Numerical Optimization of VAWT Blade Design

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Abstract- *The Need of Power is increasing day by day due to technological changes and high demand of automated systems in household to seek a solution to this problem this project is a attempt to indicate that a Portable wind turbine which is precisely calculated to sophisticate a household, in this project a vertical axis wind turbine is designed to compensate a 1kw of power that is required to run a household A 3d model of wind turbine is done with the calculated dimensions and Computational Fluid Dynamic Analysis is done to see the performance of the wind turbine to avoid the prototyping and high cost of the project Pressure Velocity and the other data related to wind flow and turbine Rotation is presented in the Document.*

Keywords- CFD Wind Turbine, Solid works , Household Power

I. INTRODUCTION

1.1 Problem statement

The need for improved alternative energy sources is ever prevalent. Wind energy is one of the most viable renewable sources today due to its year-round availability, and pollution-free nature. According to the *Wind Vision Report*, published by the U.S. Department of Energy, wind energy is the largest source of added renewable energy generation in the United States since 2000. A plan has been set by the program for 20% of the nation’s electricity to be supplied by wind by the year 2030, and 35% by 2050. The report states that a key to achieving this goal is to improve the potential of low-wind-speed locales (“ENERGY.GOV,” 2016). Because of this, many works are underway involving the efficiency of wind energy conversion systems, especially for regions with low average wind velocities.

The two primary types of conversion systems are the horizontal-axis wind turbine (HAWT) and the vertical-axis wind turbine (VAWT). HAWTs have been in practice for some time and are heavily favored over VAWTs for large-scale power generation; however, research of VAWTs has gained growing interest in recent years because of the opportunities available for small-scale and off-grid power generation which favors the use of vertical-axis turbines. The design and testing of 3D printed vertical-axis wind turbine models is presented in this work.

1.2 VAWT advantages

Vertical-axis wind turbines have many advantages for small scale wind energy applications. Interest in VAWT technology has recently grown due to potential for off-grid power supply in several different applications. One of the greatest advantages for VAWTs over traditional HAWTs is the ability to self-start in some designs. Under low wind speed conditions, many VAWTs begin to rotate without the added expense of actuators or controls. For VAWTs the generator may be located on the ground rather than high in the air. This provides much more convenient and cost efficient installation and maintenance than that of HAWTs. Another advantageous feature of VAWTs is the fact that they can accept wind from all directions.

Regardless of where the wind is coming from, the turbines generally perform equally as well. For this reason, VAWTs are preferred over HAWTs where unsteady and low speed wind conditions exist.

1.3 Savonius type

Drag-based VAWT designs are referred to as Savonius type. The first Savonius turbine was developed in 1922 and was made up of semi-circle blades (MacPhee, David, and Beyene 2012). Conventional Savonius rotors with two and three blades are displayed in Figure 1.1.

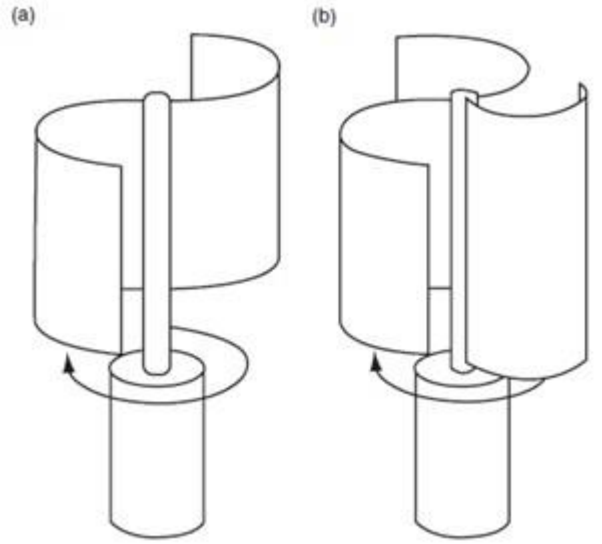


Figure 1.1. Savonius rotors with (a) two blades and (b) three blades (MacPhee, David, and Beyenne, 2012)

This type of turbines rotates due to a difference in drag caused by the shape and orientation of the blades. The blade moving with the wind experiences more drag than the blade moving against the wind due to the curvatures.

