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Design and Analysis of Shrouded Small-Scale Wind Turbine for Low Wind Speeds

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Abstract. This work presents design and analysis of a shrouded small scale wind turbine optimized for extremely low wind speeds. In-house FORTRAN code based on Glauert's method are used for preliminary design. QBlade and CFD are used for iterative optimization. Results show that power output can be increased 1.5-2.5 times by using shroud. Additionally, using shroud and optimizing for low wind speed solves starting problem that small scale wind turbines have considerably and increases sustainability of power production.

1. Introduction

Large scale wind turbines are installed at where there are feasible wind conditions. Small scale wind turbines are usually used on parks, suburban houses or in general places where there is no electrical grid(off-grid) or have grid electricity sustainability problems irrespective of wind conditions. Electricity output should be as much sustainable as possible for off-grid applications. Therefore, wind turbines for off-grid applications should be optimized for low wind speed so that electric is sustainable by lowest possible cut-in and rated speed. For preliminary design, needs for typical off-grid application is studied and it is selected as 500W. Rotor and shroud design is studied iteratively.

2. Preliminary Rotor Design

Wind speed at rated condition is selected as 5.5 m/s according to Turkey's average wind speed map [1]. Shroud is capable of accelerating incoming flow by 1.2-1.8 times [2]. Therefore, flow speed at throat section is assumed as 8 m/s. Power coefficient is assumed a typical value for small scale wind turbines as 0.40 [3]. By using power formula, equation (1), and assumed parameters, blade radius is estimated as 0.57m.

$$P = \frac{1}{2}\rho A U^3 C_P \tag{1}$$

Tip speed ratio is found by using equation (2);

$$\lambda = \frac{2\pi(RPM)\mathrm{R}}{60U} \tag{2}$$

Equation (2) needs RPM, radius and wind speed as input. RPM is selected by turbine-generator matching where Ginlong-PMG-500 is selected as the generator to be used for preliminary design. Its rated RPM is 450 and maximum RPM is about 550 [4]. Radius is estimated from equation (1) and wind speed is assumed from location.

Solidity is very important parameter especially for starting characteristic. Number of blades is selected by determining proper solidity which is found by following solidity formula, equation (3).

$$\sigma = \frac{c * B}{2 * \pi * r} \rightarrow \frac{r}{c} = \frac{B}{2 * \pi * \sigma} \tag{3}$$

Increasing solidity from the conventional 5%-7% to a range of 15%-25% yields higher power coefficient for small scale wind turbine with low TSR [5]. After trying different blade number, radius, chord and solidity combinations, blade number is selected as 5.

Proper airfoil for preliminary design is selected considering Reynold's number at rated conditions.

$$Re = \frac{\rho * U * L}{\mu} \tag{4}$$

Reynold's number is found to be about 200,000 from equation (4). Therefore, airfoils that feasible for Reynold's number between 100,000-500,000 are studied, i.e. low Reynold's number airfoils.

Table 1. Some Low Reynold's number airfoil family specifications.

Airfoil	C_{lmax} @ α	Max C_l / C_d @ α	Max Thickness @ XX x/c	Max Camber @ XX x/c
NACA 63-415	1.34@15	75.6 @ 7.25	%15 @ %34.90	%2.21 @ %50
NACA 63-412	1.26@11	77.24 @ 5.75	%12 @ %34.90	%2.2 @ %50
NREL S803	1.49@13.5	89.49 @ 6.5	%11.49 @ %36.7	%3.68 @ %46.80
SG 6040	1.36@18.25	72.93 @7.75	%16 @ %35.52	%2.5 @ %60.41

For large scale wind turbine, since Reynold's number is varying much along the blade, different type of airfoils is used along the blade. There are structural issues at root region for large scale turbines, so thicker airfoils are used at root. Additionally, tip speed is high because of long blades, thinner airfoils are used at tip sections to have low drag. Overall, high Reynolds number, thin airfoils, are used at tip and mid-low Reynolds number, thick airfoils, are used at root. However, small scale wind turbines do not have these issues. Hence, only 1 airfoil along blade is enough. Additionally, using only 1 airfoil with twisted blade lowers manufacturing costs. After studying on low Reynold's number airfoils, NACA 63-415 is selected to be worked with.

