Optimization of Small Scale Wind Turbine Blades for Low Speed Conditions

Mohammadreza Mohammadi, Alireza Mohammadi, Moona Mohammadi, and Hamid Neisi Minaei

Abstract—This paper proposes a new optimization method for blades of 4 small scale wind turbines including 5 KW, 10KW, 15KW and 20 KW wind turbines while objective function is maximum output torque. This optimization process is performed assuming a constant wind speed of 7 m/s which is classified as low speed condition. In this research based on a primary design, the blade is divided into three sections and best airfoils with optimum attack angles are determined while chord distribution, relative wind angle distribution, blade length and number of blades are considered constant. Results show that using this new optimization method can increase the output torque up to 19.5 percent.

Index Terms—Genetic algorithm, optimization, turbine blade, wind turbine.

I. INTRODUCTION

Nowadays Wind turbine industry is becoming one of the best choices for energy production among all renewable energy choices. In recent years this industry have been much more interesting than hydropower industry which has a huge environmental effects. In financial aspect, wind industry shows a very dramatic progress which is expected to compete with fossil fuel energy generation in following years [1].

Regarding the importance of turbine blade in its energy generation lots of researches have been developed to make the blade more efficient. Nicolette Arnalda Cencelli optimized a designed blade. In this research some airfoils were designed by Xfoil software for different sections. Results showed new airfoils can increase the output power [2].

Liu et al. and Xudong et al. worked on rotor blade chord and twist distributions. BEM analysis and CFD methods were used to determine the effect of design changes [3], [4].

Ozge Polat and Ismail H. Tuncer worked on aerodynamic shape optimization based on Genetic Algorithm and Blade Element Momentum theory. Optimization studies were performed to maximize power production of specific wind speed, rotor speed, and rotor diameter. In this research, XFOIL was used to provide sectional aerodynamic loads [5].

Pourrajabian et al. worked on the influence of the air density variation with altitude on the performance of a small horizontal axis wind turbine blade [6].

Sharifi and Nobari optimized pitch angle, along wind turbine blade, based on an aerodynamic code. This aerodynamic code could accurately predict the aerodynamics of horizontal axis wind turbines [7].

II. BLADE DESIGN THEORIES

Some theories have been developed for horizontal axis wind turbine blade design and performance prediction known as Blade Element theory, Momentum theory and Blade Element Momentum (BEM) theory.

Blade Element Momentum theory combines Momentum theory and Blade Element theory to calculate the blade shape and to predict the performance parameters of the rotor for ideal and steady operating conditions.

In Blade Element Momentum theory \( \lambda_r \) is defined as local tip speed ratio and calculated as equation 1:

\[
\lambda_r = \frac{r \Omega}{U}
\]  

where \( r \) is local blade radius, \( \Omega \) is blade angular velocity and \( U \) is stream velocity. Tip velocity ratio (\( \lambda \)) is defined as tip velocity to stream velocity ratio (equation 2). Tip velocity ratio is selected based on turbine performance condition and for \( \lambda \leq 10 \) and three bladed turbine, the best performance will be obtained [8], [9]. According to equation 3 angle of relative wind angle with rotation plane can be obtained.

\[
(\lambda_r)_i = \lambda \frac{r_i}{R}
\]  

\[
\phi_i = 2 \tan^{-1} \left( \frac{1}{(\lambda_r)_i} \right)
\]  

Chord distribution in each section of the blade can be obtained from equation 4:

\[
C_i = \frac{8\pi r_i}{BC_{design}} (1-\cos(\phi_i))
\]  

Pitch angle of blade chord in each section can be obtained from equation 5:
\( (\theta_p)_i = \phi_i - (\alpha_{\text{design}})_i \) \hspace{1cm} (5)

Finally axial induction factor and Angular induction factor can be obtained from equations 6 and 7.

\[
a = \frac{1}{4 \sin^2(\phi)} \frac{1}{1 + \frac{\sigma'_{\text{design}} C_L \cos(\phi)}{4}}
\]

\[
a' = \frac{1 - 3a}{4a - 1}
\]

where

\[
(\sigma')_{\text{design}} = \frac{Bc_i}{2\pi r}
\]

In equations 1 to 8 \( i \) is number of each blade section. These equations suggest primary design of the blade while tip loss effect is not considered so for final design, equations 9 to 15 should be passed.

\[
\phi_i = \tan^{-1}\left(\frac{U(1-a)}{\Omega r(1+a')}\right) = \tan^{-1}\left(\frac{(1-a)}{\lambda_r(1+a')}\right)
\]

Regarding obtained \( \phi_i \) from equation 9 attack angle is recalculated.

\[
\alpha_i = \phi_i - (\theta_p)_i
\]

In equation 10 the value of \( (\theta_p)_i \) is obtained from equation 5.