1.4 Darrieus type

The other type of VAWT is lift-based turbines, known as Darrieus type. The most commonly used Darrieus turbines include the Egg-Beater, H-type, and Gyromill designs. These common designs can be seen in Figure 1.2.

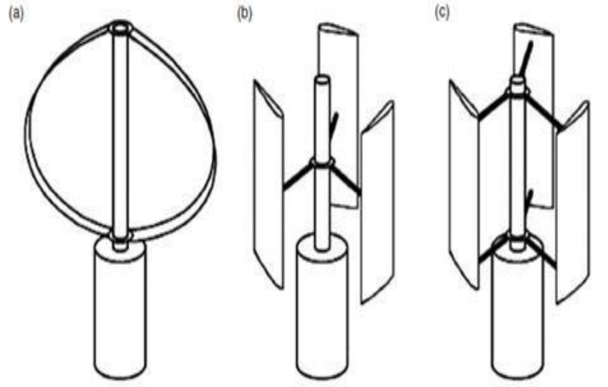


Figure 1.2. Darrieus type rotor designs: Egg-beater (a), H-type (b), and Gyromill (c) (MacPhee, David, and Beyenne, 2012)

Darrieus rotors produce higher power coefficient, or efficiency, at higher wind speeds, but do not enjoy the same self-starting ability of Savonius turbines at lower wind speeds. When experiencing high rotational speeds, though, Darrieus type VAWTs typically produce more power than drag-based designs (MacPhee, David, and Beyene 2012).

1.5 Scope of research

In the present study, six different rotor designs are analyzed with wind tunnel testing and numerical simulations. These models include a traditional Savonius with 2 blades, “CC” model, “QM” model, and 90 degree helical twist models with 2, 3, and 4 blades. Wind tunnel experiments are conducted to find reactional torque and rotations per minute (RPM) from which turbine efficiencies are calculated. Computational Fluid Dynamic (CFD) simulations are performed with ANSYS Fluent to study aerodynamic characteristics of the models. The objectives of the research are as follows:

- Increase power coefficient of Savonius turbines by creating new blade geometries
- Determine the self-starting capabilities of the new models
- Design and implement new test fixtures to accompany 3D printed turbines
- Develop a three-dimensional and transient model for VAWT simulation
- Improve the existing subsonic wind tunnel by fabricating a new model test section

II. LITERATURE REVIEW

It is hypothesized that the new “CC” and “QM” models will achieve higher maximum torque and power coefficients than the conventional Savonius model. Also, the helical models will create positive torque on the turbine shaft over all operational angles of rotation and possess the ability to self-start in lower wind speeds, increasing overall performance.

Many researchers are working to enhance performance of vertical axis wind turbines both numerically and experimentally. These works vary from computational simulations to laboratory measurements on actual models. There are two primary goals when considering VAWT research. The first is improving conversion efficiency of Savonius rotors by reducing drag losses. The second is improving self-starting characteristics of Darrieus type rotors in order to increase overall conversion efficiency for realistic wind conditions.

There are three important non-dimensional coefficients that characterize turbine performance. Tip-speed ratio (*TSR*) is the ratio of blade tip speed to the free-stream wind velocity. It is the product of angular velocity and overall radius, divided by the wind velocity. A schematic for tip-speed ratio is provided in Figure 2.1.

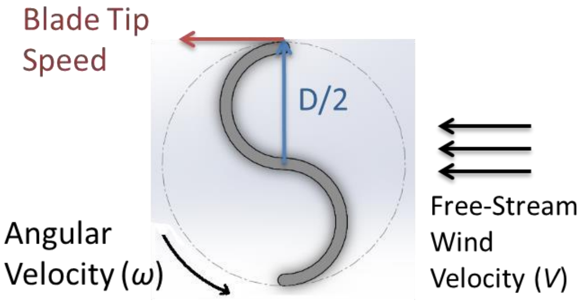


Figure 2.1. Tip-speed ratio schematic

The moment coefficient (*Cm*), also known as the torque coefficient, characterizes the amount of torque generated by the blade geometry. It is the measured torque divided by the theoretical torque value available in the wind. Power coefficient is the product of tip-speed ratio and moment coefficient. The power coefficient is the efficiency of the turbine. Procedures for calculating each of these non-dimensional coefficients is available in the analysis section of Chapter 3 in the thesis. A useful way for comparing the efficiencies of different wind turbine designs is plotting the power coefficient vs. tip-speed ratio. A graph comparing various types of wind conversion systems can be seen in Figure 2.2 (Morshed, Rahman, and Ahmed, 2013).

