# Analysis and Design of a Giromill Type Vertical Axis Wind Turbine for a Low Wind Profile Urban Area

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***Abstract:*** *This paper analyses the design parameters of giromill type vertical axis wind turbine in QBlade and Mat lab Simulink software with an appropriate practical demonstration. The significant factors like Reynolds number, numbers of blades, aspect ratio, and wake module analysis were carried out to design a wind turbine to enhance maximum power at 2 m/s wind speed. The classical 4 digit symmetrical, unsymmetrical NACA series airfoil are taken to analyze Glide ratio with proposed D shaped airfoil and it produces high lift forces at low wind speed. Based on the significant results obtained a virtual VAWT model was constructed in a Simulink which endorses QBlade analysis results. Two VAWTs with an aspect ratio of 2.5 and 0.75 were constructed with 1kW PMDC generator to validate the simulation results. The results exhibit that the low aspect ratio of 0.75, odd number blades like 3 or 5 with D shaped airfoil enables to catch more downwind and it improves the VAWT model has maximum energy efficiency to 50.49 % more than the 2.5 high aspect ratio wind turbines.*

***Keywords:*** *Giromill, Glide ratio, Aspect ratio, Wake module analysis, Virtual VAWT model, PMDC generator.*

## 1. Introduction

A wind turbine is a machine used to convert the kinetic energy of wind into electrical energy. There are two types of a wind turbine which produce electrical energy from the wind: they are horizontal-axis wind turbine (HAWT) and vertical-axis wind turbine (VAWT). The VAWT has a growing interest in power generation nowadays because it is simple construction, low cost, self-starting at low wind speed. It always orients towards the wind direction means that it is capable of capturing wind from any direction and generates electrical energy at low wind speeds and do not require yaw mechanism [1-2]. Regular wind turbines operate wind speeds between 10 m/s to 25 m/s but small wind turbines have been designed to operate even at 2 m/s. It produces lower noise level only 27-37 dB, suitable for our living condition. The VAWT mounted lower to the ground making it easy for maintenance if needed and can build at locations on the taller structures, such as the horizontal type can't. The VAWT located at the top of buildings as they do not suffer from changing wind direction and the simplicity of design produces better response even they face a turbulence flow [3]. The VAWT is mainly classified into two types; Savonius and Darrieus type. The Savonius turbine generates the electricity through the drag force but Darrieus wind turbine rotors are based on lift force. Two bladed Savonius turbine is more efficient than three blades Savonius with higher power coefficient under the same operating condition [4-5].

Darrieus turbine has more efficient power coefficient than the Savonius turbine at low wind speed but it suffers from the self-starting problem. Power coefficient of a hybrid turbine is 0.23 at low wind speed which is higher than the Savonius and Darrieus turbine [6]. The H type or Giromill type VAWTs are particularly well suited to residential wind power generation for some inherent advantages in comparing with their HAWT counterparts also it can withstand turbulent wind flow [7-9].

The selection of the airfoil plays an important role in achieving better wind turbine aerodynamic performance. One attractive advantage of VAWTs is that the blades can have a constant shape along their length and, unlike HAWTs, there is no need in twisting the blade as every section of the blade is subjected to the same wind speed. This allows an easier design, fabrication and replication of the blade which can influence in a cost reduction and is one of the main reasons to design the wind turbine with this rotor configuration.

The H type VAWTs uses, symmetric airfoils from the NACA 4-digit series like NACA0012, 0018, 0020 are commonly employed because only for these airfoils aerodynamic characteristics are the most well documented [10]. The aim of the recent researches is to maximize the annual Energy to optimize the power coefficient by suitable selection of blade profiles [11].

For a fixed cross-sectional area of the turbine, to optimize the curve of the power coefficient it is possible to use different airfoil sections and/or rotors with different aspect ratio because the VAWT that is much wider than tall is more efficient [12-13]. This discussion portrays why VAWT suitable for generating electrical energy for household application at rural and urban areas in a country like India which has huge potential and interest for the wind energy. The organization of the various section of this paper for the proposed work described in Fig 1.

Fig 1. The Article organization Flow Chart

Objective: Design of a simple & efficient VAWT for low wind profile urban area by considering significant design parameters through various analysis, simulation and practical demonstration.

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Section 2: Preliminary analysis

i. To study wind profile data of the proposed urban area from the history of data.
ii. Based on the study, the Reynolds number evaluated for the simulation.
iii. Airfoil selection for the study identified from the references.

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Section 3: Wind blade comparative analysis

i. Selection of blade profile from NACA 4 digit profile and the proposed D shaped airfoil carried in QBlade software.
ii. Selection of Number of blades
iii. Effect of Aspect ratio
iv. Lifting Line Free Vortex Wake module Analysis

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Section 4: Design of a Virtual VAWT model based on the results to validate QBlade analysis with Mat lab Simulink model.

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Section 5: Practical implementation of Two 1 kW VAWT with different Aspect ratio to validate simulation results.

## 2. Preliminary Analysis

### 2.1 Wind profile data of the proposed area

India Meteorological Department (IMD) measures the wind velocity at varying heights of 10-30 m averaged over 3 s duration [14]. The Data obtained through the Regional Meteorological Centre at 10 m height are tabulated in Table 1 for the average and gusty wind speed variations.

**Table 1.** Wind Speed (km per hour) Data for any Year at the prepared location

| WIND SPEED | JAN | FEB | MAR | APR | MAY | JUN |
|---|---|---|---|---|---|---|
| **AVE wind** | 6.4 | 8.1 | 9.1 | 11 | 11.3 | 12.3 |
| **GUSTY wind** | 52 | 37 | 85 | 56 | 48 | 80 |

| WIND SPEED | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|
| **AVE wind** | 12.6 | 8.9 | 9.4 | 6.6 | 7.2 | 6.2 |
| **GUSTY wind** | 70 | 41 | 63 | 74 | 70 | 78 |

**Fig 2**. Average vs Sustainable Gusty wind speed variation in a year

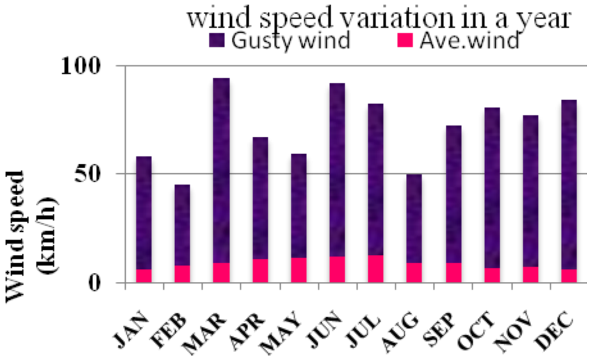



Fig 2 shows that the wind speed peak season during Indian extended summer from April to July and the Averaged Value of wind speed during this period is (January 2010 -December 2017) 9.2 km/h (or) 2.67m/s (or) 5.966 mph. The average of sustainable Gusty Wind speed in a year is 62.83 km/h (or) 17.45 m/s (or) 5.96 mph and the maximum wind speed is 23 m/s [14-15]. The above wind related to the proposed urban area data and the analysis suggests that the simulation can be started from a wind cut in speed of 2 m/s to a cut off speed of 23 m/s and the average wind speed is 12 m/s.

### 2.2 Reynolds Number Calculation

The Reynolds number is a dimensionless value that measures the ratio of inertial forces to viscous forces. Reynolds number selection highly influences the performance of vertical axis wind turbine [16]. The factor Reynolds number increases the maximum power coefficient by decreasing the drag forces and increases the lift forces hence creates the maximum power exists at low tip speed ratio so that the optimum blade set angle is increased to get optimum performance in a smaller section of the aerofoil [17]. The Reynolds number is calculated from,

$$Re = \frac{\rho v l}{\mu} = \frac{v l}{\upsilon} \tag{1}$$

$where\ \rho = density\ of\ wind\ = 1.225\ kg/m^3$

$v = velocity\ of\ fluid(wind)\ in\ m/s$

$l = chord\ width\ of\ an\ aerofoil\ in\ m$

$\mu = dynamic\ viscosity\ of\ the\ wind\ in\ Pa.s$

$\upsilon = kinematic\ viscosity\ in\ \frac{m^2}{s}$

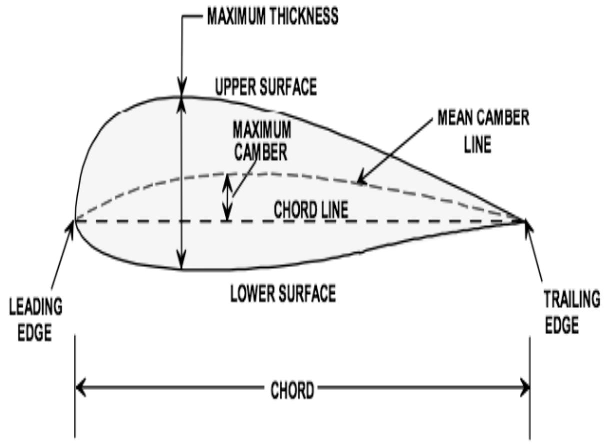
The Reynolds Number for varying wind speed from *2m/s* to *23m/s* for the proposed location from the result obtained through section 2.1 to a fixed chord length of 0.14 m calculated and it varies from a minimum value of 18530 to maximum of $0.23\times10^6$.

