Journal of Engineering and Applied Sciences 13 (8): 2202-2208, 2018
ISSN: 1816-949X

Development of a 0.5 kW Horizontal Axis Wind Turbine

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Abstract: Wind turbine is a machine that is powered by the energy from the wind. It is designed to convert the kinetic energy from the wind into electrical power (electricity). This study focus on the development of 0.5 R horizontal axis wind turbine.The major components of the wind turbine which include the blades, hub, shaft and the tower, were design and fabricated to meet the required 0.5 R and the turbine was mounted on a tower height of 5 m from the sea level. The test result showed that the wind turbine is capable of producing about 500 W, at a rotor speed of 153.5 rpm. The necessary design details that have been applied at the design and fabrication stages of the wind turbine guarantees the high hope of this wind turbine performing better.

Key words: Energy, wind turbine, turbine blade design, wind power control, machining, performing

INTRODUCTION

Energy is the basis of all manufacturing and industrial civilization. Without energy life will be very difficult. Therefore, the economy of any nation depend on the availability and regular supply of energy, hence, there is need to properly select a suitable energy source. Energy is used for transportation, heating, cooking, lighting and industrial production (Forcier and Joncas, 2012).

Wind is air in motion. The term wind is usually applied to the natural motion of air, motion in a vertical, nearly vertical direction is called a current. Winds are produced by the differences in atmospheric pressure, which are primarily attributable to differences in temperature. Variations in the distribution of pressure and temperature are caused largely by unequal distribution of heat from the sun, together with difference in the thermal properties of land and ocean surfaces. When the temperature of adjacent regions become unequal the warmed air tend to rise and flow over the colder region, heavier air. Winds initiated in this way are usually greatly modified by the earth rotation (Skrumsager *et al*., 2002). Wind maybe classified into four major types which are, the prevailing winds, the seasonal wind, the local wind and the cyclonic and anti-cyclonic winds.

Energy can be derived from different sources including traditional fuels such as fire wood and animal waste which are significant energy sources in many developing countries (Okonkwo *et al*., 2017). There is global need to increase energy conservation and hence, the use of renewable energy resources such as wind energy, solar energy, water power and geothermal energy. These are very efficient and practical but largely under-utilized alternative sources due to availability of in-expensive non-renewable fossils resources (Oyedepo *et al*., 2012).

However, this research work will make use of wind as a source of energy because of its abundant in nature, free and running cost is low, it is renewable, inexhaustible and has little or no effect on the environment. Wind may be classified into four major types. The prevailing wind, the seasonal wind, the local wind, cyclonic and anticyclone winds.

In order to convert the energy in the wind to useable energy, devices known as wind turbines are used. A wind turbine is a mechanical device that is used to convert the wind's kinetic energy into electrical power (Rasham, 2016). It is important to note that the power in the wind is proportional to the cube of the wind speed, this means that small increase in the wind speed produces large increase in the wind power (Fagbenle *et al*., 2011).

Osadolor *et al*. (2016) Focuses on the practical analysis of a small wind turbine for domestic use on latitude 7.0670n, longitude 6.2670e. The wind turbine was

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designed to generate 250 W of power at the rated speed of 6.5 m/sec. Pitch-controlled wind turbines have blades that can be pitched out of the wind to an angle where the blade chord is parallel to the wind direction. The power output is monitored and whenever it becomes too high, the blades will be pitched slightly out of the wind to reduce the produced power (Obiazi *et al*., 2009). The blades will be pitched back again once the wind speed drops. Pitch control of wind turbines requires a design that ensures that the blades are pitched at the exact angle required in order to optimize the power output at all wind speeds. Nowadays, pitch control of wind turbines is only used in conjunction with variable rotor speed. An advantage of this type of control is that it has a good power control, i.e., that the mean value of the power output is kept close to the rated power of the generator at high wind speeds. Disadvantages encompass extra complexity due to the pitch mechanism and high power fluctuations at high wind speeds (Okokpujie *et al*., 2017a-c).

Active stall-controlled turbines resemble pitch-controlled turbines by having pitch able blades. At low wind speeds, active stall turbines will operate like pitch-controlled turbines. At high wind speeds, they will pitch the blades in the opposite direction of what a pitch-controlled turbine would do and force the blades into stall. This enables a rather accurate control of the power output and makes it possible to run the turbine at the rated power at all high wind speeds. This control type has the advantage of having the ability to compensate for the variations in the air density.

