AERODYNAMIC MODELING OF WIND TURBINE BLADES AND LINEAR APPROXIMATIONS

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Abstract

In this paper, Blade Element Momentum theory (BEM) is used to design a HAWT blade for a 200 kW wind turbine. The airfoil is Risø, produced by RISØ National Laboratory, Denmark, for a class of 200KW wind turbines. Desirable properties of this airfoil are related to enhancement of aerodynamic and structure interactions. The purpose of this study is to find a simpler linear modification to the shape of blades. Design parameters considered here are wind tip speed ratio, nominal wind speed and diameter of rotor. BEM is used for obtaining maximum lift to drag ratio for each elemental constitution of the blade. Obtaining chord and twist distribution at assumed tip speed ratio of blade, the aerodynamic shape of the blade in every part is specified which correspond to maximum accessible power coefficient. In order to simplify manufacturing of the blades, a linear approximation is employed for both chord and twist distribution. The design parameters are thrust coefficient, power coefficient, angle of attack, angle of relative wind, drag and lift coefficients, axial and angular induction factors. The blade design distributions are presented against rotor radius for BEM results and also compared with the linear approximation.

Keywords: Horizontal axis wind turbine (HAWT); Aerodynamic performance; BEM theory; Blade optimization; Pitch control system.

1. Introduction

In consideration of the pertinent policies such as geographical position, environmental protection and government's tax allowance, many countries proffered huge funds on technology of wind-power electricity generation and so it developed very fast than compare with technology of thermal power. Utilizing of wind energy has been progressed by more than 50 countries in the whole world considerably [1]. Wind turbines have exhibited their ability to sustain whereas wind energy is a clean, raw material-costless, favorable renewable energy. Wind turbine are classified into two configurations based on their rotational rotor axis with respect to the ground: the older generation, lower–power vertical axis (e.g. Savonius and Darrieus rotor) and the higher power, horizontal-axis at wide commercial deployment (e.g. AWE series 54-900, 52-750, Vestas series v39, and v66, and Nordtank-300).

2. Wind Turbine Aerodynamic Design

Recently, focus has been intensified on designing wind turbine rotors for maximum aerodynamic performance [2]. According to particularly challenges and difficulties to achieve a good efficiency and thus in obtaining better economical performance, any improvement in the aerodynamic design of wind turbines infers a significant benefit that increase. Clearly, blade aerodynamic forces that are essential to turbine energy capture produce shaft torque and rotation. Hence more recent studies, is performed on lessening undesirable aerodynamic loads that wind turbines frequently endure during routine service. These high aerodynamic loads compel immoderate stresses on turbine blades and gearboxes, and shorten machine service life considerably [3]. Aerodynamic efficiency of wind turbines extremely depends on the performance of the rotor blade, the airfoil section, and the design form.

The theoretical maximum for the power coefficient, $C_p$, marked by the Betz limit $C_{p\text{max}}=16/27=0.593$. Modern horizontal axis wind turbines (HAWTs) work with $C_p$ up to 0.5, nearly the Betz limit [4]. The blade element momentum (BEM) model is the most common model used in aerodynamic and aero elastic codes for wind turbine performance. Comparison of the BEM model with more accurate induction models implies that mentioned assumption is not exact in positions on the blade with great radial variation of the loading, as e.g. close to the tip and at the root [5]. Another basic deficiency of the BEM model is that it is a steady state model, whereas due to turbulent inflow on wind turbine rotors the loading is dynamic immensely [6].

In addition, developing of accurate non-linear aerodynamic models continually, have demonstrated that state-of-the-art blade element momentum (BEM) models, have their shortcomings in accurately determining three-

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dimensional (3D) flow structures, such as separation, viscosity effects, tip and root vortices, as well as span wise flow[2].

