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EFFECTS OF DESIGN PARAMETERS ON WIND SPEED FOR LARGE THREE-BLADED UPWIND HORIZONTAL AXIS WIND TURBINE

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ABSTRACT

For large three-bladed upwind horizontal axis wind turbine, the blade spatial positions are different with the rotor running at the same time, and so, the wind speed on the blade is variable due to wind shear and tower shadow. Some specific design parameters such as rotor hub height, hub-height wind speed, wind shear coefficient, radius of the rotor disk, tower radius and overhang distance are taken into account in the wind speed model. Based on the model, the influence of wind shear and tower shadow on wind speed for a two-megawatt wind turbine is investigated. The experimental results show that due to the presence of wind shear and tower shadow, not only the above parameters can make the value of wind speed change remarkably, but also this influence is more and more serious as wind turbine capacity increases.

Keywords: *Design Parameters, Tower Shadow, Wind Shear, Wind Speed, Wind Turbine.*

1. INTRODUCTION

The wind is characterized by its speed and direction, which are affected by several factors, including geographic location, climate characteristics, height above ground, and surface topography[1]. In general, model research and aerodynamics calculation of wind turbines have been used where wind speed is represented either by hub-height wind speed or mean spatial wind speed[2]. However, the value of wind speed in the whole rotor disk plane is unequal due to wind shear and tower shadow.

For three-bladed upwind horizontal axis wind turbine, the spatial position difference of three blades in pairwise comparison is 120 deg in the whole rotor disk plane. In addition, the spatial position difference between the two points on every blade is also bigger along the blade spanwise direction even if at the same azimuthally angle. As nowadays wind turbine capacity is becoming bigger and bigger, the blade is longer and longer and the tower is higher and higher, the influence of wind shear and tower shadow on wind speed becomes more pronounced for the rotating blade[3]. This effect intensifies the periodic variation of aerodynamic load. The periodic aerodynamic load can give rise to blade dynamic response, which feedbacks to outside aerodynamic load, and eventually leads to torque and power generated by a wind turbine being much more variable than that produced by conventional generators[4]. One of the disadvantages is that this makes the output unsuitable to be directly connected to the system bus because of poor power quality. Weak power systems are more susceptible to sudden changes in network operating conditions. Any major change in the operating condition can create significant voltage and frequency fluctuation, which can in turn make the system unstable[5,6]. The other problem is that when an unbalance load occurs among three blades, this brings the rotor to vibrate and fatigue [7].

Individual pitch control (IPC) is an effective means to solve the above problems[8], which premise is the accurate calculation and analysis about the effects of design parameters on wind speed. In this study, the wind speed model in the whole rotor disk area is obtained based on wind shear and tower shadow for three-bladed upwind horizontal axis wind turbine. The design parameters, such as rotor hub height, hub-height wind speed, wind shear coefficient, radius of the rotor disk, tower radius and overhang distance[9], are taken into account, and the effects of these parameters on wind speed are studied with more details.

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2. WIND SPEED MODELING

Wind speed generally increases with height, which is known as wind shear, as shown in Figure 1. Wind shear can be expressed as [10,11]:

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

where V_h is the hub-height wind speed, h is the rotor hub height, r is the radial distance from the blade to the hub center, namely the blade radial distance, θ is the azimuthal angle, and α is the wind shear coefficient. A wind shear coefficient is not constant and depends on numerous factors, including atmospheric conditions, temperature, pressure, humidity, time of day, seasons of the year, the mean wind speed, direction and nature of terrain. $W(r,\theta)$ is the disturbance seen in wind speed due to wind shear that is added to hub-height wind speed. Linearizing $W(r,\theta)$ with a third-order-truncated Taylor series expansion yields[12]:

$$W(r,\theta)\approx\alpha\left(\frac{r}{h}\right)\cos\theta+\frac{\alpha(\alpha-1)}{2}\left(\frac{r}{h}\right)^2\cos^2\theta+\frac{\alpha(\alpha-1)(\alpha-2)}{6}\left(\frac{r}{h}\right)^3\cos^3\theta \qquad (2)$$

