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ARTICLE

Influence of Wind Turbine Structural Parameters on Wind Shear and Tower Shadow Effect

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ABSTRACT

To overcome the problems of natural decreases in power quality, and to eliminate wind speed fluctuation due to wind shear and tower shadow effect arising from wind turbine structural parameters, an improved prediction model accounting for the dual effect of wind shear and tower shadow is, in this paper, built. Compared to the conventional prediction model, the proposed model contains a new constraint condition, which makes the disturbance term caused by the tower shadow effect always negative so that the prediction result is closer to the actual situation. Furthermore, wind turbine structural parameters such as hub height, rotor diameter, the diameter of the tower top, and rotor overhang on wind shear and tower shadow effect are also explored in detail. The results show that the wind shear effect became weaker with the increase in hub height. The hub height is independent of the tower shadow effect. The rotor diameter is positively correlated with the wind shear and tower shadow effect. The tower shadow effect is positively correlated with the diameter of the tower top and negatively correlated with the rotor overhang.

KEYWORDS

Wind turbine; wind shear; tower shadow effect; dual effect; structural parameters

Nomenclature

$V(z)$	wind speed at height z from the ground
V_h	wind speed at the height of rotor hub
h	hub height
z	vertical height from the ground
α	wind shear coefficient related to surface roughness
$W_S(r,\theta)$	disturbance term of wind shear on wind speed
θ	azimuth angle
θ_1, θ_2	critical azimuth angles
r	local radius of blade
V_h	wind speed at hub height
V_0	spatial average wind speed
a	tower top radius
d	tower base radius

y	distance from the blade element to the tower axis in the direction of Y axis
x	the horizontal distance between the rotor centre and the tower centerline
$v_t(y, x)$	disturbance term for tower shadow on wind speed in Cartesian coordinate system
$v_t(r, \theta)$	disturbance term for tower shadow on wind speed in cylindrical coordinate system
R	rotor radius
m	equal to $1 + \frac{\alpha(\alpha - 1) R^2}{8h^2}$
$v_{tt}(r, \theta, x)$	tower shadow on the wind speed written as a cylindrical coordinate, it is equal to $ma^2 \frac{r^2 \sin^2\theta - x^2}{\left(r^2 \sin^2\theta + x^2\right)^2}$

1 Introduction

Wind speed is an important factor affecting the output power of horizontal axial wind turbine (HAWT). In addition to the mutation and uncertainty of natural wind, the periodic fluctuation of wind speed through blade surfaces caused by wind shear and the tower shadow effect cannot be ignored. Therefore, accurately predicting the wind speed under the action of wind shear and tower shadow effect, and analyzing the influence of structural parameters such as hub height, rotor diameter, the diameter of the tower top, and rotor overhang on the wind speed, are of great significance for optimizing the structural size, weakening the power fluctuation of the wind turbine, and slowing down the effect of the power grid.

Extensive studies have been conducted on the wind shear and tower shadow effect for HAWT. Dolan et al. [1] established a comprehensive aerodynamic torque model for three-blades wind turbine considering wind shear and tower shadow effect and showed that wind shear caused the rotor power pulsation; the tower shadow effect was more significant than the wind shear effect. Emeksiz et al. [2] first studied the effect of rotor overhang on the disturbed wind speed using the wind data from Tokat Gaziosmanpaşa University Campus. The results showed that the rotor overhang was the most effective parameter affecting the tower shadow effect. Wen et al. [3] modified the widely used tower shadow effect model and found that the tower shadow effect mainly caused the power fluctuation, and the power loss arose from wind shear. Sintra et al. [4–6] used MATLAB/Simulink, TurbSim, and FAST to simulate a three-blades variable speed wind turbine system. The results showed that wind shear and tower shadow effect significantly affected the upstream wind speed of the hub. To reduce the harm of wind turbine power oscillation, therefore, a new method was proposed by Fu et al. [7] to simulate the wind shear and tower shadow effect during wind power generation. Due to the existing equivalent wind speed model not considering the power loss, a new calculation method of equivalent wind speed based on equivalent power was proposed in reference [8]. Tian et al. [9] proposed a new pitch control scheme for a three-blade wind turbine to reduce the periodic fluctuation of aerodynamic load and torque ripple caused by wind shear and tower shadow effect. Liu et al. [10] established aerodynamic correction models, including dynamic stall, wind shear, and tower shadow effect, to study the aerodynamic performance of a floating HAWT. The spatial and temporal distribution characteristics of wind speed were explored by analyzing the wind speed of each point on the swept area of the rotor [11]. Han [12] studied the effect of wind speed characteristics such as turbulence effect, wind shear, and tower shadow effect on the power oscillation for a large-scale HAWT. Kim et al. [13] presented universal correlations between wind speed and wind shear exponent using 3D sonic anemometers collected 3-axis wind speed components.

