Design and Development of Small Capacity Vertical Axis Wind Turbine

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***Abstract*— Wind power is of increasing interest in society due to its prospects as an environment friendly source of renewable energy. Wind turbines are generally classified into two types: horizontal axis and vertical axis. The promising advantages of vertical axis wind turbines such as omni-directional, ability to take turbulent and gusty winds, and low installation and maintenance costs etc makes it suitable for small capacity domestic applications. This paper briefs about the design and development of a 1000W vertical axis wind turbine of Darrieus type. This design uses three airfoils mounted on a hub that ensues rotational symmetry. The wind power extracted by the airfoil is transmitted to the generator located at the ground through a long shaft. The analytical design shows higher safety margins (greater than 5) in the wide working ranges of wind speed 5 – 15 m/s.**

Keywords—wind turbine; Darrieus; renewable energy; VAWT; design

I. INTRODUCTION

The ever-increasing demand for energy, the threat of climate change and the dwindling fuel reserves, finding reliable, diverse, sustainable/renewable, affordable energy resources has become a priority for all countries. Many countries are now offering incentives to its industry to allow their governments to reach specific targets that will not only aid emission reduction requirements but also help in achieving the security of supply goals. The EU for instance, has a mandatory 20% target for energy production from renewable resources by 2020, with a UK's share negotiated of 15% [1]. Renewable energy has a vital role to play into the future in UAE's transition to a low-carbon economy.

As enormously powerful engineering marvels, wind turbines produce a significant amount of energy for a relatively small cost and with very little disruption to the environment. An estimated 72 terawatt (TW) of the Earth's wind power is commercially viable. Right now, total global power consumption from all sources is about 15 TW [2]. The worldwide wind capacity reached 486'661 MW by the end of 2016, out of which 54,846 MW were added in 2016. This represents a growth rate of 11.8 % (17.2 % in 2015). All wind turbines installed worldwide by the end of 2016 can generate around 5 % of the world's electricity demand [3]. Right now, the industry is virtually exploding in growth, enjoying high public acceptance and full government support. Fig. 1 shows worldwide total installed wind power capacity.

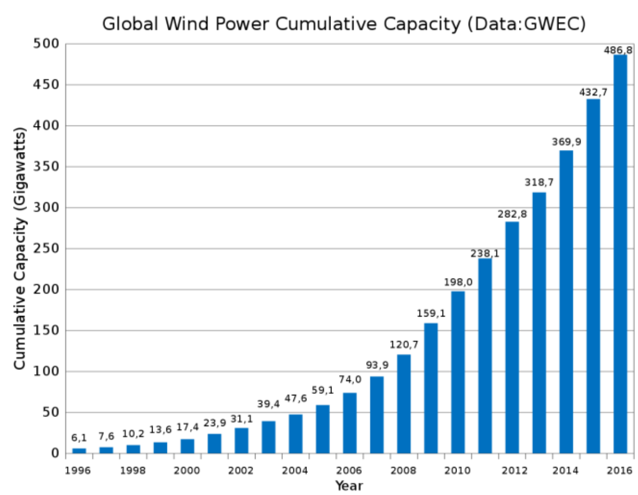

Fig. 1 World total installed wind power capacity [4]

II. WIND TURBINES

A wind turbine is a device that converts the wind's kinetic energy of wind into mechanical power. This mechanical power can be used for specific tasks (such as grinding grain or pumping water) or a generator can convert this mechanical power into electricity.

A. Wind Turbine Types

Wind turbines are generally classified into two types: horizontal axis and vertical axis. There are a number of available designs for both and each type has certain advantages and disadvantages. Fig. 2 shows wind turbine types.