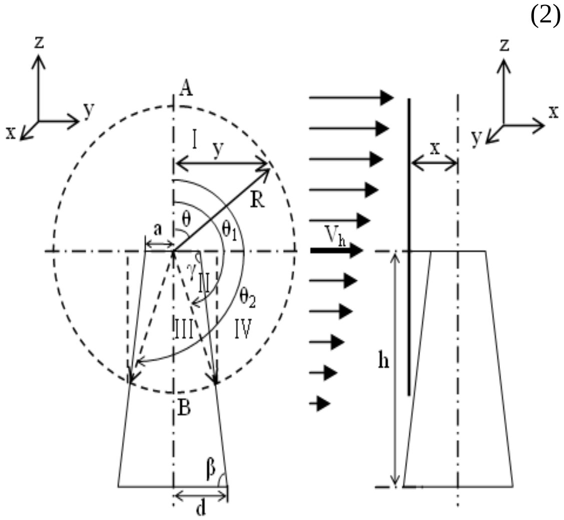

Figure 1. Structure Of Three-Bladed Upwind Horizontal Axis Wind Turbine

The distribution of wind is altered by the presence of the tower. For upwind rotors, the wind directly in front of the tower is redirected and thereby reduces the torque at each blade when in front of the tower. This effect is called tower shadow. The majority of modern wind turbines have upwind rotors. This study therefore only deals with the tower shadow wind speed in three-bladed upwind horizontal axis rotors. The wind speed only considering tower shadow, is given by [10,11]:

$$V(y,x)=V_h+v_t(y,x) \qquad (3)$$

$$v_t(y,x)=V_0a^2\frac{y^2-x^2}{(x^2+y^2)^2} \qquad (4)$$

where V_0 is the mean spatial wind speed, a is the tower radius, y is the lateral distance from the blade to the tower midline, x is the distance from the blade origin to the tower midline, namely the overhang distance, and $v_t(y,x)$ is the disturbance imposed by the tower shadow on wind speed. Because the influence of tower shadow is to reduce wind speed, it is clear from Eq. 4 that a sufficient condition for the existence of tower shadow is

$$|y|<x \qquad (5)$$

Different references of wind speed are used in models for the disturbance due to wind shear and tower shadow. The wind shear model uses hub-height wind speed (V_h) while the tower shadow model uses mean spatial wind speed (V_0). The relationship between both wind speeds is defined as follows [12]:

$$V_0=V_h[1+\frac{\alpha(\alpha-1)(R^2)}{8h^2}]=mV_h \qquad (6)$$

where R is the radius of the rotor disk, and $m=1+\frac{\alpha(\alpha-1)(R^2)}{8h^2}$.

Considering $y=r\sin\theta$ and substituting Eq. 6 into Eq. 4 results in

$$v_t(r,\theta,x)=mV_ha^2\frac{r^2\sin^2\theta-x^2}{(r^2\sin^2\theta+x^2)^2}=V_hv_{tt}(r,\theta,x) \qquad (7)$$

where $v_{tt}(r,\theta,x)=ma^2\frac{r^2\sin^2\theta-x^2}{(r^2\sin^2\theta+x^2)^2}$. It should be noted that the tower shadow is only valid for the lower half rotor disk plane, namely $0.5\pi\le\theta\le1.5\pi$.

According to different range of the radial distance from rotor axis and the azimuthal angle, the wind speed is fallen into four zones in Figure 1. Zone I: the blade works in the upper half rotor disk plane and wind speed is only affected by wind shear. Zone II, III, IV: the blade works in the lower half rotor disk plane. In zone II and III, wind shear and tower shadow have influence on wind speed, but their calculated boundaries are different and they must be calculated respectively. In zone IV, only wind shear has influence on wind speed, but its calculated boundary is different with Zone I, and the wind speed must be calculated respectively.

