

Modelling and Performance Evaluation of Vertical Axis Wind Turbine (VAWT)

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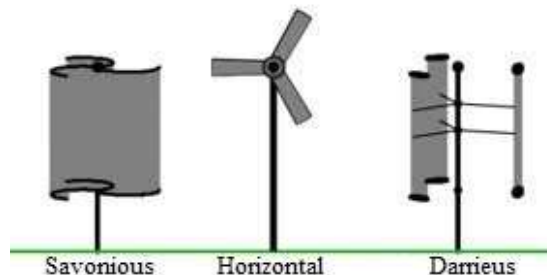
Abstract- Today, the world is facing an energy crisis and as it gets sever, our dependence will face a greater shift from non-renewable energy sources to renewable ones. In fact, one of the most efficient sources of renewable energy is ubiquitous – the wind. Currently, horizontal axis wind turbines (HAWTs) dominate the wind energy production industry, however, vertical axis wind turbines (VAWTs) can be very efficient in utilizing wind energy at low speeds and altitudes and can be used for domestic and small scale applications. One major drawback of VAWTs is their inability to self-start. This paper presents a summary of major research works carried out in the field and how a prototype of H-type Darrieus wind turbine was built and tested for its optimum performance.

Keywords: Darrieus Turbine, Renewable Energy, Wind Energy, Vertical Axis Wind Turbine, Blade profile, Giromill

I. INTRODUCTION

Wind power is unquestionably one of the most widely present and utilized renewable energy source. It is efficient and cheap to utilize. With each passing year the investment in wind power is growing and many nations have made potential plans to produce more and more of their national energy from wind.

Wind turbines can be broadly divided into two main types based on their axis of rotation, namely, Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs) as shown in Fig 1. Among the two VAWTs are the lesser known ones, primarily due to their efficiency at low wind speeds which is in contradiction to that of HAWTs which generally operate at higher altitudes.



Merits of vertical axis wind turbines over horizontal axis wind turbines are shown in Table-1 below.

Table 1. Merits of VAWT over HAWT [1]

Parameter	VAWTs	HAWTs
Tower Sway	Small	Large
Yaw Mechanism	No	Yes
Self Starting	No	Yes
Overall Formation	Simple	Complex
Generator Location	On ground	Not on Ground
Height from ground	Small	Large
Blades operation Space	Small	Large
Noise Produced	Less	Relatively high
Wind Direction	Independent	Dependent
Obstruction for Birds	Less	High
Ideal Efficiency	More than 70%	50-60%

There are basically two main designs or sub-types of VAWTs, the Savonius type and the Darrieus type. There are several sub classifications of the Darrieus type based on blade shape, profile etc. However, the focus here is on H-type straight bladed Darrieus turbines and some of the several parameters that influence its performance. They are also called ‘giromill’ turbines. Some of the most significant variables are Turbine solidity, Number of blades, Airfoil selection, Blade pitch angle and Turbine aspect ratio (H/D).

The commensurate study by Sandra Eriksson et al. [2] has shown that VAWTs are advantageous over HAWTs in several aspects. Furthermore, quite a few misconceptions about VAWTs have been discussed. When juxtaposing the two types of VAWTs considered here, the H-rotor seems more advantageous than the savonius turbine. The strength of the H-rotor concept is the possibility to keep the structure relatively simple and hassle free. The H-rotor does not require any yaw mechanism, pitch regulation or gearbox and therefore has few movable parts. Another advantage is its expected low need of maintenance. The study of the aerodynamics of a Darrieus turbine is quite intriguing [3].

El-Samanoudy et al. [4] examined the performance of VAWT by varying the design parameters such as, pitch angle, airfoil type, number of blades, its chord length and turbine radius. Large numbers of experimentations have been performed by altering the fore mentioned parameters. The effect of each parameter on the power coefficient and torque coefficient has been studied and explanation of the results was also discussed. It has been found that the turbine radius, chord length and pitch angle have a considerable effect on turbine power coefficient.

M. Payam Sabaeifard et al. [5] also carried out a computational and experimental study into the aerodynamics and performance of small scale Darrieus-type straight-bladed VAWT and as a result, it has been found that a 3-bladed turbine with 35% solidity has the best self-starting ability and efficiency among all possible configurations.