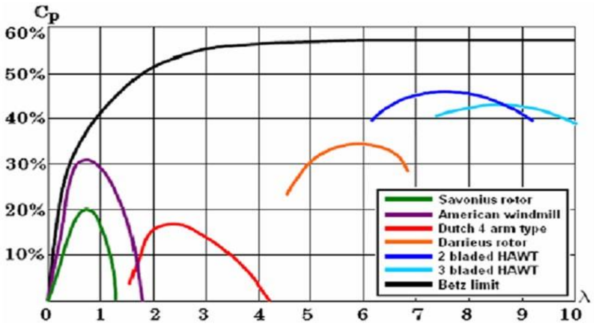


Figure 2.2. Power coefficient vs. tip-speed ratio for various wind turbine types (Morshed, Rahman, and Ahmed, 2013)

Savonius VAWTs operate in a tip-speed ratio range of 0 to 1.2 and have a maximum efficiency of 20 percent. Darrieus rotors operate in higher wind speeds and achieve a maximum efficiency of 35 percent, while HAWTs enjoy the highest power coefficients of any turbine type. This chapter provides a discussion of the various works involving performance improvement of VAWTs for low-wind-speed locales.

2.2 Savonius research

Savonius wind turbines are drag-type VAWTs with negligible lift forces. The traditional

Savonius rotor is made up of two opposite-facing semicircular buckets. Rotation is caused due to a difference in pressure between the advancing and retreating blades. When wind strikes the blades of the turbine, two components of drag force are generated on each blade surface. Normal drag force (Fn) acts perpendicular to the blade wall and tangential drag force (Ft) acts along the tangential direction of each blade (Bashar, Rahman, and Khan, 2013). The schematic diagram of the Savonius rotor cross-section with the components of drag forces on each blade is shown in Figure 2.3.

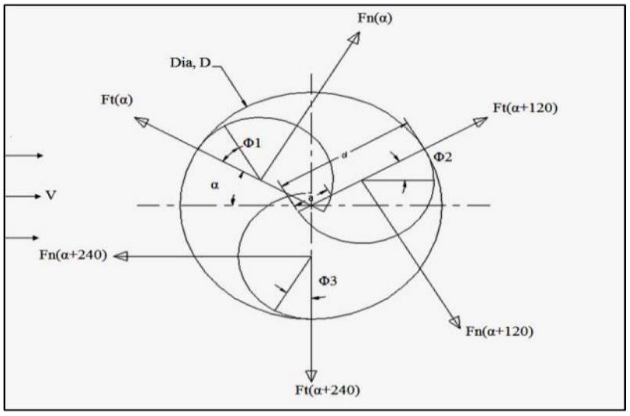


Figure 2.3. Schematic of the drag force components on model cross-section (Bashar, Rahman, and Khan 2013)

Drag-based Savonius VAWTs exemplify high starting torque and perform best at low tipspeed ratios. Much research has been conducted regarding two and three blade rotors of this type. Morshed, Rahman, and Ahmed (2013) provided analysis of three-bladed Savonius rotors with different overlap ratios. Models with overlap ratio of 0.12 and 0.26 were compared to a model with no overlap. A numerical investigation using GAMBIT and FLUENT was conducted along with wind tunnel experimentation. The overlap ratio of 0.12 can be seen from the top view drawing in Figure 2.4.

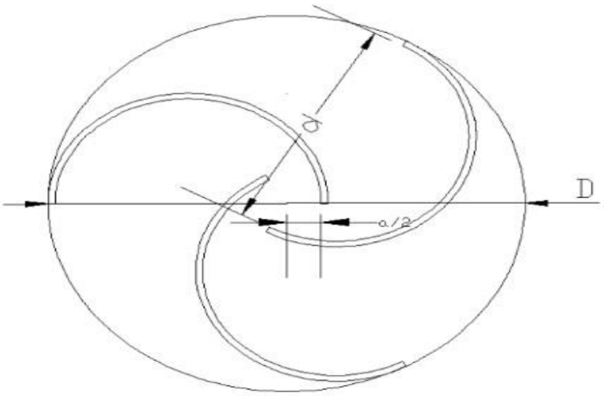


Figure 2.4. Top view of Savonius model with overlap ratio of 0.12 (Morshed, Rahman, and Ahmed, 2013)

It was concluded in the study that for all tested wind speeds, the model with 0.12 overlap attained the highest experimental torque coefficient. At higher wind speeds the same model demonstrated the best experimental power coefficient; however, the model with no overlap had the better power coefficient at low wind speed.

