PERFORMANCE EVALUATION OF 1 kW HORIZONTAL AXIS WIND TURBINE FOR RESIDENTIAL USE IN ABEOKUTA

Akinola O. A. [1] and K. A. Bakare[2]

[1,2]Department of Electrical and Electronic Engineering,
Federal University of Agriculture.
Abeokuta, Ogun State, Nigeria.

***Corresponding author: akinolaoa@funaab.edu.ng 08034831492**

ABSTRACT
The conventional energy sources are mainly use in Nigeria to generate electricity and yet, there is a critical challenge of electric power deficit. Therefore, design, modeling and simulation of 1 kW horizontal axis wind turbine as alternative power supply for residential use is considered. This paper presents the design, modeling and simulation of horizontal axis type wind turbine with power output of 1 kW at a wind speed of 4 m/s. Analysis of wind power capacity in W/m^2 was done based on the obtained wind data using Weibull probability distribution function. The results showed that the average exploitable wind power density between 4 W/m^2 and 14.97 W/m^2 was realizable. The wind turbine blades were modeled using blade element momentum theory. The rotational speed of the blades was increased by using airfoil. Mathematical equations were used to determine the tip speed ratio, lift and drag forces and the power output. The MATLAB™ AND SIMULINK™ scientific computer program was used to simulate the model of the wind turbine. The model with its required input parameters, pitch angle, rotational speed of the rotor, angle of attack, and wind speed were varied above and below its actual settings. The results showed that when the parameters were decreased, there was no power output and with the parameters values above the actual settings, the output power was increased to 2.5 kW at a wind speed of 8 m/s and generator speed of 620 rpm. The capacity is small and it is affordable for many household applications in Nigeria.

***Keywords*: Wind Turbine, Power Output, Residential Use, Wind Speed.**

1. INTRODUCTION

Nigeria has low access to electricity by the population (36%). At present only 10% of rural households and 40% of the country's total population have access to electricity [1]. The country's electrical power demand is high but actual generation is considerably below demand. As a result, Nigeria has experienced an energy supply crisis in recent years. In order to address the electricity need of most residential houses, the country needs to look towards development of the country's wind power resources to curtail the crisis. However, wind turbine can be used in remote locations that cannot be easily connected to the grid. Wind energy is a resource that is available almost everywhere, thereby generates electricity at a reasonable cost. The primary reason behind the recent peak of wind energy capacity is due to improved turbine technology. Wind energy has many benefits, including producing no direct emissions while generating electricity at a reasonable cost. The efficiency or capacity factor of wind turbines continually increases with improved manufacturing processes, siting techniques, and operating procedures. A small wind turbine, with a rotor diameter as small as a meter or less, can often be set up and stand alone on the roof of houses and buildings for electricity generation. This kind of wind energy converter is normally directly linked to battery rather than connected to the electric grid. As its capacity is small (usually <1 kW), its prime cost is not very high and is affordable for many household applications [2]. Harvesting wind energy is the conversion of kinetic energy from the wind, also called wind energy, into mechanical energy. If the mechanical energy is used to produce electricity, the device is called wind turbine or wind power plant. A statistical function known as Wiebull distribution function have been developed to assist in the predictions of the output power production of wind turbine [3]. The two-parameter Wiebull distribution function is expressed mathematically as

$$\boldsymbol{F(v) = \frac{k}{c}[(\frac{v}{c})^{K-1}]\exp\left[-\left(\frac{v}{c}\right)^{K}\right]} \quad \textbf{(1)}$$

It has a cumulative distribution function as expressed in equation below

$$\boldsymbol{M(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^{k}\right]} \quad \textbf{(2)}$$

Where v is the wind speed, K is the shape parameter and C, the scale parameter of the distribution. The parameters K (dimensionless) and C (m/s) therefore characterized the Wiebull distribution. To determine K and C, the approximations widely accepted are given in equations.

$$\boldsymbol{k = (\frac{\sigma}{v'})^{-1.09}} \quad \textbf{(3)}$$

$$\boldsymbol{c = \frac{v' \times k^{2.6674}}{0.184 + 0.816k^{-2.7385\ 9}}} \quad \textbf{(4)}$$

The analysis of the aerodynamic behaviour of wind turbines can be started without any specific turbine design just by considering the energy extraction process.