N.C. Batista et al. [6] posits a new methodology for a brisk development of new blade profiles, in order to have Darrieus wind turbines capable of self-starting which is a

convoluted and tedious task. A new technique is introduced in cooperation with the JavaFoil computational tool, to study these phenomena, as a quick approach for juxtaposing the several blade profile design alterations and improvements in new airfoil developments. Kinloch Kirke Brian [7] studied several possibilities for self starting of the turbine, prediction of performance and different parameters of airfoil which affect the performance subsequently. Travis J. Carrigan et al [8] presented a fully automated process for optimizing the airfoil cross-section of VAWT. This work successfully illustrated a completely automated process for optimizing the airfoil cross-section of a VAWT. Haris Hameed Hammad Rahman et al. [9] practised a detailed experimentation for symmetric blade profiles. The results were for TSR range from 1.0 to 4.0 and for a range of oncoming wind velocities from 6 m/sec to 14 m/sec. it was concluded from his study that even though NACA 0022 profile gave the best performance, it was NACA 0012 and NACA 0015 that gave a better performance at a TSR of 4.

II. CONCEPT DEVELOPMENT OF DARRIEUS TURBINE

The name of this turbine is derived from the name of a French engineer Georges Darrieus. It consists of generally two or three blades connected to a vertically erected shaft. In the earlier versions of the Darrieus design, the aero foils are arranged so that they are symmetrical and have zero rigging angle that is, the angle at which the aero foils are set relative to the structure on which they are mounted.

A. Nomenclature

- A. A = cross section area
- B. C_p = performance coefficient
- C. c = chord (m)
- D. D = diameter of the wind turbine (m)
- E. R = radius of the wind turbine (m)
- F. σ = solidity
- G. t = time in seconds
- H. U_∞ = free stream velocity (m/sec)
- I. U_{rot} = rotational Speed of Turbine
- J. α = angle of attack
- K. β = azimuth angle
- L. ω = rotational speed (rad/sec)
- M. ρ = density of air
- N. TSR = tip speed ratio

B. Working Principle:

The Darrieus turbine utilizes the concept of lift v/s drag force to spin the rotor blades and thereby generate kinetic energy and ultimately torque. When the Darrieus rotor is spinning, the aero foils are moving forward through the air in a circular path. Relative to the blade, this oncoming airflow is added vectorially to the wind, so that the resultant airflow creates a varying small positive angle of attack (AoA) to the blade. This generates a net force pointing obliquely forwards along a certain 'line-of-action'. As the aero foil moves around the back of the apparatus, the angle of attack changes to the opposite sign, but the generated force is still obliquely in the direction of rotation, because the wings are symmetrical and the rigging angle is zero. When distinguished into components, the thrust component contributes to the turbine rotation; whereas the fluctuating radial component can lead to turbine vibration and blade fatigue (see Figure 2). The preset blade pitch angle, β , is defined as the angle between the blade chord and the tangent to the swept arc at the mount point, as can be seen in Figure 2.

C. Operating Characteristics of Wind- Mill:

1. **Effect of speed on power:** The area from rated speed to cut-out speed is called constant power output area and above 25 m/sec, the power will begin to fall and consequently the turbine will come to a stop.
2. **Axial force characteristics:** The effect of tip speed ratio on thrust force coefficient can be seen further, taking the number of blades as parameter. For the same tip speeds, the thrust force increases as the blade number increases. (i.e. solidity).
3. **Dynamic characteristics:** Here the main concern is the turbine speed ratio to power coefficient. With increase in speed ratio, the power coefficient attains maximum value at a given tip speed ratio. This power output decreases with too close or too far spacing of rotating blades.

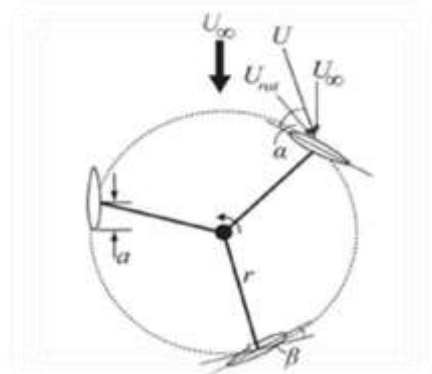


Fig 2: Plan view of turbine showing the preset blade pitch angle (β), angle of attack (α), the incident wind speed due to U_∞ and rotational speed U_{rot} and mount location offset (a).