Rather than conventional Savonius types, some have investigated alternative drag-based designs. Ghatage et al (2012) researched the effects of twisted rotors. It was found that twisting the blades provided enhanced efficiency of the turbine. The experimental results agreed with CFD simulations. It was also concluded that a twisted two-blade arrangement outperformed a twisted design with three blades. The optimum twist angle for this study was found to be 30o. The use of stacked Savonius rotors also show increases in wind conversion efficiency compared to a single rotor (Abraham et al 2011). This is one promising example of a multistage turbine.

Several other improvements to conventional drag-type rotors were also implemented in this case.

Circular caps were added to the top and bottom of the blades. Venting apertures were applied to the middle of the rotating blades in an attempt to reduce advancing drag. The vents are pictured in Figure 2.5.

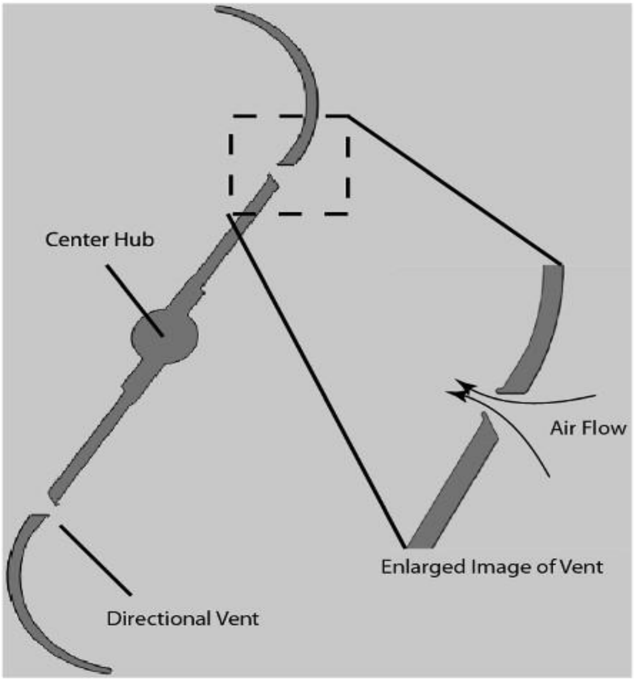


Figure 2.5. Directional vents for reducing drag on advancing blade (Abraham et al. 2011)

The proposed vertical axis turbine by Abraham et al (2011) met specific needs for powering an off-grid cellular tower. The research concluded that the added caps and vents increased performance of rotors by increasing drag on the retreating blade side while decreasing drag on the advancing side. Another attempt to reduce advancing drag was completed by Altan and Atilgan (2008) with the use of curtains. The curtains directed flow to the retreating side by blocking flow to the convex blade on the advancing side. The curtain arrangement can be seen in Figure 2.6.

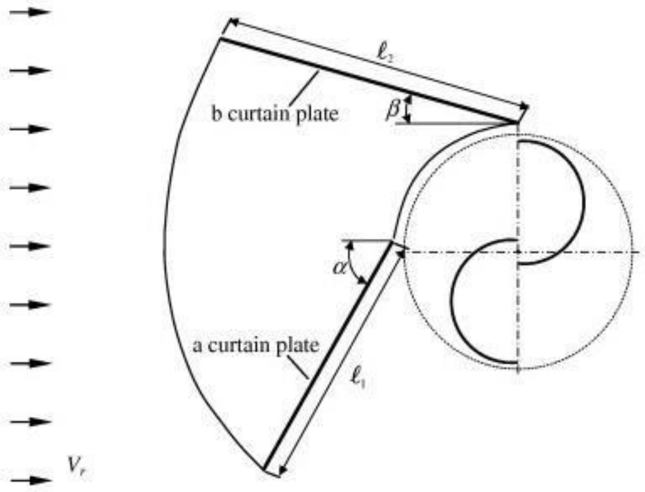


Figure 2.6. Curtain arrangement in front of Savonius rotor (Altan and Atilgan 2008)

Static torque measurements were taken on the blades with and without the curtain. The best results were obtained from use of the curtain. Different curtain lengths were then used, and long curtain dimensions provided significantly higher static torque values. The results of the experiment agreed with numerical analysis which was completed with FLUENT 6.0 trade software.