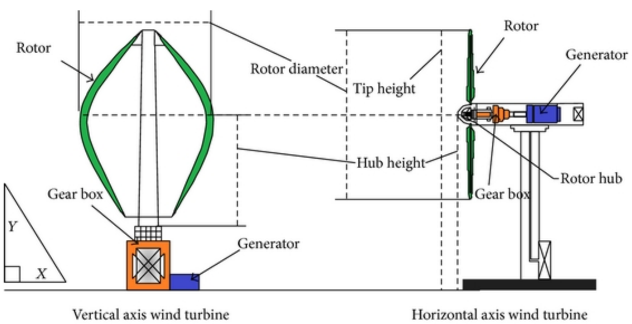

Fig. 2 Wind turbine types [4]

B. Horizontal Axis Wind Turbine (HAWT)

A horizontal axis wind turbine (HAWT) has its blades rotating on an axis parallel to the ground. Horizontal axis wind turbines are the most common type used (Figure 2.1) and (Figure 2.2). All of the components (blades, shaft, and generator) are on top of a tall tower, and the blades face into the wind. The shaft is horizontal to the ground. The wind hits the blades of the turbine that are connected to a shaft causing rotation. The shaft has a gear on the end which turns a generator. The generator produces electricity and sends the electricity into the power grid.

Parts of the HAWT

Blade: the blades are of lifting style. These are the most efficiently designed, especially for capturing energy of strong fast winds. Some European companies actually manufacture a single blade turbine. The drag style wind turbine blade, most popularly used for water mills, as seen in the old Dutch windmills. The blades are flattened plates which catch the wind. These are poorly designed for capturing the energy of heightened winds.

Rotor: the rotor is designed aerodynamically to capture the maximum surface area of wind in order to spin the most ergonomically. The blades are made of lightweight, durable and corrosion-resistant material. The best materials are composites of fiberglass and reinforced plastic.

Gear box: the gear box magnifies or amplifies the energy output of the rotor. The gear box is situated directly between the rotor and the generator.

Generator: the rotor rotates the generator (which is protected by a nacelle), as directed by the tail vane. The generator produces electricity from the rotation of the rotor. Generators come in various sizes, relative to the output you wish to generate.

Nacelle: the nacelle is the housing or enclosure that seals and protects the generator and gear box from the elements. It is easily removed for maintenance of the wind. The tail vane directs the turbine to gather maximum wind energy.

C. *Vertical Axis Wind Turbine (VAWT)*

The Vertical Axis Wind Turbine (VAWT) is the most popular of the turbines that people are adding to make their home a source of renewable energy. While it is not as commonly used as the Horizontal Axis Wind Turbine, they are great for placement at residential locations and more. VAWT can work even when the wind is very unstable making them suitable for urban and small-scale applications [5]. Their particular axial symmetry means they can obtain energy where there is high turbulence.

Vertical axis wind turbine are classified into two main types:

1. Lift type

2. Drag type

Lift types is one which use the lift forces produced by the moving air to produce the rotation of turbine blades and drag type wind turbine is one which use the drag force of wind to produce the rotation motion of blades. The Darrieus wind turbine is an example of lift type vertical axis wind turbine. This turbine consists of a number of aerofoils usually - but not always - vertically mounted on a rotating shaft or framework. Savonius turbines are drag-type turbines, consisting of two or three scoops. Looking down on the rotor from above, a two-scoop machine would look like an "S" shape in cross section. Because of the curvature, the scoops experience less drag when moving against the wind than when moving with the wind.

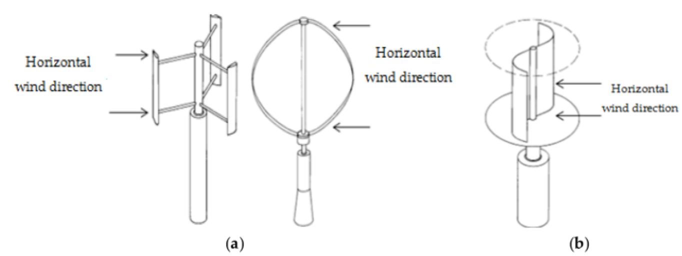

Fig. 3 Two distinct types of VAWT operating under any horizontal wind direction [6]. (a) Darrieus rotors; (b) Savonius rotor.

Compared to horizontal designs lift-based (Darrieus) vertical-axis wind turbines (VAWT) offer several advantages including low noise, accessibility, and omni-directionality. However, they also suffer disadvantages like a lower-efficiency, high cyclic loadings on the supporting structure and the blades, and difficult-to self-starting. The difficulties associated with self-starting of a VAWT are well known. Kirke [8] have stated that the self-starting of VAWT is possible with a careful selection of blade geometry. Dominy et al. [9] experimentally showed that a three-bladed VAWT can self-start even using fixed-geometry, symmetric airfoils, but that two-bladed designs can only self-start under particular conditions.

