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Optimization of Small Scale Wind Turbine Blades for Low Speed Conditions

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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 λ_r is defined as local tip speed ratio and calculated as equation 1:

$$\lambda_r = \frac{r\,\Omega}{U} \tag{1}$$

where r is local blade radius, Ω is blade angular velocity and U is stream velocity. Tip velocity ratio (λ) is defined as tip velocity to stream velocity ratio (equation 2). Tip velocity ratio is selected based on turbine performance condition and for λ =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.

$$(\lambda_r)_i = \lambda \frac{r_i}{R} \tag{2}$$

$$\phi_i = \frac{2}{3}\tan^{-1}\left(\frac{1}{(\lambda_r)_i}\right) \tag{3}$$

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

$$C_i = \frac{8\pi r_i}{BC_{L\text{design}}}\left(1-\cos(\phi_i)\right) \tag{4}$$

Pitch angle of blade chord in each section can be obtained from equation 5:

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$$(\theta_p)_i = \phi_i - (\alpha_{\text{design}})_i \tag{5}$$

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

$$a = \frac{1}{1 + \frac{4\sin^2(\phi)}{\sigma'_{\text{design}} C_{L\,\text{design}} \cos(\phi)}} \tag{6}$$

$$a' = \frac{1-3a}{4a-1} \tag{7}$$

where

$$(\sigma')_{\text{design}} = \frac{Bc_i}{2\pi r} \tag{8}$$

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.

$$\phi_i = \tan^{-1}\left(\frac{U(1-a)}{\Omega r(1+a')}\right) = \tan^{-1}\left(\frac{(1-a)}{\lambda_r(1+a')}\right) \tag{9}$$

Regarding obtained ϕ_i from equation 9 attack angle is recalculated.

$$\alpha_i = \phi_i - (\theta_p)_i \tag{10}$$

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.

$$F = \frac{2}{\pi}\cos^{-1}\left(\exp\left(-\frac{\frac{B}{2}(1-\frac{r}{R})}{\frac{r}{R}\sin(\phi)}\right)\right) \tag{11}$$

Thrust force coefficient can be obtained from equation 12.

$$C_T = \frac{\sigma'(1-a)^2(C_L\cos(\phi) + C_d\sin(\phi))}{\sin^2(\phi)} \tag{12}$$

In equation 12 if $C_T < 0.96$ then:

$$a = \frac{1}{1 + \frac{4F\sin^2(\phi)}{\sigma'_i C_L \cos(\phi)}} \tag{13}$$

And if $C_T > 0.96$:

$$a = \frac{1}{F}\left[0.143 + \sqrt{.0203 - 0.6427(0.889 - C_T)}\right] \tag{14}$$

New Angular induction factor will be obtained from equation 15.

$$a' = \frac{1}{\frac{4F\cos\phi}{\sigma'_i C_L} - 1} \tag{15}$$

In equation 12 to 15 σ'_i can be obtained from equation 16.

$$\sigma'_i = \frac{Bc_i}{2\pi r} \tag{16}$$

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.

$$P = \frac{1}{2}\rho\pi R^2 U^3 C_p \eta_m \eta_g \tag{17}$$

where P_e is output power, R is rotor diameter (m), ρ is air density (1.225kg/m^2), U is relative wind velocity (7m/s), C_p is power coefficient (0.47), η_m is mechanical efficiency (0.9) and η_g 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].

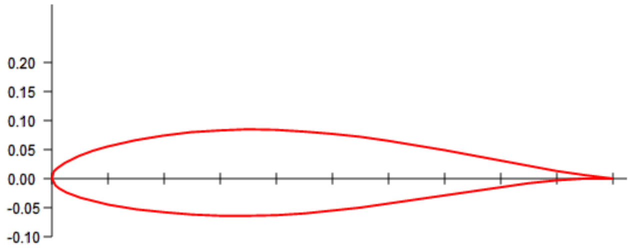

Fig. 1. One meter profiles NACA 63-215 [11].

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

Objctive Function	Output torque
Variables	Attack Angle , Airfoil type
Attack angle range	0-12 degrees
Constants	Turbine Diameter, Number of blades,chord length, relative wind angle

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

TABLE II: Airfoil Data Base

1	NACA 63-215	24	FX 61-168
2	NACA 63-218	25	FX 61-184
3	NACA 63-221	26	FX 38-153
4	NACA 63-415	27	FX 66-S-161
5	NACA 63-418	28	FX 66-S-196
6	NACA 63-421	29	FX 66-S-196 V1
7	NACA 64-415	30	FX 66-17A-17
8	NACA 64-421	31	FX 66-17AII-182
9	NACA 65-415	32	NACA 4415
10	NACA 65-421	33	NACA 4412
11	FX S 02/1-158	34	S814
12	FX S 03-182	35	S809
13	FX S 02-196	36	E387
14	FX 60-126/1	37	SD2030
15	FX 60-157	38	S822
16	FX 60-177	39	S834
17	FX 63-137	40	SG6043
18	FX 63-143	41	SG6040
19	FX 63-145	42	SG6041
20	FX 63-147	43	SG6042
21	FX 63-158		
22	FX 61-147		
23	FX 61-163		

V. Results

TABLE III: Results of Four Wind Turbine Blades Optimization

	First section	Second section	Third section
Section radius for 4.5m blade	0.45	2.25	4.38
Section radius for 6.5m blade	0.65	3.25	6.33
Section radius for 8m blade	0.8	4	7.8
Section radius for 9m blade	0.9	4.5	8.77
Optimized airfoil	FX 66-S-196 v1	FX 66-S-196 v1	FX 66-S-196 v1
Optimized attack angle (degree)	8	8	8

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

	Output torque in Primary design	Output torque in optimized blade	Increase percentage
4.5 m blade	414.34	446.45	7.7
6.5m blade	1262.7	1448.1	14.6
8m blade	2373.4	2800	17.9
9m blade	3397.5	4059.7	19.5

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 radiuses 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.

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