Economic aspects the ideal wind turbine design is not dictated by technology alone but by a combination of technology and economy (Okeniyi *et al*., 2015; Okokpujie *et al*., 2017a-c). Wind turbine manufacturers wish to optimize their machines, so that, they deliver electricity at the lowest possible cost per unit of energy. In this context, it is not necessarily optimal to maximize the annual energy production if that would require a very expensive wind turbine. Since, the energy input (the wind) is free, the optimal turbine design is one with low production costs per produced kWh (Salawu *et al*., 2018; Azeta *et al*., 2016)

The choice of rotor size and generator size depends heavily on the distribution of the wind speed and the wind energy potential at a prospective location. A large rotor fitted with a small generator will produce electricity during many hours of the year but it will only capture a small part of the wind energy potential. A large generator will be very efficient at high wind speeds but inefficient at low wind speeds. Sometimes it will be beneficial to fit a wind turbine with two generators with different rated powers (Rasham, 2016). A shaft is a rotating machine element which is used to transmit power from one place to another (Okokpujie *et al*., 2017a-c).

The power is delivered to the shaft by the process of the rotation of the blades and the resultant torque or twisting moment set up within the shaft permits the power to be transferred to the alternation (Okokpujie *et al*., 2017a-c). The shaft should be able to with stand the power, it is going to transmit to the alternator, the design will take one shaft which one end of the shaft will be connected directly to the rotor blades to the hub and the other end is coupled to the alternator (Nwoke *et al*., 2017). Machining is the process of removing precise amount of material from the work piece to attain the desired shape (Okokpujie *et al*., 2017a-c, 2018). Machining is one of the important aspects duringdeveloping the wind turbine. The surface of the wind blade has to be determined during the machining operation in other to avoid the corrosion, vibration and to produce good quality turbine (Orisanmi *et al*., 2017).

Furthermore, the uniqueness of this wind turbine is in the design. The wind turbine was built to work in a low wind speed region and in the process, a lot of research were carry out on why will wind turbine does not work in the South-South of Nigeria because it falls on the low wind speed region. Therefore, this wind turbine was built by eliminating some mechanical system that will lead to mechanical losses during operation. Also, when a wind turbine is designed and constructed locally, the knowledge will be documented for further improvement. This knowledge will go a long way to enhance the much-needed indigenous technological bases.

MATERIALS AND METHODS

In the design and construction of a wind turbine, through locally available materials an intensive study were carried out taking into consideration the complexity of the blade, hub diameter, understanding the effect of the wind impact in a given region, the height to which the wine turbine is mounted or erected, the size of the shaft diameter and tower. The blade of the wine turbine will be design base on the best aerofoil method to transmit maximum energy for electricity generation. The wind turbine was built and installed very closed to river Niger in Asaba Delta State Nigeria.

Design theory and calculation of the wind turbine parameters: The wind turbine designed should be able to generate electricity power of 500 W at an average prevailing wind speed of 20.9 m/sec, height of 5 m with 1.293 kg/m^3 density of air. To design the wind turbine, we know the following parameters:

- Expected power generated, P = 500 W
- The average prevailing wind speed of the area, V = 20.9 m/sec
- Density of the wind at height of the tower of 5 m is l = 1.293 kg/m^3

Assumed values:

- Length of each blade L = 1.3 m or 1300 mm
- Thickness of the blade, t = 0.4 m
- Orientation angle of 120°, no. of blades = 3
- Density of the mild steel material, l = 7850 kg/h^3
- Length of tail vane T_{Lv} = 610 mm
- Width of tail vane T_{wv} = 370 mm
- Factor of safety, f.s = 3

The unknown parameters to be determined:

- The area of the blades A, the width of the blades b
- Speed of the blade, N, diameter of the shaft, d_s
- Diameter of the hub, D_h, length of the hub, L_h

Design of the wind turbine blades: Figure 1 shows one of the turbine blade:

- The turbine blades are made up of 3 blades with an angle of 120°
- To carry out the design the following parameters are known and assumed as follows
- Length of each blade, L = 1.3 m
- Expected power to be generated P = 500 W
- Prevailing wind speed, V = 20.9 m/sec
- Area of each blade, width of each blade

Therefore, Osadolor *et al*. (2016):

$$P = \frac{\ell A V^3}{2} \quad (1)$$

Swept area is given as:

$$A = \frac{P\times 2}{\ell V^3} = \frac{500\times 2}{1.293\times 20.9^3}$$
$$A = \frac{1000}{11804.2224}$$
$$A = 0.0847\,m^2$$

