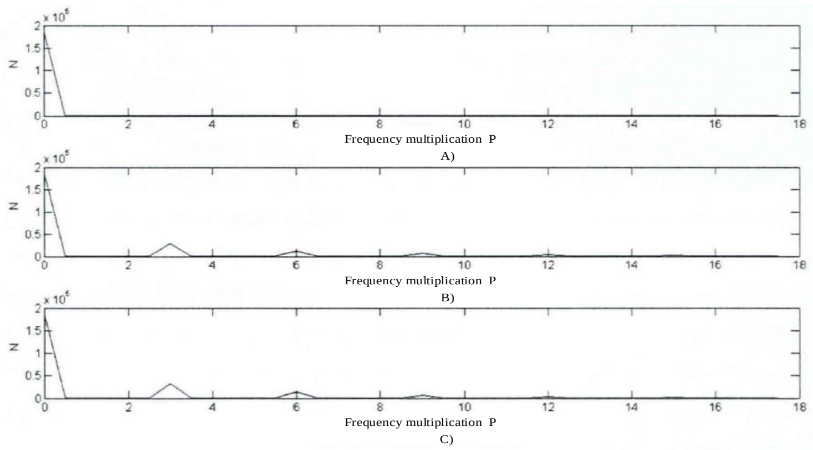


**Figure 3.** FFT wave-forms of wind wheel thrust force.A)The FFT waveform of wind wheel thrust force under wind shear condition;B)The FFT waveform of wind wheel thrust force under tower shadow condition;C)The FFT waveform of wind wheel thrust force under wind shear and tower shadow condition

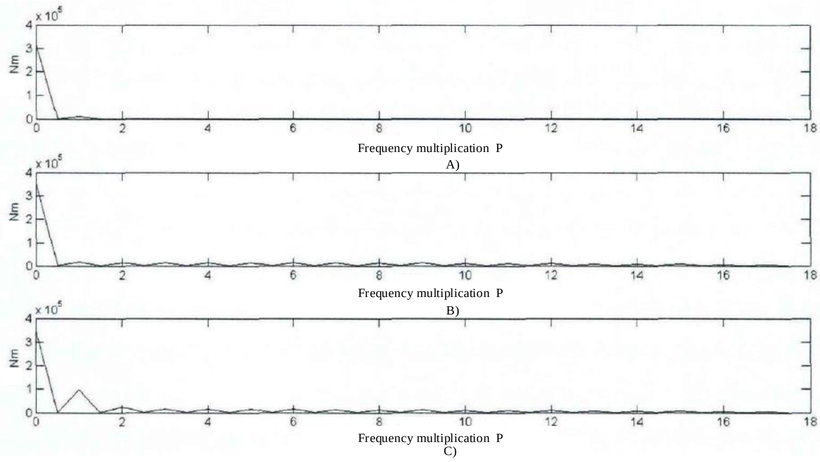


**Figure 4.** FFT wave-forms of blade force moment in tangential direction. A) The FFT waveform of blade force moment in tangential direction under wind shear condition; B) The FFT waveform of blade force moment in tangential direction under tower shadow condition; C) The FFT waveform of blade force moment in tangential direction under wind shear and tower shadow condition.

Figure 4A) shows that the tangential moment fluctuation of 1P frequency is generated due to the wind shear during the rotation of the blade. B) shows that the tangential torque fluctuation of the blade due to the tower shadow effect during the rotation of the blade is relatively obvious, which can be decomposed into a stable torque component and high-order harmonic components such as 1P, 2P, 3P, and 4P in the frequency domain overlay. C) shows that the tower shadow effect leads to rapid changes in the tangential torque in a short period of time, which is the main cause of blade tangential torque fluctuations. The frequency domain of the torque fluctuations is an integer multiple of the wind rotor rotation frequency such as 1P, 2P, 3P, and 4P.

Figure 5 A) shows that the tangential torque fluctuation of the wind rotor due to the wind shear effect during the rotation of the wind rotor is not obvious, and only the torque fluctuation of 1P frequency with a small amplitude is generated. B) shows that the tangential torque fluctuation of the wind rotor due to the tower shadow effect during the rotation of the wind rotor is relatively obvious, and its tangential torque can be decomposed into a stable torque component in the frequency domain and 3P, 6P, 9P, 12P, etc. Superposition of higher harmonic components. C) shows that the tower shadow effect leads to rapid changes in the tangential driving torque of the blade in a short period of time, which is the main reason for the fluctuation of the tangential driving torque of the wind rotor. The frequency domain of the torque fluctuation is 3P, 6P, 9P, 12P, etc. (N is Integer) times the rotation frequency of the wind rotor, and the 1P fluctuation generated by the wind shear can basically be ignored because the amplitude is too small.