Having all the basic parameters for preliminary design, optimum chord and twist distribution is found. In-house FORTRAN code is developed that uses Glauert's optimum rotor theory with tip wake loss included. The code uses TSR, radius of blade, root section starting point (hub radius), number of sections to divide blade, airfoil's lift coefficient at specified angle of attack and blade number as input. It gives optimum twist and chord distribution along blade at divided elements of blade. Hub radius is selected as considering generator's geometry. QBlade is used to get rotor performance simulations. QBlade [6] is an open-source software that have many tools including rotor simulation by using Blade Element Momentum theory(BEM) which is commonly used model for preliminary design of wind turbines. Preliminary design is studied by turbine BEM simulation.

3 different blades with design tip speed ratio 3,5 and 7 are created by using the FORTRAN code.

Figure 1. TSR 3 optimized

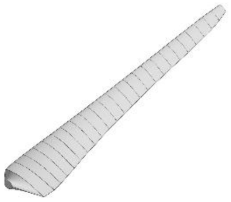


Figure 2. TSR 5 optimized

Figure 3. TSR 7 optimized

These 3 configurations are examined by using Rotor BEM Simulation and Turbine BEM Simulation in QBlade.

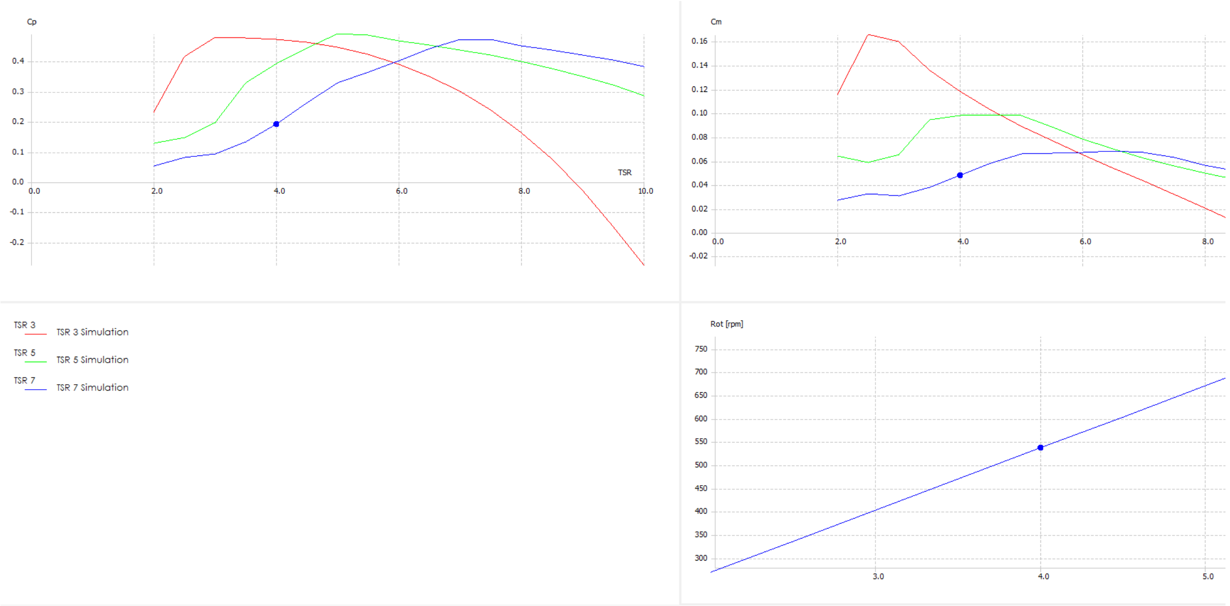
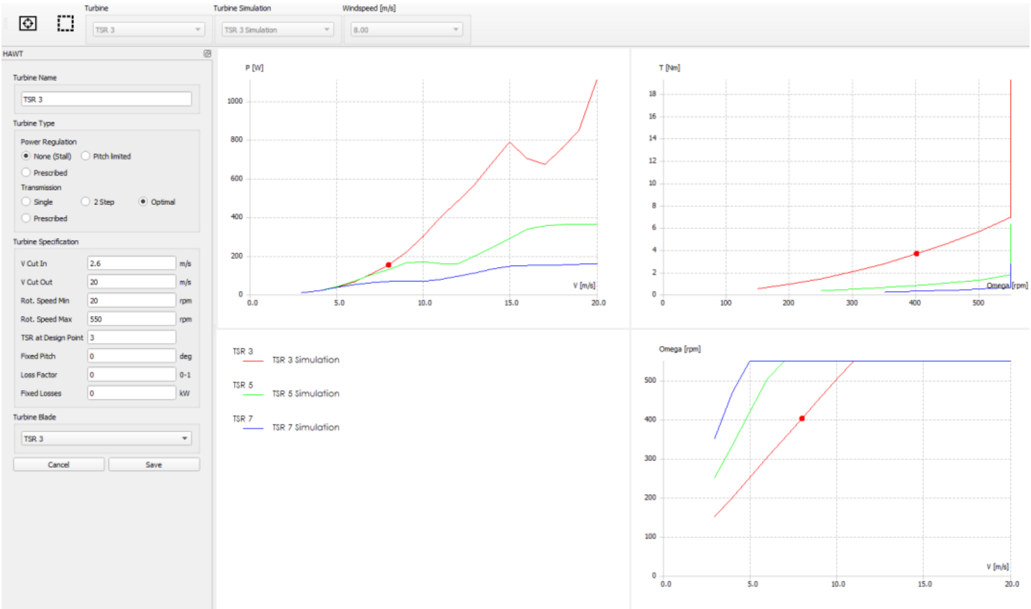