2.3 Helical twisted blades

The traditional Savonius rotor consists of 2 opposite facing semicircular buckets and constant cross-section. The addition of a helical twist to the blade tips alters turbine performance (Lee et al. 2016). An example Savonius rotor and one with helical twist, developed by Can et al.
(2013), may be seen in Figure 2.7.


(a) (b)

Figure 2.7. Conventional Savonius turbine (a) and turbine with helical twist (b) (Can et al. 2013)

It was found that the Savonius rotor produced a negative torque coefficient within two narrow ranges of rotation, reflecting an intermittent disturbance to the flow field. In contrast, the torque coefficient for the spiral design remained positive during the entire rotational cycle. The maximum torque coefficient (*Cq*) for the twisted blade was 0.43 while the maximum *Cq* recorded with the traditional bade was less than 0.30 with more severe fluctuation (Can et al. 2013). In addition to a standard S-blade (Savonius) and helical rotor, Diaz et al. (2015) added a three-bladed Savonius model and a two-stage model to their study. The helical rotor showed a 20% improvement in efficiency over the other models, and the three-bladed Savonius model attributed the lowest recorded power coefficient in the study. In another study, numerical analysis was performed on a Savonius rotor with 45 degree twist angle. It was found that significant power coefficient increase occurred at rotor angle of 90 degrees in respect to incoming air velocity (Bachu, Gupta, and Misra 2013). Saha and Rajkumar (2006) concluded that varying twist angle on Savonius turbines with three blades affects starting performance. All twist angles in the study, from 0 to 25 degrees, improved the self-starting characteristics. Larger twist angles were recommended for lower wind velocities, and the 15 degree twist model produced maximum power coefficient.Kamoji et al. (2009) proposed a helical Savonius rotor with a 90 degree twist angle. It was found that torque coefficient remained positive for all operating angles, and the maximum power coefficient was obtained by the helical model with no overlap, no shaft, and aspect ratio of 0.88. Ricci et al. (2016) developed different configurations of Savoinus rotors for the purpose of street lighting applications. The experiment was conducted in a closed loop wind tunnel. Three models were tested: straight blade, 90 degree twist, and 105 degree twist. The best results were obtained with the 105 degree twist helical rotor with end plates and central gap. The maximum *Cp* of 0.251 occurred at tip-speed ratio of 0.899.

2.4 Addition of end plates

The effects of various end plates were presented by Jeon et al. (2014). The researchers added four different end plates of various shape and size to helical models. The twist angle for these models 180 degrees. The use of end plates on top and bottom increased the power coefficient by up to 36%, compared to a model with no end plates. It was determined that circular plates with area the same as that of the swept area of the turbine maximized power.

2.5 Blade overlap conditions

Overlapping the blades allows for airflow to occur between them, and the overlap condition is defined by the gap between blade and shaft, relative to the turbine radius. Deb et al. (2014) experimented with a 20 degree twist helical Savonius rotor at different overlap conditions. Six different overlap ratios ranging from 0 to 20% were investigated. It was concluded that rotor performance increases with increasing overlap ratio up to a certain limit. The maximum power coefficient obtained was 0.289 with an overlap ratio of 12.76%. The recommended tip-speed ratio for best performance of this design was 0.51-0.90.

2.6 Changing number of blades

A study performed by Wenehenubun et al. (2015) addressed the influence of increasing number of blades on turbine rotation. Two, three, and four straight-blade Savonius models were analyzed with wind tunnel testing and numerical simulation using ANSYS software. It was found that the four blade turbine performed best at lower tip-speed ratios. At higher tip-speed ratios, the model with three blades produced the highest power coefficient. Saha et al. (2008) found that for multistage systems, maximum power coefficient is produced with two twisted blades and two stages.

2.7 Darrieus research

Lift-based VAWTs is a popular research area because of the higher power coefficient potential. Typically Darrieus rotors consist of straight, vertical airfoils. The most prevalent work in this area is the optimization of airfoil shape. This is done by testing different designs by the use of two-dimensional Computational Fluid Dynamics. Aerodynamic investigations are performed numerically in order to improve maximum output torque and power coefficients (Mohamed 2012).

