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Design and Analysis of Vertical Axis Wind Turbine (VAWT) for Small-Scale Applications

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Abstract: The rise in global demand of sustainable and renewable energy has created the need for innovation and new development to use the resources of energy for many purposes. Wind energy is one such form of energy. This work presents a study on a three-bladed helical vertical axis wind turbine. It is designed using a CAD software and various simulations for different wind speeds to determine the speed of rotation and power. The purpose of this study is to find the optimum wind turbine dimensions and wind speed to produce electrical energy from mechanical energy. This study particularly aims to produce enough electrical energy to supply electricity for domestic purposes.

Keywords: Renewable energy, wind energy, vertical axis wind turbine (VAWT), CAD, electrical energy

I. Introduction

Until recent times, fossil fuels were the primary source of energy in power plants, transport and other sectors where generation or transmission of any form of energy is required. It is estimated that coal and natural gas is the primary source for the generation of more than 90% of the global electrical energy.[1] There is a growing concern to reduce the harmful effects, such as global warming, of these fossil fuels on the climate.[2] For this purpose, new and innovative methods to use sustainable and renewable energy have to be developed. Renewable sources of energy such as solar energy, wind energy, etc. are cleaner and do not have harmful effects on the environment. For a long time now, wind energy has been in use to generate electricity. [3]

Wind energy is one such form of renewable energy. Wind energy uses wind to convert mechanical energy into electrical energy using wind turbines. When the wind hits the blades of the wind turbine, the kinetic energy of the wind is converted into mechanical energy which makes the blades of the turbine to rotate. With the help of a generator this mechanical energy can be converted into electrical energy.[4] The wind turbines use the phenomenon of lift and drag to rotate the blades of the turbine. When the wind hits the turbine blades, the air pressure on the side of the blade that comes in contact with the wind, decreases. This creates a pressure difference between the two sides of the blades which induces both lift and drag. The lift force is much higher than the drag force which causes the blades to rotate. The rotor to which the blades are attached, is connected to a generator which converts this mechanical energy into electrical energy.

There are mainly two types of wind turbines:

- Horizontal-Axis Wind Turbine (HAWT)
- Vertical-Axis Wind Turbine (VAWT)

Horizontal-axis wind turbine is the most commonly used wind turbine. In horizontal-axis wind turbines, the axis of rotation is parallel to the ground as well as the wind stream. Fig. 1 shows a horizontal axis wind turbine. HAWTs are mostly seen to have two or three blades. The rotor is used to convert the linear motion of air into the rotary motion of the blades. These turbines are usually placed at high altitudes which allow them access to stronger wind sites.

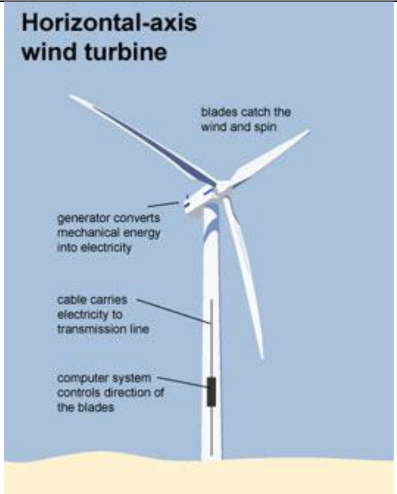

Fig. 1. Horizontal-axis wind turbine

Vertical Axis Wind Turbine (VAWT) is also called ‘cross-flow wind turbine’, or ‘transverse axis wind turbine’ since the rotor shaft is placed transverse to the direction of wind. The axis of the VAWT is perpendicular to the direction of flow of wind and vertical with the ground surface.

A VAWT has several advantages. The servicing of a VAWT is much easier because the generator is mounted closer to the ground because of its vertical shaft. [5] It does not have to orient with the direction of wind because the blades rotate about a vertical axis and hence are always facing the wind. A VAWT, unlike a HAWT, does not have to be mounted at higher altitudes. It can be mounted at much lower altitudes such as rooftops and can still generate electricity. The maintenance required for a VAWT is also less because they are mounted on rooftops and the height of the tower is less. [6] Other advantage of a VAWT over a HAWT is that it produces less noise, which makes it suitable for domestic applications.

