Numerical Study of Giromill-Type Wind Turbines with Symmetrical and Non-symmetrical Airfoils

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ABSTRACT

The vertical axis wind turbines (VAWTs) are the simple type of wind turbines to convert wind energy into electricity or mechanical output. Unlike horizontal axis wind turbines (HAWTs), the VAWT can be effectively used in urban areas where wind has characteristics of unsteadiness with turbulence. Blade aerodynamics in VAWT has significant effect on turbine efficiency. Numerical study of three-bladed fixed pitch giromill-type VAWT aerodynamic performance has been presented in this study. Two different solidities (0.2 and 0.4) are considered with symmetrical and unsymmetrical airfoils at wind velocities of 3 m/s and 5 m/s. The NACA0018, NACA0015 and S1210 airfoils were selected. To predict and analyze flow around turbine blades, an overlapping moving grids technique is employed. It is observed that for the cases with solidity of 0.2, the power coefficient of NACA0018 and S1210 are close to theoretical analysis at the wind velocity of 3 m/s and 5 m/s. The maximum efficiency of the modeled airfoils occurs around a tip speed ratio of 3. The highest power coefficient is about 0.4, given by NACA0018 at a wind velocity of 5 m/s. For the cases with solidity of 0.4, the NACA0015 airfoil shows good performance at a wind velocity of 5 m/s but failed to produce expected power output at a wind velocity of 3 m/s. The highest power coefficient by NACA0015 is 0.42 at a tip speed ratio of 2. The S1210 airfoils produce a relatively lower power output but the trend between the power coefficient and tip speed ratio is similar to other cases.

Keywords: vertical axis wind turbines, simulation, airfoils
NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>cross section area of turbine (m²)</td>
</tr>
<tr>
<td>c</td>
<td>blade chord (m)</td>
</tr>
<tr>
<td>$C_P$</td>
<td>power coefficient</td>
</tr>
<tr>
<td>d</td>
<td>diameter of turbine (m)</td>
</tr>
<tr>
<td>$F_\theta$</td>
<td>tangential force (N)</td>
</tr>
<tr>
<td>$F_{\theta,ave}$</td>
<td>average tangential force (N)</td>
</tr>
<tr>
<td>H</td>
<td>height of blade (m)</td>
</tr>
<tr>
<td>N</td>
<td>number of turbine blades</td>
</tr>
<tr>
<td>P</td>
<td>total power (W)</td>
</tr>
<tr>
<td>Q</td>
<td>total torque (Nm)</td>
</tr>
<tr>
<td>R</td>
<td>radius of turbine (m)</td>
</tr>
<tr>
<td>$V_\infty$</td>
<td>air velocity (m/s)</td>
</tr>
</tbody>
</table>

$\omega$  | angular velocity (rad/s) |
| $\theta$ | azimuth angle |
| $\sigma$ | turbine solidity |

1. INTRODUCTION

Energy plays the most important role in people’s daily life today. Modern industries depend heavily on convectional energy such as coal, natural gas, oil, and nuclear power. However, convectional energy resources are limited and becoming expensive because of the consistent rise in energy demand. There is a great need to increase renewable energy usage, which will also be helpful in control of emission into the environment. Wind energy, solar energy, and geothermal energy are the example of renewable energy. Wind energy is one of the renewable energy resources with least pollution.

To convert wind energy into electrical or mechanical energy, a wind turbine is the most effective way by operating as a lift or drag device. Wind turbines are classified into horizontal-axis wind turbine (HAWT) and vertical-axis wind turbine (VAWT). Compared to the horizontal axis wind turbines, the vertical-axis wind turbines can be effectively used in urban areas where wind has characteristics of unsteadiness with turbulence. The VAWT can be broadly divided into three basic types: Savonius type, Darrieus type, and Giromill type. Giromills are popular for simple configuration and simple design of blades (Mathew 2006).