Tip loss effect can be calculated from equation 11 and would be applied in equations 13, 14 and 15.

\[
F = \frac{2}{\pi} \cos^{-1}\left(\exp\left(-\frac{B}{2 (1-R)}\right)\right)
\]

Thrust force coefficient can be obtained from equation 12.

\[
C_T = \frac{(1-a)^2 \left(C_L \cos(\phi) + C_D \sin(\phi)\right)}{\sin^2(\phi)}
\]

In equation 12 if \( C_T < 0.96 \) then:

\[
a = \frac{1}{F} \left[0.143 + \sqrt{0.203 - 0.6427 (0.889 - C_T)}\right]
\]

New Angular induction factor will be obtained from equation 15.

\[
a' = \frac{1}{4F \cos(\phi)} \frac{1}{\sigma'_{C_L} - 1}
\]

In equation 12 to 15 \( \sigma'_{C_L} \) can be obtained from equation 16.

\[
\sigma'_{C_L} = \frac{Bc_i}{2\pi r}
\]

New axial and angular induction factors will be used to recalculation of parameters and this loop will continue until the difference of two frequent values of axial induction factors and difference of two frequent values of angular induction factors become less than a certain amount and reaches to a certain accuracy.

III. PRIMARY DESIGN

Rotor radius for each turbine blade can be calculated by equation 17.

\[
P = \frac{1}{2} \rho \pi R^2 U^3 C_p \eta_m \eta_s
\]

where \( P_r \) is output power, \( R \) is rotor diameter (m), \( \rho \) is air density (1.225kg/m\(^2\)), \( U \) is relative wind velocity (7m/s), \( C_p \) is power coefficient (0.47), \( \eta_m \) is mechanical efficiency (0.9) and \( \eta_s \) is Transition coefficient (0.9).

According to equation (17), 5KW, 10 KW, 15KW and 20KW turbine blade would have 4.5m, 6.5 m, 8m and 9m blade radius for this wind condition respectively. This wind speed (7m/s) is average speed of many windy sites in low speed countries such as South Africa and Iran.

Different airfoils have been designed for wind turbines while each one has its own special aerodynamic properties and generated power. NACA 63-215 series airfoil have been used in many modern horizontal axis wind turbines [10] so primary design was performed assuming this airfoil for all the blade span. Fig. 1 shows One meter profiles NACA 63-215 [11].

![Fig. 1. One meter profiles NACA 63-215 [11].](image)
IV. IMPLEMENTATION OF OPTIMIZATION

Analytical optimization process was used to find optimum airfoils and attack angles using a written code in MATLAB. In this code Blade Element Momentum analysis was used to select best airfoils with optimum attack angles.

In this research, airfoil type and attack angle are optimization variables while chord distribution, relative wind angle distribution, blade length and number of blades considered as constants. Table I shows optimization problem briefly.

Three sections of blade were considered: root, mid and tip. Root of the blade is considered at 20% of the blade. Selected section for optimization is middle of the root. The second part of the blade is mid which is between root and tip; selected section in this part is middle of the blade (50% of blade radius). The third part is tip which is 5% of blade end.

TABLE I: OPTIMIZATION PROBLEM DEFINITION

<table>
<thead>
<tr>
<th>Objective Function</th>
<th>Output torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variables</td>
<td>Attack Angle, Airfoil type</td>
</tr>
<tr>
<td></td>
<td>0-12 degrees</td>
</tr>
<tr>
<td>Constants</td>
<td>Turbine Diameter, Number of blades, chord length, relative wind angle</td>
</tr>
</tbody>
</table>

Airfoils are selected from Table II. These airfoils were designed and used for wind turbine blade [12]-[16].

TABLE II: AIRFOIL DATA BASE

<table>
<thead>
<tr>
<th>No.</th>
<th>Airfoil Type</th>
<th>Section</th>
<th>Chord (m)</th>
<th>Relative Wind Angle (°)</th>
<th>Attack Angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NACA 63-215</td>
<td>1st</td>
<td>0.45</td>
<td>2.25</td>
<td>4.38</td>
</tr>
<tr>
<td>2</td>
<td>NACA 63-218</td>
<td>2nd</td>
<td>0.65</td>
<td>3.25</td>
<td>6.33</td>
</tr>
<tr>
<td>3</td>
<td>NACA 63-221</td>
<td>3rd</td>
<td>0.8</td>
<td>4</td>
<td>7.8</td>
</tr>
<tr>
<td>4</td>
<td>NACA 63-415</td>
<td></td>
<td>0.8</td>
<td>4</td>
<td>7.8</td>
</tr>
<tr>
<td>5</td>
<td>NACA 63-418</td>
<td></td>
<td>0.9</td>
<td>4.5</td>
<td>8.77</td>
</tr>
</tbody>
</table>

V. RESULTS

TABLE III: RESULTS OF FOUR WIND TURBINE BLADES OPTIMIZATION

<table>
<thead>
<tr>
<th>Section radius for</th>
<th>First section</th>
<th>Second section</th>
<th>Third section</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5 m blade</td>
<td>0.45</td>
<td>2.25</td>
<td>4.38</td>
</tr>
<tr>
<td>6.5 m blade</td>
<td>0.65</td>
<td>3.25</td>
<td>6.33</td>
</tr>
<tr>
<td>8 m blade</td>
<td>0.8</td>
<td>4</td>
<td>7.3</td>
</tr>
<tr>
<td>9 m blade</td>
<td>0.9</td>
<td>4.5</td>
<td>8.77</td>
</tr>
</tbody>
</table>

Optimization results show for three sections all considered small scale turbine blades, for all three sections, FX 66-S-196 v1 was selected while attack angle was 8 degree (shown in Table III).