Fig. 2. Savonius type VAWT

Fig. 2 shows a Savonius type VAWT. Aerodynamically, these turbines are drag-type turbines, which means that the electricity is generated due to drag force.[7] Savonnius type wind turbine can operate at low wind velocities and has a very low power coefficient which can go upto 0.2.

Fig. 3. Darrieus type VAWT

Fig. 3. shows a Darrieus type VAWT. Aerodynamically, these turbines are lift-type turbines, which means that the electricity is generated due to lift force. It produces more power than the Savonius type VAWT because it operates at a much higher rotational speed. [8] This type of turbine uses blades of airfoil cross-section and the blades are usually semi circular in shape. These blades are evenly placed so that they are at equal distances from each other. The ends of the blades are connected at each end of the shaft. Fig. 4 shows this configuration which is taken from the patent registered by Darrieus for his turbine. In Darrieus type VAWT, the angle of attack of the wind keeps on changing which causes fatigue in the turbine blades and makes it prone to fatigue failure in parts and joints. [9]

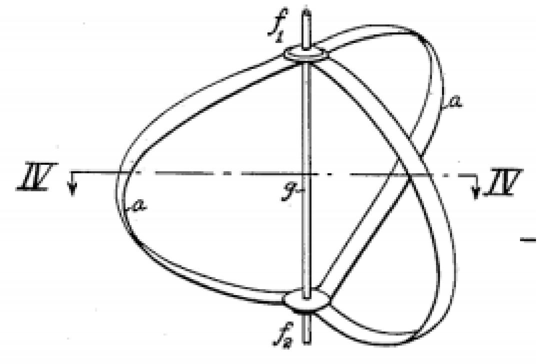

Fig. 4 Darrieus' patent for his turbine

Gorlov designed a helically bladed vertical axis wind turbine to reduce this effect. Gorlov's design is based on the Darrieus VAWT. Turbines with helically shaped blades produce less power than the blades used in Darrieus' turbine but are more stable as compared to them. [10]

II. Methodology

The helical blades used have an Airfoil cross-section. For the selection of an airfoil cross section, which is relatively easy to manufacture even using low end rapid prototyping/3D printing machines and at the same time having a high enough lift coefficient to initiate adequate starting torque, three airfoil cross sections were considered- NACA0012, NACA0015 and NACA0018 having maximum lift coefficients of 1.44, 1.45 and 1.39 respectively. And out of the three, NACA0015 was selected owing to its higher lift coefficient. Fig. 5 shows the NACA0015 airfoil cross-section.

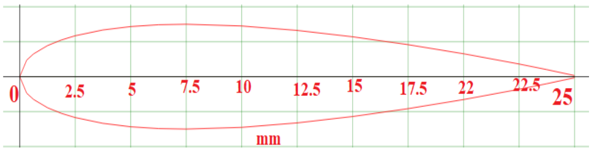

Fig. 5 NACA0015 airfoil

The coordinates of the NACA0015 airfoil cross section were imported from the NACA airfoil database and were scaled so as to have the required chord length of 25mm.These scaled coordinates were then used in the 3D modelling and simulation software (Solidworks) to obtain the airfoil geometry.

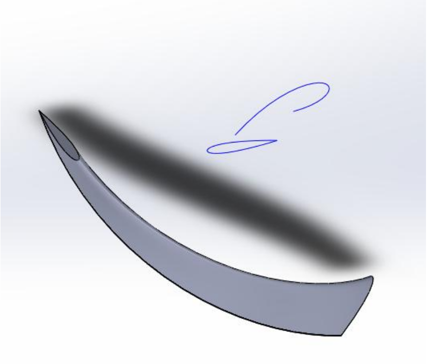

Fig. 6. Helically protruded blade

A helical path of 150mm height, 0.33 no. of revolutions and 120 degree helix angle was created and the airfoil geometry was protruded along this path to form the helical blade. Fig. 6 shows the helically protruded turbine blade. This blade was duplicated two times to obtain three blades. And these blades were arranged on a circular rotor(of 50mm radius and thickness 20mm)120 degrees apart from each other. And another rotor of the same radius but of thickness 5mm was attached on top of the blades.And a shaft of 10mm diameter and height 150mm was created between the top and bottom rotors to add sturdiness and rigidity to the design. Fig. 7 shows the final model that was used in the flow simulation.