In this paper, Blade Element Momentum theory (BEM) is used to design a HAWT blade for a 200 kW wind turbine. The airfoil is RISO, produced by RISO National Laboratory, Denmark, for a class of 200KW wind turbines. Desirable properties of this airfoil are related to enhancement of aerodynamic and structure interactions. The purpose of this study is to find a simpler linear modification to the shape of blades. Design parameters considered here are wind tip speed ratio, nominal wind speed and diameter of rotor. BEM is used for obtaining maximum lift to drag ratio for each elemental constitution of the blade. Obtaining chord and twist distribution at assumed tip speed ratio of blade, the aerodynamic shape of the blade in every part is specified which correspond to maximum accessible power coefficient. In order to simplify manufacturing of the blades, a linear approximation is employed for both chord and twist distribution. The design parameters are trust coefficients, power coefficient, angle of attack, angle of relative wind, drag and lift coefficients, axial and angular induction factors. The blade design distributions are presented against rotor radius for BEM results and also compared with the linear approximation.

2.1. Choosing Design Parameters

The design of the blade requires a great number of design variables parameters to control rotor shape and airfoil characteristics including: the rotor diameter D, the number of blade B, the chord of sections c, and twist angle θt across the blade and the lift that depend on the angle of attack. However at first the family of airfoil should be specified. Fundamentally, the determination of the rotor size depends on the required energy and blown mean wind speed. As relative wind speed is the resultant of the stream wind speed, blade section speed and rotor induced flow. Lift force is the main force for operating the wind turbine to produce useful power. Thus Maximum lift-to-drag ratio is criterion for choosing the airfoil family.

Airfoils for HAWT is often designed to be used at low attack angle, where the drag coefficient is usually much lower than the lift coefficient. Especially, at blade tip airfoils with high Lift-Drag-Ratio (LDR), low roughness sensitivity, low noise character should be selected to insure the nearest optimum aerodynamic performance. Griffiths [7] showed that the output power is greatly affected by the airfoil lift-to-drag ratio. A general aviation airfoil shape is NACA series, and dedicated airfoil shapes used in modern wind turbines are: S8 series developed by National Renewable Energy Laboratory (NREL) in USA, FFA-W series developed by FOI in Sweden, RISO-A1 series developed by RISO in Denmark, DU series developed by Delfi University of Technology in Netherlands. It has been found in some applications that more than one airfoil shape can be used for the wind turbine blade design, but there will be bending between these airfoils which may add to uncertainties in the design process.

A generalized analysis on manufacturing, industrialization, and costs shows that the obtained chord length and twist angle from the theoretical analysis should be modified. Whereas the chord length and twist angle of the wind turbine’s design are not linear, one procedure for this goal (e.g. simplification in CNC machining for blade’s mold manufacturers) is applying fitted linear relationship on the chord length and twist angle curves separately. For this purpose, a computer code has been prepared in MATLAB program for implementing the developed model on the computer.

First, the required output power from turbine should be specified. The rated wind speed is required to calculate the diameter of rotor. Cp and η are the power coefficient and the electrical-mechanical efficiency, respectively, and are used to estimate the diameter of the rotor. For the design wind turbine power of 200 kW, the maximum allowable generated power is 200 KW; hence the rotor diameter is calculated based on the rated (mean cubic) wind speed which is defined as:

\[
U_{\text{mean_cubic}} = \sqrt[3]{U^3_{\text{hub}} \int_{f_{\text{hub}}} U \, dU}
\]

For Haddadeh region in province of Semnan in Iran, the average wind speed and the corresponding rated wind speed is calculated to be 5.85 and 8, respectively [8].

According to the type of application, we can choose a tip speed ratio, λ. For a water pumping windmill, for which greater torque is needed, we use 1<λ<3. For electric power generation, we normally use 4<λ<10. The machines with higher speeds use less material in the blades and have smaller gearboxes, but require more sophisticated airfoils [9].

It is normally chosen three blades. If fewer than three blades are selected, there will be a number of structural problems that must be considered in the hub design. In this work, we used a better method for selection of λ and Cp. The method uses figures of Cl-α and Cd-α from experiment and approximate by a linear equation in flat regions and a quadratic equation in curve regions. Thus a maximum value for (Cl/Cd) can be obtained that in this case is 143. Choosing B=3, the values λopt and Cp,max can be obtained from the following [9]:

\[
\text{Choosing B=3, the values } \lambda_{\text{opt}} \text{ and } C_{p,\text{max}} \text{ can be obtained.}
\]
\[ C_{p, \text{max}} = \left( \frac{16}{27} \right) \lambda \left[ \frac{1.32 + \left( \frac{\lambda - 8}{20} \right)^2}{B^{2.5}} \right]^{1.5} - \frac{(0.57) \lambda^2}{C_l} \left( \frac{\lambda}{Cd} + \frac{1}{2B} \right) \] (2)

Figure 1 shows a group of \( C_p - \lambda \) curves where optimum values of tip speed ratio, \( \lambda_{\text{opt}} \), correspond to the maximum power coefficient, \( C_p, \text{max} \).

