Design and fabrication of NACA 0018 straight bladed vertical axis wind turbine

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Abstract. The most important advantage in generation of electric power using renewable sources of energy, like wind, are the non availability of toxic exhaust emission products, highly uncluttered and the infinite presence of wind that is finally transformed into electricity. The generation and utilization of wind has been considered as one of the mature and cost effective resources among the various available renewable energy technologies. A wind turbine is a rotating machine that is converting the winds kinetic energy initially to mechanical energy, which finally getting converted into electric power. The wind turbines basically are of two types, i.e. Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT). The main point of difference between the two is the position of their axis of rotation. When wind blows over the VAWT, only a fractional part of the blades generates the torque whereas the remaining parts simply rotate. The end result of this is a comparably reduced efficiency in power generation. Here, a miniature Darrieus type VAWT with straight blade - NACA 0018 Airfoil, is designed and fabricated so as to develop maximum possible power output. The blades are designed in way were majority of the air covers majority of blade surface area and thus rotating it at its maximum possible speed. The results shows that the system we developed could produce power of 23.45 watts, with blades designed for aspect ratio of 0.24. This is the maximum possible result that can be attained for this dimension. The entire system is made of strong material so that it could also withstand high wind speed and high energetic wind possible.

Keywords: Wind Turbine; NACA 0018; Turbine blade; Darrieus type; VAWT

1. Introduction
The utilisation of wind for generation of power has been used from long back itself especially in water pumping, milling of grains and various other mechanical operations. Wind power extraction is never a novel idea. The application areas of VAWT are so large as they have the ability to catch the wind from different directions and will work without any yaw mechanisms, rudders etc [1, 2]. The electrical generators of VAWT can be placed very near to the ground level and hence making it more accessible. Inability to self start is one of the common drawbacks in most of the designs. These units are capable of working even during unsteady or non-stable flow conditions and thereby, they are apt for small scale as well as urban applications [3-5]. Since they are axially symmetrical, energy production doesn’t interrupt even if there is higher wind turbulence condition. In case of VAWT system, the maximum power coefficient condition or the optimum operating condition depends on the two factors i.e. Rotor solidity and Tip speed ratio [6]. Also, the rotor solidity is depending on the factors like
blades numbers, air foil chord and radius of the rotor. The Tip speed ratio is a function of mainly three factors i.e. angular velocity, free steam wind speed and rotor radius.

Aerodynamic design of the turbine blades is one of the important aspects of consideration in design process. Researchers are concentrating on the improvement of the performance of the blades [6, 9]. The primary aim is to maximise the energy production per year by the optimisation of the curve between Power coefficient and Tip speed ratio [8]. So, for the optimisation of the curve, various airfoil sections and rotors with different solidity can be used, if the total area of cross section remains constant [9-11]. Guide vanes [12] and/or blades with variable pitch angle is employed in order to improve the wind energy extraction. Selection of turbine blades with proper aspect ratio is another factor in judging the overall efficiency of the system as it may lead to the decrease in power coefficient. The experts in design tend to select the proper aspect ratio for the blades based on their experience. They do not consider the scientific aspects of this.

There are mainly two categories of VAWT: The Darrieus type and the Savonius type. The R and D division of Sandia National Laboratories, USA had developed the Darrieus type of the system in early 1980’s [1]. Various novel design concepts of VAWT are developed such as the helical types, which are having low speed of rotation and hence can be used safely in urban environment. As per the investigations of symmetrical airfoils ranging from NACA 0012 to NACA 0021, it was found that NACA 0018 airfoils yield the best results in terms of aerodynamic performance for a wide range of Tip speed ratios [13-16]. Darrieus wind turbine will be achieving the maximum Power coefficient of nearly 0.4 at the Tip speed ratio of 5-6 [17]. At lower values of tip speed ratios, dynamic stalling effects will be occurring and also at higher values of Tip speed ratios (above 6), the aerodynamic effects of the rotor elements plays a major role in reducing the net rotor power coefficient [18-19]. The tip speed ratio is one of the factors in determining the local Reynolds number.

In this present investigation, the design and fabrication of a miniature H-rotor Darrieus type 4 bladed VAWT is done. The blades selected are a straight type with NACA 0018 Airfoil cross section and their design is considered by optimising the aspect ratio and local Reynolds number. The core essence of this paper involves understanding the various developments in the area of VAWT, selection of suitable materials, designing of turbine blades based on optimised conditions, performance analysis of the design and finally, the fabrication of the end product. The performance calculations are performed as per the predetermined dimensions so as to maximise the power developed.

2. Principle elements and Material selection

2.1. Principle elements of the system
The major elements of our system are as follows:

- **Battery**: The system uses Lead-acid wet battery with lead peroxide (PbO₂) and spongy lead (Pb) as anode and cathode respectively and sulphuric acid (H₂SO₄) as electrolyte. This cell is more advantageous in comparison to other secondary cells because they have the highest output voltage, which means that only few cells are required to be used to meet the specified battery voltage.