The above studies evaluate the wind shear and tower shadow effect of HAWT in detail. The disturbance term due to wind shear can be approximated by a third-order Taylor series in the references [1,6,7,9], and the study on the tower shadow effect is divided into two areas in the reference [3]. However, the disturbance term generated by the tower shadow effect is a little different from the actual situation. In fact, the blade elements with the local radius $r \geq x/|\sin\theta|$ are only subjected to wind shear. Therefore, an improved prediction model containing a new constraint condition is built, which makes the disturbance term caused by the tower shadow effect always negative. Meanwhile, to enhance the prediction accuracy, the model is established using the fourth-order Taylor series. The rotor swept area is divided into three areas according to both the azimuth angle and spanwise position of the blade. Furthermore, wind turbine structural parameters such as hub height, rotor diameter, the diameter of tower top, and rotor overhang on the wind shear and tower shadow effect are further explored.

The rest of the manuscript is organized as follows. In Section 2, the numerical models such as wind shear, tower shadow effect, and the dual effect are introduced to divide the swept area of the rotor into three areas. In Section 3, case analysis for testing the accuracy of the numerical model is conducted, and the influence of wind turbine structural parameters on wind shear and tower shadow effect are analyzed in detail. In Section 4, the conclusions and discussion are presented.

2 Numerical Models

2.1 Wind Shear Model

Wind shear coefficient is used to illustrate the wind speed distribution along the vertical direction. There is a large velocity gradient at different spanwise positions of the blade during the rotor rotation for a large-scale HAWT, as shown in Fig. 1. For megawatt-scale HAWT, the distribution difference of wind velocity in the vertical direction must be considered. Usually, the exponential model is usually used to express the wind shear effect [7]:

$$V(z) = V_h \left(\frac{z}{h}\right)^{\alpha} \tag{1}$$

where $V(z)$ is the incoming wind speed at height z from the ground; V_h is the wind speed at the height of the rotor hub; h is the hub height; z is the vertical distance from the ground; α is the wind shear coefficient related to surface roughness. To analyze the wind shear effect during rotor rotation, Eq. (1) can be transformed into the form of local radius r and the azimuth angle θ in the way of [8]:

$$V(r,\theta) = V_h \left(\frac{r\cos\theta + h}{h}\right)^{\alpha} = V_h\left[1 + W_S(r,\theta)\right] \tag{2}$$

where $W_S(r,\theta)$ is the disturbance term of wind shear on incoming wind speed. It can be converted to the form of the fourth-order Taylor series as follows [6]:

$$W_S(r,\theta) \approx \alpha\left(\frac{r}{h}\right)\cos\theta + \frac{\alpha(\alpha-1)}{2}\left(\frac{r}{h}\right)^2\cos^2\theta + \frac{\alpha(\alpha-1)(\alpha-2)}{6}\left(\frac{r}{h}\right)^3\cos^3\theta + \frac{\alpha(\alpha-1)(\alpha-2)(\alpha-3)}{24}\left(\frac{r}{h}\right)^4\cos^4\theta \tag{3}$$

2.2 Tower Shadow Model

Tower shadow effect refers to the phenomenon that when the incoming wind flows through the tower, the spatial variation in the flowfield will affect the wind direction and reduce the inflow velocity in the upstream and downstream of the tower. The tower will cause fluctuations in the aerodynamic performance of the wind turbine due to interference with the airflow flowing through the blade.

Meanwhile, the generator performance will be reduced subsequently. It is fully a negative effect for power quality and stability. According to the wind energy handbook [14], the velocity loss caused by the tower shadow effect for upwind wind turbines can be expressed as follows [14]:

$$V(y,x) = V_h + v_t(y,x)$$

$$v_t(y,x) = V_0 a^2 \frac{r^2 \sin^2\theta - x^2}{\left(y^2 + x^2\right)^2} \tag{4}$$

where V_0 is the spatial average wind speed; a is the radius of tower top; r is the local radius of blade; y is the distance from the blade element to the tower axis in the direction of Y axis; x is rotor overhang, the horizontal distance between the rotor centre and the tower centerline; $v_t(y,x)$ is the disturbance term of tower shadow effect.