Plenty of models are available for study of the aerodynamic performance of Giromill-type VAWT. Because the flow around the Giromill rotor is quite complicated, empirical aerodynamic models were developed earlier based on data from wind tunnel experiments. These models were improved after more data was available. Lazauskas (1992) used the extended double disk multiple streamtube model to predict aerodynamic performance of a three-blade VAWT with a blade chord length of 0.4 m and a rotor radius of 3.0 m, which yields a turbine solidity of 0.4. The effects of the blade offset angle and the pitch amplitude angle on power coefficient under two tip speed ratios were obtained. Staelens et al. (2003) improved the performance of Giromill-rotor by varying the blades pitch angle. An aerodynamic code was developed based on the double multiple streamtube model. Three modifications were considered: (a) the local angle of attack was kept below the stall angle throughout the whole rotation period; (b) if local angle of attack exceeds the
stall angle the local angle of attack would replace the stall angle, and (c) a sinusoidal correction function was added for the correction of local angle of attack.

Although the empirical models are still useful, rapid development in computers and algorithms made computational fluid dynamics more feasible for research of Giromill rotor. Detailed blade aerodynamics of the VAWT shall affect the turbine efficiency. EI-Samanoudy et al. (2010) studied the effect of different design parameters on the performance of Giromill-rotor by wind tunnel experimental and CFD simulations on NACA0024, NACA4420 and NACA4520. The pitch angle of wind turbine varies from $-10^\circ$ to $60^\circ$, and as the pitch angle increases the performance of wind turbine increased. In addition, there was a significant increase in turbine performance when the blade number increases from two to three but not much increase as the number becomes four. The interaction of blades becomes stronger as the turbine radius decreases, which also leads to lower performance. Howell (2010) also studied the performance of a small scale VAWT with both wind tunnel and CFD modeling. The experiment showed that the rotor performance was affected by surface roughness of blades. Under a critical Reynolds number the rougher blade doesn’t affect much. However, good performance can also be achieved at higher Reynolds number, where the smoother blade surface would benefit. It was found that the power coefficient was slightly higher for rotor with high solidity. The 3D model showed more reasonable results while the 2D model showed a higher power coefficient because 2D simulations did not present the existence of tip vortices.

Carrigan (2010) demonstrated a fully automated process for optimizing the airfoil cross-section of a VAWT by coupling the differential evolution algorithm subjected to tip speed ratio, solidity, and blade profile design constraints with generation of NACA airfoil geometries, hybrid mesh generation, and unsteady CFD. The efficiency of the optimized case can be 2% higher than the baseline case. To study the effect of camber airfoil on self-starting of VAWT, Beri and Yao (2011) conducted a CFD simulation on NACA2415. A 2D unsteady flow with three fixed-pitch blades was analyzed, and it shows that camber airfoils have potential to self-start but the power predicted by simulation indicates a reduction in peak efficiency when compared to conventional non-self-starting airfoils. Gupta and Biswas (2010) carried a 2D analysis to evaluate the performance of twisted three-blade Giromill-rotor. Unlike the symmetric airfoil, a positive lift at zero azimuth angle was observed for the twisted blade, which means the twisted bladed Giromill-rotor has a self-starting capability.

The primary goal of the present research is to investigate the aerodynamic characteristics of three-bladed fixed pitch giromill-type wind turbines. Wind turbine of two different solidities (0.2 and 0.4) with symmetrical and unsymmetrical airfoils at wind velocity of 3 m/s and 5 m/s is investigated numerically. Flow field around the model airfoils is analyzed. The torque coefficient and power coefficient are calculated and compared with the literature.

2. PROBLEM SETUP

In this study, the proper airfoils are first selected, together with the cord length and the solidity. After that, the computational domain is determined and the boundary conditions are applied accordingly. The domain is created and meshed with Gambit, and the problem is then solved in Fluent.

2.1 Blade Profiles and Computational Domain

Traditionally, symmetrical airfoils, such as NACA0012, 0015 and 0018, are considered the best for fixed pitch VAWT. It is also known that increase in airfoil thickness results in improved performance of VAWT (Claessens 2006). So NACA0015 and NACA0018 are selected over NACA0012 in this study. In
addition, unsymmetrical airfoils are also adopted to examine the aerodynamic behavior when applied to the VAWTs. For unsymmetrical airfoil, S1210 is selected, which is the best for Darrieus type VAWT for its self-starting capability without help of variable pitch (Kirke 1998). This kind of unsymmetrical airfoils is also called as “cambered airfoil”. Figure 1 shows the profiles of NACA0015 and S1210. The profile of NACA0018 is similar to NACA0015 except that the latter is a little bit thinner.