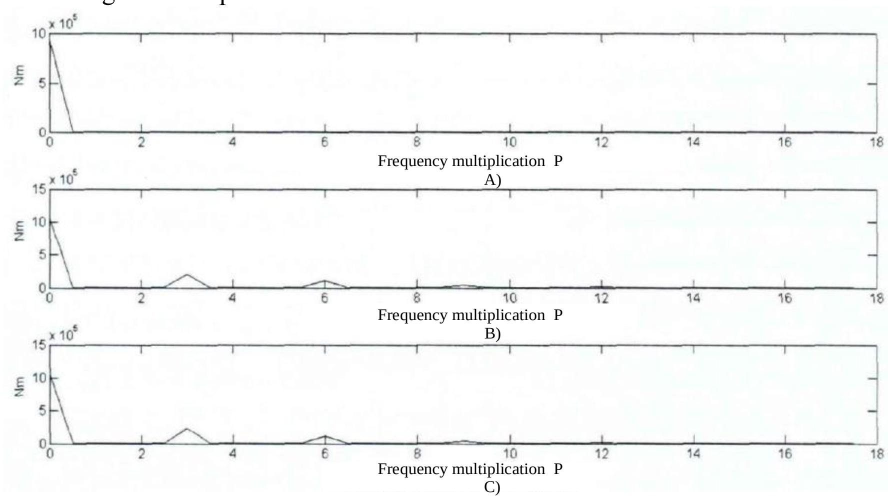


**Figure 5.** FFT wave-forms of wind wheel force moment in tangential direction. A) The FFT waveform of wind wheel force moment in tangential direction under wind shear condition; B) The FFT waveform of wind wheel force moment in tangential direction under tower shadow condition; C) The FFT waveform of wind wheel force moment in tangential direction under wind shear and tower shadow condition.

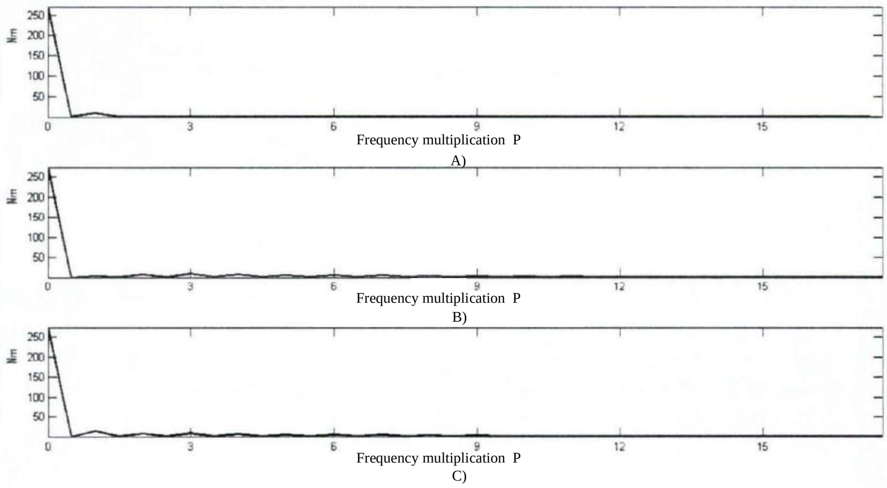


**Figure 6.** FFT wave-forms of blade pitching force moment. A) The FFT waveform of blade pitching force moment in tangential direction under wind shear condition; B) The FFT waveform of blade pitching force moment in tangential direction under tower shadow condition; C) The FFT waveform of blade pitching force moment in tangential direction under wind shear and tower shadow condition.

Figure 6 A) shows that the torque fluctuation of 1P frequency with small amplitude is generated due to wind shear during the rotation of the wind rotor. B) shows that during the rotation of the wind rotor, due to the tower shadow effect, the torque fluctuation on the blades is more obvious, and its pitching torque can be decomposed into a stable torque component and higher harmonics such as 1P, 2P, 3P, 4P in the frequency domain superposition of components. C) shows that the rapid change of the pitching moment in a short period of time due to the tower shadow effect is the main reason for the fluctuation of the pitching moment of the blade.

# 4. Conclusion

In this paper, by comparing the above simulation results with the actual field analysis data, it is shown that the aerodynamic load characteristics of wind turbines have the following inherent characteristics under the joint action of wind shear and tower shadow effect: The tower shadow effect is the main cause of blade thrust fluctuation. The single blade thrust can be decomposed into steady components with large amplitude in frequency domain and fluctuation components such as 1P, 2P, 3P and 4P that gradually attenuate by integer times the rotation frequency of the wind turbine. The load fluctuations of the three blades cancel each other out, the overall aerodynamic load fluctuation amplitude of the wind rotor plane caused by the wind shear effect is small, compared with the actual field test data, in the case of normal wind shear index, the fluctuation of aerodynamic characteristic load caused by wind shear can basically be ignored.

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