According to Eq. (4), the constrained condition of the tower shadow effect is $\left|r^2 \sin^2\theta\right| \leq x^2$, and the blade is located in the lower half swept area of the rotor. The relationship between wind speed V_h at hub height and spatial average wind speed V_0 in the model is described as:

$$V_0 = V_h\left[1 + \alpha(\alpha - 1)R^2/8h^2\right] = mV_h \tag{5}$$

In Eq. (5), m is equal to $1 + \alpha(\alpha - 1)R^2/8h^2$. R is the rotor radius. To study the tower shadow effect under different azimuth angles during rotor rotation, $v_t(y,x)$ is written as a cylindrical coordinate $v_t(r,\theta,x)$ as follows [7]:

$$v_t(r,\theta,x) = mV_h a^2 \frac{r^2 \sin^2\theta - x^2}{\left(r^2 \sin^2\theta + x^2\right)^2} = V_h v_{tt}(r,\theta,x) \tag{6}$$

where $v_{tt}(r,\theta,x)$ is equal to $ma^2 \frac{r^2 \sin^2\theta - x^2}{\left(r^2 \sin^2\theta + x^2\right)^2}$.

2.3 Dual Effect Model

The wind speed fluctuation caused by wind shear and the tower shadow effect changes with rotor azimuth angle. The wind speed through the blade element significantly varies with different azimuth angles and spanwise positions. The dual effect of wind shear and tower shadow effect aggravates the periodic fluctuation of blade aerodynamic load. According to the blade azimuth angle θ and local radius r, the rotor swept area is divided into three areas [15,16], as shown in Fig. 1.

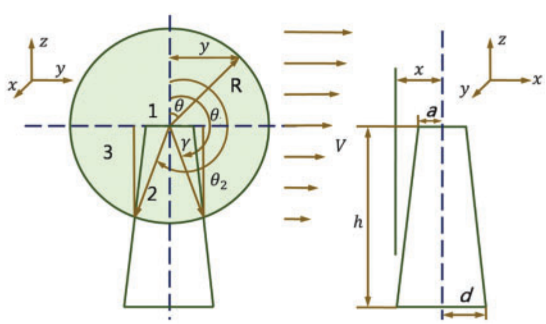

Figure 1: Wind turbine structural parameters

Area 1: The blade is located in the upper half swept area, and it is only subjected to wind shear effect. The mathematical model is created in the way of [3]:

$$\begin{aligned} & v_t(r,\theta) = V_h\left(\frac{r\cos\theta + h}{h}\right)^{\alpha} = V_h[1 + W_S(r,\theta)] \\ & 0 \le r \le R \\ & 0 \le \theta < 0.5\pi, 1.5\pi < \theta \le 2\pi \end{aligned} \tag{7}$$

Area 2: The blade is located in the lower half swept area, and its azimuth angle is between the critical azimuth angles θ_1 and θ_2. At this time, the blade bears the dual effect of wind shear and tower shadow effect. The mathematical model is expressed as:

$$\begin{aligned} & v_t(r,\theta) = V_h[1 + W_S(r,\theta) + v_{tt}(r,\theta,x)] \\ & 0 < r \le R \\ & \theta_1 \le \theta < \theta_2 \end{aligned} \tag{8}$$

The calculation methods for critical azimuth θ_1 and θ_2 are obtained as [3]:

$$\begin{aligned} & \theta_1 = \sin^{-1}(x/R), \quad 0.5\pi < \theta_1 \le \pi \\ & \theta_2 = \sin^{-1}(-x/R), \quad \pi < \theta_1 \le 1.5\pi \end{aligned} \tag{9}$$

Area 3: The blade is located in the lower half swept area, but the blade azimuth angle is beyond the critical azimuth angles θ_1 and θ_2. At this time, the blade elements with the local radius $r < x/|\sin\theta|$ are subjected to both wind shear and tower shadow effect. However, the blade elements with the local radius $r \ge x/|\sin\theta|$ are only subjected to wind shear. The mathematical models are described as [3]:

$$\begin{aligned} & v_t(r,\theta) = V_h[1 + W_S(r,\theta) + v_{tt}(r,\theta,x)], \quad \text{if } r < x/|\sin\theta| \\ & v_t(r,\theta) = V_h[1 + W_S(r,\theta)], \quad \text{if } r \ge x/|\sin\theta| \\ & 0.5\pi \le \theta < \theta_2, \ \theta_2 < \theta \le 1.5\pi \end{aligned} \tag{10}$$