For the tower in Figure 1

$$\tan\beta=\frac{h}{d-a} \qquad (8)$$

where a is the top radius, d is the bottom radius , h is the rotor hub height.

Considering $h>>d-a$ for modern large wind turbines, the top angle of tower can be given approximately:

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$$\gamma = \pi - \arctan(\frac{h}{d-a}) \approx \pi - \frac{\pi}{2} = \frac{\pi}{2} \quad (9)$$

Therefore, during calculating the effect of tower shadow on wind speed, it can be think that the radius elsewhere equals the top radius approximately. In zone II, according to the Eq. 5, the blade radial distance can be deduced as follows

$$\begin{cases} r < \frac{x}{\cos(\theta - \frac{\pi}{2})} = \frac{x}{\sin\theta} & 0.5\pi \le \theta < \theta_1 \\ r < \frac{x}{\cos(\frac{3\pi}{2} - \theta)} = \frac{x}{-\sin\theta} & \theta_2 < \theta \le 1.5\pi \end{cases} \quad (10)$$

where θ_1, θ_2 are the boundary azimuthal angle during $r = R$ for zone II in Figure 1, they are derived as

$$\begin{cases} \sin\theta_1 = \frac{x}{R} & 0.5\pi < \theta_1 < \pi \\ \sin\theta_2 = -\frac{x}{R} & \pi < \theta_2 < 1.5\pi \end{cases} \quad (11)$$

Eq. 10 can be represented as

$$r < \frac{x}{|\sin\theta|} \quad 0.5\pi \le \theta < \theta_1, \theta_2 < \theta \le 1.5\pi \quad (12)$$

In zone III, the whole blade is affected by tower shadow, the radial distance from the blade to the hub center can be written as

$$0 < r \le R \quad \theta_1 \le \theta \le \theta_2 \quad (13)$$

The calculated model of wind speed for four zones can be given by

Zone I:

$$\begin{cases} V(r,\theta) = V_h(\frac{r\cos\theta + h}{h})^{\alpha} = V_h[1 + W(r,\theta)] \\ 0 < r \le R \\ 0 \le \theta < 0.5\pi, 1.5\pi < \theta \le 2\pi \end{cases} \quad (14)$$

Zone II:

$$V(r,\theta) = V_h[1+W(r,\theta)][1+v_{tt}(r,\theta,x)] = V_h[1+W(r,\theta)+v_{tt}(r,\theta,x)+W(r,\theta)v_{tt}(r,\theta,x)]$$

$$V(r,\theta) = V_h[1+W(r,\theta)][1+v_{tt}(r,\theta,x)] = V_h[1+W(r,\theta)+v_{tt}(r,\theta,x)+W(r,\theta)v_{tt}(r,\theta,x)]$$

(15)

As $W(r,\theta)v_{tt}(r,\theta,x)]$ would be small compared to other terms, Eq. 16 is a valid approximation of Eq. 15.

$$V(r,\theta) \approx V_h[1 + W(r,\theta) + v_{tt}(r,\theta,x)] \quad (16)$$

$$\begin{cases} V(r,\theta) = V_h[1 + W(r,\theta) + v_{tt}(r,\theta,x)] \\ 0 < r < \frac{x}{|\sin\theta|} \\ 0.5\pi \le \theta < \theta_1, \theta_2 < \theta \le 1.5\pi \end{cases} \quad (17)$$

Zone III:

$$\begin{cases} V(r,\theta) = V_h[1 + W(r,\theta) + v_{tt}(r,\theta,x)] \\ 0 < r \le R \\ \theta_1 \le \theta \le \theta_2 \end{cases} \quad (18)$$

Zone IV:

$$\begin{cases} V(r,\theta) = V_h(\frac{r\cos\theta + h}{h})^{\alpha} = V_h[1 + W(r,\theta)] \\ \frac{x}{|\sin\theta|} \le r \le R \\ 0.5\pi \le \theta < \theta_1, \theta_2 < \theta \le 1.5\pi \end{cases} \quad (19)$$

