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EVALUATING THE EFFECT OF BLADE SURFACE ROUGHNESS IN MEGAWATT WIND TURBINE PERFORMANCE USING ANALYTICAL AND NUMERICAL APPROACHES

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ABSTRACT

Past experiences show that the blade surface roughness can affect negatively on the performance of a wind turbine and consequently a reduction in its annual energy production (AEP). In this work, we use the computational fluid dynamics (CFD) tool, model the roughness at wind turbine blade surface, obtain the blade aerodynamics coefficients, and calculate the output power for megawatt wind turbine blade. In these procedures, we also validate our CFD results against the available experimental data reported for a megawatt wind turbine airfoil section. Similar to past experiences, our CFD solutions approve that the blade roughness can effectively reduce both C_{l_α} *and* $C_{l_{Max}}$ *coefficients as well as the stall angle of a clean airfoil. Normally, any reduction in aerodynamics performance of an airfoil would inversely affect the performance of its corresponding wind turbine blade. To achieve a better understanding of the inverse effect of blade surface roughness on the performance of a megawatt wind turbine blade, we carefully simulate the blade sections for a megawatt wind turbine considering both clean and rough surface situations. In this regard, we use the blade element momentum (BEM) theory to calculate the power for the chosen megawatt wind turbine blade. To enrich our study, we consider both the Reynolds number variation along the blade span and the three-dimensional flow effects in our BEM calculations. The achieved results show that a megawatt wind turbine with a rough surface would noticeably perform less power generation than an equivalent wind turbine with a clean airfoil surface. Our calculations show that the megawatt wind turbine can be faced with 25% reductions in its AEP in a wind velocity about 11-16* m/s.

INTRODUCTION

Nowadays, the energy generator stations are promoted to use clean energy approaches due to a fast growth of energy consumption and the fact that a higher consumption of fossil-based fuels would harm the environment more adversely. Todays, wind turbine power generators are considered one major source of clean energy generations. Indeed, wind turbines have had an increasing role in producing world clean energy since the two past decades. However a large demand in clean energy production has caused the technology to seek for larger the wind turbine sizes. Therefore, larger wind turbine rotor, e.g. a megawatt wind turbine, has become the essence of vast current researchers because of a larger demand on clean energy production. Since the megawatt wind turbine energy production has become very important, the researchers have focused on identifying and improving the effective factors, which can decrease the efficiency of megawatt wind turbines inversely. Among different recognized factors, one important one is the blade roughness which can inversely affect the wind turbine performance. There are different reasons to return clean blades to rough blades. For example, the atmosphere dust can produce such roughness. The reduction in blade surface quality has been reported by many wind turbine stations in practice.

Corten and Veldkamp [1] showed that insects could decrease the wind turbine performance effectively. Their investigation on the chosen wind turbine showed that the blade would experience some prematured stall occurring in low wind speeds. They proposed different hypotheses to justify this phenomenon and the cause for such prematured stall occurrences. They eventually reported that such prematured stalls would be a consequent of colliding insects with the blade leading edge. These insects were piled up around the airfoil. Khalfallah and Koliub [2] examined the changes in power output of a 300 KW wind turbine after considering different roughnesses with various thicknesses, areas, types, etc. Their results showed that there would be around 50 percents drop in *power after a period of 9 months. Indeed, a significant part of the past activities on the wind turbine roughnesses return to the basic design behind wind tribune blade sections. Beside the numerical investigations, there have been numerous efforts to elaborate the sensitivity of various airfoils to the roughness area at the blade leading edge [3, 4]. Studying the past performed activities show that the roughness on the wind turbine blade surface could affect its aerodynamics performances in two general ways, i.e., accelerating the transition occurrence and consequently affecting the flow features in the turbulent regions. Referring to the principal studies, Schilichting [5] has also raised these two effects of the roughness in airfoil aerodynamic study*

The past activities in wind turbine roughness studies have been performed more experimentally. Ferrer and Munduate [6] used the computational fluid dynamics CFD to predict the transition via distributing different roughnesses over their wind turbine airfoil. They used a commercial software and validated their results against experimental data reported by NREL. Pechlivanoglou, et al. [7] used the Xfoil software to calculate the effect of blade surface roughness for a wind turbine airfoil section. They eventually used blade element momentum BEM theory to calculate the resulting power.