The air flow over the blade airfoil generate lift and drag forces which are the driving forces behind lift-based Darrieus VAWT. The flow around the airfoil blade in a VAWT is highly directional and the inflow angle can vary anywhere between -180◦ to +180◦ depending on the azimuthal location, local incident velocity and tip speed ratio as shown in Fig. 4 [7].

III. DESIGN FEATURES

This design of vertical axis wind turbine is of lift type having three airfoils made of light weight material. The capacity of the turbine is about 1kW, and is designed keeping in mind the requirements of electricity for the farms in desert regions where the electricity supply is not economically feasible. The minimum operating wind speed is about 5m/s, which is common in the desert regions of UAE and most of the time the wind speed is much higher than 5m/s in deserts. The design features of this turbine is shown in Table.1

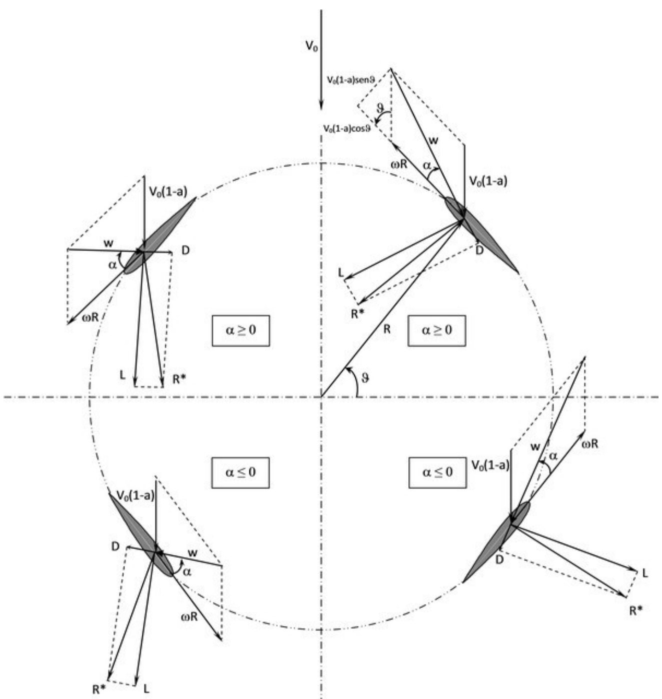

Fig. 4 Wind rotor rotational plane [7]

TABLE 1. DESIGN FEATURES

Type	Darrius VAWT
Number of airfoils	3
Airfoil aspect ratio (h/R)	1.1
Minimum operating wind	5m/s
Rated wind speed	9m/s
Cut-off wind	15m/s
Power capacity	1000W at 9m/s
Drive	Gearbox (gear ratio 1:10)
Height of the assembly	6m

The detailed design of various components of the turbine are briefed in the following subsections:

A. *Airfoil*

Airfoil is designed for obtaining maximum power from the wind. High rotor efficiency is desirable for increased wind energy extraction and should be maximized within the limits of affordable production. Therefore the profile is shaped such that it will produce maximum lift force and minimum drag losses. The width of the airfoil is 450mm and its height is 150mm. The material selected is glass fiber reinforced plastic (GFRP) The power of a wind turbine with a vertical axis can be expressed as per Eq. 1 [7]:

$$P = \frac{1}{2} \rho \; V_o^3 \, 2R \, h \, c_p \qquad (1)$$

Where, V_o is the free stream wind speed, ρ is the air density (kg/m^3), R is the rotor radius (m), h is the blade length (m), and c_p is the power coefficient.