D. Performance Evaluation:

Wind turbine performance is commonly characterized by the relationship of the coefficient of performance (C_p) to the turbine tip speed ratio as shown in Figure 3. The turbine C_p is defined as:

$$C_p = \frac{P_{out}}{0.5\rho U_{\infty}^2 S}$$

Where U_{∞} is the nominal wind speed, ρ is the air density, and S is the swept area of the turbine (for an H-Darrieus, $S = L \times D$, where L is the blade length, and D is the turbine diameter).

Tip-Speed Ratio:

The ratio of blade tip velocity to the undisturbed wind velocity. The Equation is as represented under:

$$TSR = \frac{\omega R}{U_{\infty}}$$

III. PRINCIPLE OF WIND POWER GENERATION (MOMENTUM THEORY)

The basic and simple principle behind utilizing wind power is that when the high velocity wind passes through the rotor blades, a part of the kinetic energy (K.E.) of wind is converted to mechanical energy and that in turn is used to rotate the wind turbine. For calculation purposes, the wind blade is considered very small and an assumption is made that the density of air passing through the wind turbine remains constant.

After the mathematical calculation, the following equation is derived as a conclusion:

$$\therefore \frac{W_{max}}{W_{total}} = 0.593$$

This indicates that the maximum possible η (efficiency) of the wind turbine system is 59.3%. This ratio is also called as power coefficient (C_p) and given by,

$$(C_p)_{max} = \eta_{max} = 0.593$$

This is known as Bitz Limit, names after the scientist who developed this equation the very first time. Hence, the maximum actual work developing efficiency of the wind rotor will be 60%.

$$\therefore \eta_{possible} = 0.593 \times 0.6 = 0.35 = 35\% \text{ only}$$

Hence, from the above conclusion it has to be noted that the universal maximum turbine efficiency possible can only be 35%. Thus while designing the turbine, Bitz limit is to be kept in mind in selecting the numerical values for parameters.

IV. SELECTION OF BLADE PROFILE AND NUMBER OF BLADES

When it comes to selecting blades for H-Type Darrieus turbine, there are two most popular standards followed worldwide.

- National Advisory Committee for Aeronautics U.S. (NACA)
- National Renewable Energy Laboratory U.S (NREL)

NREL have fewer profiles as compared to NACA as it has been developed in recent years. Now, NACA has various aerofoil profiles, the profiles are coded by generally 4 digits, with each digit standing for a quantitative value of a particular factor that affects the performance.

Example: NACA 2412, which designate the camber, position of the maximum camber and thickness. If an airfoil number is

NACA MPXX

e.g.

NACA 2412

Then,

- M is the maximum camber divided by 100. In the example M=2 so the camber is 0.02 or 2% of the chord
- P is the position of the maximum camber divided by 10. In the example P=4 so the maximum camber is at 0.4 or 40% of the chord.
- XX is the thickness divided by 100. In the example XX=12 so the thickness is 0.12 or 12% of the chord.

E. Rotor Design Calculation:

Considering the kinetic energy of wind,

$$K.E. = \frac{1}{2} mV^2$$

$$= \frac{1}{2} (\rho AV) V^2$$

$$= \frac{1}{2} \rho AV^3$$

Where,

A= Swept Area of blades

ρ = Air Density

$$= 1.225$$

V = Wind Velocity

Now, for 30W power

Taking turbine efficiency (η_t) = 30%

Generator efficiency (η_g) = 85%

Thus from the equation of power, we get

$$P = \frac{30}{0.30 \times 0.85}$$

$$= 117 \text{ W}$$

Now taking wind velocity = 7 m/s, equating the K.E. of wind to the value of power obtained we get,

$$117 = \frac{1}{2} \rho A V^3$$

Hence, we get, swept area (A) = 0.56 (Approx)

But, A = D x h

Where, D = diameter

h = height

Thus, from swept area obtained above we select the diameter of turbine as 0.90 m and height of the blades as 0.6 m. It has been known that keeping the D/h ratio equal to about 1:1 is found to be optimum. Hence the selected values for parameters are found to be optimum.

F. Preparing a computer aided design of rotor blades:

Using Creo 1.0 a computer aided design of rotor blades bearing NACA 0012 profile and the remaining assembly was generated. It can be seen in the figures below.