NOMENCLATURE

$C_{l,3D}$	*The lift coefficient for an airfoil considering the 3D influences.*
$C_{l,2D}$	*The lift coefficient for two-dimensional situations.*
$C_{l,2D,Linear}$	*The two-dimensional lift coefficient for an airfoil without experiencing any separation.*
c	*Length of the chord at each section*
$f(c/r)$	*3D model function (it is described more with in the text as is used)*
r	*The distance between the root and each section of the blade*
V_{rel}	*Relative velocity*
ΔC_l	*The differences between the lift coefficients for an airfoil without experiencing any separation and that of the data taken from wind tunnel experiment.*
θ	*The angle between the airfoil's chord and horizon*
ω	*Rotational speed*

CLEAR ROTOR CONFIGURATIONS AND PERFORMANCES

Before presenting the results, we are required to introduce the chosen configuration for our one megawatt wind turbine blade. It consists of three different airfoils located at mid and tip sections with 30 and 20 per cent thicknesses respectively. Additionally, a circular section at root. There are different choices to perform the aerodynamics and structural characteristics of one blade turbine and the entire rotor.

Figures 1 to 5 present the performance charts and configuration diagrams related to the current 1MW designed wind turbine. Figure 1 shows the chord and pre-twist angle distributions along the span of this blade. It is known that the chord distribution not only affect the aerodynamics performances of the blade but also its structural strength.

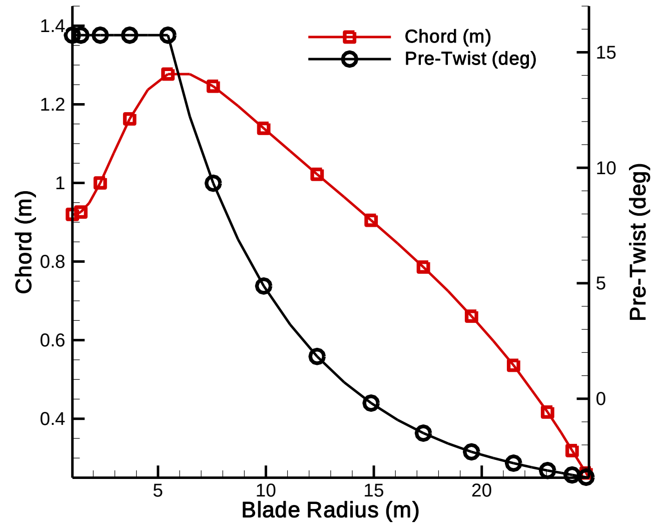

Figure 1 *The variations of blade chord length and its pre-twist angle with blade radius*

Figure 2 shows the airfoil thickness distribution along the wind turbine blade span. The thicknesses are given both dimensionally and non-dimensionally. Normally, it is expected to have increases in blade thickness from root to tip of blade if we wish to achieve better performances for both aerodynamics and structure parts.

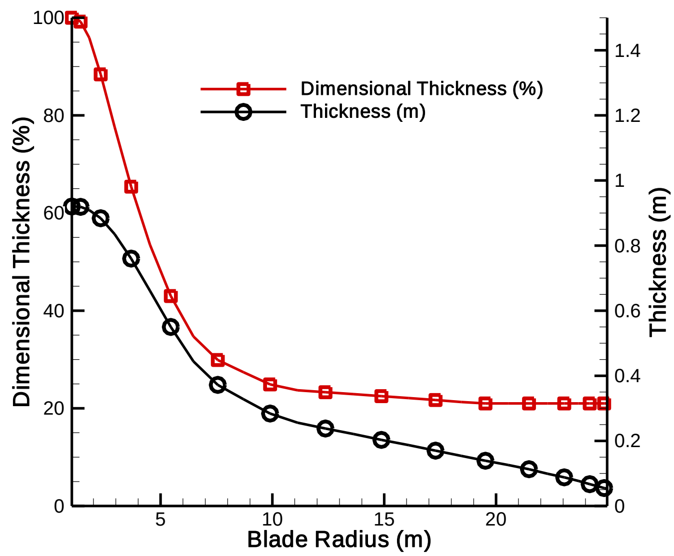

Figure 2 *The variations of blade thickness percentages and its dimensional thickness with blade radius*

Figure 3 shows both the rotor power and the power coefficient for the current one megawatt turbine. The figure shows that the turbine achieves one megawatt power at a nominal wind speed of 12.2 m/s. the power coefficient is about

0.47 at this nominal wind speed. In other words, the current wind turbine has been able to capture about 47% of the total wind power available in such wind velocity.