### 2.3 Airfoil selection for VAWT

The National Advisory Committee for Aeronautics (NACA) develops the airfoil for aircraft wings which is further revolutionarily extended for Wind Turbines. In this analysis, the most popular and effective airfoil shape symmetrical NACA 0012, 0015, 0018 and unsymmetrical 4518, 8612 [16, 17-18] with another a proposed D-shaped profile taken for the study.

The semi cut elliptical or circular blade provides better Drag forces that improve the power coefficient (Cp) [19]. This point motivates to propose a D shaped airfoil to the VAWT analysis and C shaped foil in the practical model to self start the Giromill type wind turbine.

Fig 3.Airfoil Terminology




The NACA airfoil section is created from a camber line and a thickness distribution plotted perpendicular to the camber line. The equation for the camber line is split into sections either side of the point of maximum camber position as shown in Fig 3. In order to calculate the position of the final airfoil envelope later the gradient of the camber line is also required. The following equations are describing these dimensions,

Front $(0 \le x < p)$ Back $(p \le x \le 1)$

camber $y_c = \frac{M}{p^2}(2Px - x^2)$ $\quad y_c = \frac{M}{(1-p)^2}(1-2P+2Px-x^2)$ (2)

Gradient $\frac{dy_c}{dx} = \frac{2M}{p^2}(P - x)$ $\quad \frac{dy_c}{dx} = \frac{2M}{(1-p)^2}(P - x)$ (3)

The thickness distribution is given by the equation:

$$y_t = \frac{T}{2}\left(a_0 x^{0.5} + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4\right) \quad (4)$$

*where* $a_0 = 0.02969$ $a_1$=-0.126 $a_2$ = -0.3516 $a_3 = 0.2843$ U

$a_4$=-0.1015 or -0.1036

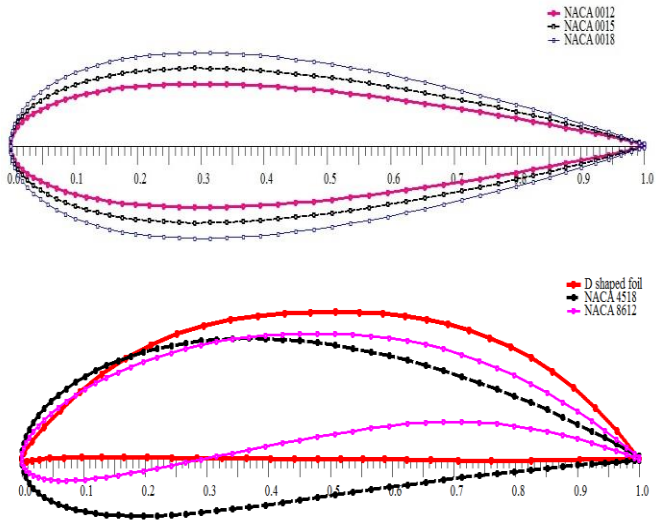
sing the equations 2-4 for a given value of $x$ it is possible to calculate the camber line position $y_c$, the gradient of the camber line and the thickness. The position of the upper and lower surface can then be calculated perpendicular to the camber line.

$$\theta = a\tan\left(\frac{dy_c}{dx}\right) \quad (5)$$

Upper Surface $x_u = x_c - y_t \sin(\theta)$ $\quad y_u = y_c + y_t \cos(\theta)$ (6)

Lower Surface $x_l = x_c + y_t \sin(\theta)$ $\quad y_l = y_c - y_t \cos(\theta)$ (7)

Fig 4. NACA symmetrical and unsymmetrical Airfoil shapes and a D shaped foil




The most popular and effective airfoil shapes and simple D-shaped semicircular foil and its thickness and camber are shown in Fig 4 and dimensions in percentages are tabulated below in Table 2 for the airfoils derived from equation 2-7. For an example, if the airfoil is NACA 4518 means where M is the maximum camber divided by 100.M=4 so the camber is 0.04 or 4 % of the chord and P is the position of the maximum camber divided by 10. P=5 so the maximum camber is at 0.5 or 50% of the chord. Then 18 is the thickness divided by 100. Here the thickness is 0.18 or 18 % of the chord exists at 29.1% chord length and the foils have an angle of criterion equal 29 degrees and the maximum panel angle is 58 degrees exists at a 30-panel position.

Table 2. Thickness and camber size for the airfoils

| Name | Thickness $y_t$ (%) | At (%) | Camber $y_c$ (%) | At (%) | θ (deg) |
|---|---|---|---|---|---|
| 0012 | 12 | 29.1 | 0 | 0 | 29◦ max panel angle 58◦at panel No.30 |
| 0015 | 15 | 29.1 | 0 | 0 | |
| 0018 | 18 | 29.1 | 0 | 0 | |
| 4518 | 18 | 29.1 | 4 | 50 | |
| 8612 | 12 | 29.1 | 8 | 50 | |
| D shaped | 14 | 50.0 | 7.67 | 50 | |

**3. Wind Blade Comparative Analysis**

This wind blade comparative analysis takes the Reynolds number factors and the classical airfoils mentioned in the previous section which is good in both symmetrical and unsymmetrical shapes including a proposed D shaped airfoil chosen to identify a best-suited airfoil for low wind profile area. Apart from blade profile selection the factors like numbers of blades, aspect ratio, and wake analysis also carried for the most effective airfoil from the blade profile discussions. All this analysis will be carried out in a QBlade open source software seamlessly integrated into XFOIL, airfoil design and analysis tool [20,21].

The purpose of this software is to design and aerodynamic simulation of wind turbine blades. The VAWT design in Q-Blade starts with the NACA airfoil selection and it analyzed for the pressure and lift to drag force calculation for the fixed Reynolds number then Polar extrapolation for 360◦ and the blade design aerodynamics, wind field generation and aero elastic simulation carried out in the simulation to identify the performance of wind turbine at the wind field variations. The scale and chamber of the airfoils can also be adjusted in the XFOIL analysis. After importing suitable airfoil then the Blade design and optimization and Multiparameter rotor simulation, Visualization of rotor blades will be carried out in an order [22].

**A. Blade Profiles**

The VAWT blade profiles selection need more care because it rotates perpendicular to the flow, causing the blades to produce an oscillation in the torque about the axis of rotation. The VAWT blades are designed such that they exhibit good aerodynamic performance throughout an entire rotation at the various angles of attack. To study the glide ratio the minimum to maximum Reynolds numbers are loaded to the airfoil selection and in the XFOIL analysis.

Fig 5.Symmetrical blades profile glide ratio (2m/s)

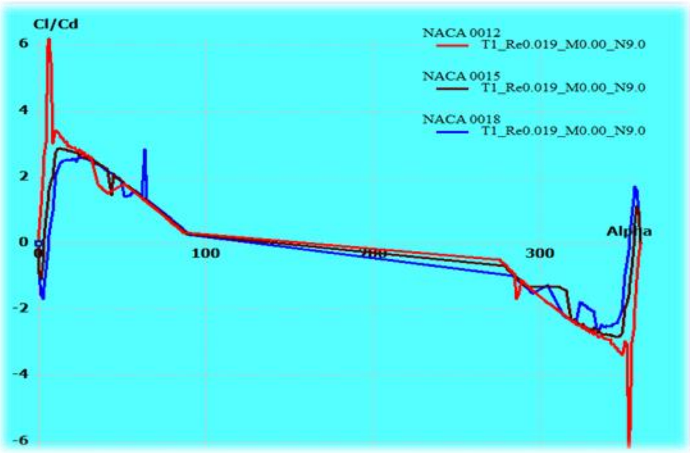
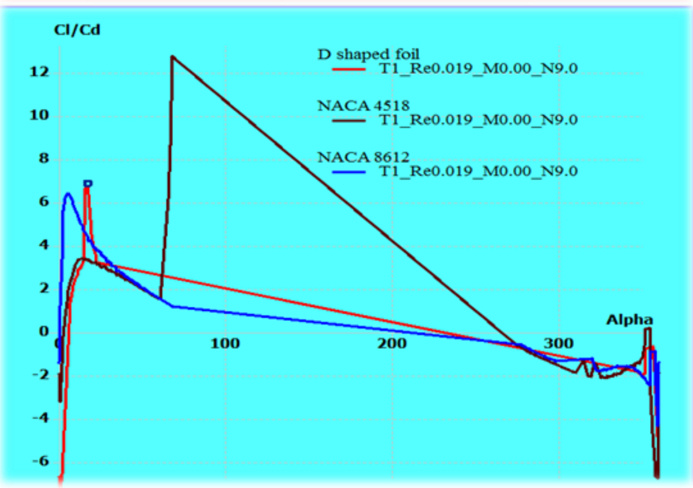