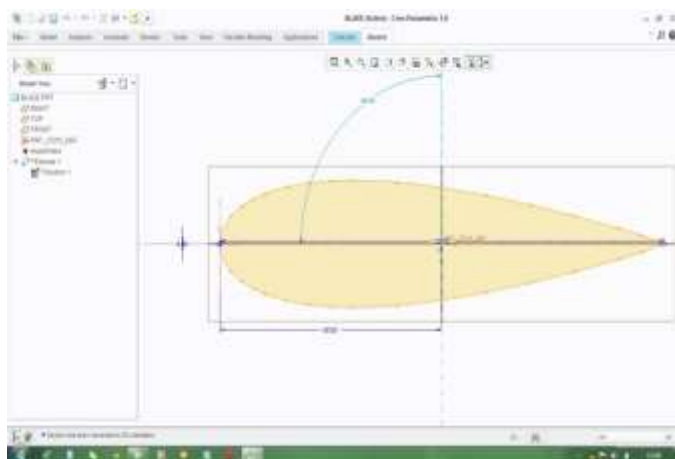


Fig 3. NACA 0012 profile generated using Creo 1.0

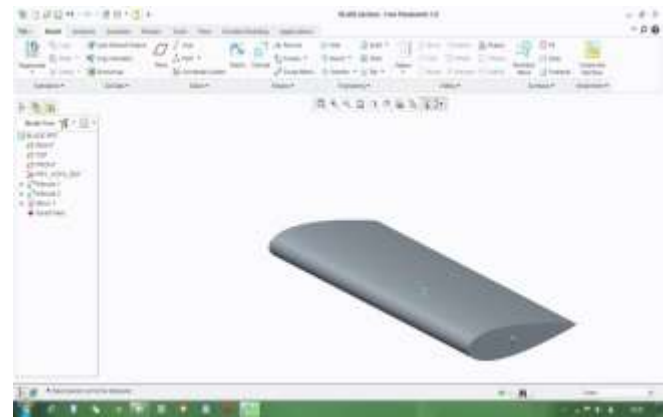


Fig 4. An extended 3-D view of a single NACA 0012 profile

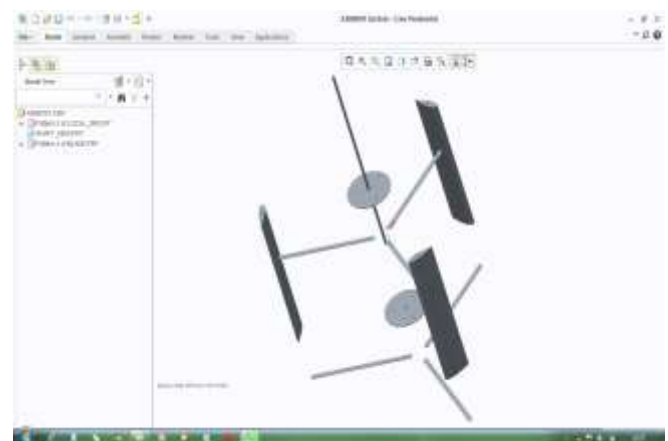


Fig 5. An exploited view of all components

G. Fabrication of the designed model:

Blades were made out of Deodar wood, with a chord length of 120 mm and span of 700 mm. On both ends bolts were provided for assemblage with the main links. Thereafter two Artelon disks with 10 mm thickness and 150 mm diameter were used to transmit power to the main shaft. The light weight and robust nature of the disks enhanced power transmission without any jerks during rotation of the blades. Mild Steel strip of 2mm thickness, 10mm width and length of 400 mm are used as main links. Main links connect the blades with disc which in turn transfer lift from blade to disk and then to shaft. Holes were drilled on to the disc with a drilling machine, after measuring equal angles on the disc. Nuts clamped tightly on to the screws hold them in place and thus minimize the vibrations and add to the stability. The other end of the main links is attached to the blades. The same drilling operation was performed on the blades as well to make accurately placed holes with drill bits of suitable diameter. Two ball bearings with inner diameter of 12mm were used to reduce friction between the shaft and the fixed frame, moreover the bearings were placed in a flange to make them suitable to mount on the disks. At the end a DC generator was attached to the rotor by means of gears to help measure the power available at the output of the shaft.

H. Experimental Setup:

For this experiment, a wind tunnel available at our college facility was utilized and the air flow was kept constant using a butterfly valve. For sake of experimentation a velocity of 7 m/s was considered. In addition a vane type digital anemometer was used to measure the speed of wind. Along with that a digital tachometer was also used to measure the rpm of the rotating shaft. The wind turbine was started and speed was adjusted by the butterfly valves till it displayed a speed of 7m/s on the anemometer, thereafter the speed of the shaft of constantly measured with the tachometer and the power output of the shaft was measured with the help of a wattmeter attached to it. The procedure was repeated three time for elimination of possible errors.