Figure 4. QBlade Rotor BEM Simulation Results

Small scale wind turbines have low radius blades, so moment arm is small. Additionally, due to low Reynold's number characteristics of blades, aerodynamic performance is not so fine. Also, if designer wants to not use gearbox to regulate torque, because gearbox increases cost, complexity and losses, there will be very limited torque especially at extremely low wind speeds. Therefore, the bottleneck of small scale wind turbines that using direct drive technology is producing enough torque at low wind speeds to start and maintain generator rotation. To have continues energy production is important especially for off-grid applications which is the main field that small scale wind turbines are used. Therefore, designer should concern more about turbine-generator matching at low wind speeds and low RPMs even more than at rated point of generator.

As we can see from Figure 4, C_{p-max} are about the same for all 3 blades, however peak points are different that TSR 3 optimized blade peaks at lower TSR then TSR 5 and TSR 7 blade as expected. Considering selected generator's maximum RPM, RPM vs TSR curve at 8 m/s wind speed reveals that maximum TSR can be achieved for this condition is about 4. It should be noted that maximizing RPM at this low wind speed, 8 m/s, is not the objective but somehow defining design limits and gain intuition about different TSR characteristics. C_m performance of TSR 3 optimized blade is superior than others at low TSR.



Turbine: TSR 3
Turbine Simulation: TSR 3 Simulation
Windspeed [m/s]: 8.00

HAWT

Turbine Name: TSR 3

Turbine Type

Power Regulation
● None (Stall) ○ Pitch limited
○ Prescribed

Transmission
○ Single ○ 2 Step ● Optimal
○ Prescribed

Turbine Specification

V Cut In	2.6	m/s
V Cut Out	20	m/s
Rot. Speed Min	20	rpm
Rot. Speed Max	550	rpm
TSR at Design Point	3	
Fixed Pitch	0	deg
Loss Factor	0	0-1
Fixed Losses	0	kW

Turbine Blade: TSR 3

Figure 5. QBlade Turbine BEM Simulation Results

Figure 5 is obtained from QBlade Turbine BEM Simulation. Stall type power regulation and Optimal type transmission is selected. Other inputs of the simulation can be seen on the figure. Simulation is conducted wind speed between 1 m/s and 20 m/s with increment of 0.25. As we can see clearly, low TSR optimized design has more power and torque production.

3. Shroud Design

In literature, there are cases that airfoil geometry is used for shroud cross-section [7]. However, it increases manufacturing cost and complexity with very little gain which is not a desired feature especially for small scale wind turbines. Therefore, curvilinear segments are used. Shroud geometry formed of mainly 3 components; converging duct, diverging duct and flange. Geometry is defined with 8 design parameters.