As discussed earlier, the performance of wind turbines is affected by the number of blades together with the chord length. Given a rotor diameter, more blades can apparently generate more power if there is no interaction between blades. However, the upstream airfoils will obviously impact those in downstream. A combined non-dimensional parameter, the solidity, can be used in design, and its definition can be given as

\[
\sigma = \frac{Nc}{d}
\]  

(1)

where \(c\) is the chord length, \(N\) is the number of blades, and \(d\) is the diameter of the rotor. In this study, three-bladed fixed-pitch Giromill-type VAWTs with two different solidities (0.2 and 0.4) are considered. Figure 2(a) shows the layout of the wind turbine with a solidity of 0.2. The blade has a chord length of 0.4 m, and the rotor has a diameter of 0.6 m. Also shown in the figure, the small cycle with a diameter of 0.1 m is for meshing purpose and the big cycle with a diameter of 1.2 m is for sliding mesh. Figure 2(b) presents the computational domain for the 3-bladed wind turbine. To allow a full development of the wake, the computational domain is divided into two zones, which are (a) a rectangular outer zone (fixed) and (b) a circular inner zone (rotating). The rotation of the circular inner zone is implemented by unsteady sliding mesh technique. The inlet and outlet were placed at 18 and 30 rotor diameters in upwind and downwind with respect to the rotor section. The huge domain width, which is around 40 rotor diameters, is necessary to avoid solid blockage (Castelli 2012). Only a 2D model is considered since the fundamental mechanism of Giromill-type VAWTs helps to accomplish a two-dimensional geometry.

2.2 Mesh Generation and Grid Independence Study

Figure 3 presents the general structure of the mesh as well as the grid details near the blade. The mesh was generated with GAMBIT. Unstructured mesh is used to compromise the complex geometry. The grids close to the wind turbine, especially around the airfoil, are much denser than those far away from the wind turbine. To ensure the mesh quality, the skewness is kept under 0.5 for all the zones. In addition, the y plus, which is non-dimensional distance from the wall to the first grid point that quantifies to what degree the boundary layer is resolved, is monitored in the appropriate range.

To obtain a reliable result, grid independence study is one of the essential procedures in numerical simulation. In general, the grid independency is said to be achieved if the results of key relevant variables do not change considerably when the grid is further refined. Rather than doing grid independence study for all the cases, the grid independence study is only carried out on (1) NACA0015-bladed wind turbine with a solidity of 0.4 at a tip speed ratio (\(\lambda\)) of 1.0 and a wind velocity of 5 m/s and (2) NACA0018-bladed wind turbine with a solidity of 0.2 at a tip speed ratio (\(\lambda\)) of 4.0 and a wind velocity of 3 m/s. The tip speed ratio (TSR) is defined as

\[
\lambda = \frac{R\omega}{V_{\infty}}
\]  

(2)
where $R$ is the rotor radius, $\omega$ is the angular rotation speed, and $V_\infty$ is the incoming wind velocity. The finer mesh is achieved by increasing node density of inner circular zone from a coarse mesh. Table 1 shows the power coefficient under different number of cells for the two blades. It can be observed that the power coefficient only changes marginally when the mesh changes from medium to fine. Therefore, the number of cells for the fine mesh is used in simulation.

The power coefficient is one of the key variables in wind turbines. Its definition can be given as

$$C_p = \frac{P_m}{(\frac{1}{2} \rho A V_\infty^3)}$$

where $P_m$ is the mechanical power extracted from the wind, $\rho$ is air density, and $A$ is the area of turbine $(d \times H)$. $H$ is the length of the airfoils, and it is taken as 1 in this study. It’s convenient to correlate the turbine output with available power in term of power coefficient ($C_p$). The power coefficient is subject to the Bentz limit of 0.593, which is derived from linear momentum theory. This limit provides the theoretical maximum power extracted for a wind turbine.