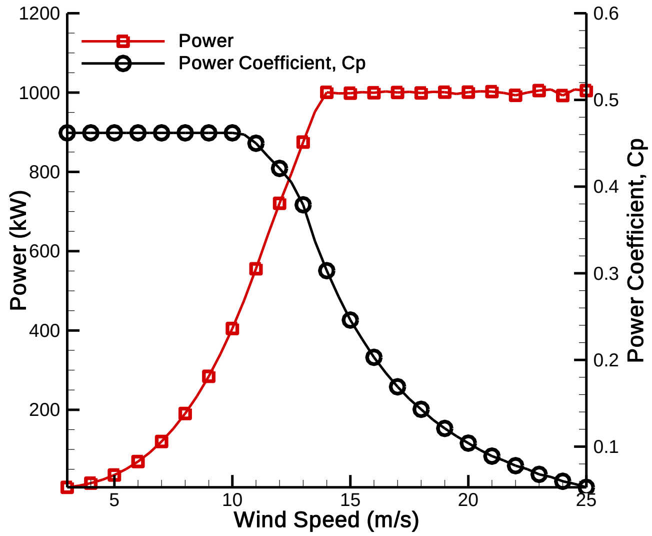

Figure 3 *The variations of rotor power and rotor power coefficient with wind speed*

Figure 4 presents the blade rotational speed and blade pitch angle in terms of wind speed. Indeed, the current pitch angle has been designed in a manner to guarantee the nominal power required at higher wind speeds. The designed power is guaranteed up to a wind speed of 25 m/s.

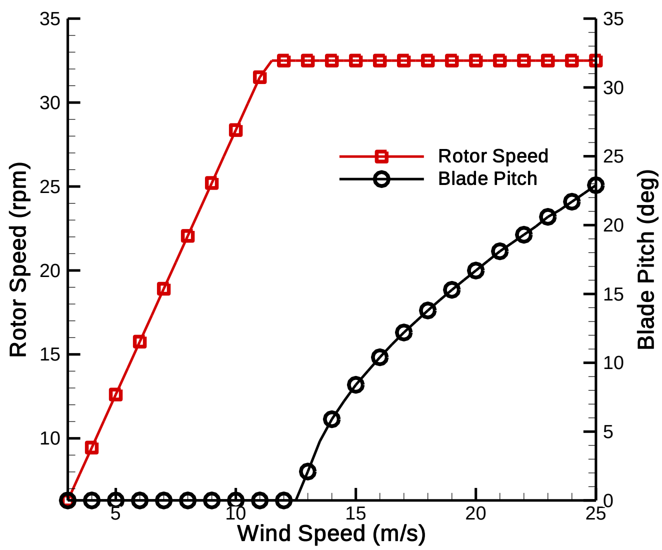

Figure 4 *The variations of rotor rotational speed and blade pitch with wind speed*

Figure 5 illustrates the variations of wind turbine torque and thrust as the wind speed increases. As is expected there is a pick in thrust distribution at a wind speed of 12.2 m/s.