3 Case Analysis

To test the model accuracy in this study, the proposed model is used to calculate the wind speed at the blade tip for 5-MW HAWT from the National Renewable Energy Laboratory (NREL). The Gross properties chosen for the NREL 5-MW baseline wind turbine are listed in Table 1, and the details of blade section parameters are given in [17]. The calculation results are comprehensively compared with the conventional model. Compared to the conventional prediction model, the proposed model contains a new constraint condition of the blade elements with the local radius $r \ge x/|\sin\theta|$, which makes the disturbance term of incoming wind speed caused by the tower shadow effect always negative so that the prediction result is closer to the actual situation. Furthermore, the influence of structural parameters such as hub height, rotor diameter, the diameter of tower top, and rotor overhang on wind shear and tower shadow effect is analyzed in detail.

Fig. 2 shows the variation trend of wind speed of blade tip with azimuth angle considering wind shear and tower shadow effect. Fig. 2a shows that the wind speed of the blade tip periodically fluctuates around 11.4 m/s, and reach to 12.7, 9.1 m/s respectively when the blade is located at the highest and lowest position, and the fluctuation range is about 3.6 m/s. Figs. 2b and 2c show a comparison of the wind speed of the blade tip under the tower shadow effect model in this paper with the conventional tower shadow effect model. According to the mathematical model of the tower shadow effect of upwind wind turbine (Eq. (4)), the constraint condition $\left|r^2\sin^2\theta\right| \le x^2$ is further increased, so that the disturbance term $v_t\,(y, x)$ generated by the tower shadow effect is always negative. Compared to the problem that the wind speed increases near the critical azimuth angle in the conventional model, the wind speed of the blade tip in this study was maintained at 11.4 m/s until the tower shadow effect occurred between critical azimuth angles of 175.5° and 184.5°. The improved model in this manuscript more realistically reflects the effect of the tower shadow effect on the wind speed. Fig. 2c shows the variation trend of wind speed of blade tip under the dual effect of wind shear and tower shadow effect. The tip wind speed changes periodically with the azimuth angle, and decreases to 7.5 m/s at the azimuth angle of 180°.

Table 1: Gross properties chosen for the NREL 5-MW baseline wind turbine

Structural parameters	Numerical values	Wind turbine model
Rated power, rated rotational speed	5 MW, 12.1 rpm	
Rotor, tower top diameter, hub height	126, 3.87, 90 m	
Rotation direction, number of blades, wind shear coefficient	Upwind, 3, 0.2	
Cut-in, cut-out, and rated wind speed	3, 25, 11.4 m/s	
Airfoils	NACA64_A17, DU series	
Blade set angle, rotor cone angle, tilt angle	0°, 2.5°, 5°	
Blade weight, rotor weight	17,740, 110,000 kg	

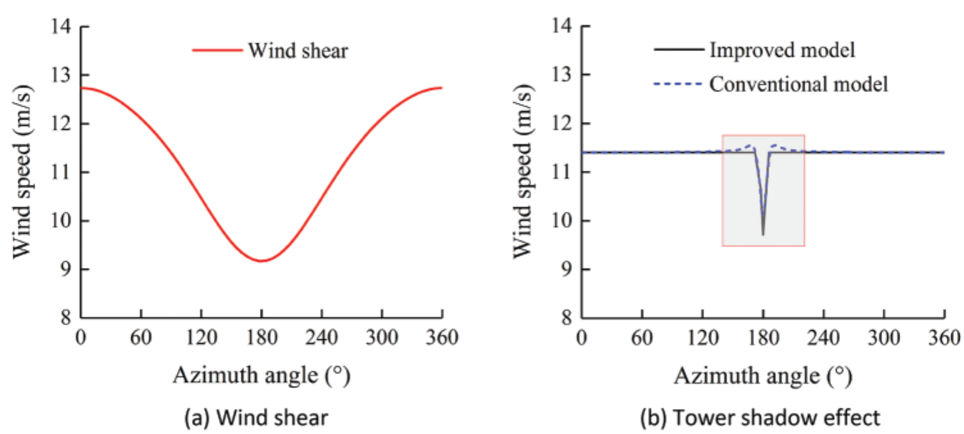

Figure 2: (Continued)