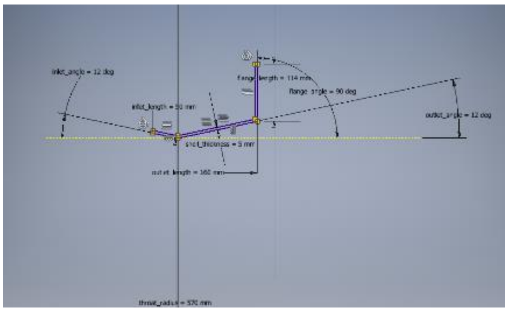


Figure 6. Shroud defining variables

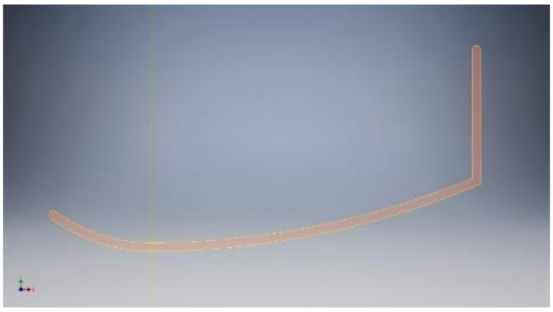


Figure 7. Smoothed geometry concept

Different configurations are formed and some of the duct geometries are smoothed using mathematical functions. This turbine prototype will be tested in a local wind tunnel. Total shroud diameter, L, will be equal to 1.4m due to limited local wind tunnel maximum specimen size. Firstly, different configurations of shroud geometry is analyzed in 2D. Following solution domain, Figure 8, is created with boundary conditions of 8 m/s normal velocity at inlet, slip/symmetry at bottom and 0-gauge pressure at outlet. Mesh independent study is conducted and 110k mesh is used for analysis. Incompressible flow assumption with SST k-omega turbulence model is used for analysis.

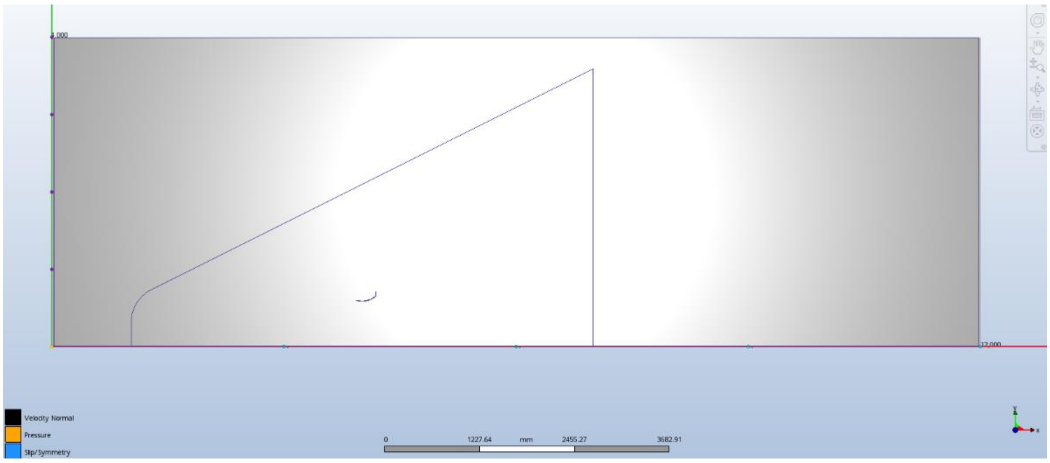


Figure 8. Shroud 2D analysis solution domain

Different configurations are examined in analysis. Some of the velocity contours are shown as an example.