2.3 Numerical Scheme

The simulation is done with the commercial CFD package, Fluent 13.0, in this study. The RNG k-\omega turbulence model with standard wall function was applied to the simulation. The SIMPLE scheme is used for the coupling between pressure and velocity. Second order upwind algorithm is adopted for spatial discretization of the momentum and turbulence equations. An overlapping moving grids technique is employed to explore unsteady interaction between the stationary and rotating components. As explained earlier, the entire computational domain is divided into two fluid zones. The circular inner zone is classified as a moving mesh by specifying a certain angular velocity determined by the tip speed ratio ($\lambda$). All the interior boundaries in circular inner zone are defined as interfaces. The turbine blades were identified as no slip walls and set as stationary relative to the rotating grids. All cases were run till the torque graph does not change any more for each revolution of turbine. For each time step, the convergence criteria of a solution have been insured when the residual of all variables is less than a specific value ($10^{-5}$) for continuity, momentum, and turbulence. Simulations start with computation of the steady flow around a fixed position of turbine blades. From this initial condition, a transient simulation begins. The time step is set different for different cases, ranging from 0.5 to 7.0 milliseconds.

3. RESULTS AND DISCUSSION

In this section, the result of a baseline is presented first, followed by parametric studies on tip speed ratio, wind velocity, blade profiles, and blade solidity. The performance of wind turbine is presented as the power coefficient ($C_p$) as defined in Eq. (3) and the torque ($Q$). The torque is generated by the tangential force on all the airfoils. As discussed earlier, the downstream airfoils will be affected by the wake flow from upstream blades. The total torque can be given be

$$Q = N F_{\text{tave}} R$$
where \( N \) is the number of airfoils and it is 3 in this study. The tangential force (as well as the normal force) is a function of azimuth angle (\( \theta \)). Therefore, an average force is needed to calculate the total torque. The average tangential force (\( F_{\theta, ave} \)) on one blade can be given below (Carrigan, 2010).

\[
F_{\theta, ave} = \frac{1}{2\pi} \int_0^{2\pi} F_{\theta}(\theta) d\theta
\]

Once the total torque is calculated, the total power output can be obtained by

\[
P = Q \times \omega
\]

Note that the azimuth angle (\( \theta \)) can start at any position because of the cyclic feature of a wind turbine. For convenience in this study, the azimuth angle is specified in Figure 4.

### 3.1 Baseline Case

To explore the fundamentals of the VAWT performance, a baseline is examined first. In this case, NACA0018 is considered with a solidity of 0.2. The wind velocity is 3 m/s. Figure 5 shows the total torque as a function of azimuth angle when the tip speed ratio is 2.5. It can be observed that at a zero azimuth angle, NACA0018 produces a negative total torque at TSR of 2.5 for the wind velocity of 3 m/s. From 15\(^\circ\) azimuth angle in this case, the torque begins to increase because the lift direction is preferable to make more contribution to the positive torque and the lift also increases with the angle of attack. The total torque reaches to the maximum at an azimuth angle of around 90\(^\circ\). The dynamic stall then happens as a result of the increasing angle of attack, and the torque starts to decrease until to the lowest point. For each revolution, there are three peaks, which are corresponding to three airfoils. The maximum total torque in this case is about 0.1 Nm and the lowest value is about -0.05 Nm.

Figure 6 shows the vorticity contours and velocity vectors at two different azimuth angles: one is 45\(^\circ\) and the other is 180\(^\circ\). The vortices in both the leading and trailing edges are generated, develop, separate from the surface, and then regenerated within a full revolution. From the vectors, the vortexes are shown as a low velocity zone. Based on the details of this figure, plus the results at other azimuth angles, the preferable location can be identified. It is also observed that this pattern is the same when the wind speed or turbine solidity change.