This model of a wind turbine is the called actuator disc model where the turbine is replaced by a circular disc through which the airstream flows with a velocity U_∞ and across which there is a pressure drop from P_u to P_d as shown in figure 1. At the outset, it is important to stress that the actuator disc theory is useful in discussing overall efficiencies of turbines but it cannot be utilized to design the turbine blades to achieve a desired performance. Actuator disc model is based on the assumptions like no frictional drag, homogenous, incompressible, steady state fluid flow, constant pressure increment or thrust per unit area over the disc, continuity of velocity through the disc and an infinite number of blades.

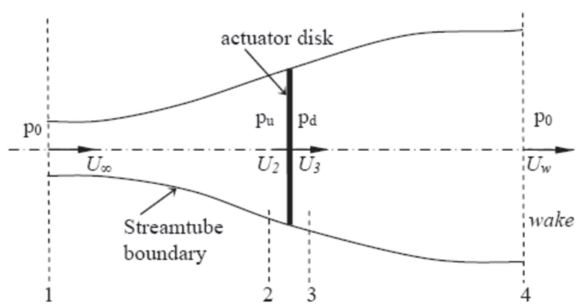

Fig. 1: Actuator Disc Model [4]

2. LITERATURE REVIEW

The review of basics of blade element theory was done by Lakshmi N. Sankar [5]. The blade is divided into strips/elements. On each strip/element, the angle of attack and the corresponding lift and drag coefficients from a table of airfoil characteristics were found. The tip losses, root losses, stall delay, swirl losses were corrected as needed. The lift forces, drag forces, propulsive force (in the plane of rotation) and the torque contribution of that strip were calculated. The report of Lakshmi N. Sankar [5] indicated that once the angle of attack (α) is known, , the lift and drag coefficients C_L and C_D were found. It was stated that these quantities influence the axial induction factor and the tangential induction factor a. The results indicated a strong correlation between rotor rotation rate and blade angle of attack. Design and analysis of Horizontal Axis Wind Turbine Rotor was done by Arvind Singh Rathore et.al [6]. An optimization model for rotor design of 750 kW horizontal axis wind turbine was presented.. In this work a blade of length 21.0 m is taken and airfoil for the blade is S809. The airfoil taken is same from root to tip. All the loads caused by wind and inertia on the blades are transferred to the hub. The stress and deflection were calculated on blades and hub by Finite element analysis method. The design of a HAWT rotor is formulated as a constrained of multi-objective optimization problem with respect to geometric and operational characteristics, as maximization of output generated, minimization of generated blade vibrations, minimization of blade material cost, minimization of stress and deflection in rotor, fulfillment of appropriate strength requirements by the blade structure. A mathematical model and user-interface computer program for aerodynamic design of Horizontal Axis Wind Turbine Rotor was developed to calculate Load on Wind turbine rotor Components (Blade and Hub) for Indian wind conditions [6].

3. METHODOLOGY

The kinetic energy extracted from the wind is influenced by the geometry of the rotor blades. Determining the aerodynamically optimum blade shape, or the best possible approximation to it, is one of the main tasks of the wind turbine designer. The aerodynamic design addresses the selection of the optimum geometry of the blade external surface normally referred to as the blade geometry which is defined by the airfoil family and the chord, twist and thickness distributions. The forces on the blade elements are solely determined by the lift and drag coefficients [7]. In this design, NACA 4412 airfoil was used. Coefficient of lift and coefficient of drag over the airfoil selected are according to the pressure distribution over the airfoil surface. And they are found to be 1.1 and 0.03 respectively.