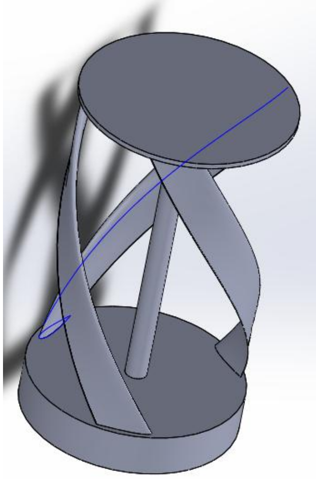

Fig.7. Final design of the VAWT

To perform the flow simulation first a wind tunnel of dimensions 300mmx300mmx600mm was created and the model was placed centrally in this enclosure. Fig. 8 shows the wind tunnel domain.

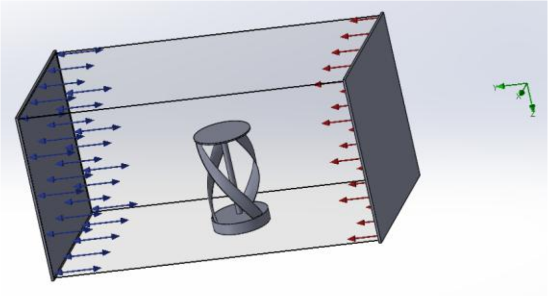

Fig. 8. Wind Tunnel Domain

In the flow simulation wizard the fluid used is air at atmospheric pressure. Then gravity and rotational axis(along the axis of the design) are defined. The velocity of the fluid flow is then defined. (simulations were run for velocities of 3,5,7,10,15,20 m/s) and the simulation was run and various results were obtained such as the velocity and pressure flow trajectories. Fig. 9 shows the velocity flow trajectory and fig. 10. Shows the pressure flow trajectory.

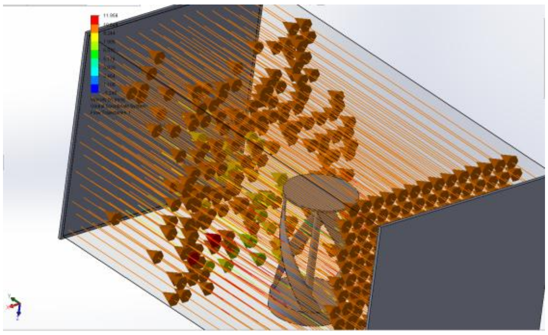

Fig. 9 Velocity flow trajectory

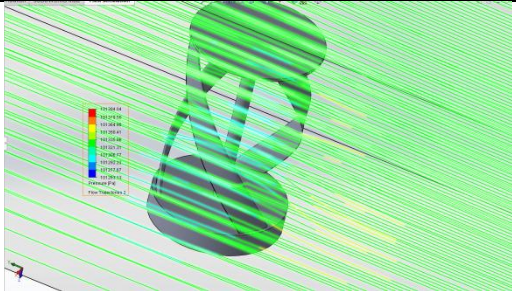

Fig. 10 Pressure flow trajectory

III. Results and Discussions

After the design of the helical vertical axis wind turbine, the power generated from it is calculated for a scaled up design of the turbine (ratio 20:1) using the formula:

$$P=0.5\rho Av^3\eta_G\eta_T$$

P= Power output (W)
A= Swept Area (m^2)
ρ= Air density (kg/m^3)
v= Wind velocity (m/s)
η_T= Wind turbine efficiency
η_G= Generator efficiency

This formula shows that the power generated from the wind turbine is directly proportional to the cube of the wind velocity (v^3), the air density, swept area, wind turbine efficiency, and generator efficiency.[11]

A wind turbine must be manufactured keeping these specific conditions in mind and for the purpose that it has to be used for. For the generation of electrical energy for domestic applications, the amount of electrical energy used by an average household per year is taken to be 1500kW/year. Bengaluru City's air density is found to be $\rho= 0.93kg/m^3$.