### 3.2 Effect of Tip Speed Ratio

The wind turbine can be designed to operate under different tip speed ratio. Given the same blade solidity and wind speed, the effect of the tip speed ratio on the VAWT performance with NACA0018 is illustrated in Figure 7. When the TSR increases from 2.5 to 3.0, the maximum total torque becomes slightly bigger, which means a better turbine performance. However, when the TSR goes beyond 3.0, the overall distribution of total torque moves lower, indicating the total power output becomes less. Although it is not shown in the figure, the turbine performance does not show any good when the TSR is lower than 2.5. Therefore, there is a highest total torque for all the tip speed ratios. In this case, the highest total torque is 0.1137 Nm and the power is 3.47 W, which gives a power coefficient of 0.35, which occurs at the tip speed ratio of 3. The low power output is due to the size of the turbine as well as the wind speed. Since in theory the turbine power is proportional to the cube of wind speed, a higher wind speed will produce much higher power output.
3.4 Effect of Wind Velocity

Note that although in theory the turbine power is proportional to the cube of wind speed, the actual effect of wind speed on turbine performance might be a little bit different from the theory due to the interaction between different blades, i.e., the wave from the upstream blade will affect the performance of the blades in the downstream. Figure 8 shows the cyclic distribution of total torque for NACA0018 with a solidity of 0.2 at a wind speed of 5 m/s. Compared to Fig. 7, the shapes of these curves are in general the same. The main difference is apparently the magnitude of the torque. When the wind speed is 5 m/s, the most favorable tip speed ratio is still 3.0. The highest torque in this case is 0.3638 Nm, which gives a power of 18.37 W and a power coefficient of 0.39.

3.3 Effect of Blade Profiles

As discussed earlier, the airfoils NACA0015 and S1210 are also examined in this study in addition to the airfoil NACA 0018. The unsymmetrical airfoil, S1210, is considered the best for Darrieus type VAWT for its self-starting capability without help of variable pitch. It is therefore of interest to examine its performance for the Giromill type of VAWTs. Figure 9 shows the total torque as a function of the azimuth angle with different tip speed ratios. There is a positive torque when the TSR is 2.5, 3.0 and 3.5 for S1210. Furthermore, the magnitude of the fluctuation for TSR of 2.5 and 3.0 is smaller than those in the case of NACA0018 as seen in Fig. 7. The highest torque produced by S1210 for a 3-m/s wind velocity is 0.1114 Nm, which is very similar to the case with NACA0018. Therefore, it should be said that S1210 can perform slightly better than NACA0018 under the specified conditions.

Figure 10 gives the power coefficient for two different cases of NACA0018 and S1210 with different tip speed ratios varying from 0.5 to 4.5 and a comparison to the theoretical analysis. It can be seen that the maximum efficiency of the modeled airfoils is appeared around a tip speed ratio of 3. Moving away from this tip speed ratio, the aerodynamic performance/power coefficient shows a decreasing trend. At a wind velocity of 3 m/s, the highest power coefficient is about 0.34. The turbine is usually operated around this TSR to transform the wind power as much as possible. It can also be observed that the results of NACA0018 and S1210 are close to each other, and they are also consistent with the literature. Not shown in this figure, the highest power coefficient becomes 0.4 for the cases with wind velocity 5 m/s, and the results are also consistent with the literature. Notice that the more important to numerical simulation is to predict the trend of the performance envelope. Although the model in this study is two dimensional only, the same trend as those reported in the literature can partially validate the numerical method.

3.5 Effect of Blade Solidity

To study the effect of blade solidity on the turbine performance, the cases with solidity of 0.4 are examined. The higher solidity means the smaller rotation diameter, which is 0.3 m in this case. Figure 11 shows the vorticity contour of the three NACA0015 blades at different azimuth angles. The vortices in both the leading and trailing edges can be seen. However, this figure fails to show the effect of the upstream blade on the downstream blade.
More results are presented in Table 2 for the cases with a solidity of 0.4. Compared to the cases with solidity of 0.2, the power output is much lower, which is mainly due to the smaller area that the turbine sweeps. Furthermore, it can be observed that for the two wind speeds considered, the performance of the cases with S1210 blades is lower than those with NACA0015.

The power coefficient for solidity of 0.4 is plotted in Figure 12. It can be seen that the TSR with the highest power coefficient becomes 2.0. On the other hand, the NACA0015 blades produce a power coefficient as high as 0.42, while the S1210 blades can only give a power coefficient of about 0.28. However, the trend remains the same.