A physical limit exists for the quantity of energy that can be extracted, which is independent of design. The energy extraction is maintained in a flow process through the reduction of kinetic energy and subsequent velocity of the wind. The magnitude of energy extracted is a function of the reduction in air speed over the turbine. 100% extraction would imply zero final velocity and therefore zero flow. The zero flow scenario cannot be achieved hence all the winds kinetic energy may not be utilized. This principle is widely accepted and indicates that wind turbine efficiency cannot exceed 59.3%. This parameter is commonly known as the power coefficient c_p, where max c_p = 0.593 referred to as the Betz limit [10]. The Betz theory assumes constant linear velocity therefore, any rotational forces such as wake rotation, turbulence caused by drag or vortex shedding (tip losses) will further reduce the maximum efficiency. Efficiency losses are generally reduced by:

- Avoiding low tip speed ratios which increase wake rotation
- Selecting airfoils which have a high lift to drag ratio
- Specialized tip geometries

The shape the airfoil profile used in this design is shown in Fig. 5.

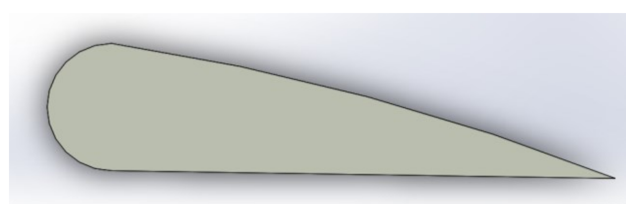

Fig. 5 Airfoil profile

In this design, the tip speed ratio is estimated as 5 and the power coefficient is assumed as 0.4, which is a standard value followed by designers (it needed to be optimized further in this case). Accordingly, the calculated mechanical power output using (1), from a wind speed of 10m/s is 1288W. However, the electric power output is less than this because of the transmission losses in gearbox and the energy conversion losses in the electric generator. By assuming an efficiency of 95% for the gearbox (in this case use spur gears) and 90%

efficiency for the generator. The electrical power output is estimated as 1099W.

The skin friction of the airfoil as the air moves over it is reduced by increasing the surface finish to the maximum possible by manufacturing techniques. The wall thickness of the airfoil is maintained throughout at 6mm. The airfoil is further stiffened by steel structure, which prevent bending of the airfoil at higher speeds, and also twisting about the mounting due to pitching action. The airfoil is attached to this structure by means of M6 bolts. To enable the airfoil to connect with the rotor arm, a steel mount has been welded to the steels structure. The mount has threads which match with the rotor arm. The total weight of the airfoil with the steel structure and mount is about 9.5 kg.

B. *Rotor Arm Assembly*

The rotor arm is designed to hold the three airfoils at equidistant from the center of the rotation and also equi-spaced along the periphery. The vertical alignment of each airfoil and the center distance from the rotation axis are the two important parameters to be accurately controlled to avoid undue forces on the rotor shaft.

The size of the rotor arm is determined through stress analysis by considering the maximum allowable wind speed (cut-off speed), which is taken as 15m/s. The various forces acting on the rotor arm are:

- The weight of the airfoil assembly acting downward
- The tensile force due to the rotation of the airfoil

The speed of the rotor corresponding the cut-off wind speed can be calculated from:

$$n = \frac{60 V \lambda}{2 \pi R} \tag{2}$$

Where V is the wind speed m/s, λ is the tip-speed ratio (in this design λ = 5), and R is the rotor radius. Therefore the calculated rotor speed at the cut-off wind speed is 470 rpm. The corresponding centrifugal tension is 34.48kN. The loading diagram is shown in Fig. 6.

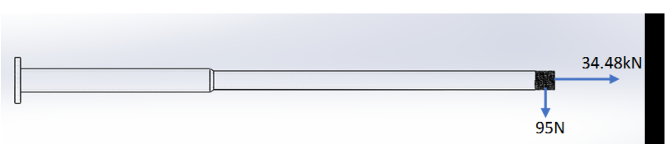

Fig. 6 Loads acting on the rotor arm

The stress on the arm at the critical location, which is the point that join with the flange on the left (see Fig. 6) due to the combined bending and tension is obtained by (11):

$$\sigma = \frac{Mc}{I} + \frac{F}{A} \tag{3}$$

Where M is the bending moment due to the weight of the airfoil in N-mm, c is the radius of the pipe in mm, I is the moment of inertia of the pipe in mm^4, F is the force due to the rotation of the airfoil about the rotor axis in N, and A is the cross sectional area of the pipe in mm^2.