Fig 6. Unsymmetrical blades profile glide ratio (2m/s)




The QBlade simulation results shown in Fig 5-6 and the corresponding results shown in Table 3. The results show that the NACA symmetrical blades suffers at low wind profiles and the NACA 0012 provides better characteristics at low wind speed at an angle of attack of

Table 3. Lift to Drag force variations for Airfoil

| Reynolds Number(minimum) 18530 at 2 m/s wind speed | | | | | | |
|---|---|---|---|---|---|---|
| Factors on significance | Symmetrical airfoil (no camber) | | | Unsymmetrical airfoil ( with camber) | | |
| Airfoil type | NACA SERIES 0012 | 0015 | 0018 | 4518 | 8612 | D SHAPED |
| Lift to Drag Ratio | 6.15 | 2.85 | 2.5 | 3.4 | 6.4 | 6.9 |
| The angle of attack (α) Deg (Minimum) | 7 | 12 | 22 | 14 | 5 | 17 |
| Reynolds Number (minimum) 230000 at 24 m/s wind speed | | | | | | |
| Factors on significance | Symmetrical Airfoil (no camber) | | | Unsymmetrical Airfoil ( with camber) | | |
| Airfoil type | NACA SERIES 0012 | 0015 | 0018 | 4518 | 8612 | D SHAPED |
| Lift to Drag Ratio | 49 | 52 | 52 | 75 | 75 | 20 |
| The angle of attack(α) Deg (Minimum ) | 5 | 6 | 8 | 7 | 8 | 8 |

7 degrees but the proposed D shaped airfoil signifies and provides better Lift to Drag Ratio $\left(\frac{C_l}{C_d}\right) = 6.9$ (Glide Ratio) at low wind velocity at 2m/s at an angle of Attack (Alpha) 17 degrees. Even though the unsymmetrical NACA blades produce a high glide ratio than symmetrical aerofoils the D-Shaped profiles may be the suitable choice for the VAWT at the low wind profile urban areas. The unsymmetrical airfoil NACA 4518, 8612 are producing dominant lift characteristics on high wind profile flow at 23m/s. considering the simplicity the D shaped foil produces reasonably good lift forces which makes it suitable for low wind profile areas, NACA0015, 0018 is also equally good at high wind speed but it produces less lift forces than the all the other type of airfoils proposed in this analysis.

**B. Number of Blades**

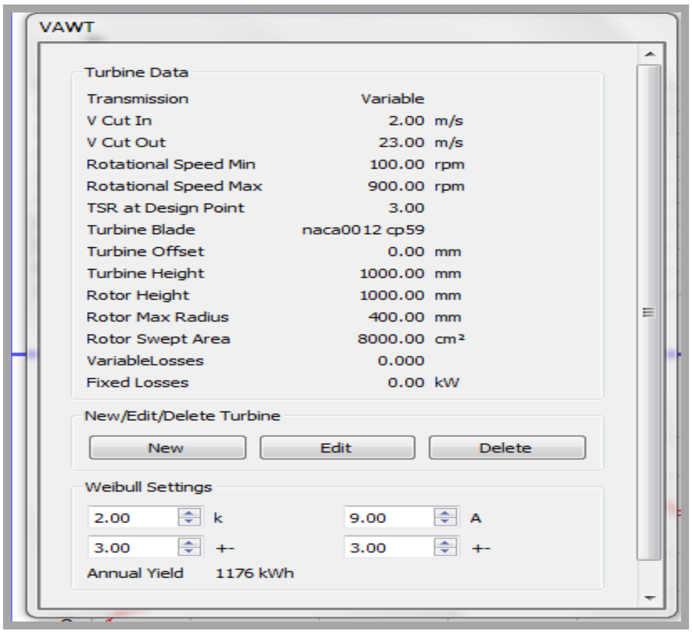
The Number of blade affects the speed of the wind turbine, tip speed ratio, power coefficient and the efficiency of the turbine. The most commonly used wind turbines use three blades and each blade draws some amount of power so that the blade numbers are so significant at we should take care on the blade effect on another blade [16, 17]. In the selection of aerofoil for low wind speed area the unsymmetrical NACA airfoils are eliminated because of its complexity in design and also it has low glide ratio at low wind speed area shown in Table 3. The analysis preferred only NACA 0012 and a proposed D Shaped foil from the optimal number blades 3 to 6 and results are tabulated in Table 4.

Table 4. The effect of No of blades on VAWT Performances on NACA 0012 & D-Shaped airfoil.

| No of blades | NACA 0012 | | D - SHAPED | |
|---|---|---|---|---|
| | 3 | 6 | 3 | 6 |
| The angle of attack (Alpha) Deg | 5 | 5 | 10 | 17 |
| Lift to Drag Ratio $\left(\frac{C_l}{C_d}\right)$ | 28 | 34 | 12 | 14.2 |
| Reynolds No | Varied from 59000 to 89000* | | | |
| Wind speed (m/s) | Varied from 6m/s to 9 m/s* | | | |
| Tip Speed Ratio(TSR) | 4.2 | 3 | 2.8 | 2.5 |
| Power coefficient ($C_p$) | 0.43 | 0.47 | 0.22 | 0.4 |
| Power(Watt) @900 rpm | 160 | 450 | 402 | 652 |
| Energy Generated /Annum (kWh) | 1048 | 1176 | 727 | 1331 |

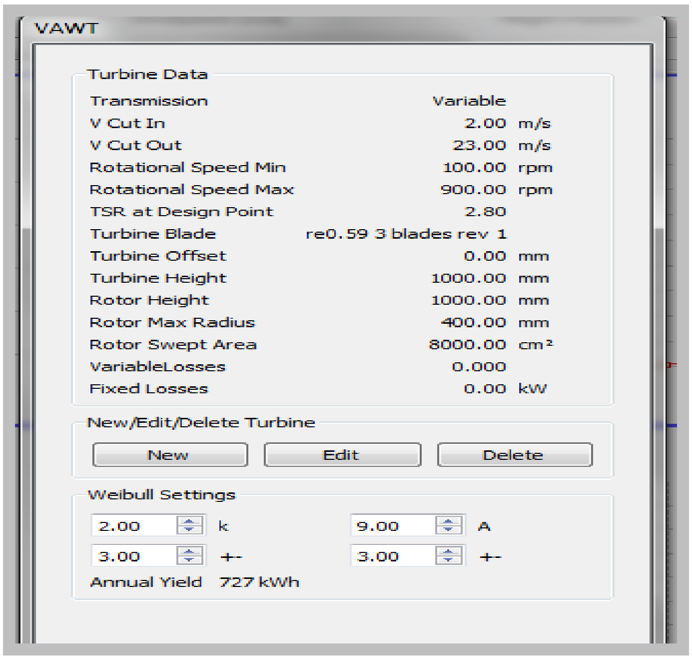
*Values are adjusted to avoid negative Lift to Drag Ratio.

Fig 7.NACA 0012 profile wind turbine results




The simulation results are shown from Fig 9-12 and the tabulated results in Table 4 validate that the D shaped foil is good in producing maximum power and generates energy even at less TSR than the NACA 0012. Increasing the No of blades increases the TSR means even at low wind we get good Lift force than the Drag, but when we increase more than the 6 blades the drag force dominating and bring negative lift to Drag Ratio. The interesting information from the tabulation is that the proposed D shaped airfoil produces the maximum power generation

Fig 8. D-Shaped profile wind turbine results




at the Tip speed ratio for 6 blades combination shows that it is well suited for low wind speed. The energy harvested per annum is 1176 units at 900 rpm as shown in fig 7 which is 11.6 % higher than the NACA 0012 airfoil. This analysis carried out with turbine height taken as 1m and chord length is considered to be 0.14m and the radius is taken as a 0.4 m. The simulation results show that the peak of power coefficient lowers with the increase of rotor solidity, while it moves to lower tip speed ratio. This means that a larger number of blades allow reaching the maximum power coefficient for lower angular speeds but are penalized as far as efficiency is concerned [16, 17]. The power coefficient is an important factor calculated using equation 8 and it is listed in Table 5.

$$C_p = \left[\frac{P}{\frac{1}{2}\rho V_\infty^{\ 3} A}\right] \quad \text{.....................(8)}$$