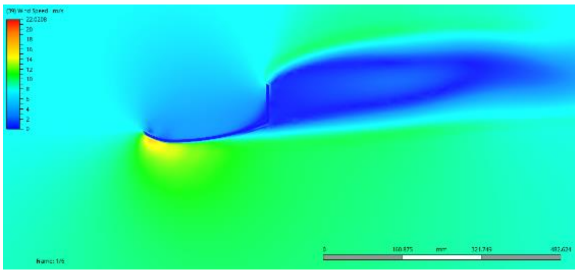


Figure 9. Velocity contour for configuration 1

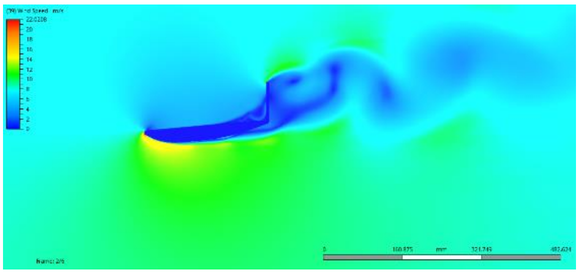


Figure 10. Velocity contour for configuration 2

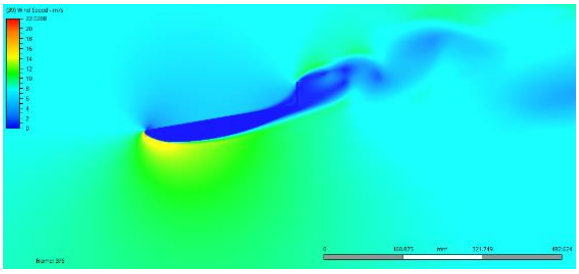


Figure 11. Velocity contour for configuration 3

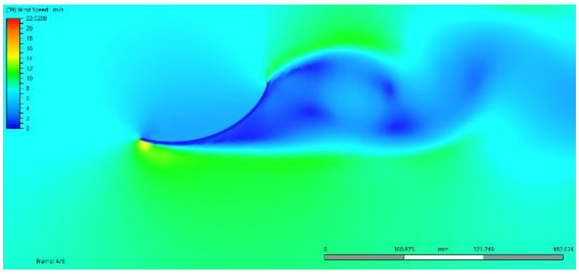


Figure 12 Velocity contour for configuration 4

Average velocity at throat section to inlet velocity ratio is found for different configurations. The design that have highest average velocity ratio is selected which is found to be about 1.3.

3D analysis is conducted to verify 2D analysis result with highest velocity ratio configuration. Solution domain is defined with cylindrical geometries as such.

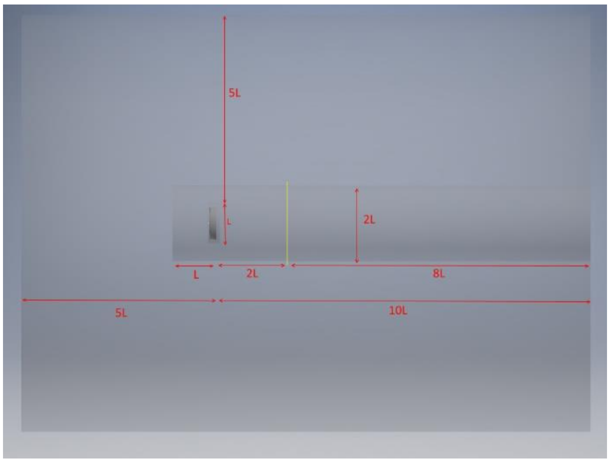


Figure 13. Shroud 3D analysis solution domain

Total length of the domain is 15L, 5L is to front and 10L to back. Total diameter is 11L, 5L to each side. There are 3 different regions defined for refining mesh. First one just covers the shroud geometry. Second one with length of 3L, 1L to front and 2L to back, and diameter of 2L. Third one is to capture wake region accurately, length of 8L and diameter of 2L. Totally, about 800k grid element is constructed. Boundary conditions of 8,12,20 m/s normal velocity at inlet, slip/symmetry at bottom and 0-gauge pressure at outlet is applied. Incompressible flow assumption with SST k-omega turbulence model is used for analysis. Velocity contour for 12 m/s case is shown in Figure 14.

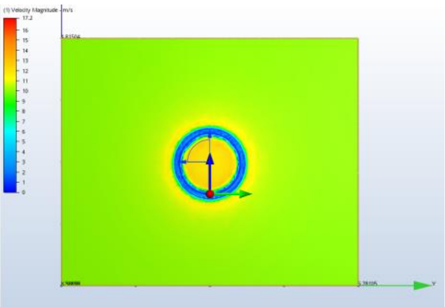


Figure 14. Shroud 3D analysis velocity contour 12 m/s

Velocity increase ratio is verified to be 1.3. This value is reasonable among this type of shrouds.

4. Conclusion

In this paper, small scale wind turbine design and analysis methodology is studied. Glauert optimization method is used for the rotor and analysis is conducted by QBlade software that uses Blade Element Momentum theory. It is shown that low tip speed ratio optimized design is capable of producing more power and torque than others especially at extremely low wind speeds. 2D and 3D shroud design concepts are analyzed using CFD tools. Different shroud configurations are compared by their velocity increase ratio at throat section. And it is found that 1.3 velocity increase ratio is achievable which means about 2.2 times power augmentation from the turbine.

Authors want to note that further investigations and validations are needed for low tip speed ratio optimized rotor characteristics and rotor-shroud interactions.

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