To get the swept area of one blade is given by:

$$A = \frac{0.0847}{3} = 0.0282\ m^2$$

To determine the width of one blade using Eq. 2:

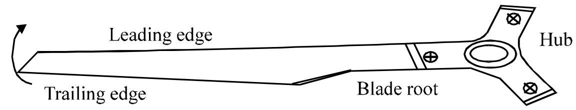

Fig. 1: Aeroedynamic blade of the wind turbine

$$Area = Length\times width \quad (2)$$

The area of one blade calculated is = 0.0282 m^2, width of the blade b, therefore:

$$A = d_r\times b$$
$$0.0282 = 1.3\times b$$
$$b = \frac{0.0282}{1.3} \quad (3)$$
$$b = 0.018\,m$$

Therefore, the width of one blade b = 0.018 m

The shaft: The rotor shaft should be subjected to two types of actions which are (a) bending moment, due to the weight of the blades (b). A twisting moment or torque due to the effect of the power transmitted. To determine the diameter of the shaft the following are known:

- The thickness of the blade, t = 0.32 m
- Distance of the bearing from the blade = 0.125 m
- Diameter of the blade is = 2×L = 2×1.3 = 2.6
- Density of the mild steel material l = 7850 kg/h^3
- There the following are to be calculated, bending moment Mb
- Twisting moment T_e
- Diameter of the rotor shaft d

For the rotor shaft, the total force acting on it will be given as: W_t= mass x gravitation force. That is:

$$W_t = m\times g \quad (4)$$

where, mass of the blade is given as m. M is density of the material x volume of material. Volume is area of the blade x thickness of the blade. Therefore, Kennedy *et al*. (2017):

$$m = \ell\times a\times t$$
$$m = 7850\times 0.0282\times 0.32 \quad (5)$$
$$m = 70.84\,kg$$

The mass of the three blades becomes:

$$M = 70.84\times 3 = 212.52\,kg$$

Therefore, the total weighty of the blade is the bending moment of the blade is given as:

$$W_t = Mb = m\times g$$
$$W_t = 212.52\times 9.81 \quad (6)$$
$$W_t = 2804.82 \text{ N}$$

This force will tend to create a bending moment M_b about the first bearing, if the blade is 0.125 m from the bearing, then:

$$M_b = 2084.82\times 0.125$$
$$M_b = 260.60 \text{ N}$$

The angular velocity of the wind turbine is given as:

$$W = \frac{2\pi N}{60} \quad (7)$$

And N which is the speed of the blade is given as:

$$N = \frac{60\times V}{\pi D}$$
$$N = \frac{60\times 20.9}{3.142\times 2.6} \quad (8)$$
$$N = 153.5 \text{ rpm}$$

Therefore:

$$W = \frac{2\pi\times 153.5}{60}$$
$$W = 16.1 \text{ rad/sec}$$

The twisting moment or torque can be determined by:

$$T_r = \frac{\text{Power}}{\text{Angular velocity of the wind turbine}}$$
$$T_r = \frac{500}{16.1} \quad (9)$$
$$T_r = 31.06 \text{ Nm}$$

Therefore, the equivalent twisting moment is given as follows, Okokpujie *et al*. (2017a-c):

$$T_e = \sqrt{(M_b + T_r)^2 \, (5b)}$$
$$T_e = (260.60)^2 + (31.06)^2$$
$$T_e = 262.44 \text{ Nm}$$

Therefore, the equivalent bending moment, M_e:

$$M_e = \frac{M_b + T_e}{2}$$
$$M_e = \frac{260.60 + 262.44}{2} \quad (10)$$
$$M_e = 261.52 \text{ Nm}$$

Hence, the rotor shaft should be able to withstand the equivalent bending moment in order to obviate premature failure in operation. Bending moment is a form of tensile stress but the allowable working stress (σ_w) of a material is generally given as:

$$\sigma_w = \frac{\text{Ultimate tensile stress}}{\text{Factor of safty}}$$
$$\sigma_w = \frac{\text{U.T.S}}{\text{F.S}} \quad (11)$$

For a stainless steel, the UTS range from 350-370 MN/m^2, therefore safety factor of 3:

$$T_e = \sqrt{(M_b + T_r)^2 \, (5b)}$$
$$T_e = (260.60)^2 + (31.06)^2 \quad (12)$$
$$T_e = 262.44 \text{ Nm}$$