3. EXPERIMENTAL RESULTS AND DISCUSSION

Considering the effect of wind shear and tower shadow on wind speed, the wind speed with the change of the blade radial distance and the azimuthal angle is calculated and analysed for two megawatt three-bladed upwind horizontal axis wind turbines. Because cone angle and tilt angle are generally very small, this study take them as 0 deg, which means that the blade rotates in the rotor disk plane perpendicular to the main shaft axis. The following basic values are: $h = 60$ m, $V_h = 12$ m/s, $\alpha = 0.2$, $R = 38$ m, $a = 1.5$ m and $x = 2.9$ m for design parameters. In order to fully explain the design parameters' influence on wind speed when wind shear and tower shadow are considered, tow values of them are selected to calculate and analyse based on the basic values respectively, as shown in Table 1. What calls for special attention is that it is guaranteed that the overhang distance (x) is greater than the top radius (a) in any case. This is the only way to ensure the wind turbine can work normally, and experimental results can be achieved in the following figures.

In zone I, i.e. $0 \le \theta < 0.5\pi$ and $1.5\pi < \theta \le 2\pi$, the blade works in the upper half rotor disk plane and wind speed is only affected by wind shear. Wind speed increases with the blade radial distance (r) under the condition of the same azimuthal angle (θ). The maximum value of wind speed appears when the azimuthal angle is 0 or 2π and the blade radial distance is the radius of the rotor disk (R), namely at the peak of rotor disk plane (point A) in Figure 1.

Table I: The Experimental Value Of The Design Parameters

Design parameter	Value 1	Value 2 (basic)	Value 3
h (m)	*50*	*60*	*70*
V_h (m/s)	*11*	*12*	*13*
α	*0.15*	*0.2*	*0.25*
R (m)	*33*	*38*	*43*
a (m)	*1.1*	*1.5*	*1.9*
x (m)	*2.4*	*2.9*	*3.4*

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In zone $0.5\pi \le \theta \le 1.5\pi$, the blade works in the lower half rotor disk plane. In zone II, wind speed is affected by wind shear and tower shadow, and tower shadow is more serious near the center of the rotor disk plane, namely the wind speed is smaller with the decrease of the blade radial distance (r) under the condition of the same azimuthal angle (θ). As the blade radial distance (r) gets longer, entering zone IV, wind speed is only affected by wind shear, namely the longer the blade radial distance (r), the smaller the wind speed. In zone III, both wind shear and tower shadow have effects on wind speed. The minimum value of wind speed appears when the azimuthal angle is π and the blade radial distance is the radius of the rotor disk (R), namely at the lowest point of rotor disk plane (point B) in Figure 1. Considering the rotor disk plane is bilaterally symmetrical, wind speed of the right half rotor disk plane is studied by the simulation experiment in this study, i.e. $0 \le \theta \le \pi$.

The value of the rotor hub height (h) is chosen to compare and analyse at 50, 60, and 70 m, respectively. Figure 2 illustrates that as the rotor hub height becomes bigger, the maximum value of wind speed tends to get smaller and the minimum value of wind speed bigger. In other words, the range of wind speed gets narrower with the increase of rotor hub height.