$\eta_T= 0.35$
$\eta_G= 0.9$
r=1.04m
L=3m
$A=3.4m^2$
The power output for a wind velocity of v=5m/s is:

$$P= \frac{0.5x0.93x3.4x5^3x0.35x0.9}{1000}$$

P= 0.0623kW/h
No. of hours in a year= 8760
Power output per year= 8760x0.0623= 545.33 kW/h per year.
Table 1 shows the speed at which the shaft rotates for different values of wind velocity. The speed of rotation of shaft increases with the increase in wind velocity.

TABLE 1
SHAFT SPEED

Wind Velocity (m/s)	Shaft Speed (rpm)
3	46.96
5	78.44
7	109.40
10	160.37
15	234.81
20	298.30

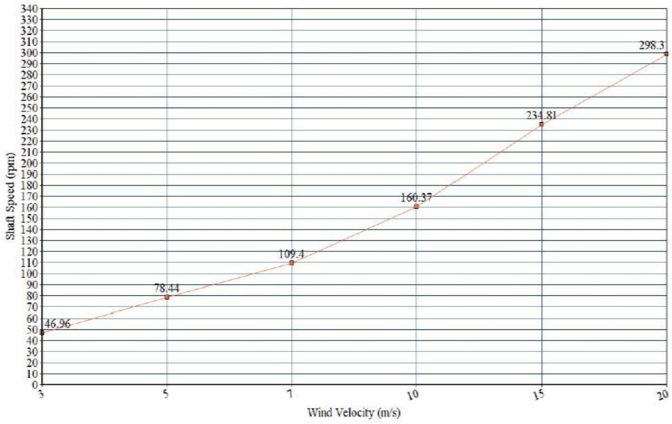

Fig. 11. Shaft Speed v/s Wind Velocity

TABLE 2
POWER OUTPUT

Wind Velocity (m/s)	Power Output (kW/h)	Power Output (kW/h) per year
3	0.0134	117.79
5	0.0623	545.33
7	0.1708	1496.38
10	0.4980	4362.61
15	1.6808	14723.81
20	3.9841	34900.89

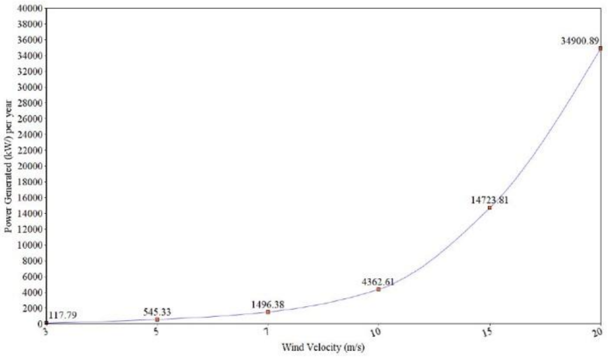

Fig. 12 Power generated v/s Wind Velocity

Table 2 shows the power output for different values of wind velocity. The power output increases with the increase in wind velocity.

Figure 11 shows the variation of shaft speed with the wind velocity. It shows that shaft speed is directly proportional to the wind velocity. Figure 12 shows the variation of power output with the wind velocity. As there is an increase in the wind velocity, there will be a rise in the amount of power generated. The graph varies non-linearly.

The table shows that at 7 m/s wind velocity, the power output is approximately the same power required for an average household per year.

IV. Conclusion

A helical VAWT was designed using SolidWorks. This design was subjected to various simulations to analyse its performance for different wind velocities. The speed of the rotation of shaft was noted down and the power output for each wind velocity was calculated. It was found that at 7 m/s wind velocity, the power output is approximately the same power required for an average household per year which is 1500kW/year. Wind power has seen a considerable growth in its use in the past few decades. New and innovative methods have to be developed for optimum utilisation of wind energy. Considering the aforementioned benefits of the VAWT, such as less construction and maintenance costs, and ease of operation, this rotor mechanism could be a viable solution, which has a significant expansion potential to address the current renewable energy demands.

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