Hence:

$$\sigma_w = \frac{Md_s}{2} / \frac{d_s^4}{64} \quad (13)$$

$$\sigma_w = \frac{Md_s}{2\pi} \times \frac{64}{d_s^4} \quad (14)$$

$$d_s^4 = \frac{32M_b}{\sigma_w}$$
$$d_s^4 = \frac{32\times 261.52}{3.142\times 116.52\times 10^6} \quad (15)$$
$$d_s = 3\sqrt{2.342267\times 10^{-5}}$$
$$d_s = 0.0296\text{m} = 30 \text{ mm}$$

Computation of hub diameter: The hub diameter in terms of shaft diameter can be calculated by using Eq. 15:

$$d_h = 1.5d_s + 25 \text{ mm} \quad (15)$$

where, diameter of the shaft, d_s = 30 mm, diameter of the hub, d_h:

$$d_h = 1.5d\times 30 + 25 = 70 \text{ mm} \quad (16)$$

Therefore, the length of the hub is also calculated using the diameter of the shaft. Length of the hub:

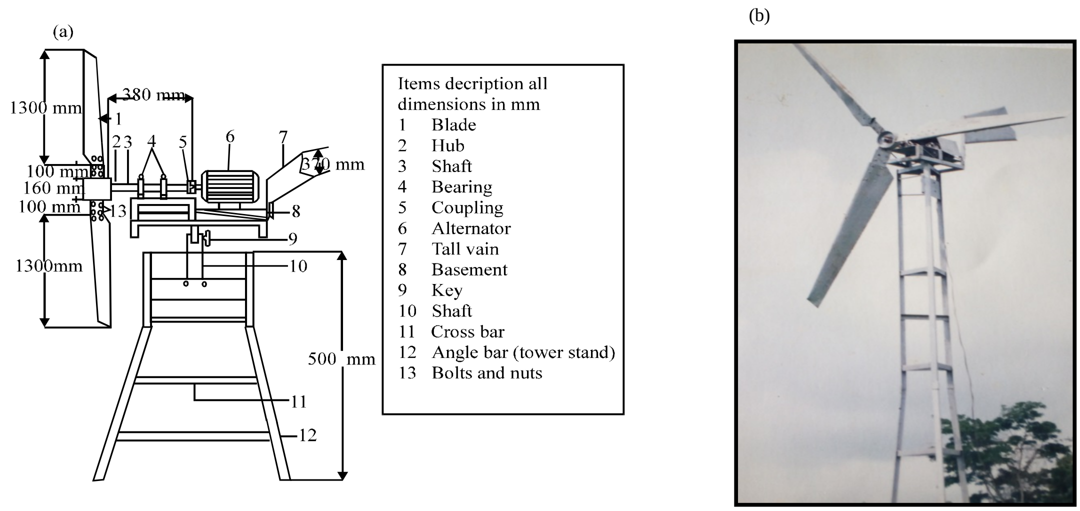

Fig. 2: a) The side view of the wind turbine and b) The complete design of the wind turbine

$$L = \frac{\pi ds}{2}$$
$$L = \frac{3.142\times 30}{2} \qquad (17)$$
$$L = 50 \text{ mm}$$

The tower: The tower of the wind turbine was made from mild steel. The angle should be strong enough to carry the entire weight of the system. The cross bar to give rigidity, should also be of mild steel. The weight acting on the tower will be the weight of the blades, shaft and basement of the receiver.

The weight of the shaft:

$$Wts = \ell \times g \times v \qquad (18)$$

But volume:

$$V = \frac{\pi}{4}\times d_s^2 \times 1$$
$$V = \frac{\pi}{4}(0.03)^2 \times 0.36 \qquad (19)$$
$$V = 2.545\times 10^{4}$$

Therefore:

$$W_{ts} = 7850\times 2.545\times 10^{-4}\times 9.81 \qquad (20)$$
$$W_{ts} = 19.599 \text{ N}$$

The weight of the basement of the shaft and the bearing:

$$W_{tb} = \ell xgxv$$
$$v = 0.24\times 0.13\times 0.31$$
$$v = 9.672\times 10^{-3} \qquad (21)$$
$$W_{tb} = 7850\times 9.81\times 9.672 10^{-3}$$
$$W_{tb} = 744.83 \text{ N}$$

The weight of the basement of the receiver:

$$v = 0.23\times 0.31\times 0.082$$
$$v = 5.847\times 10^{-3}$$
$$W_{tr} = 450.24 \text{ N}$$

Therefore, the total weight of the system is given as:

$$W_{total} = W_{ts} + W_{tb} + W_{tr}$$
$$W_{total} = 2086.6+19.59+744.83+450.22 \qquad (22)$$
$$W_{total} = 3301.269\text{N}.$$

Hence, from the design by E.E Steely Structural Steel, angle 120×100 mm will serve the purpose effectively. Now, the tower shall be mounted on a concrete footing, and the height of the tower is assumed to be 5.70 m that is the 0.7 m will be mounted to give rigid firm.