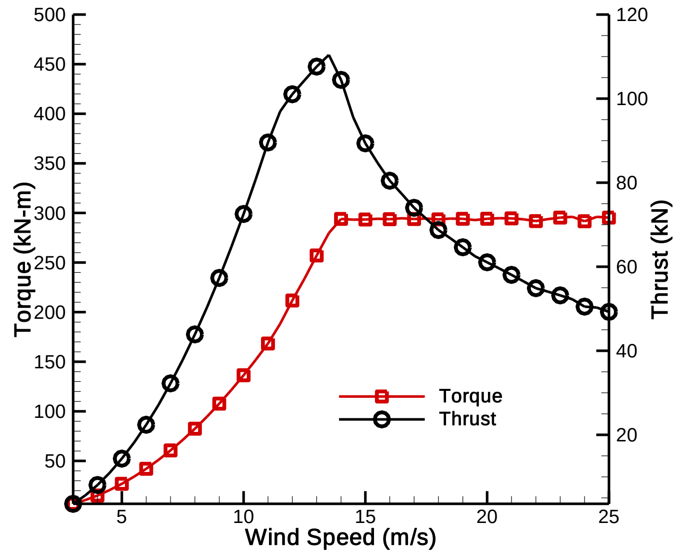

Figure 5 *The variations of torque and thrust with Speed*

THE EFFECT OF 3D INFLUENCESS

Experimental observations show that the aerodynamic performances in 3D turbine blade flow is different than those of two dimensional flow [3, 4, 6]. In other words, the aerodynamic characteristics for blade sections are somehow different than those for its corresponding 2D airfoils. This is mainly due to the velocity component induced in the third direction. The BEM theory predicts this induced velocity, which can be implement in the practical calculations. There is another important 3d effect, which shows up near to stall condition. This phenomenon can alter the lift and drag coefficients effectively. The measurements also show that the airfoil lift coefficient is higher for a real blade than that measured in a wind tunnel in same conditions. Himmelskamp [6] was the first to report this phenomenon. He found that the maximum lift coefficient, especially at the root of blade, is more than that measured in a wind tunnel, i.e., equivalent 2D results. Following this discovery, there have been numerous efforts to elaborate more this phenomenon properly. The conclusion is that the data taken from wind tunnel would be would be reliable for 3D applications as long as they are before any stall occurrence. The 2D data should be suitably modified for conditions over this region if they are needed to be implemented in 3D applications. This modification can be performed suitably using BEM theory. In this modification, the BEM suitably improves the 2D airfoil results for 3D blade applications. This strategy is known as the 3D correction for 2D airfoil results. The above described phenomenon is performed as stall delay correction. It means that the consequence of a 3D flow is to delay the stall condition as the angles of attack increases for that airfoil. The observations also show that the changes in aerodynamics characteristics would observe more seriously in the separation zone. In other words, *the flow either laminar or turbulent can be affected slightly in the attached flow regions. The observations also show that the separation line is almost the same for both the 2D and 3D cases although their maximum lift coefficients perform differently. The measured maximum lift coefficients for both 2D wind tunnel results and 3D blade data show that there is an increase in maximum lift coefficient about 30-40% near the blade root. Additionally, they show that the lift coefficient is almost the same for the blade mid-span part. However, the lift coefficient decreases near the blade tip corresponding with the 2D results. Considering these points, we decided to consider the stall delay correction in our calculations for the designed one-megawatt turbine blade. There are different models to take into account this 3D effect. A few of them are elaborated here.*

Models for three-dimensional correction of airfoil characteristics

The 3D correction models benefit from similar parameters, which are described here properly. The amount of $C_{l,3D}$, is The lift coefficient for an airfoil considering the 3D influences and $C_{l,2D}$, is The lift coefficient for dimensional situations. The amount of ΔC_l is The difference between the lift coefficients for an airfoil without experiencing any separation ($C_{l,2D,Linear}$) and the data from wind tunnel experiment($C_{l,2D}$). In this relation, the function f(c/r) will be different based on various models offered so far. Considering these definitions, they can be written as

$$C_{l,3D} = C_{l,2D} + f\left(\frac{c}{r}, \dots\right)\Delta c_l$$
$$C_{d,3D} = C_{d,2D} + f\left(\frac{c}{r}, \dots\right)\Delta c_d \qquad (1)$$

Snel, et al. [11] numerically investigated the sectional presentation of 3D effects for stalled flow over the rotating blades. They validated their predictions experimentally. Their correction is suggested as

$$f_{cl} = 3\left(\frac{c}{r}\right)^2 \qquad (2)$$

Lindenburg, et al. [12] modelled the rotational augmentation considering engineering considerations and data measurements. Their correction function is suggested as

$$f_{cl} = 3.1\left(\frac{\omega r}{V_{rel}}\right)^2\left(\frac{c}{r}\right)^2 \qquad (3)$$