Total amount of torque increase is shown in Table IV.

TABLE IV: COMPARISON OF OPTIMIZED BLADE WITH THE PRIMARY DESIGN

<table>
<thead>
<tr>
<th>Blade Length</th>
<th>Output torque in Primary Design</th>
<th>Output torque in optimized blade</th>
<th>Increase percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5 m blade</td>
<td>414.34</td>
<td>446.45</td>
<td>7.7</td>
</tr>
<tr>
<td>6.5 m blade</td>
<td>1262.7</td>
<td>1448.1</td>
<td>14.6</td>
</tr>
<tr>
<td>8 m blade</td>
<td>2373.4</td>
<td>2800</td>
<td>17.9</td>
</tr>
<tr>
<td>9 m blade</td>
<td>3397.5</td>
<td>4059.7</td>
<td>19.5</td>
</tr>
</tbody>
</table>

VI. CONCLUSION

In this paper four small scale wind turbines were optimized. Design and optimization was performed for conditions where average wind velocity is lower than International wind energy market. This different condition causes different design parameters distribution in same output power. Reynolds number across the blade will be different too. Regarding many windy sites in considered low speed countries like Iran, South Africa etc. have average wind speed of 7m/s, this research is based on this velocity.

In this paper three sections in root, mid and tip of the blade were considered. The reason of different section selection was different conditions in root, mid and tip of the blade like Reynolds number, relative wind angle, axial induction factor etc. Considering airfoils designed for wind turbines, the best airfoils with the best attack angles were selected for each section.

This research showed despite three sections were selected across the blade, just one airfoil and one attack angle were selected for all sections. Comparing blades of different turbines shows this results is deduced in all of them.

Although this result may not be satisfying at the first time, comparing these information with results of optimization of medium scale wind turbine blades [17], [18] with exactly same sectioning method where three different airfoils were selected across the blade shows in small scale blades and in assumed wind condition, blades are not long enough to have various condition across the blade. In other words primary condition such as Reynolds number and axial induction factor do not cause of different airfoil selection while in previous studies of medium scale turbines [17], [18] regarding considered blade radiiuses were up to 20 m different airfoils were selected for each section.

These results also show FX 66-S-196 v1 is a very suitable airfoil for small scale blades for low speed condition for all root, mid and tip of the blade.

REFERENCES

Mohammadreza Mohammadi was born in 1987 in Ahvaz, Iran. He got his bachelor degree of mechanical engineering from IAU Ahvaz, Iran in 2005 and received his master degree of mechanical engineering from University of Sistan and Baluchestan, Iran, in February 2014. Since Dec. 2013, he has been with the Iranian National Company as an expert of hydro power turbine, Ahvaz, Iran since 2005. In recent years, he has 12 publications in conferences and journals and her research activity is governor of hydro power turbines. Some of her published papers are: 1). Analysis of cooling air jet and air distributor in a co-current spray dryer, published in Iranian Journal of Science and Technology, 2009. 2). Simulation of spray dryer with cooling air jet and air disposer by computational fluid dynamics, published in 13th International Heat Transfer Conference, Sydney, Australia, 2006. 3). Optimizing hydro power turbines in order to secure the passage of fishes in Khuzestan province, published in the Journal of Applied and Computational Mechanics, 2014. 4). Optimizing of 60 KW wind turbine blade using genetic algorithm, published in the 3rd International Conference on Emerging Trends in Energy Conservation-ETEC 2014, Tehran, Iran. 5). Optimizing heat exchanger in order to secure the passage of fishes in Khuzestan province, published in the 22nd Annual International Conference on Mechanical Engineering, Shahid Chamran University of Ahvaz, Mechanical Engineering, April 2014, Ahvaz, Iran.

Moona Mohammadi was born in 1976 in Abadan, Iran. She got her bachelor degree of mechanical engineering from the Tehran University of Science and Technology and her master degree of mechanical engineering from Shiraz University. She has been with the Koueztan Water & Power Authority (KWPA) as an expert of hydro power turbine, Ahvaz, Iran since 2005. In recent years, she has 12 publications in conferences and journals and her research activity is governor of hydro power turbines. Some of her published papers are: 1). Analysis of cooling air jet and air distributor in a co-current spray dryer, published in Iranian Journal of Science and Technology, 2009. 2). Simulation of spray dryer with cooling air jet and air disposer by computational fluid dynamics, published in 13th International Heat Transfer Conference, Sydney, Australia, 2006. 3). Optimizing hydro power turbines in order to secure the passage of fishes in Khuzestan province, published in the Journal of Applied and Computational Mechanics, 2014.