Tail vane: The tail vane is used to control the wind turbine reference to the change of the wind direction. In this case, the length of 610 mm and width of 370 mm in order to get a good control of the direction of the wind turbine (Fig. 2a, b).

Operation of the wind turbine: After mounting the wind turbine on the tower, the operation of the wind turbine starts when the wind flows through the wind turbine blade inducing a rotational motion via lift by the impact of the wind on the blade. The turning motion is transmitted by means of the rotor shaft to which the blade is fixed. This rotor shaft turns the shaft of the alternator, electric power is generated.

Table 1: Results from the 1st testing

No. of testing	Rotor shaft speed (rpm)	Voltage (V)	Current (A)	Power (W)
1	139	23.6	20.17	476
2	150	24.7	19.72	487
3	164	26.1	19.73	515
4	154	25.3	19.49	493
5	161	25.8	19.61	506

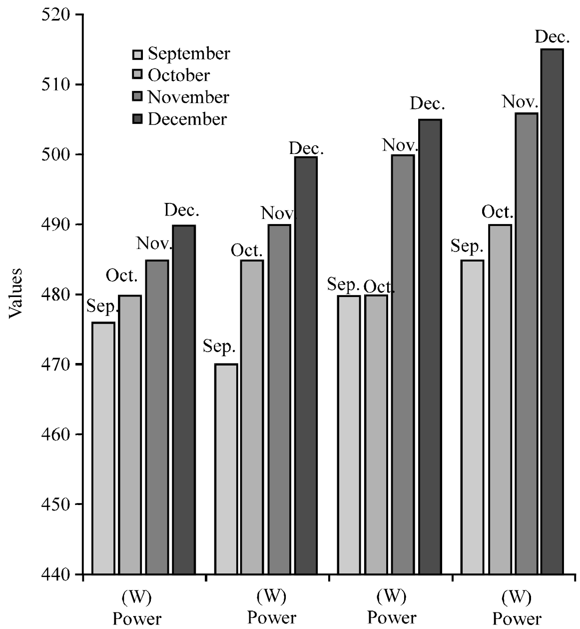

Fig. 3: Graph showing power generated per weeks

RESULTS AND DISCUSSION

The wind turbine was mounted on a tower height of 5 m and the rotor speed, Voltage (V) and current (A) was measured. The following reading were obtained using tachometer to measured rotor shaft speed, ammeter to measured the current produce, voltmeter to measure the voltage produced as shown in Table 1.

From Table 1, it can be clearly seen that the power (W) produce by the wind turbine varies for the period which the test was carried out and analysised also the current (Am), Voltage (V) and the rotor speed (rpm). This shows that a slight increase in the velocity of the wind will increase the generated power, whereby increases the electricity generate.

2nd test: The test was also repeated the second time, within the period of (4) months that is from September- December (Fig. 3).

The generation of power from the wind turbine depends majorly on the wind when there is increase in the wind (velocity) the power generated will also increase, the second test was carried out within an interval of four months, September to December. The graph clearly show that during the December period the wind speed increases and the power generated also increased to 510 W. This selected region is suitable for the technology in terms of the available wind speed. With an average wind speed of 20 m/sec, adequate power could be generated that would be sufficient for electricity generation.

CONCLUSION

The feasibility study of the design and construction of this research shows that it is possible to generate electricity via wind power to support alternative means of power generations. The wind turbine was tested and it performed well. Average rotor speed of 153.5 rpm was achieved and this was accompanied with an average current of 19.77 A and an average voltage of 25.1 V which gives an average power of 500 W.

The materials used in the fabrication of this design are locally available. However, the cost of developing the wind turbine is a little bit cheap but when it is mass produced, the cost per unit will be greatly reduced thereby rendering it easily available to consumers at a very cheap rate.

ACKNOWLEDGEMENT

The researchers wished to acknowledge the management of Covenant University for their part sponsorship and contribution made to the success of the completion of this research study.

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