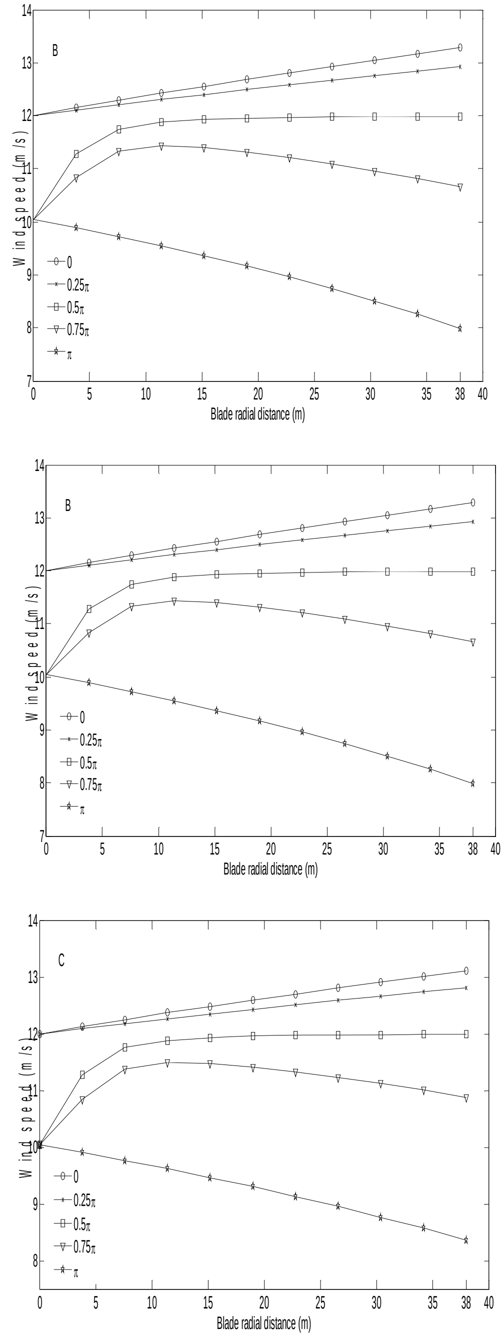

Figure 2. Wind speed for different h ($V_h = 12$ m/s, $\alpha = 0.2$, $R = 38$ m, $a = 1.5$ m, $x = 2.9$ m): (A) $h = 50$ m. (B) $h = 60$ m. (C) $h = 70$ m.

The hub-height wind speed (V_h) is chosen to compare and analyse at 11, 12, and 13 m/s. It is obvious that the mean wind speed, the maximum and minimum wind speed rise with the increase of the hub-height wind speed in Figure 3.

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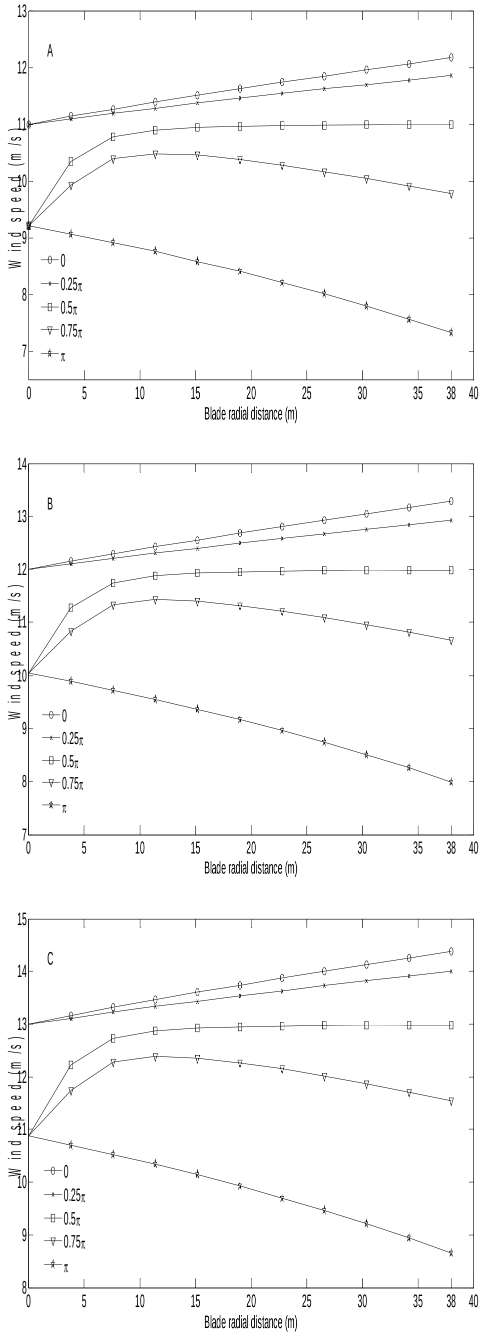

Figure 3. Wind speed for different V_h (h = 60 m, α = 0.2, R = 38 m, a = 1.5 m, x = 2.9 m): (A) V_h = 11 m/s. (B) V_h = 12 m/s. (C) V_h = 13 m/s.