Fig 9. D-Shaped blades Cp vs. TSR variations for 3, 4, 5, 6 blades

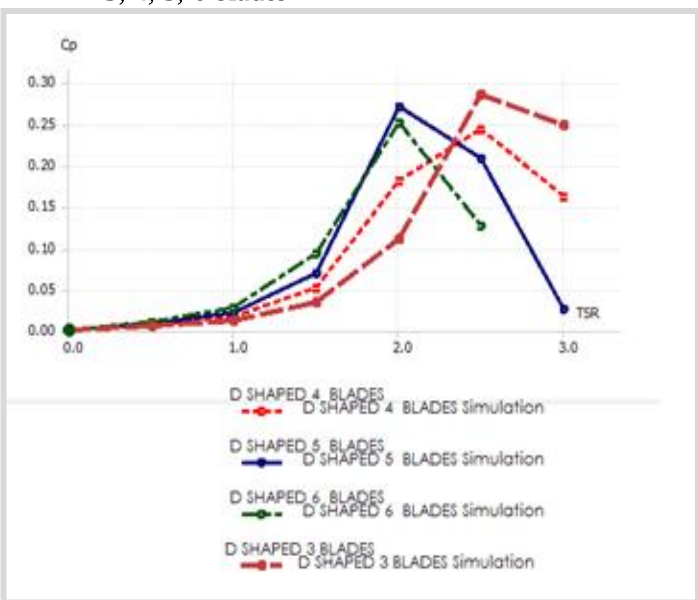


Fig 10. D-Shaped blades power variations with wind Velocity [Electrical characteristics].

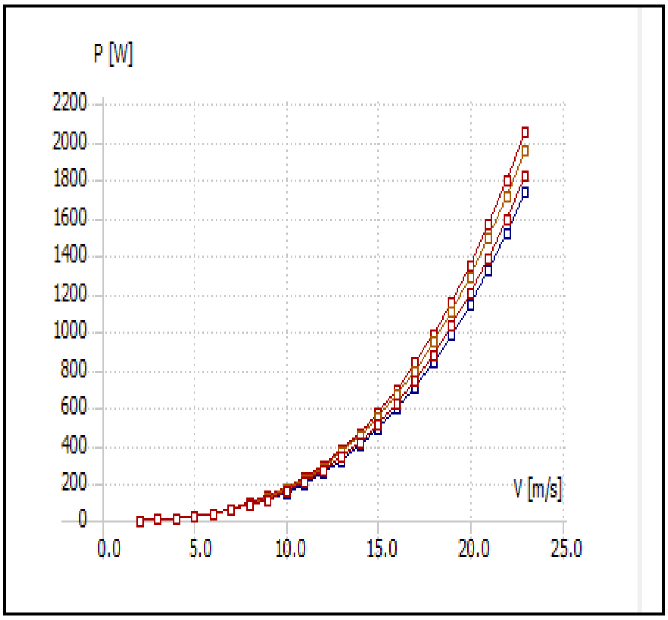
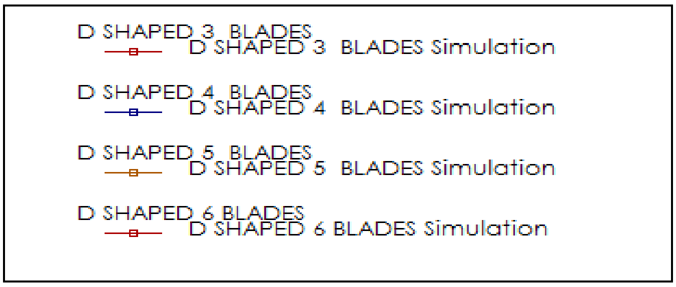
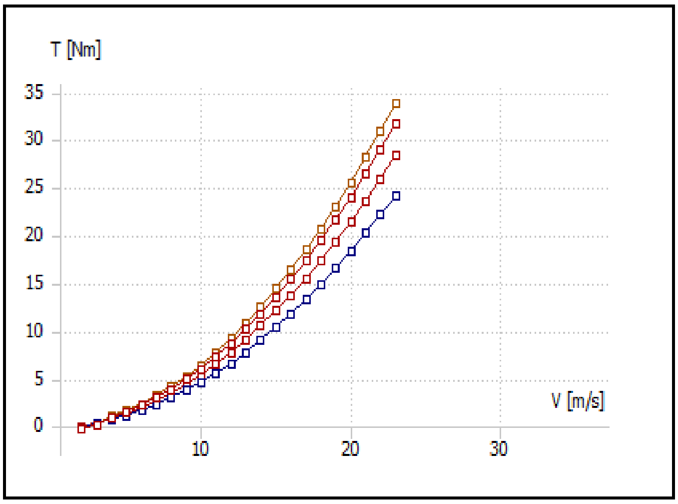



Fig 11.D-Shaped blades Rotor Torque variations with Wind Velocity [Mechanical characteristics]




In the design process of a vertical-axis wind turbine, a wrong choice of the dimension of the wind turbine may cause a low value of the power coefficient (wind turbine efficiency). Their optimum operating conditions (maximum power coefficient) depend on rotor solidity and tip speed ratio [6]. Table 5 exhibits that the even number of blades produces more drag forces than the odd no blades so that the even no blades 4 and 6 has reduced power and energy values than the odd no of blades, between 3 and 4 blades even though it has the same TSR but the energy(kWh) harvesting Variations of 15.68% observed.

Table 5. The Effect of TSR on power coefficient on No. of D- Shaped blades.

Similarly, in between 5 and 6 blades the energy (kWh)

| No of Blades (-) | Power Coefficient (-) | TSR (-) | Max Power (W) | Energy Annual (kWh) | Rotor Torque (N-m) |
|---|---|---|---|---|---|
| 3 | 0.28 | 2.52 | 2050 | 1403 | 29 |
| 4 | 0.24 | 2.5 | 1732 | 1183 | 24 |
| 5 | 0.27 | 2.01 | 1810 | 1338 | 34 |
| 6 | 0.25 | 2.0 | 1820 | 1243 | 32 |

harvesting variations of 7.09% observed. The results in Table 5 shows that the 3 numbers of blades are the best choice because of the maximum power 2050 W and the maximum energy 1403 units which are highest compared with all the other no blades for HAWT or VAWT turbine. But at low wind profile area to see the wind turbine catch more wind and harvesting energy we can use 3, 5 and a symmetrical 6 blades may also be suggested.

**C. Aspect Ratio**

The Aspect Ratio (AR) of a wind turbine is defined as the ratio between blade height (h) and the rotor radius(r). The turbine with the lowest AR will have the highest power coefficient and the lowest rotational velocity. To maximize the power coefficient, the rotor's aspect ratio should be as small as possible [18, 19]. In this analysis, there are two aspect ratio one with $\frac{h}{r} = \frac{600}{800} = 0.75$ and the second one with $\frac{h}{r} = \frac{1000}{400} = 2.5$ are tried to signify the importance of aspect ratio. These dimensions are fixed in the turbine to deliver 1kW power at the maximum wind flow conditions. From the study of the simulation results from Table 6 and Fig 13-14 clearly shows how to high efficiency from a wind turbine design.

Fig12. Simulation result on the effect of Aspect Ratio=0.75 on NACA 0012.

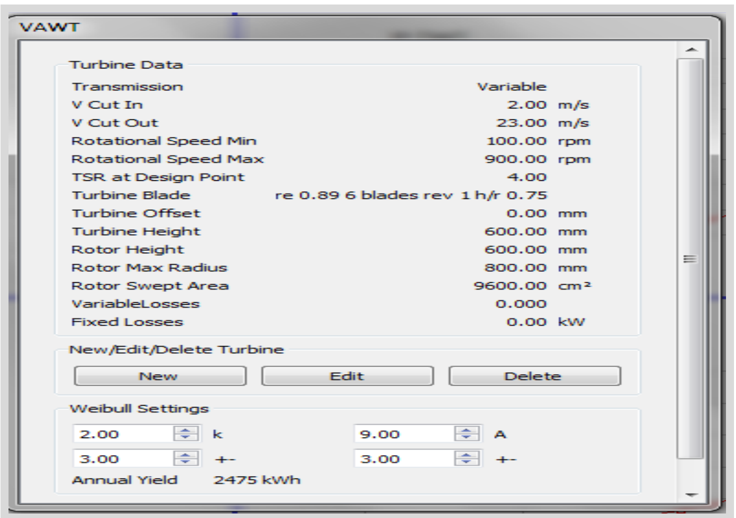
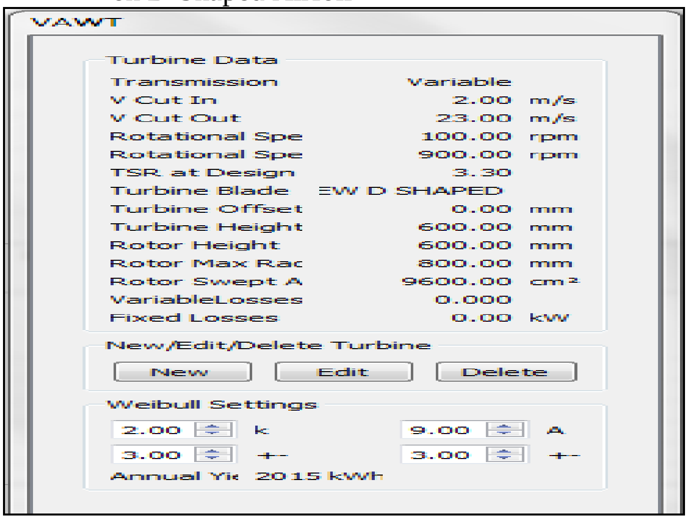