![Figure 1. Inverter and battery](image-url)
• **Frame**: The material used for the frame is mild steel. The entire assembly is to be mounted on this frame. During assembly of all the components, the bearings have to be aligned properly. For that, the boring of bearing sizes and open bores are done in a single setting. Grease is applied at necessary points in the bearings and arrangements are made for that also.

• **Bearing**: Ball and roller bearings is selected so that the frictional loss as well as the power loss can be very well minimized. The Bearings are made up of steel and bearing cap is made with mild steel.

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**Figure 2. Frame**

• **Gear mechanism**: The spur gear mechanism is selected to transmit power between the parallel shafts.

• **DC Generator**: A DC Ferro magnet generator (12 V - 14 A – 100 rpm) is selected to convert the mechanical power into the electrical power.

• **Inverter**: Thyatron Inverter is selected to convert the supplied DC power to AC power output.

• **Shaft**: The important power transmitting unit, shaft is designed and arranged to connect the blades with bearings and generator. Bearing supports the shaft. The power is transmitted when the shaft rotates a set of gears or pulleys. The material used for the shaft is plain carbon steel, which is produced by hot-rolling. The advantages of plain carbon steel include lower cost, good machinability, great wear resistance and toughness and much higher value of impact resistance. The shaft arrangements are shown in Figure 3.

• **Turbine Blades**: The blades are aerodynamically designed in a way that they will fix on a direction at all 4 power extracting units. The blade design used is a straight blade with NACA 0018 Airfoil section.

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**Figure 3. Shafts arrangements**
2.2. Material selection
The list of various components and their specifications/dimensions are given in Table 1 below:

| Components       | Specifications/Dimensions                                      |
|------------------|--------------------------------------------------------------|
| 1. Shaft         | $l = 91.44 \text{ cm, } d = 20 \text{ mm, material – Plain carbon steel}$ |
| 2. Bearing       | Type - Ball bearing, ISI no - 6204                           |
| 3. Round plate   | $l = 10.16 \text{ cm, } t = 6 \text{ mm}$                  |
| 4. Gear mechanism| Type - Spur gear, Ratio - 1:6                               |
| 5. Blade         | Type - Mild steel, $L = 0.6 \text{ m, } b = c = 0.2 \text{ m, } t = 1 \text{ mm, NACA 0018}$ |
| 6. Generator     | Type - DC Ferro magnet $12V - 14 \text{ A - 100 rpm}$       |
| 7. Battery       | Type - Lead acid, Volt $=12V$, Amp $= 7\text{A}$             |
| 8. Diode         | Amp $= 1\text{A}$                                           |

3. Working principle
The experimental setup consists of Turbine blades mounted on the shaft. The shaft along with the blades is mounted on the frame and a set of spur gears are provided at the end of the shaft. The larger gear drives the smaller gear. A DC generator is mounted on the smaller spur gear such that the generator rotates along with the spur gear. The spur gears are used to speed up the rotation of the shaft. Highway blades are used instead of conventional wind mill blades, since this can be mounted on low altitudes and also the wind from any direction can hit the blades of the turbine and rotates the wind mill. As the wind hits the blades of the wind mill, the wind mill rotates and tends to rotate the shaft of the wind mill. This makes the gears to rotate and sufficient speed ratio is attained in the smaller spur gear. As the gear is connected with the generator, power generation is done. The generated power is stored up in the battery. While using it, it must be inverted. Hence a suitable inverter circuit is provided and then connected with a load, usually a bulb or a fan.
4. Design of turbine blade

The turbine blade selected for our fabrication purpose is a straight blade with NACA 0018 Airfoil section. From the numerical results during the literature survey, it is observed that NACA0018 airfoil is the most appropriate airfoil section that can be used in a lift-type vertical axis wind turbine rotors because it could permit the wind turbine to attain the highest value of wind energy utilization efficiency along with lower cost of production compared to other designs. Also, in case of Darrieus type with NACA0018 airfoil sections, the value of maximum values of power coefficient can be attained based on the values of tip speed ratios. So, the blades are designed by considering the values of tip speed ratios so as to maximize the power coefficient values.

The two important factors considered while designing the blades are: Blade aspect ratio (AR) and local Reynolds number (Re).

We have,

\[
\text{Aspect Ratio, } AR = h/R \tag{1}
\]

Where, \( AR = \text{Aspect ratio}, \ h = L = \text{Length of blade (m)}, \ R = \text{Rotor radius (m)} \)

Also,

\[
\text{Local Reynolds Number, } Re = \frac{c \ w}{\nu} \tag{2}
\]

Where, \( w = \text{Relative airfoil wind speed (m/s)}, \ c = \text{Airfoil chord (m)}, \ \nu = \text{Kinematic air viscosity (m}^2/\text{s}) \)

![Figure 5. 3D model of Straight turbine blade with NACA 0018 Airfoil section](image)

From the literature survey, the turbines with lowest value of AR will have the maximum value of power coefficient. Also, the turbines with lower value of AR posses other advantages like in-service stability or greater rotor inertia [20]. If we want to maximise the power coefficient, the aspect ratio must be as small as possible. This reduction in aspect ratio has other advantage like the rise in value of local Reynolds number. So, to fix the dimensions of the blade, we need to optimise between the AR and Re as the terms like \( h, c, \) and \( R \) are the depending factors.