The wind shear coefficient (α) is chosen to compare and analyse at 0.15, 0.2, and 0.25, respectively. Figure 4 shows that the vertical change of wind speed is related to the wind shear coefficient and its value embodies the changing ratio of wind speed with vertical height. The bigger the value of wind shear coefficient, the faster the change of the wind speed with vertical height, namely the wind speed gradient is big; the smaller the value of wind shear coefficient, the slower the change of the wind speed with vertical height, namely the wind speed gradient is small.

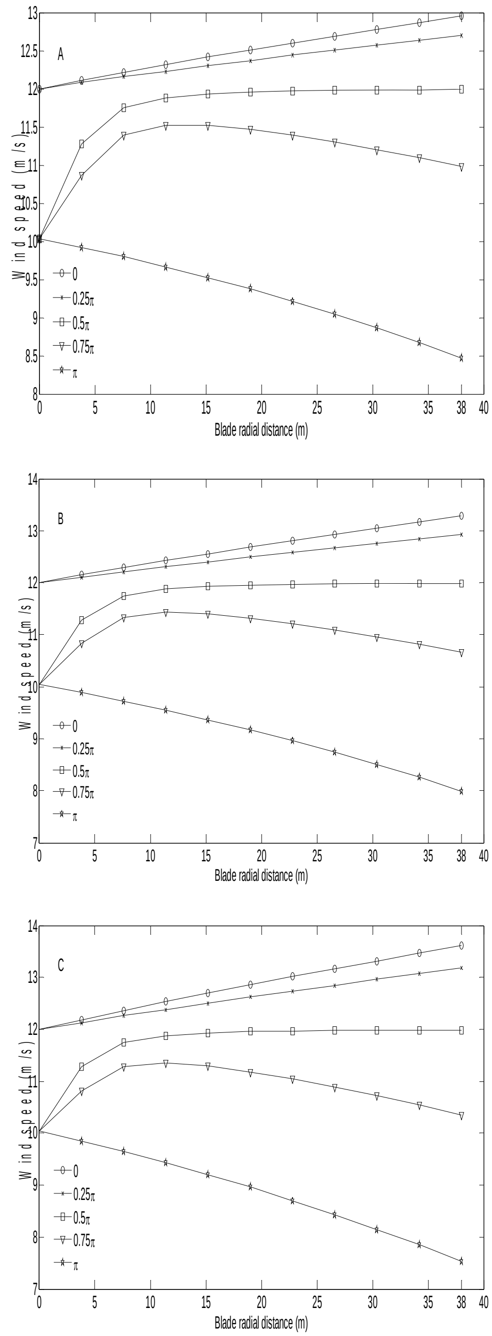

Figure 4. Wind speed for different α (h = 60 m, V_h = 12 m/s, R = 38 m, a = 1.5 m, x = 2.9 m): (A) α = 0.15. (B) α = 0.2. (C) α = 0.25.

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The radius of the rotor disk (R) is chosen to compare and analyse at 33, 38, and 43 m, respectively. Figure 5 indicates that similar to the change of wind shear coefficient, the bigger the value of the blade radius, the larger the difference between the maximum and the minimum value of wind speed, namely the range of wind speed tends to be wider with the increase of the radius of the rotor disk.