Table 6. The effect of Aspect Ratio on NACA0012

| Number of blades | NACA 0012 | | | |
|---|---|---|---|---|
| | 3 Blades | | 6 Blades | |
| | $\left(\frac{h}{r}\right)=2.5$ | $\left(\frac{h}{r}\right)=0.75$ | $\left(\frac{h}{r}\right)=2.5$ | $\left(\frac{h}{r}\right)=0.75$ |
| Tip Speed Ratio (TSR) | 4.2 | 4.0 | 3 | 4.0 |
| Power coefficient ($C_p$) | 0.43 | 0.41 | 0.47 | 0.52 |
| Power (Watt) @900 rpm | 160 | 1720 | 450 | 2340 |
| Energy Generated /Annum (kWh) | 1048 | 2040 | 1176 | 2475 |

Fig 13. Simulation result on the effect of Aspect Ratio on D-Shaped Airfoil




Simulation result clearly exhibits that NACA 3 blades combination 48.62% and with 6 blades 52.48% increased energy is obtained. Similarly in D shaped aerofoil increased energy from 28.01% with 3 blades to 33.94% means that in VAWT design the high-efficiency turbine is obtained by keeping the aspect ratio to 0.75.

**D. Lifting Line Free Vortex Wake module Analysis (New LLFVW 3D Analysis)**

The air flow over wind turbine blades could be controlled fully, the generation efficiency and thus the energy production would increase by 9%. Like Wind Tunnel used to study the aerofoil in real time turbine blade 3D wind analysis the Wind Field used in simulation analysis [21-22]. Air flows over wind turbine blades are typically

Table 7. The effect of Aspect Ratio on D-Shaped airfoil

| Number of blades | D-SHAPED | | | |
|---|---|---|---|---|
| | 3 Blades | | 6 Blades | |
| | $\left(\frac{h}{r}\right)=2.5$ | $\left(\frac{h}{r}\right)=0.75$ | $\left(\frac{h}{r}\right)=2.5$ | $\left(\frac{h}{r}\right)=0.75$ |
| Tip Speed Ratio (TSR) | 2.8 | 2.7 | 2.5 | 3.3 |
| Power coefficient ($C_p$) | 0.22 | 0.2 | 0.25 | 0.42 |
| Power (Watt) @900 rpm | 402 | 1500 | 652 | 2900 |
| Energy Generated /Annum (kWh) | 727 | 1010 | 1331 | 2015 |

complex and to unsteady turbulent features due to the changes in the angle of attack and to unsteady flow separation at high angles of attack. To accurately capture and optimal design wind turbine blades the 3D Visualization techniques can be very helpful in achieving this goal [23-24, 25].

Fig 14. Wind field Generated for the Average wind Velocity of 12 m/s

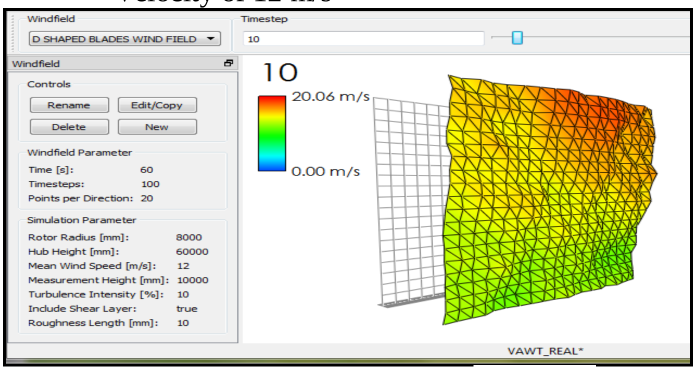
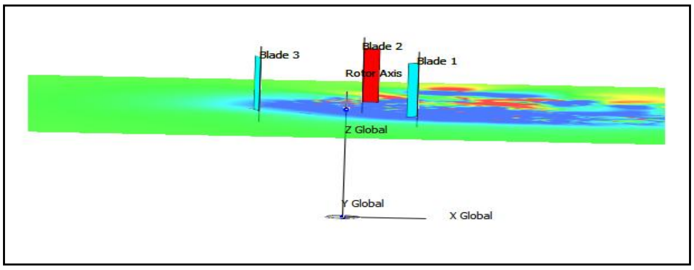


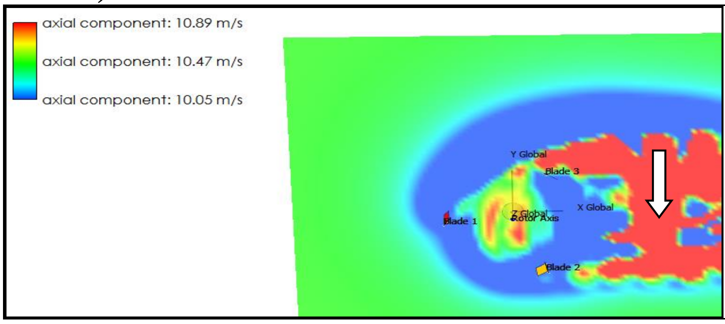

Fig 15. Velocity Cut plane for 3 Blades (The 2D surface at an arbitrary channel location).



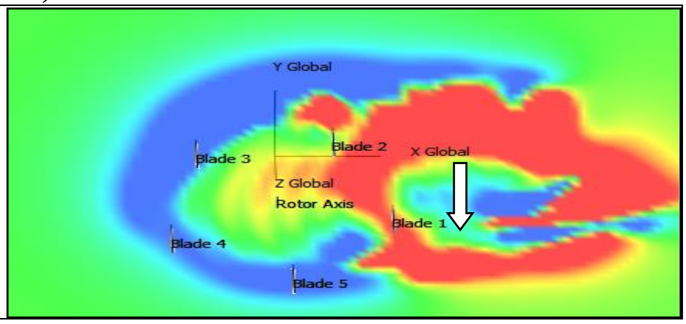

The wind field shown in Fig 15 generates wind 0 to 20.6 m/s speed with an average of 12m/s wind speed and this wind field arbitrarily located as a velocity cut plane to blow on wind blades to study about the VAWT blade profiles.

Fig 16. Wind Flow around the rotor in the axial direction and vortex formation in catching downwind produces Negative drag force after a t=0.02 sec.