I. Observation Tables:

For sake, let us consider the following TSR formula:

$$TSR = \frac{NK}{V}$$

$$N = \frac{TSR * V}{R}$$

$$N = \frac{3 * 7}{.40}$$

$$N = 52.5 \text{ RPM}$$

The following observation tables show the results for various wind speeds. It is essential to note that the power output is measured for predetermined speed for different Tip- Speed Ratios

Table 2. Tip Speed Ratio (TSR)

TSR	Speed related to given TSR	Electrical Power output (Watt), P_E			
		Experiment 1	Experiment 2	Experiment 3	Averaged
1	17.5	1.63	1.71	1.72	1.68
2	35	7.21	7.15	7.07	7.14
3	52.5	11.58	11.25	12.30	11.71
4	70	12.78	12.63	12.91	12.77
5	87.5	17.5	17.12	17.31	17.31
6	105	15.01	14.21	13.28	14.16
7	122.5	14.96	14.80	14.95	14.90

J. Calculation for power:

Mechanical Power Output, P_m :

$$P_m = \frac{P_E}{0.80}$$

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It has been assumed that the efficiency of transmission and conversion is 80%

Coefficient of Performance, C_p :

$$C_p = \frac{P_m}{\frac{1}{2} \rho A V^3}$$

Where,

P_m = Power output (Watt)

A = Swept Area (.56 m^2)

C_p = Coefficient of performance.

ρ = density of air (1.225 Kg/ m^3)

V = Wind velocity (7 m/s)

Sample Calculation:

$TSR = 3$

For $TSR = 3$ we get,

$N = 52.5 \text{ RPM}$

Averaged Electrical Power $P_E = 11.71 \text{ watt}$

Mechanical power P_m :

$$P_m = \frac{P_E}{0.80}$$

$$P_m = \frac{11.71}{0.80}$$

$$P_m = 14.64 \text{ Watt}$$

Coefficient of Performance, C_p :

$$C_p = \frac{P_m}{\frac{1}{2} \rho A V^3}$$

$$C_p = \frac{14.63}{\frac{1}{2} * 1.225 * 0.56 * 7^3}$$

$$C_p = 0.1244$$

Similarly, we can calculate Coefficient of performance at different TSR value and plot performance curve. The following table and curve show results for wind speed of 7 m/s.

Table 3. Co-efficient of Performance C_p

TSR	P_t (Watt)	P_m (Watt)	C_p
1	1.68	2.11	.017935
2	7.14	8.93	.075904
3	11.71	14.64	.01244
4	12.77	15.97	.0135743
5	17.31	21.64	.183937
6	14.16	17.71	.150533
7	14.90	18.63	.158352

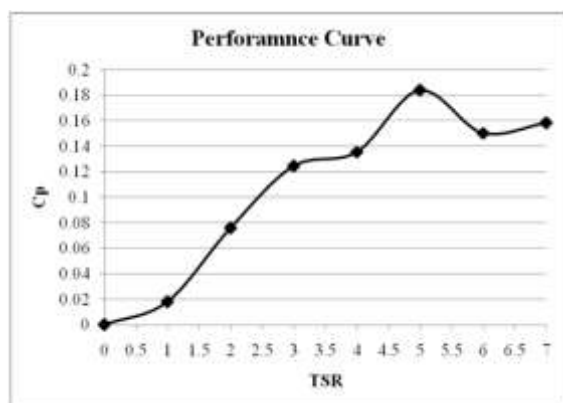


Fig 6. Graph for wind speed of 7 m/s

Here from experimentation we can conclude that coefficient of performance increases with increase in TSR first up to TSR 5 and then starts to decline with increase in TSR. Maximum coefficient of performance is 0.18 at TSR = 5.

A comparative graph of all three wind speeds is shown in the figure below. From that we can conclude that, the performance is comparatively low at speed of 5 m/s. whereas the performance stays pretty much same for speeds of 7 m/s and 8 m/s. Thus from the combined graph analysis, it can be concluded that wind speed of 7m/s is suitable for optimum performance of the turbine. Too low speeds maybe insufficient to start the turbine while too high speeds may damage the blades and hinder the performance.