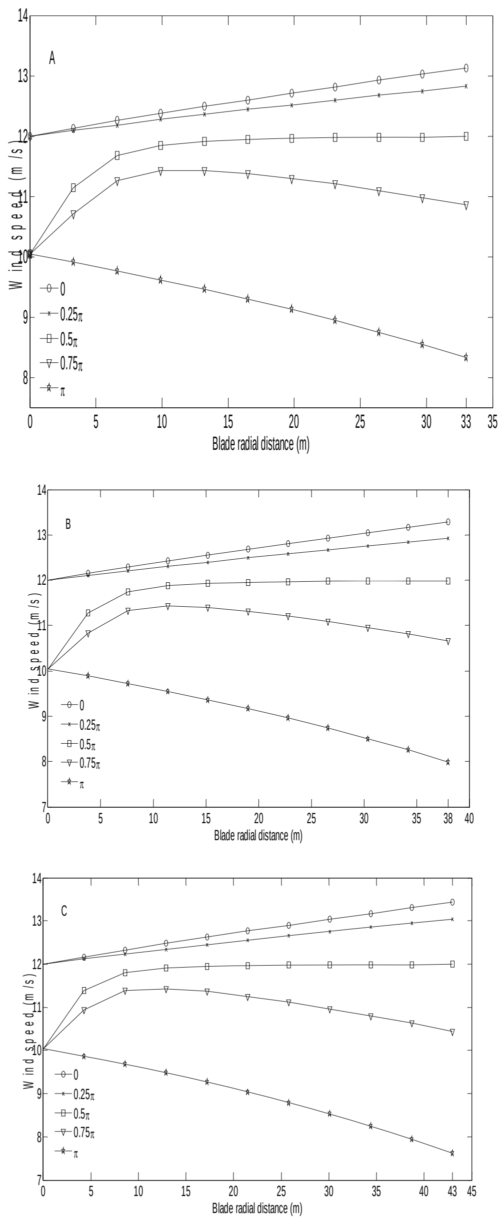

Figure 5. Wind speed for different R (h = 60 m, V_h = 12 m/s, α = 0.2, a = 1.5 m, x = 2.9 m): (A) R = 33 m. (B) R = 38 m. (C) R = 43 m.

The top radius (a) is chosen to compare and analyse at 1.1, 1.5, and 1.9 m. The influence of the change of the top radius on wind speed in the upper half rotor disk plane is small enough to be negligible, but the wind speed in the lower half rotor disk plane decreases with the increase of the top radius. The reason is that wind shear is basically irrelevant to the top radius, but tower shadow is positively correlated to the top radius. This may be correlated to the trend exhibited in Figure 6.

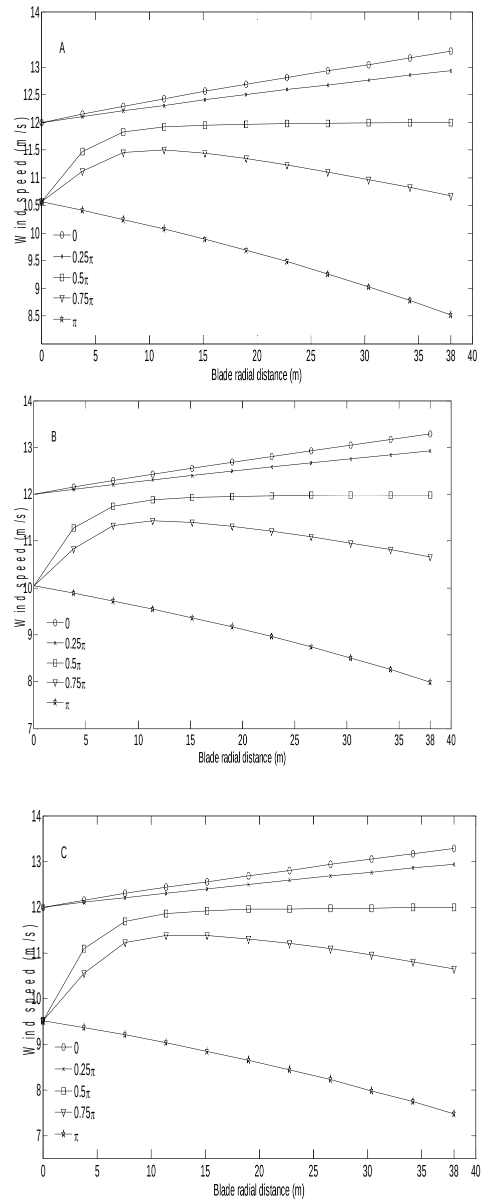

Figure 6. Wind speed for different a (h = 60 m, V_h = 12 m/s, α = 0.2, R = 38 m, x = 2.9 m): (A) a = 1.1 m. (B) a = 1.5 m. (C) a = 1.9 m.