Designs for lift-based VAWTs are not limited to only vertical blades. Armstrong et al (2012) analyzed the effects of canted blades and canted blades with fences in comparison to straight blades. The turbine with canted blades is shown in Figure 2.8.

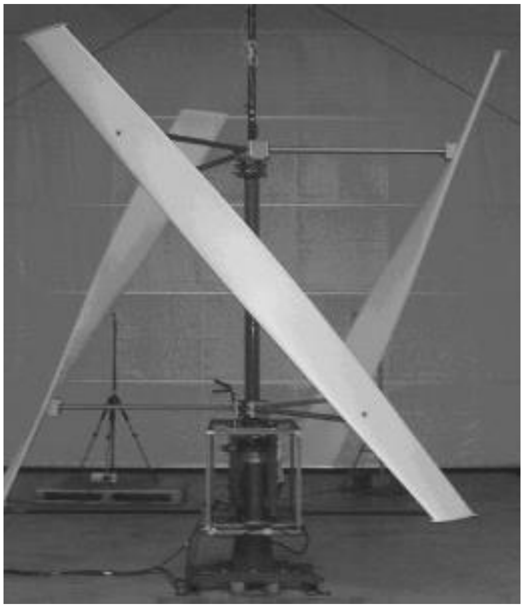


Figure 2.8. Derrius-type turbine with canted blades (Armstrong et al. 2012)

The straight-blade and canted-blade H-Darrieus turbines were tested at very high Reynolds numbers. The experiment indicated that rotors with canted blades experienced much less flow reversal than that of the vertical blades. The addition of fences on the canted blades increased power and decreased the tip-speed ratio at which maximum power occurred.

2.8 Self-starting performance

Much work is being done in the area of self-starting turbines. The ability for a turbine to start rotation at low wind speeds improves overall performance. Also, the absence of sensors and controllers can greatly reduce cost. Savonius rotors typically enjoy better self-starting performance than Darrieus types. Many techniques have been researched to improve the start-up of lift-based Darrieus rotors. Beri, Habtamu, and Yingxue (2011) performed simulations of modified airfoils with a hinged tail using FLUENT. A conventional NACA0018 airfoil model was allowed to flex 15o at the trailing edge. The hinge was located back 70% of the blade length. Moving mesh technique was utilized to investigate two-dimensional flow around the model.

Unsteady flow simulations were performed at low tip-speed ratios ranging from 0.1 to 1.0 and compared to simulations of a known self-starting airfoil model. The simulation results indicated that the hinged model had better self-starting performance for all flow conditions.

2.9 Multistage turbines

Another effort to enhance performance of VAWTs involves stacking multiple rotors on one axis. Multistage turbines consist of at least two tiers containing separate blade configurations. Gorelev and Krivopitsky (2008) designed two-tier wind turbines made up of straight-bladed Darrieus rotors. The full-scale models achieved self-start rotation without any added devices. Two separate configurations were fabricated with levels of staggered airfoils. The first used six blades in total of three on top and three on bottom. The second model was built with two blades on the top tier and two on the bottom. Of all the experimental tests, a maximum efficiency of 40% was reached for a 3kW apparatus.

2.10 Hybrid research

Hybrid VAWTs include combinations of multiple types of rotors in one turbine. The goal of hybrid turbines is to attain higher power coefficient or better starting performance than in one type of rotor alone. Gavalda, Massons, and Diaz (1990) experimented with a Darrieus and Savonius hybrid turbine. The central part of the turbine was a Savonius drag-based rotor. Outstretched armatures contained lift-based Darrieus blades. Their design was successful in achieving higher starting torque than that of the Darrieus only rotor. An example of this type of hybrid configuration is depicted in Figure 2.9.