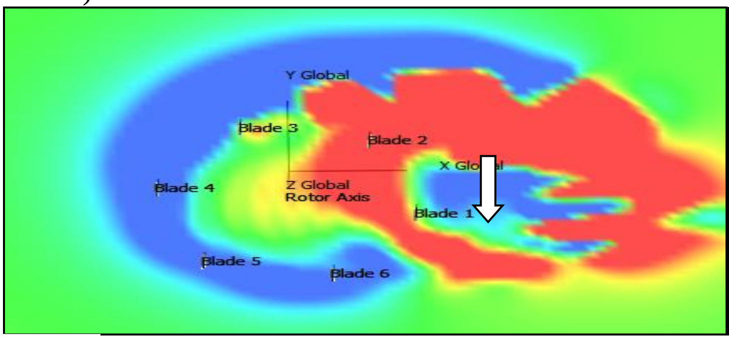
a) For 3 blades



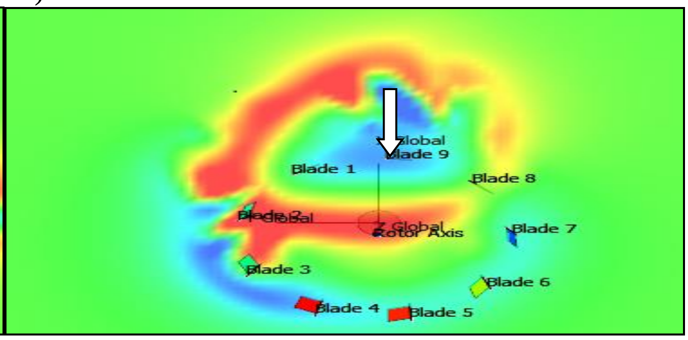

b) For 5 blades



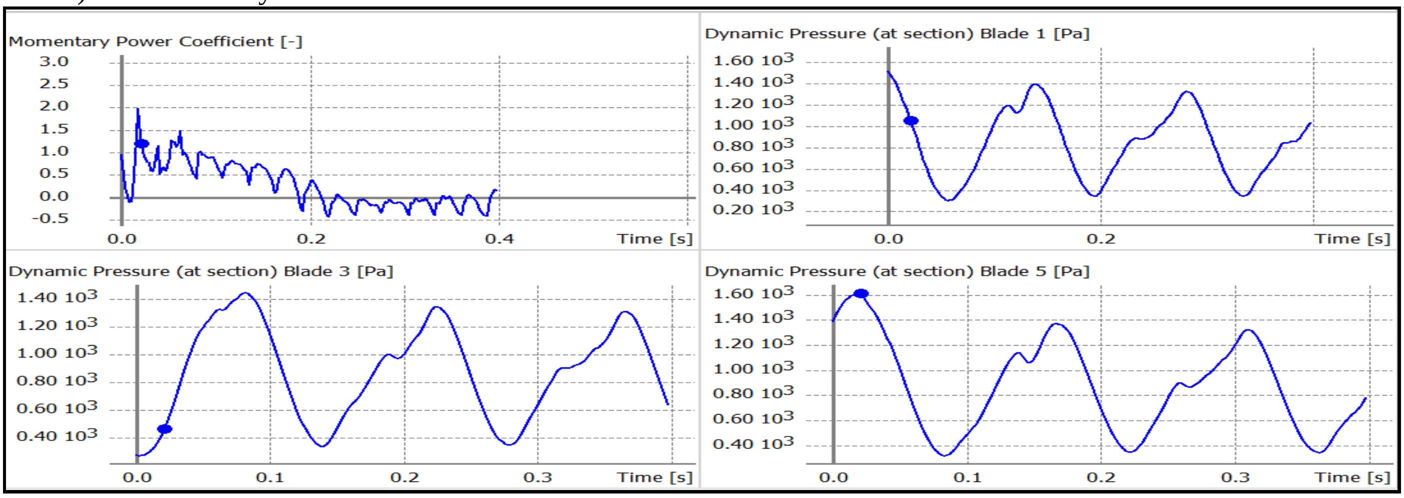

c) For 6 blades




d) For 9 blades




e) Pressure Analysis of wind flow at t=0.02 sec




For this analysis, QBlade uses a new theory called Lifting Line Free Vortex Wake module Analysis (New LLFVW 3D Analysis) which specially designed for VAWT. A large benefit of the Lifting Line Theory over the Blade Element Momentum (BEM) method is the velocity distribution in the flow field around the rotor can be obtained. The lifting line does not have any convergence problems and the accuracy is drastically improved. In Fig 15a – 15d, 3, 5, 6, 9 blades's the LLFVW 3D Analysis shows good uniform low velocity and high pressure is available around the rotor in 3 blades but this variation is poor in case of 6 and 9 blades which is shown in the arrow at the figures. Hence the use of an extremely wide VAWT that with low aspect ratio most of the wind passing through the upwind blade passes has time to speed up to close to the wind speed before reaching the downwind blade passes. The upwind VAWT blades capture 80% of the energy and the other downwind blades capture only 20%. In the case of odd number blades, the downwind captured by blades increased to increase the efficiency of VAWT. In the low aspect ratio, the *Cp* could be still higher and torque could be increased without lowering the tip speed ratio, due to reduced back pressure. In conclusion 3 and 5 blades with wider diameter give good efficiency than the huge height even number blade rotor design. Fig 20 shows the pressure exerted in all the three blades at 0.02 sec and it shows the highest pressure forced in the blade number 3 and at that instant shows that the wake wind in a three blade effectively utilizing the downwind for originating good pressure in the odd number blades. Same kind pressure is seen at blade number 5 in a 5 bladed VAWT showing that the odd number blades are good in efficiently converting the downwind much better than the even number symmetrically placed VAWT.

## 4. Design of Virtual Simulink Model for VAWT

The study and analysis of various types of blade profiles and no of blades, the aspect ratio for a VAWT give significant and encouraging results to construct a real-time wind turbine with high efficiency in the field of optimum utilization wind energy [23, 24].

$$P_m = C_p(\lambda,\beta) A V^3_{wind} \text{(Watt)} \ldots\ldots\ldots(9)$$

where

$P_m$ = Mechanical output power of the turbine (W)

$C_p$ =Power Coefficient(-)

$\lambda$=Tip Speed Ratio(-)

$\beta$=Bladepitchangle(deg)

$\rho$=Air density (kg/m$^3$)=1.23

A=Turbine swept area (m$^2$)

$V^3_{wind}$ =Wind speed (m/s)

Normalized in p.u

$$P_{m\text{-}pu} = k_p C_{p\text{-}pu} V^3_{wind} \ldots\ldots\ldots\ldots\ldots(10)$$

$P_{m\text{-}pu}$ = power in p.u for the particular values of $\rho$ and A

$$\text{Revoltion(rpm)} = \frac{V_{wind} \times TSR \times 60}{2 \times \pi \times R} \ldots(11)$$

where

R=Radius of the wind turbine(m)

In order to take these results and to study it in the Matlab-Simulink Environment for the further analysis like Fuzzy and Neural network optimization application a virtual VAWT model constructed using Equations 9-11. In this model TSR values obtained from the QBlade analysis used input values and Cp values calculated from the Subsystem shown in Fig17. The complete virtual model shown in Fig 18a, 18b which has five sections) Wind area calculation section 2) Revolution of turbine calculation 3) Cp calculating Subsystem 4) Energy calculation unit 5) Display section. This model is simulated for 3600 seconds and to convert this into kWh and the result obtained is tabulated in Table 6.and Waveform is shown in Fig 19. The Simulink results show the similar ranges of values of Cp, Power, Energy at average 12m/s wind speed and maximum 23m/s wind speed. For $\left[\frac{h}{r}\right]$=2.5 for 6 blades the error percentage in power -3.4 and for $\left[\frac{h}{r}\right]$ =0.75 error percentage +7.1.Since the error percentage looks ±10% hence the virtual Model can be uploaded for optimization of wind energy in home energy automation using Fuzzy and Neural network simulation.

Table 8. The Virtual Simulink Model for VAWT Results with the proposed D Shaped blades

| Aspect Ratio $\left(\frac{h}{r}\right)$ | TSR (-) | Cp (-) | Power (W) Ave. wind 12 m/s | Power (W) Max. wind 23 m/s | Energy (kWh) Ave. wind 12 m/s | Energy (kWh) Max wind 23 m/s |
|---|---|---|---|---|---|---|
| 2.50 | 2.5 | 0.25 | 95.8 | 675 | 0.095 | 0.675 |
| 0.75 | 3.3 | 0.41 | 382 | 2694 | 0.382 | 2.694 |

Fig 17. VAWT subsystem Model to calculate power Coefficient (Cp)