The overhang distance (x) is chosen to compare and analyse at 2.4, 2.9, and 3.4 m, respectively. It is clear from Figure 7 that the influence of the change of the overhang distance on wind speed in the upper

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half rotor disk plane is small enough to be negligible, but the wind speed in the lower half rotor disk plane decreases with the decrease of the overhang distance. In other words, the closer the rotor disk plane from the tower, the more evident the effect of tower shadow.

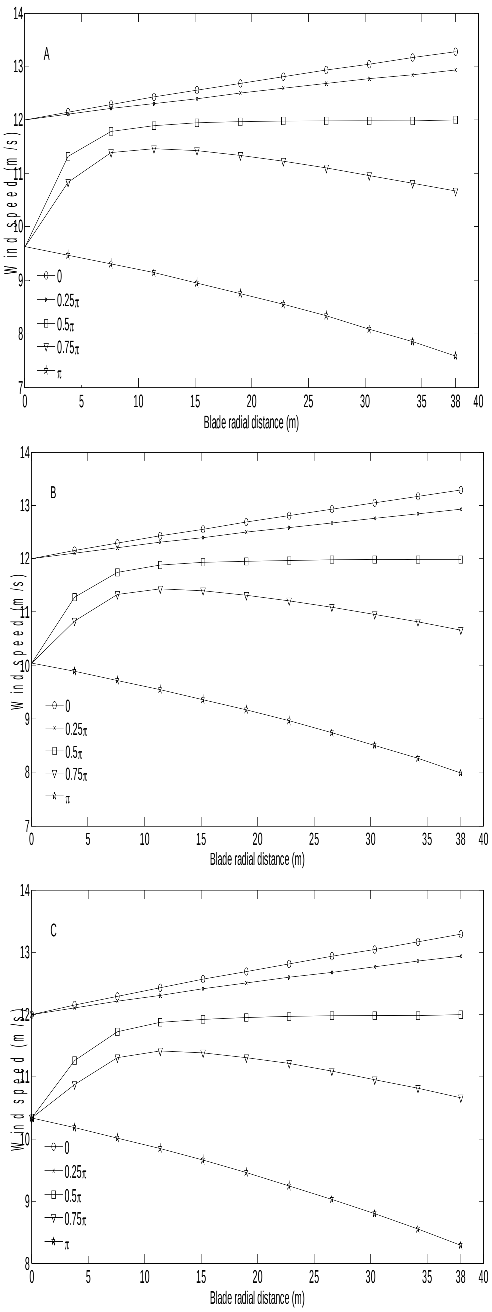

Figure 7. Wind speed for different x (h = 60 m, V_h = 12 m/s, α = 0.2, R = 38 m, a = 1.5 m): (A) x = 2.4 m. (B) x = 2.9 m. (C) x = 3.4 m.

4. CONCLUSION

Due to the presence of wind shear and tower shadow, wind speed is not fixed in the whole rotor disk plane, and moreover it is closely related to rotor hub height, hub-height wind speed, wind shear coefficient, radius of the rotor disk, tower radius and overhang distance. As nowadays wind turbine capacity is becoming bigger and bigger, the blade is longer and longer and the tower is higher and higher, and the influence of wind shear and tower shadow on wind turbine is more serious. It is obvious that simplifying or neglecting wind shear and tower shadow is not precise and reasonable in design and calculation for wind turbine. Based on the in-depth research of wind shear and tower shadow, this study implements the dynamic response model of wind speed with the change of the blade radial distance and the azimuthal angle, and analyse the effects of design parameters on wind speed for large horizontal axis wind turbine. This work lays a foundation for further study of the individual pitch, power control, fatigue, dynamic stability and etc. for wind turbine.

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