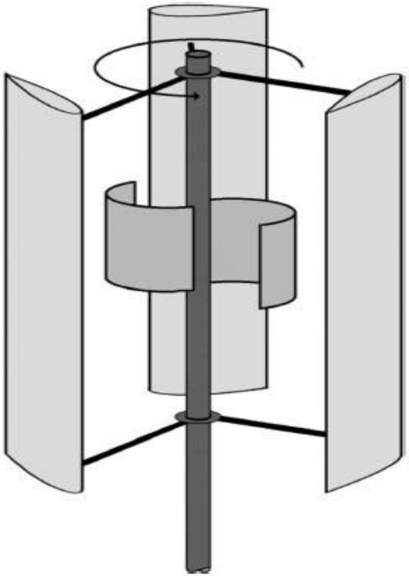


Figure 2.9. Typical hybrid turbine consisting of Savonius and Darrieus rotors (MacPhee, David, and Beyenne, 2012)

Work by Kou et al (2011) involved a multitier Savonius rotor combined with a three-bladed Darrieus gyromill rotor. The addition of the Savonius rotor enhanced conversion efficiency compared to only gyromill. Also, the required wind speed for self-starting was successfully lowered for the hybrid design. Gupta, Biswas, and Sharma (2008) combined a Savonius with an egg-beater type Darrieus rotor. Their design consisted of three-bladed Darrieus and three-bladed Savonius. Varying overlap ratios were implemented in the Savonius rotor. The model was tested in a subsonic wind tunnel and compared to a simple Savonius rotor. For the hybrid turbine configuration, it was found that maximum performance occurred with no overlap geometry in the Savonius rotor. It was concluded in the study that the power coefficient was significantly greater for the hybrid model than for that of the Savonius rotor at all overlap conditions.

Few researchers have explored the performance of hybrid VAWTs consisting of dragbased rotors along with unsymmetrical lift-based airfoil blades. The Darrieus H-type rotor has among the highest power coefficients of any VAWT design, but it does not exhibit good starting behavior. This is due to the straight, symmetrical airfoil blades. Cambered S818 airfoil blades display better self-starting characteristics at most azimuthal angles, and Savonius rotors provide the best start-up performance. In order to achieve a completely self-starting rotor at all azimuthal positions, a hybrid system was modeled. The H-Savonius rotor contained a three-bladed cambered Darrieus rotor with a Savonius rotor as its starter. Self-starting capability was determined by positive static torque coefficient values at all angles. The model was then fabricated and tested in a wind tunnel at a range of Reynolds numbers. Five different overlap conditions were tested for the Savonius part of the rotor. Efficiency of the hybrid model was compared with a simple H-rotor. The optimum overlap ratio was found to be 0.15 at a tip speed ratio of 2.29 and Reynolds number of 1.29 **.** 10^5. The optimized hybrid model achieved a maximum power coefficient of 0.34 which resulted in a significant increase in power performance from the H-rotor only model. The hybrid H-Savonius model in this study provided better power performance than most existing VAWT rotors while possessing the ability to selfstart (Bhuyan and Biswas 2014).

III. RESULTS

The initial conditions of the Simulation is Considered with No angular Velocity . where with the Air flow of the Model The turbine Starts Rotating and Reaches the Angular velocity required Cases for TSR ratios of 0.5 , 1 ,1.5 , 2 and Graphs are Plotted For Better Understanding.

From the Literature The Calculations is Done using Excel

$$C_m = \frac{T}{\frac{1}{4}\rho ADV^2}$$

$0.125=\frac{T}{1/4(1.225*(D*H)*(6)^3}$

$T=0.125*\frac{1}{4}*(1.225*1.261*1.22*(6)^3$

T=126.44 N-m

Where

Cm =Coefficient of moment which obtained From the Fluent =0.125

T=Torque Generated=16.16 N-m

□□ Density of the Air =1.225kg/m^3

A= Swept Area=D*H=1.261*1.22=1.53842m^2

D=Diameter of the Rotor.

V= Velocity =15m/s

$$\lambda = \frac{\omega D}{2V}$$

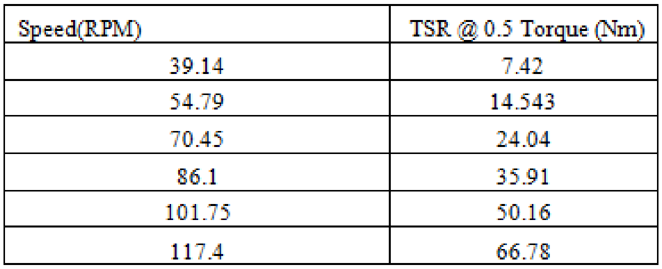
□□Tip Speed Ratio

□□Angular Velocity.

D=Diameter of the Rotor.