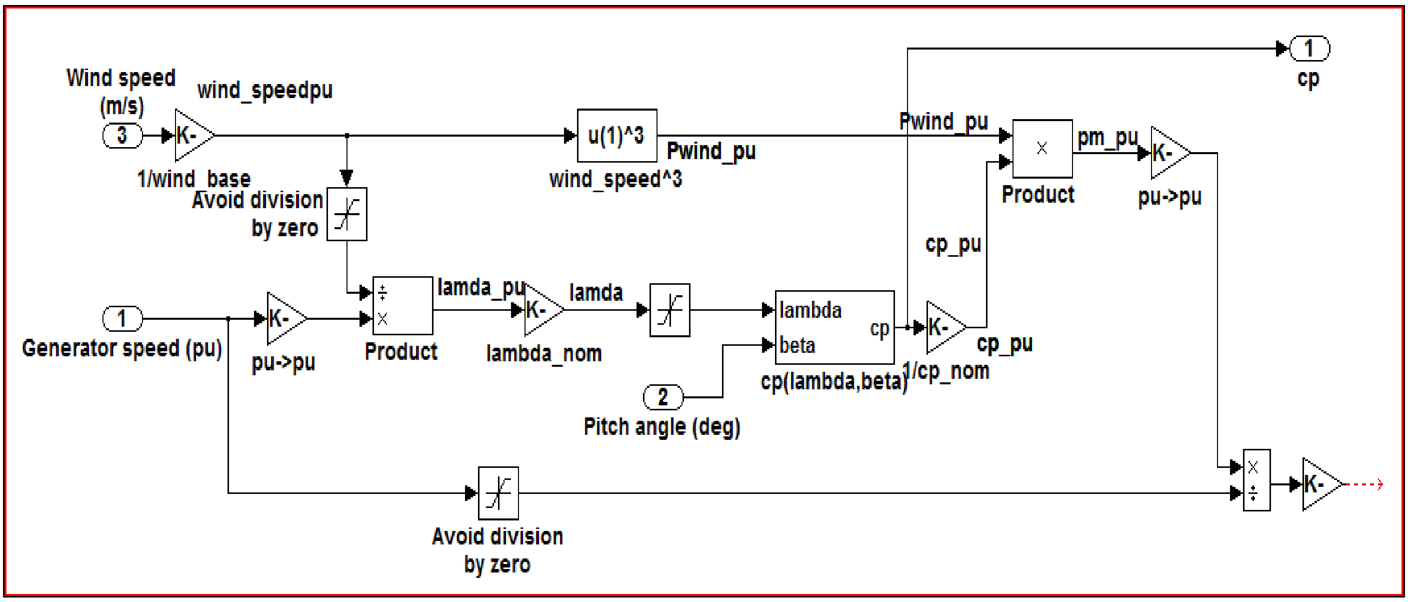
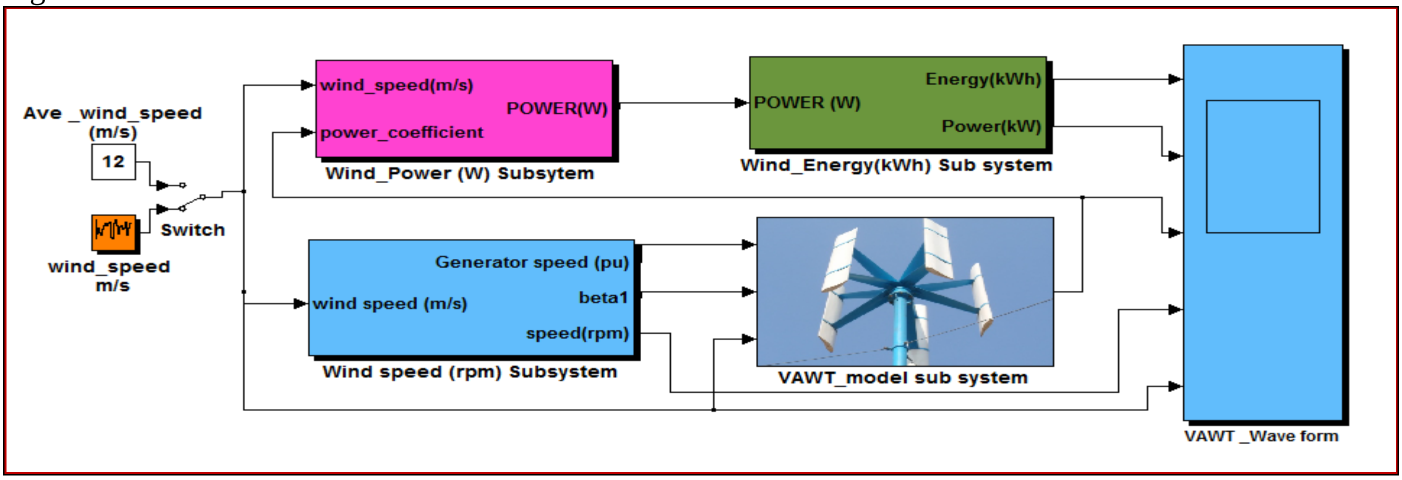
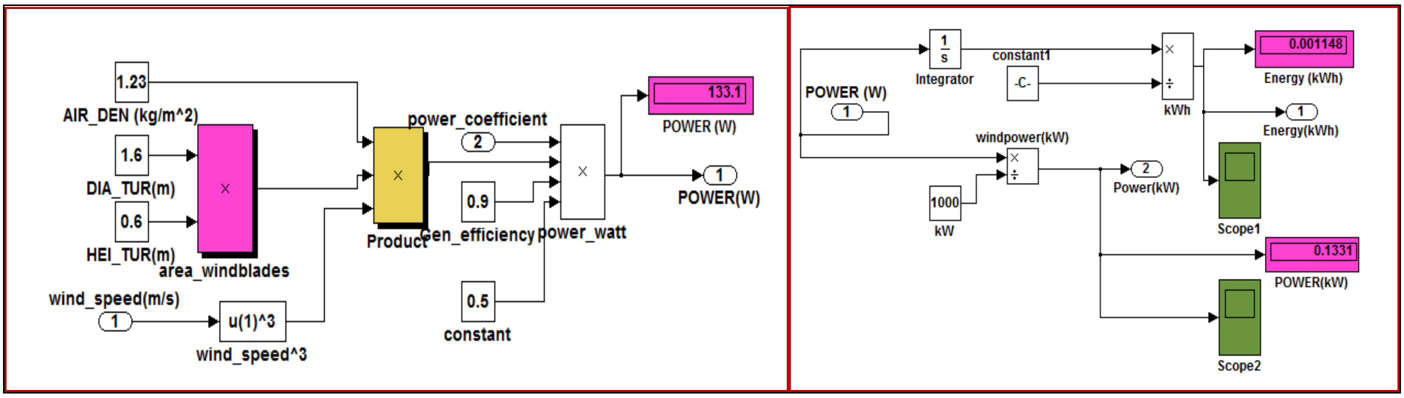


Fig 18. Virtual Simulink Model for VAWT




a) Subsystem: wind power and energy calculation




b) Subsystem: wind speed calculation

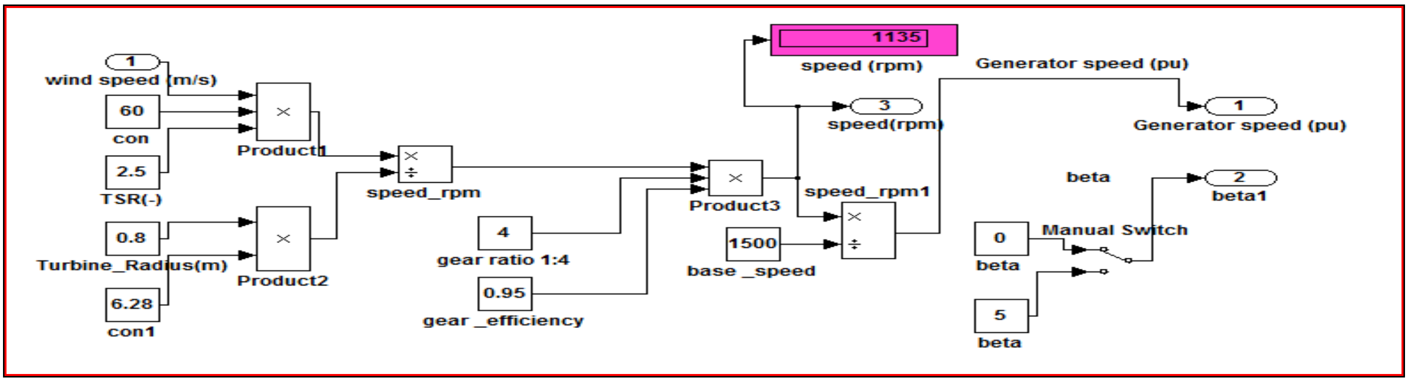
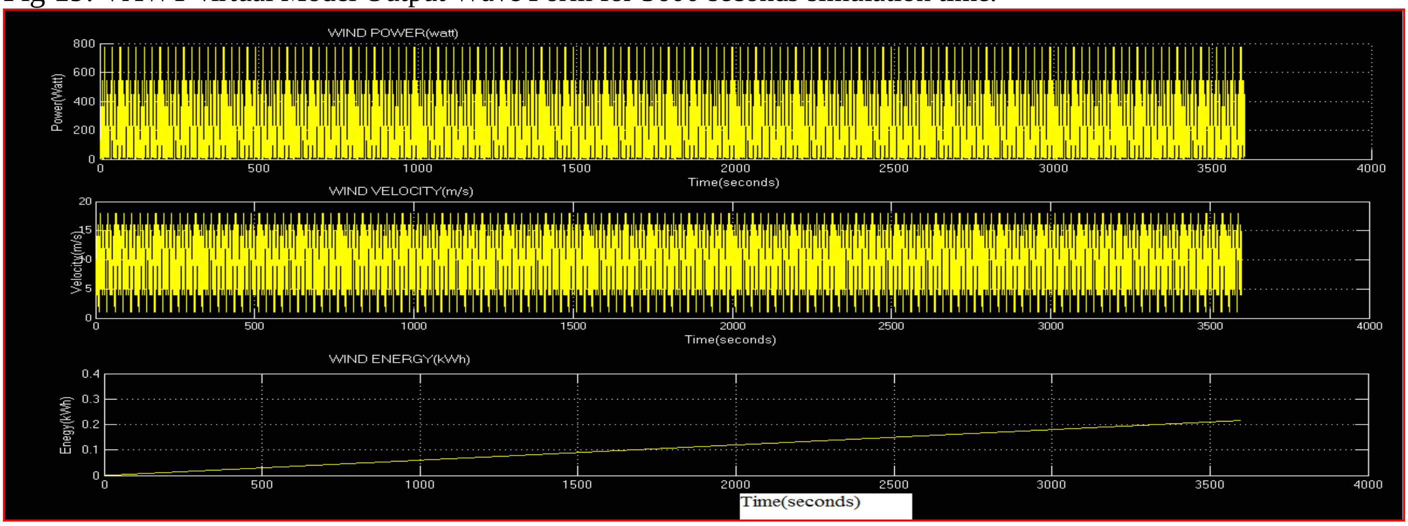



Fig 19. VAWT virtual Model Output Wave Form for 3600 seconds simulation time.