The rotor arm is made of AISI 1020 steel pipe (schedule 40) having 40.94mm inner diameter and 48.3mm outer diameter. The calculated moment of inertia is 129187.42mm^4, and the cross sectional area is 656.81mm^2. The calculated combined stress is 79.16MPa. The tensile strength of the material of the arm is 420MPa. This will give a design factor of safety of 5.3, which ensures safety up to a wind speed of 15m/s. For added safety against bending, the arm was constructed as two sections and welded together. The flange side is made of 60.3mm diameter pipe as shown in Fig.6. The rotor arm assembly is shown in the Fig. 7.

Fig. 7 The rotor assembly

C. *Shaft and Housing*

The rotor assembly is connected to the main shaft that transmits the wind power extracted by the airfoils to drive the generator. The shaft is made of AISI 1020 schedule 80 pipe having outer diameter 48.3mm and inner diameter 38.1mm. The shaft is supported inside the housing by a pair of ball bearings. The housing is made of schedule 40 pipe having an inner diameter of 158.74mm. The bearing holders are welded to the housing. The top bearing is angular contact and the bottom one is deep groove bearings. The features of the bearings are provided in the Table 2.

TABLE 2. BEARING DETAILS

Bearing type	Angular contact (7410BM)	Deep groove (7410NR-SP130)
Dynamic capacity, kN	95.6	87.1
Static capacity, kN	64	52
Fatigue load limit, kN	2.7	2.2
Limiting speed, rpm	6700	7500
Outer Diameter, mm	130	130
Inner Diameter, mm	50	50

The shaft is designed by considering the cyclic load acting on it. The main load acting on the shaft is wind force as bending load and the torque cause by the rotation of the rotor. Here the calculated maximum bending force at the cut off wind speed is 96.3N, and the maximum torque is 144.5 N.m. The corresponding bending moment is 21.66N.m. The maximum shear stress in the shaft is calculated by:

$$\tau_{max} = \frac{16T_e}{\pi\left(\frac{D^4 - d^4}{D}\right)} \quad (4)$$

Where, T_e is the equivalent twisting moment given by

$$T_e = \sqrt{\left[\left(K_m \times M^2\right) + \left(K_t \times T^2\right)\right]} \quad (5)$$

Where, M is the bending moment, T is the torque, K_m and K_t are the shock and fatigue factors for bending and twisting and in this case it is taken as 1.5 and 2.0 respectively. Thus the calculated equivalent twisting moment is 206.0696N.m and the shear stress is 15.206MPa. Considering yield failure, the shear yield strength of the material is 0.5 S_y = 0.5 x 352MPa = 176MPa. Therefore the obtained safety margin is 11.5, which ensures high safety in the working range of wind speed.

In this design, the generator, the gear box and the electrical control are located in the bottom part of the housing as shown in Fig. 8. The generator used is a 1000W permanent magnet ac generator, having rated speed 500rpm and 19.1N.m torque. Whereas the speed and torque of the main shaft at the rated wind speed of 10m/s is 318rpm and 30N.m respectively. Therefore to reduce the torque and increase the speed a single stage spur gear system is used.

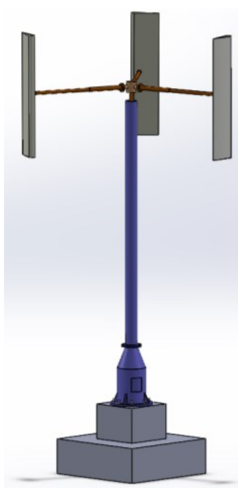

Fig. 8 The turbine assembly

The turbine is installed on a concrete foundation and have a trial run. A series of experiments are planned to evaluate its performance. The preliminary results shows that the design is capable of extracting 210W from a wind of around 5m/s.

IV. CONCLUSION

Considering the advantages of vertical axis wind turbines over horizontal axis type, a 1000W vertical axis wind turbine for domestic application has been analytically designed, manufactured, installed and tested. This lift type turbine uses a specially designed airfoil, which can extract maximum energy from wind. The analytical design shows very high safety factor for the critical components such as the rotor arm and the main shaft. The rotor arm safety margin is 5.3 under the combines bending and tensile loading. The main shaft shows a safety margin of 11.5. Thus the turbine is safe under the maximum operating wind speed of 15m/s.

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