In Figure 1, the RISO-A-24 aerofoil data was used for the maximum lift to drag ratio equals to 143 to obtain the optimum tip speed ratio. The optimal tip speed ratio is obtained to be \( \lambda_{\text{opt}} = 8.9327 \) for the corresponding maximum power coefficient of \( C_p, \text{max} = 0.5183 \). Using the optimum blade shape as a guide, a blade shape, i.e. chord length and twist angle, can be modified for ease of manufacturing and to reduce costs. For ease of fabrication, linear variations of chord and twist may be chosen. For example, if \( a_1, b_1 \), and \( a_2 \), are coefficients for the chosen chord and twist distributions, then the chord and twist can be expressed as [9]:

\[ c_i = a_i r_i + b_i \]

\[ \theta_{T,i} = a_i (R - r_i) \]

3. Results and Discussion

Figure 2 shows that chord length distribution as well as twist angle is bigger at inner sections of blade (near the root) and it is smaller at outer sections of blade. The corrected chord length and twist angle distributions are shown in Figs. 2a, 2b. The chord length of the blade’s root and tip is obviously smaller than the result of the theoretical calculation. Also the twist angles of the blade’s root are smaller than the result of the theoretical calculation. The linear fit cannot be used for the first element due to complex numbers obtained at this point. Twist angle of blade tip is about -5.63 degree in nonlinear state which causes less startup speed. The negative twist angle causes the elements of blade tip had a proper attack angle in startup slow wind speeds. Although in high wind speeds, stall probably occur in blade edge sections. Therefore modification in twist distribution should lead to finding the real attack angle until optimal attack angle can be estimated correctly. In Figure 3a, it can be seen that the angle of relative wind is larger than the optimized theoretical distribution at all parts of the blade especially in sections near the blade root. Favorably, the part of the blade at the tip does not contribute too much to the power.
Figure 3b shows a constant angle of attack, $\alpha$, on full length of the blade with slightly decrease at the tip of blade for the nonlinear blade, while for linear blade this curve has a maximum near the blade root and suddenly decrease up to $r/R=0.225$ and then decrease slightly across the middle sections up to the last elements at the blade tip.

![Figure 3. a) Angle of relative wind; b) Angle of attack.](image)

From Figure 4a, for any angle of attack, $C_l$ is smaller than the theoretical design. As observed at near the root (where $\alpha$ is larger than 10°), $C_l$ drop is very big that cause to be negative. Thus this causes reduction of the mechanical power of the wind turbine. As shown in Figure 4b, where the angle of attack is larger than 10° near the root; therefore, $C_d$ by sequence of linear curve fitting is larger than the design $C_d$.

![Figure 4. a) Lift coefficient; b) Drag coefficient.](image)

In Figure 4b, because of the values of the attack angle is not higher than 10 degrees in the case without linearization, then the drag coefficient curve remain constant at 0.01. Figure 5a shows that the axial induction factor is about 1/3 on most of the blade elements ($0.125<\alpha<0.875$) for the nonlinear blade, deviated near blade tip from $a=1/3$.

![Figure 5. a) Axial induction factor; b) Angular induction factor.](image)

Figure 6a shows the local thrust coefficient, $C_t$, which is constant for the nonlinear blade except at the blade tip that decrease. The deviations are observed in the innermost parts of the linear blade. From $r/R=0.225$ to forward, $C_t$ is slightly decreased to the blade tip. Figure 6b shows comparisons of power coefficient between the theoretical and linear optimized rotors in each section. From the figure, it is seen that the theoretical designed rotor has power coefficient more than the linear optimized rotor.
Referring to Figure 7, it is observed that $C_p$ increases with $\lambda$ up to its optimum value, then it decreases with a quickly rate. As it is expected, maximum power coefficient in nonlinear case is at $\lambda = 8.9327$ that in linear case changes and translates to the left side and causes the total power coefficient is decreased.