Du and Selig [13] investigated a 3D stall-delay model for horizontal axis wind turbine performance. Their 3D correction function is defined by

$$f_{cl} = \frac{1}{2\pi}\left[\frac{1.6\left(\frac{c}{r}\right)}{0.1267}\cdot\frac{a-\left(\frac{c}{r}\right)^{\frac{d}{\Lambda}\frac{R}{r}}}{b+\left(\frac{c}{r}\right)^{\frac{d}{\Lambda}\frac{R}{r}}}-1\right]$$
$$f_{cd} = -\frac{1}{2\pi}\left[\frac{1.6\left(\frac{c}{r}\right)}{0.1267}\cdot\frac{a-\left(\frac{c}{r}\right)^{\frac{d}{\Lambda}\frac{R}{r}}}{b+\left(\frac{c}{r}\right)^{\frac{d}{\Lambda}\frac{R}{r}}}-1\right] \qquad (4)$$

in which

$$\Lambda = \omega R/\sqrt{V^2{}_{Wind} + (\omega r)^2} \qquad (5)$$

and

$$a = b = d = 1 \qquad (6)$$

Cahviaropoulos, et al. [14] investigated the three-dimensional and rotational effects on wind turbine blades using a quasi-3D Navier Stokes solver. Their correction function is given by

$$f_{cl} = a\left(\frac{c}{r}\right)^h \cos^n\theta \qquad (7)$$

in which a=2.2, h=1and n=4 and θ is the angle between the airfoil's chord and horizon.

EVALUATING THE EFFECT OF ROUGHNESS IN PERFORMANCE OF MEGAWATT WIND TURBINE

In order to study the performance of a wind turbine in both clean and rough conditions, we used the BEM approach and designed a megawatt wind turbine, whose airfoils' sections were taken from clean airfoils database. This turbine is designed based on a pitch to feather control system having three blades with 25 meters in length. In designing this turbine, we chose three different airfoils sections with 30%, 25% and 20% thickness. Its layout can be found in Figure 6.

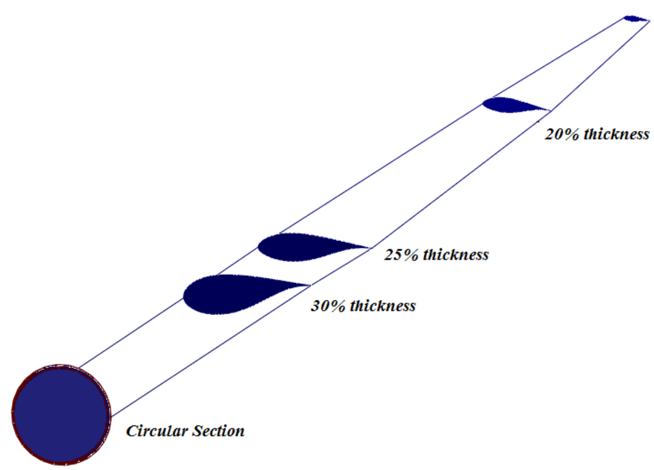

***Figure 6** The layout of current one megawatt wind turbine blade*

COMPARING THE WIND TURBINE POWER AT TWO CLEAN AND ROUGH CONDITIONS

After taking the primary step in simulating the airfoils in two states of clean and rough conditions and running the BEM code for the designed one megawatt wind turbine, we are required to evaluate its performance at two conditions with clean and rough blades. Figure 7 presents the wind turbine power considering a pith control system for the blade. The right *axis indicates the wind turbine power. The left axis indicates the pitch of blade. The horizontal axis also shows the speed of wind. As is seen in this figure, the two clean and rough blades eventually arrive to the nominal power generation status, i.e., one megawatt. The main difference between these two statuses can be attributed to their control system and their slope of power curve. As was pointed out before, the airfoils aerodynamic features are different in clean and rough conditions. The consequences of such differences along the entire length of blade would have resulted in such different behaviours for their pitch control system. As is observed, a wind turbine with a clean blade arrives to its nominal power generation in a wind velocity of 12.2 meters per second while the nominal number is achieved at a wind speed of 17 meters per second in rough blade case. As is observed, the expected megawatt power for the wind turbine with a rough blade is less than that for its equivalent clean blades. In other words, the one megawatt power is achieved at a speed of 17 meters per second. Eventually such reduction in wind turbine power generation in lower wind speed would affect the annual energy production (AEP) for this designed megawatt wind turbine. This is going to be explained in detail in the following section.*