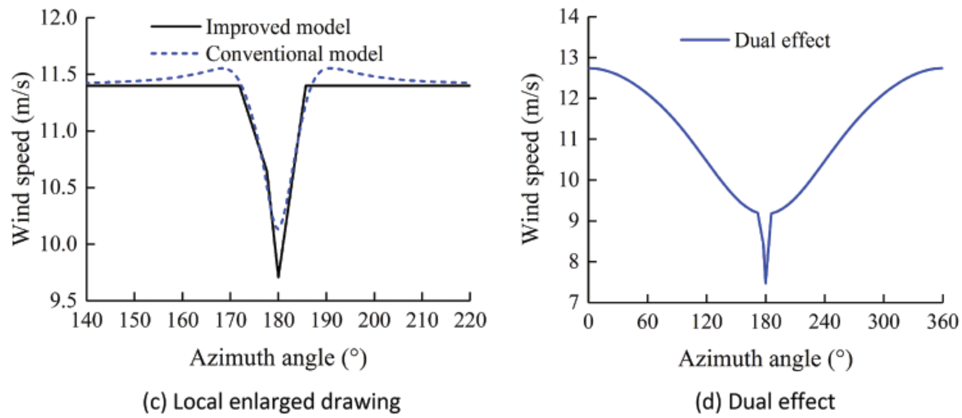

Figure 2: Wind speed of blade tip considering wind shear and tower shadow effect

To study the influence of structural parameters of a wind turbine such as hub height, rotor diameter, the diameter of tower top, and overhang on wind shear and tower shadow effect, wind speed of blade tip under different structural parameters are explored using the improved model. The detailed wind turbine structural parameters are shown in Table 2, and number 2 are the design parameters for a 5-MW baseline wind turbine.

Table 2: Wind turbine structural parameters

Numbers	Hub heights	Rotor diameters	Diameters of tower top	Rotor overhangs
1	85 m	116 m	3.00 m	4 m
2	90 m	126 m	3.87 m	5 m
3	95 m	136 m	4.50 m	6 m

Fig. 3a shows that the maximum wind speed of blade tip tends to decrease from 12.8 to 12.6 m/s with the increase of hub height. The minimum wind speed tends to increase from 7.2 to 7.6 m/s. It shows that the wind shear effect tends to decrease with the increase of hub height.

Fig. 3b shows the opposite trend compared with Fig. 3a. The larger the rotor diameter, the more significantater the difference between the maximum and minimum wind speed. This shows that the variation range of wind speed tends to increase with the rotor diameter increase. The rotor diameter is positively correlated with the wind shear and tower shadow effect.

Fig. 3c and its local enlarged drawing 3-d show that the diameter of the tower top slightly affects the wind speed of the blade tip beyond the critical azimuth angles of 175.5° and 184.5°, while the wind speed decreases sharply between the critical azimuth angles with the increase of top diameter. The speed drop caused by the change in tower top diameter is 1.3 m/s when the azimuth angle is 180°. It is shown that there is no correlation between the wind shear and the diameter of the tower top, and the tower shadow effect is positively correlated with the diameter of the tower top.

Fig. 3e shows the same variation trend as Fig. 3c when it is beyond the critical azimuth angle, indicating that the wind shear effect is independent of rotor overhang. However, within the critical azimuth angle, Fig. 3f shows the opposite trend to Fig. 3d, and the wind speed of the blade tip grows obviously with the increase of overhang. It indicates that the tower shadow effect is negatively correlated with the rotor overhang. The closer the rotor is to the tower, the more pronouncedious the tower shadow effect.