According to Figure 8, a third degree polynomial curve as a function of $U$ is obtained (the values of $C_p$ remain constant at maximum points before reaching to $U_{rated}$. The power control regions of wind turbine are shown as a function of wind speeds, its results are shown in Figure 9. Clearly, the primary predicted wind rotor output power at the rated power is about 246 kW, which is larger than the rated power (200 kW) of this HAWT, the difference between values is due to electrical and mechanical losses.

Figure 8 shows the power coefficient versus the rotor rotational speed with linear approximation for chord and twist distributions. This figure for six wind speeds such as 5-10 (m/s) is shown. According to $U_{rated} = 8$ (m/s) and putting it in above equation, $P = 196794.78$ W is obtained (almost equal to rated power of 200 kW, HAWT), namely that more than the mentioned rated speed, the power curve is shown as a constant value which is equal to power 200 kW. It emphasizes correct solution method that is obtained from linear.

Thus, the predicted aerodynamic characteristics of the mentioned 200KW HAWT are reasonable and reliable. Figure 10 shows output power of rotor versus rotor rotational speed with linear chord and twist distributions, with considering mechanical and electrical losses. In this figure, output power of rotor for the case with constant rotational speed and variable speed is shown. One way of obtaining variable speed with an asynchronous generator is to apply a so-called double feed induction generator (DFIG). Some stall and pitch regulated wind turbines using asynchronous generators, in other words running at a fixed rotational speed, therefore have two generators, one which is efficient at lower wind speeds and one which is efficient at higher wind speeds. If another type of generator had been used, one which is able to run at different rotational speeds, the turbine could be operated at the optimum rotational speed for each wind speed, as indicated in Figure 10 by the operational line that intersects all the top points in the curves for the different wind speeds. All points on this line correspond to the highest $C_p$ that can be obtained for the applied pitch angle.

The maximal rotational speed of HAWT can be obtained as $\Omega_{max} = 78/R = 3.39$ rad/s ($\omega_{max} = 32.38$ rev/min). By considering the behavior of DFIG it is supposed that $\omega_{max}/\omega_{min}$ is 2.2, and therefore the lowest rotor rotation speed
is $\omega_{\text{min}}=14.72\ \text{rev/min}$ and $\Omega_{\text{min}}=1.54\ \text{rad/s}$. Also the maximal design wind speed is $V_{\text{max}}=78/\lambda D=8.73\ \text{m/s}$ and the minimum design wind speed is $V_{\text{min}}=\Omega_{\text{min}}R/\lambda D=3.97\ \text{m/s}$. Between $V_{\text{max}}$ and $V_{\text{min}}$ HAWT operates at optimum design point. Therefore in this case the turbine is equipped with an asynchronous generator forcing the blades to rotate at the constant $\omega_{\text{max}}= 32.38\ \text{r/min}$, indicated by the vertical line. It is seen that the turbine is running most efficiently at a wind speed higher than rated wind speed. As mentioned above, due to noise emission, the tip speed is limited to approximately 78m/s.

![Figure 9. Power curve of the linearized blades 200 KW wind turbine](image1)

![Figure 10. Output power versus rotational speed (Constant rotational speed and variable speed control system)](image2)

4. Conclusion

The purpose of this study is to find an optimized aerodynamic design method based on BEM method which maintains ease of manufacturing. Design parameters considered here are wind tip speed ratio, nominal wind speed and diameter of rotor. BEM is used for obtaining maximum lift to drag ratio for each elemental constitution of the blade. Also in this paper, tip speed ratio (TSR) choosing for HAWT was investigated from another viewpoint. The overall power coefficient $C_P$ reached a value of slightly above 0.49 whereas in design with linear blades is merely obtained the value of 0.36. More results have indicated that a considerable reduction in the power output occurs when the linear simplified aerodynamic design is used to decrease manufacturing costs. Also in this study the pitch control system was used that is the most common methods to control the generated wind turbine rotor power and the corresponding annual power generation for the province of Semnan using a simplified linear rotor was evaluated.

References