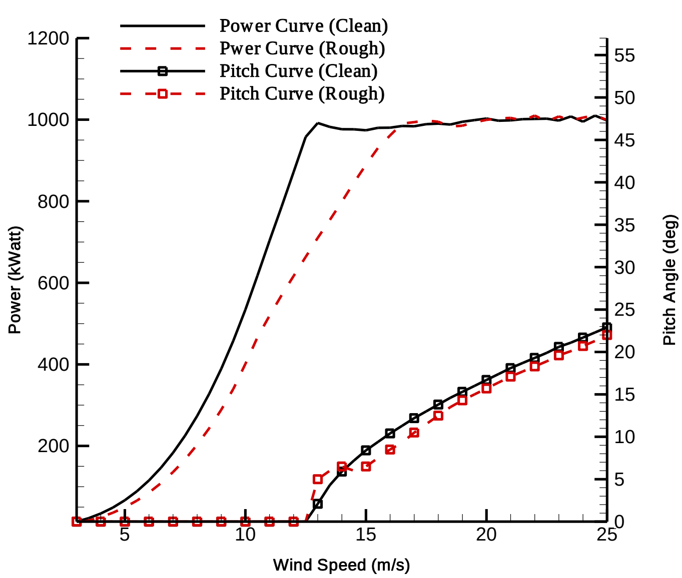

***Figure 7** Comparing power and pitch curves for the one megawatt wind turbine working in both clean and rough blade conditions*

CALCULATING THE RESULTING ANNUAL ENERGY PRODUCTION (AEP)

After calculating the amount of drop in power generation for a wind turbine with a blade at rough condition, we can now estimate the effect of contaminated blade on the annual energy production. In order to compare the AEP produced in clean and rough conditions, we use the Weibull distribution to take into account the wind speed variation during one full year. Figure 8 presents the probability of different wind speeds at the left axis. The achieved power is illustrated at the right axis based on the given probability of wind speed occurrence. Based on the collected data from the region under study, the mean wind speed should be considered around 6 meters per second. This figure provides the achieved power magnitudes for the two states of clean and rough conditions if we suitably take into account the distributed probability for our local wind speed. The figure indicates that the annual energy production under rough wind turbine blade condition is about 430 MWh less than the clean condition. In other words, there are about 25 per cents drop in energy production due to a contaminated blade in power generation process.

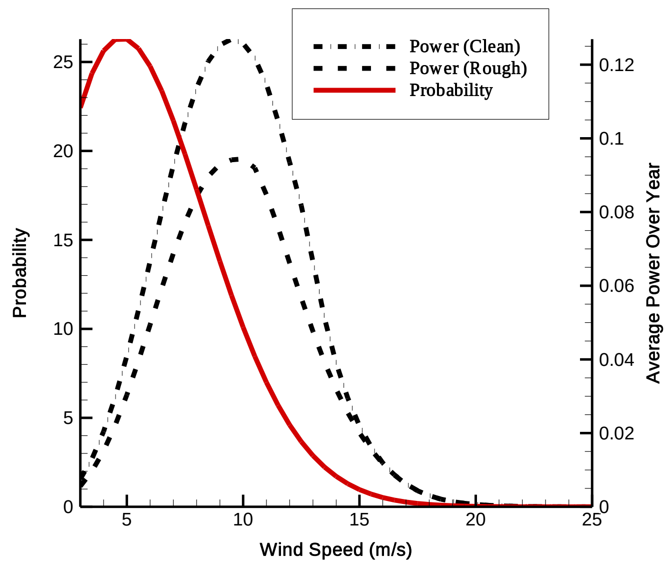

***Figure 8** Weibull distribution and comparing output power between clean and rough blade condition*

CONCLUSION

We performed a mixed analytical-computational procedure to evaluate the effect of blade roughness in its power generation performance. In this regard, we performed several steps with some interesting conclusions, which are briefly described here. Our calculations showed that the wind turbine airfoils' performances would be reduced in rough operations. It was shown that C_{l_α}, the angles of attack at stall condition, and the maximum airfoil lift coefficients are subject to reductions for rough airfoil. Therefore, such reduction in airfoil would subsequently affect the main wind turbine performance as well. In other words, we would expect to have a reduction in performance of the wind turbine. Considering a Weibull probability distribution for the wind speed for the region under study, we found that the annual energy produced by a rough turbine would be 25 percents less than its normal work condition with clean blade. To avoid such reductions, there are some suggestions. First we should choose airfoils with least aerodynamic performance sensitivity to the surface roughness in our wind turbine blade design. Second, it is essential to plan periodical inspections and regular maintenances to maintain *the wind turbine blade performances in clean normal conditions.*

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