**5. Practical Implementation of VAWT model**

The Encouraging study and the results obtained through the various analysis need to be verified by the practical implementation. For this purpose, two different VAWT Model constructed with aluminum blades. They are,

1) Diameter (D) =1.6 m and Axial Length= 0.6 m with an aspect ratio of 0.75 constructed .This Model constructed with 1:4 gear ratio and 1kW,180V, 2000 rpm, PMDC Generator as shown in Fig 20. The blades are fixed at an angle of 30◦ which the optimum angle to the geographical location. The straight C shaped blades are used to make the giromill type wind turbine self-starting using the huge amount of drag forces than the lift forces are generated even at low wind speed.

Fig 20.VAWT model with aspect ratio = 0.75 with PMDC Generator 1:4 gear ratio Assembly.

The VAWT Generator may be selected with the low RPM because of the reason in low wind profile areas the rated wind may be 10 - 16m/s. so that the rpm of the wind generator approximately equal to

$$Revolution(RPM) = \frac{V_{wind} \times TSR \times 60}{2 \times \pi \times R}$$

$$= \frac{10 \times 3 \times 60}{2 \times \pi \times 0.8} = 715 \text{ rpm}$$

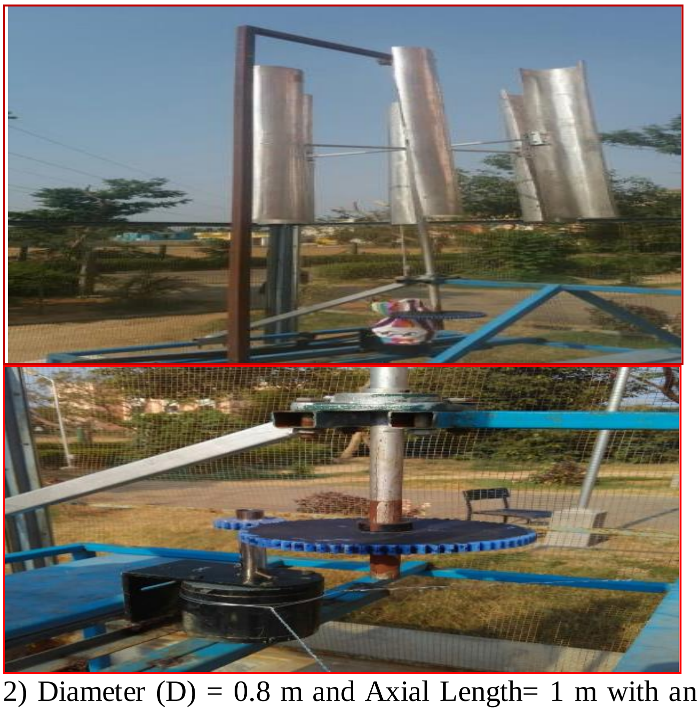
But the Non-availability of low-speed PMDC generator the high-speed generator could not give the rated voltage at average wind speed available in the proposed area. For this reason, we constructed a gear with 1:4 gear ratio in a suitable material. In case, if the 1000 rpm generator available we may avoid the Gearbox. Because the Design without gear saves 1/3rd of the VAWT cost and the gearbox costs more also need periodic maintenances. This can be solved by making the generator bigger with better control aspects. Table 9 shows the test results taken at the 1 kW VAWT Model low wind profile proposed area at a 10ft height from the ground level.

Table 9. Reading taken at VAWT model with Aspect Ratio= 0.75

| S.No | Wind Velocity (m/s) | Generated Voltage (volt) |
|---|---|---|
| 1 | 1.24 | 3.1 |
| 2 | 2.80 | 5.6 |
| 3 | 4.91 | 10.3 |
| 4 | 6.40 | 14.9 |
| 5 | 7.09 | 20.7 |
| 6 | 9.48 | 25.3 |
| 7 | 10.99 | 30.8 |
| 8 | 12.43 | 35.2 |
| 9 | 14.06 | 40.6 |
| 10 | 15.07 | 45.9 |

The readings are taken through a Tachometer at the gear side and then converted into the linear velocity. The reading shows that even at the 15 m/s only 45.9V generated because it is a high rpm generator even with reasonable gear ratio but when the turbine is rotating high torque was sensed in the shaft. It means the VAWT has a huge variation in the aspect ratio.

Fig 21.VAWT model with Aspect Ratio= 2.5 with PMDC Generator 1:7 gear ratio Assembly.



2) Diameter (D) = 0.8 m and Axial Length= 1 m with an aspect ratio of 2.5 constructed .This Model constructed with 1:4 gear ratio and 1kW,24V, 1500 rpm PMDC Generator as shown in Fig 21. This turbine generates 7.5 V at 6m/s wind velocity means that VAWT with low aspect ratio 0.75 generates 14.9 V in the same wind speed shows the,

$$\% \text{ increase in Volts } \frac{14.9\text{-}7.5}{14.5} \times 100 = 49.6\%$$

This confirms the low aspect ratio 0.75 is an effective aspect ratio in VAWT model design and this is established through simulation results through various analyses.

## 6. Results and Discussion

1) Reynolds Number is a sensitive factor in the wind turbine analysis. In low wind profile urban areas for a cut in speed from 2m/s to cut out speed 23 m/s, for the fixed chord length 0.14m calculated Reynolds Number varies from 18530 to $0.23\times10^{6}$. But in this simulation, the Reynolds number in the ranges from 59000 to 89000 used to support low wind profile areas and lesser than this value produces negative values in Lift to Drag $\left[\frac{C_l}{C_d}\right]$ coefficient and also in energy harvested.

2) NACA unsymmetrical aerofoil 4518 and 8612 give highest Glide ratio but only at high wind speed (23m/s) but poor performance for low wind profile areas. The proposed D-Shaped airfoil capable of producing a good glide ratio better than both symmetrical (NACA 0012) and unsymmetrical airfoils.

3) Low wind profile areas necessitate more no of blades to give startup with increased TSR, in this analysis 3, 4, 5, 6 blades are discussed. The Odd Number of blades (3 or 5) produces much better energy than the even number of blades (4 or 6). This result was confirmed by the 3D Lifting Line Theory which implies that because of the increase in efficiency due to catching more downwind effectively than the symmetrical even number of blades.

4) Lower Aspect Ratio $\left[\frac{h}{r}\right] = 0.75$ VAWT machines are nearly 49.6% more efficient than the high Aspect ratio $\left[\frac{h}{r}\right] = 2.5$ turbines because of the effective usage of downwind by the wider spaced blades which is confirmed in the New LLFVW 3D Analysis.

5) The new virtual Simulink VAWT model Designed with fixed TSR gives more reliable results with ±7 % error and can be implemented to Wind flow analysis in Mat lab-Simulink environment.

6) Instead of high lift generating D shaped foil a C shaped straight bladed semi-circular cut type foil with 0.14m chord length is used to self start with highest drag force at low wind speed. Interestingly wind turbine rotates even at 2 m/s wind speed. This practical turbine looks like a hybrid of Savonius and Darrieus wind turbine which can give higher units of energy at low wind speed and it called as Hybrid H type VAWT machine which useful model for low wind profile area.

## 7. Conclusion

Aspect Ratio of 0.75 with Odd Numbers blades of either 3 or 5 with D shaped airfoil with 500 - 1000 rpm range PMDC generator suitable for the low wind profile areas which improve the overall efficiency in the simple way. The maintenance cost is quite low for this simple combination and also once it seeded can harvest Energy even for 25 years. The virtual VAWT model created and validated with simulation results can be a useful tool for the analysis of VAWT model in Mat lab simulation environment for the optimum Wind Energy usage for Home Energy Automation (HEM) using Demand Side Management (DSM). The practical model created with 0.75Aspect ratio VAWT machine shows that the

$$\%\ \text{Energy Efficiency} = \frac{2040-1010}{2040} = 0.5049 \text{ (or) } 50.49\%$$

(Maximum Power) more efficient than the 2.5 aspect ratio reciprocated dimension VAWT model. Hence with D or C shaped 3 bladed 1000 rpm PMDC generator without any gear mechanism can give simplest and more efficient VAWT can give a minimum of 1010 units per annum as seen from the simulation results at Average wind speed. It reduces stress in National Grid that too during heavily loaded summer season fortunately during that period wind season attains its peak harvesting in India.

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