Hence, the method adopted is an iterative one to select the dimensions by considering the values of AR and Re as AR value should be low and Re should be a higher value. Also, the economic aspect is considered as it has to be manufactured for the development of the final product.

The dimensions of the blades are therefore taken as given in Table 1:

Length (Height), \( L = h = 0.6 \text{ m} \), Breadth (Chord), \( b = c = 0.2 \text{ m} \), Thickness, \( t = 1\text{ mm} \), Rotor radius, \( R = 2.5 \text{ m} \).

The 3D model of the blade is shown in Figure 5 and the actual blade is shown in Figure 6.
Now, calculating the AR and Re values based on the selected dimensions,

From equation 1 and 2,

\[ AR = \frac{h}{R} = \frac{0.6}{2.5} = 0.24 \]

\[ Re = \frac{c}{\nu} \]

For calculating Re, the values we know are, \( c = 0.2 \text{ m} \), \( \nu \) (at 20 °C) = \( 15.06 \times 10^{-6} \text{ m}^2/\text{s} \) (Page no.34 H.M.T Data Book, Seventh Edition by C.P.Kothandaraman & S.Subramanyan)

To find \( w \):

\[ w = \frac{\lambda}{R} \quad \text{(3)} \]

Where, \( \lambda = \) Tip speed ratio = Blade speed / Wind speed, \( V_0 = \) Free stream wind speed (m/s)

Blade speed = 25 km/h, Wind speed = 11 km/h

So,

\( \lambda = \frac{25}{11} = 2.27 \text{ (2.3 app.)} \)

On calculating, we get,

\[ Re = 0.3 \times 10^5 \]

The higher values of Re means higher turbine performance due to the decrease in values of the drag coefficients and increase in values of the blade’s lift coefficient, finally providing greater torque. Hence, the dimensions are based on the optimized values of AR and Re so that the entire system develops the maximum power output along with cost effectiveness.

5. Performance calculations

Power produced by the turbine is given by,

\[ P = \frac{1}{2} \rho (V_0)^3 (2R) h C_p \quad \text{(in Watts)} \quad (4) \]

Where,

\( \rho = \) Density of air (kg/m³), \( V_0 = \) Wind speed at free stream (m/s), \( h = \) Blade length (m), \( R = \) Rotor radius (m), \( C_p = \) Power coefficient
Values we know are:
Density, $\rho = 1.225$ kg/m$^3$, Wind speed, $V_0 = 11$ km/h = 3.055 m/s, Rotor radius, $R = 2.5$ m, Blade length, $h = 0.6$ m
Value yet to know, $C_p = \text{Power output / Power input}$

$$C_p = \frac{\text{Electric power produced}}{\text{Wind power into turbine}}$$ (5)

Figure 8. Power coefficient to Tip speed ratio graph

Figure 8 curves are generated using a calculation code on the basis of MSTM (Multiple Stream Tube Model) theory [21]

From the following data, as given by NASA (National Aeronautics and Space Administration)
We have,

$$\sigma = \frac{(N*c)}{R}$$ (6)

Where,
$\sigma = \text{Rotor solidity}$, $N = \text{Number of blades}$, $R = \text{Rotor radius (m)}$, $c = \text{Airfoil chord (m)}$

On substituting the known values,
$\sigma = 4*0.2/2.5 = 0.3$

We know that,
$$\lambda = \frac{\text{Blade speed (km/h)}}{\text{Wind speed (km/h)}}$$
$$= \frac{25}{11} = 2.27 \text{ (2.3 app.)}$$ (7)

From Figure 8, for $\sigma = 0.3$ and $\lambda = 2.3$, we get, $C_p = 0.45$
So, from equation (4), Power produced,
$$P = (0.5) * 1.225 * 28.37 * 2(2.5) * 0.6 * 0.45$$
$$= 23.45 \text{ W}$$

Therefore, the net power production by this VAWT is 23.45 W

6. Conclusions
In this project, we developed a novel miniature Vertical Axis Wind Turbine (VAWT), which gives maximum power output. Here, we have fabricated H-rotor straight bladed NACA 0018 Airfoil Darrieus type VAWT as shown in Figure 9. The blades are designed by optimising the aspect ratio and local Reynolds number. The system we developed has blades with aspect ratio of 0.24 and the Reynolds number value is the maximum possible for this dimensions. The Power coefficient value is 0.45, which is in the maximum range for the Darrieus type of VAWT. The size of system is relatively reduced compared to other conventional type of VAWT for same power output. This type of system is
cost-effective, where it could be reduced even further on mass production. This maximum efficiency is achieved and the power output of about 23.45 W, where the cost for the total product is just below ₹3000. The application areas of this miniature system can be in lighting of lamps at residential area, power source at Wifi stations etc whereas the higher order versions with higher scale, with same design, can be employed for large power requirements.

Figure 9. Finished product

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