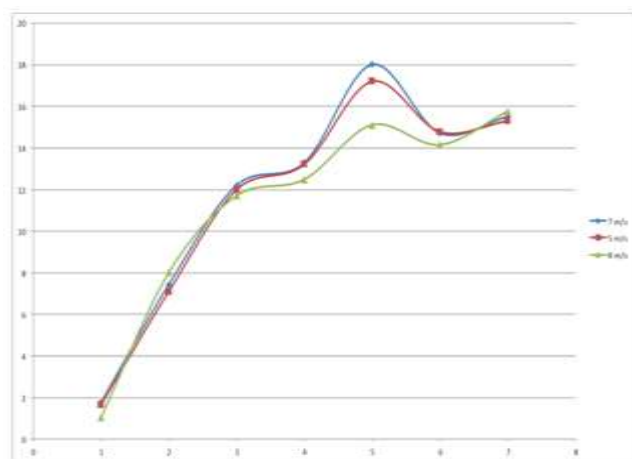


Fig 7. Combined graph for 5 m/s, 8 m/s and 7 m/s

V. CONCLUSION

From the experiment and analysis discussed above, the following conclusions can be substantiated:

1. VAWTs are omni-directional and the absence of yaw mechanism and lower transmission losses make them more advantageous than HAWTs for low altitudes.
2. VAWTs have a greater capacity to utilize wind energy at low speeds and altitudes and hence can be employed for domestic and small scale uses at home or offices or high- rise buildings.
3. H-Type Darrieus turbine is relatively the simpler and hassle free in design and fabrication as compared to troposkien curved ones.
4. NACA 0012 profile gives the best results.
5. Pitch angle, wind velocity and TSR are some of the most influential factors for performance of the turbine.
6. A wind speed of 7 m/s and Tip – Speed Ratio (TSR) of 5 give the optimum performance and power output of the turbine prototype built.

VI. REFERENCES

- [1].Muhammad Mahmood Aslam Bhutta, Nasir Hayat, Ahmed Uzair Farooq, Zain Ali, Sh Rehan Jamil and Zahid Hussain, "Vertical axis wind turbine – A review of various configurations and design techniques" in *Renewable and Sustainable Energy Reviews*, vol. 16, 2012, pp 1926–1939.
- [2].Sandra Eriksson, Hans Bernhoff and Mats Leijon, "Evaluation of different turbine concepts for wind power" in *Renewable and Sustainable Energy Reviews*, vol. 12, 2008, pp 1419–1434.
- [3].Kleine Windräder, Berechnung und Konstruktion, "Brief introduction to the Darrieus wind turbines", Book, Berlin, Bauverlag, 1989.
- [4].M. El-Samanoudy, A.A.E. Ghorab and Sh.Z. Youssef "Effect of some design parameters on the performance of a Giromill vertical axis wind turbine" in *Ain Shams Engineering Journal*, 2010, pp 85–95.
- [5].Payam Sabaeifard, Haniyeh Razzaghi and Ayat Forouzandeh "Determination of Vertical Axis Wind Turbines Optimal Configuration through CFD Simulations" in *International Conference on Future Environment and Energy*, 2012, pp 109-113.
- [6].N.C. Batista, R. Melício, J.C.O. Matias, and J.P.S. Catalão "Self-Start Performance Evaluation in Darrieus-Type Vertical Axis Wind Turbines: Methodology and Computational Tool Applied to Symmetrical Airfoils" in *Center for Innovation in Electrical and Energy Engineering, Instituto Superior Técnico*, 2010.
- [7]. Kinloch Kirke Brian, "Evaluation of self-starting vertical axis wind turbines for stand-alone applications", Ph.D. thesis, Griffith University, Brisbane, Australia, 1998.
- [8]. Travis J. Carrigan, Brian H. Dennis, Zhen X. Han, and Bo P.Wang "Aerodynamic Shape Optimization of a

Vertical-Axis Wind Turbine Using Differential Evolution”
in *International Scholarly Research Network ISRN
Renewable Energy* Vol.12, 2012.

[9].Naveed Durrani, Haris Hameed, Hammad Rahman and
Sajid Raza Chaudhry “A detailed Aerodynamic Design and
analysis of a 2D vertical axis wind turbine using sliding
mesh in CFD” in *49th AIAA Aerospace Sciences Meeting
including the New Horizons Forum and Aerospace
Exposition*, Jan 2011, Orlando, Florida.