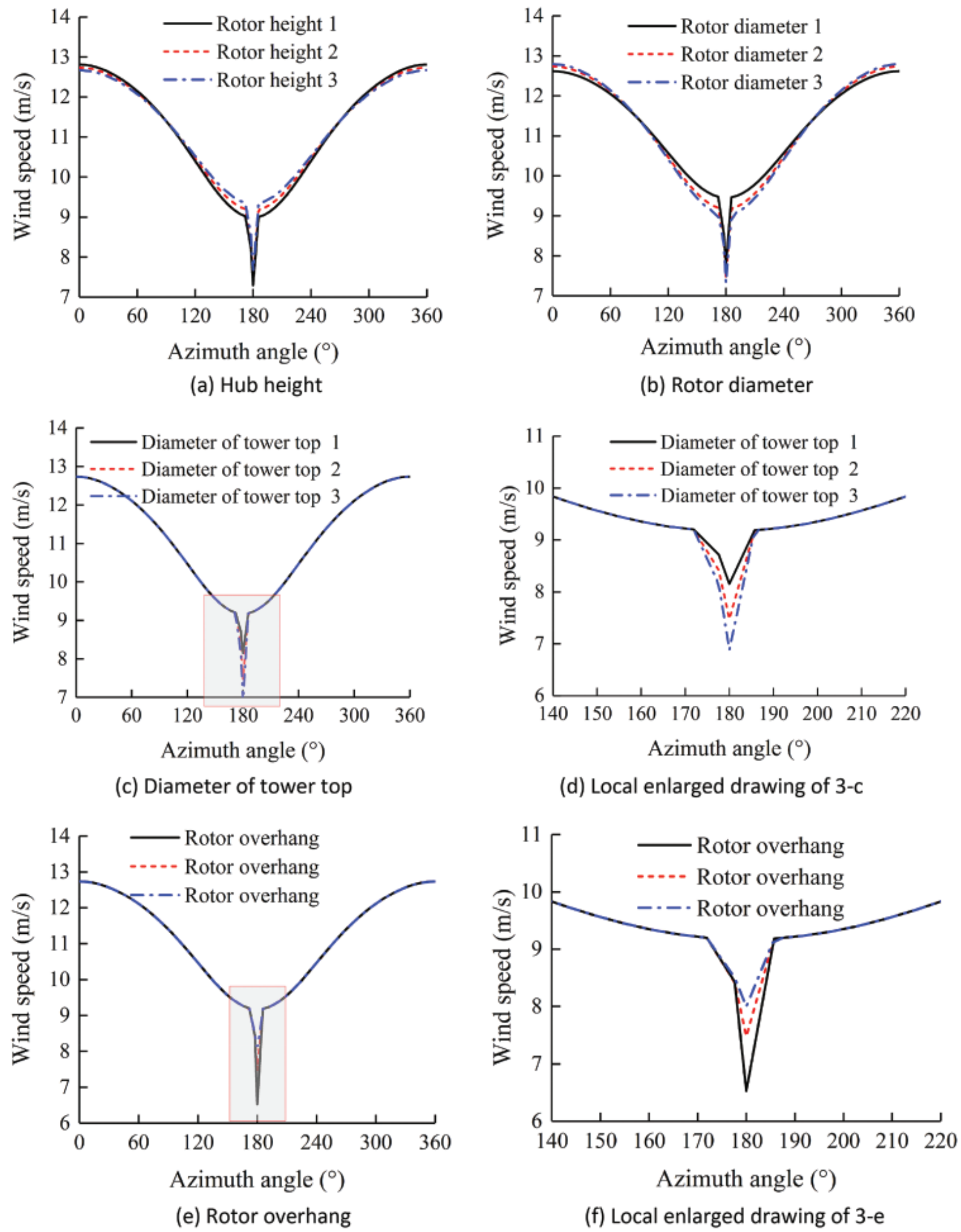

Figure 3: Wind speed of blade tip with different structural parameters

4 Conclusions and Discussion

(1) An improved model accounting for the wind shear and tower shadow effect is established in the way of unified cylindrical coordinate using the fourth-order Taylor series, and the boundary of

rotor swept area is further refined. Compared to the conventional model, the proposed model more realistically reflects the influence of the tower shadow effect on the incoming wind speed.

(2) Wind shear effect becomes weaker with the increase of hub height. It causes the maximum wind speed of the blade tip decreases, the minimum wind speed tends to increase, and the range of wind speed tends to decrease. The hub height is independent of the tower shadow effect.

(3) The larger the rotor diameter, the greater the difference between the maximum and minimum wind speed. The rotor diameter is positively correlated with the wind shear and tower shadow effect.

(4) Beyond the critical azimuth angles of 175.5° and 184.5°, the diameter of the tower top and rotor overhang does not affect the wind speed of the blade tip. Between the two critical azimuth angles, the wind speed decreases sharply with the increase in the diameter of the tower top but grows with the increase of rotor overhang. This is mainly because there is no correlation between wind shear and the diameter of the tower top, while the tower shadow effect is positively correlated with the diameter of the tower top, and negatively correlated with the rotor overhang.

This study focused on the relationship between wind turbine structural parameters with wind shear and the tower shadow effect. The future work will further analyze the influence of structural parameters on the rotor power and operation performance of wind turbines.

Data Availability: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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