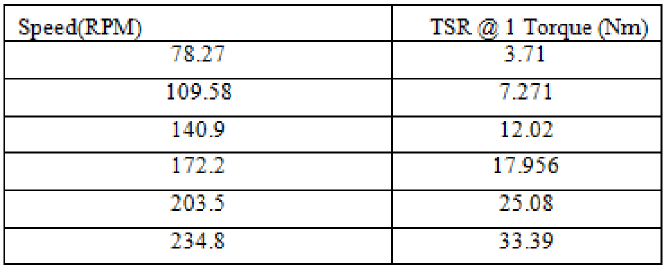
Where For power Generate P=□□□16.16□49.1□□795.0506 watts

Table 3.1 Speed and Torque Generated For TSR =0.5



Speed(RPM)	TSR @ 0.5 Torque (Nm)
39.14	7.42
54.79	14.543
70.45	24.04
86.1	35.91
101.75	50.16
117.4	66.78

Table 3.2 Speed and Torque Generated For TSR =1



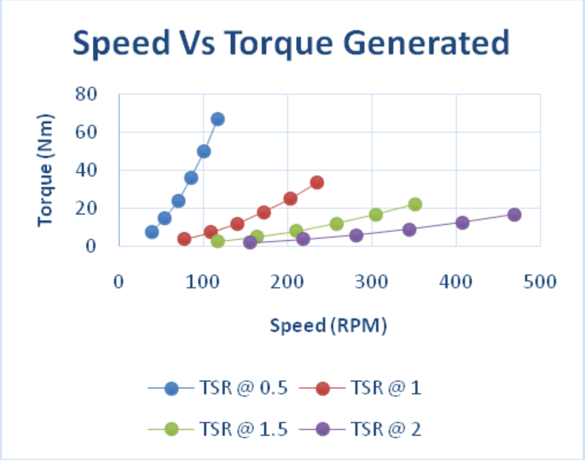
Speed(RPM)	TSR @ 1 Torque (Nm)
78.27	3.71
109.58	7.271
140.9	12.02
172.2	17.956
203.5	25.08
234.8	33.39

Table 3.3 Speed and Torque Generated For TSR =1.5

Speed(RPM)	TSR @ 1.5 Torque (Nm)
117.4	2.473
164.37	4.848
211.34	8.013
258.3	11.97
305.26	16.72
352.2	22.26

Table 3.4 Speed and Torque Generated For TSR =2

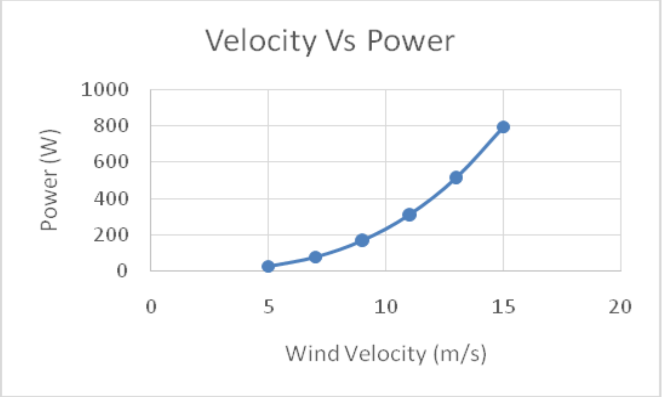
Speed(RPM)	TSR @ 2 Torque (Nm)
156.55	1.855
219.16	3.636
281.8	6.01
344.4	8.978
407	12.54
469.6	16.694



Plot 1 Speed Vs Torque For Different Tip Speed Ratio

Table 3.5 Wind Velocity Vs Power Generated

Velocity (m/s)	Power (W)
5	29.44632
7	80.8007
9	171.7309
11	313.5444
13	517.5485
15	795.0506



Plot 2 Wind Velocity Vs Power Generated

IV. CONCLUSION

- The Comprehensive work of Deign and performance evaluation is done in the project to seek the Power that need to run a household of 0.75 KW is obtained.
- where the selection of turbine is thoroughly calculated from the known factors and is designed using the solid works , to Avoid high scale mockups like prototyping and testing the solution is done using the advanced simulation technique with computational fluid dynamics.
- where the 3d model is imported meshed and simulated to obtain the results. The results obtained from the simulation is evaluated with theoretical formulae. The pressure velocity contours have been put it to document.

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