4. CONCLUSIONS

Based on the numerical results in this study on 3-bladed Giromill type VAWTs under different operational conditions, the following conclusions can be drawn.

i. Numerical simulation can predict in a reasonable way the vortexes at both the blade leading and trailing edges for different azimuth angles. The process of vortex generation, development and separation from the surface can be clearly seen.

ii. Both the symmetrical airfoils (NACA 0015 and 0018) show good aerodynamic performance for solidity of 0.2 and 0.4. For solidity of 0.2, the highest power output is at a tip speed ratio of 3, while for solidity of 0.4, the highest power output is at a tip speed ratio of 2. In another word, as the solidity of turbine increases a higher power output can be achieved at lower tip speed ratio.

iii. The unsymmetrical airfoil (S1210) shows good performance when the solidity is 0.2 but fails to produce desired power output for solidity of 0.4. However, the trend of power coefficient versus azimuth angle is the same for all the cases and consistent with literature.

iv. Wind turbines are generally operated around a tip speed ratio to transform the maximum wind power by starting from a low or zero speed. External power support is needed when the turbine fails to produce enough positive torque at low speed. In this study, both symmetrical and unsymmetrical airfoils are failed to produce the sufficient positive starting torque.

5. REFERENCES


Figure 1 Profiles of NACA0015 and S1210

(a) Three-Bladed Giromill-type VAWT with a Solidity of 0.2
(b) Computational Domain for the 3-Bladed Giromill-type VAWT with a Solidity of 0.2

Figure 2 Three-Bladed Giromill-type VAWT with a Solidity of 0.2 and its Computational Domain

Figure 3 Mesh of Computational Domain and Grid Details near one of the Blades
Figure 4 Location of Zero Azimuth Angle and its Relation to the Wind Direction

Figure 5 Total Torque for NACA0018 with a Solidity of 0.2 at a Wind Speed of 3 m/s

Figure 6 Vorticity Contours and Velocity Vectors at Different Azimuth Angles
Figure 7 Effect of TSR on Total Torque of NACA0018 (Solidity = 0.2 and Wind Speed = 3 m/s)

Figure 8 Total Torque for NACA0018 with a Solidity of 0.2 at a Wind Speed of 5 m/s

Figure 9 Total Torque for S1210 with a Solidity of 0.2 at a Wind Speed of 3 m/s

Figure 10 Power Coefficient versus Tip Speed Ratio for Giromill type VAWTs with a Solidity of 0.2 and a Wind Speed of 3 m/s
Figure 11 Vorticity Contour of 3-Bladed VAWT with NACA0015 Airfoils with a Solidity of 0.4 (Speed Ratio: 1.5, and TSR: 1.5)

Figure 12 Power Coefficient versus Tip Speed Ratio for Giromill type VAWTs with a Solidity of 0.4 and a Wind Speed of 5 m/s

Table 1 Results for Grid Independence Study

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<th>Number of Cells</th>
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<td>NACA0015</td>
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<tr>
<td>Coarse</td>
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<td>0.1446</td>
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<tr>
<td>Medium</td>
<td>98,748</td>
<td>0.1339</td>
</tr>
<tr>
<td>Fine</td>
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<td>0.1306</td>
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<tr>
<td>NACA0018</td>
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<td></td>
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<tr>
<td>Coarse</td>
<td>52,190</td>
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<tr>
<td>Medium</td>
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<tr>
<td>Fine</td>
<td>67,548</td>
<td>0.0520</td>
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Table 2  Performance of VAWT with a Solidity of 0.4

<table>
<thead>
<tr>
<th>Airfoils</th>
<th>NACA0015</th>
<th>S1210</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Velocity (m/s)</td>
<td>3 m/s</td>
<td>5 m/s</td>
</tr>
<tr>
<td>Maximum Torque (Nm)</td>
<td>0.0309</td>
<td>0.1438</td>
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<tr>
<td>Angular Velocity (rad/s)</td>
<td>40</td>
<td>66.67</td>
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<tr>
<td>Power (W)</td>
<td>1.24</td>
<td>9.64</td>
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