Total swept area is taken to be $4.52m^2$, where the diameter is 2.40m, in which blade length is of 1.20m and the radius of hub is 1.07m.The Tip Speed Ratio (TSR)is an extremely important factor in wind turbine design, before it can be calculated, there is need to figure out the tip speed of blade. To do this, distance and time are needed. The distance is how far the tip of a blade goes to make one revolution. In order to find this rotor radius, length of one blade is needed. The equation for the circumference of a circle, $C = 2\pi r$, can then be used to find the total distance travelled by the blade tip. Time is how long it takes the rotor to make one full revolution.

For optimum TSR for maximum power output, this formula has been empirically proven:

$$\boldsymbol{\lambda\ (\text{max power}) = \frac{4\pi}{n} = 4} \qquad (5)$$

where, n = number of blades = 3

With 4 as tip speed ratio, the blade is not so broad but slightly long designed to run fast under low wind. The number of blades used is 3, which shows that speed is needed more than torque.Extra blades help the machine to start to turn slowly, but as the speed increases the extra drag of all those blades will limit how much power it can produce.

For relative velocity of the wind,

$$\boldsymbol{U_{rel}^2 = u^2 + v^2} \qquad (6)$$

v = average wind speed = 4 ms^{-1}

$$\boldsymbol{u = \Omega r} \qquad (7)$$

where, the angular speed of the rotor

$$\boldsymbol{\Omega = \frac{2\pi n}{60}} \qquad (8)$$

n = rotational speed of the rotor = 500 rpm

Therefore, $\boldsymbol{U_{rel} = \sqrt{(5\ \ 24r)^2 + 4^2}}$

Then, the value of lift force and drag force can be calculated by assuming air density to be 1.2 kg/m^3 as follows:

$$\boldsymbol{F_L = {}^1/_2 \times 1.2 \times 1.1 \times [(5\ \ 24r)^2 + 4^2]}$$

Three angles are involved, the angle of attack α, the angle of relative wind φ and the pitch angle Θ_p. The coefficient of lift and drag both depend on the angle of attack. For angles of attack higher than typically 15-20^o the air is no longer attached to the blade, a phenomenon called “stall”. The ratio C_L/C_D is called the glide ratio. Normally interest lies in the high glide ratio for wind turbines. Values up to 100 or higher is not uncommon and the angles of attack giving maximum are typical in the range 5-10^o. The maximum lift/drag ratio is 88.72 at attack angle α = 6^o. So for the purpose of this project attack angle of 6^o is chosen.

The pitch angle $\Theta_p = 4^o$.

Therefore, angle of relative wind

$$\boldsymbol{\varphi = \alpha + \Theta_p = 10^o} \qquad (9)$$

The total power output of the rotor can be calculated by integrating the power of each differential annular element from the radius of the hub to the radius of the rotor.

$$\boldsymbol{P = \int_{1.07}^{1.20} \Omega B\ {}^1/_2\ \rho U_{rel}^2\ (C_L \sin\varphi - C_D \cos\varphi) c dr} \qquad (10)$$

where B = number of blades = 3

ρ = Density of air = 1.2 kg/m^3

c = chord length = 0.12 m

$$\boldsymbol{P = \int_{1.07}^{1.20} \{5\ \ 24 \times 3 \times {}^1/_2 \times 1.23 \times [(5\ \ 24r)^2 + 4^2] \times (1.1 \sin 10^o - 0.03 \cos 10^o) \times 0.12\} dr}$$

P = 869 W

4. EXPERIMENT

Equations 1-10 were coded using MATLAB platform and all the required parameters such as generator, main controller, environment, gear train, yaw actuation and nacelle requirements were considered. Table 1 shows the blade requirements as used in the simulation. The parameters were varied above and below the actual values.

The simulation showed how a live wind turbine would work under the required parameters. Fig. 2 is the wind turbine model used for the simulation on the MATLAB AND SIMULINK software.

Table 1: Blade Requirements

Blade length	**1.2 m**
Material	Carbon/wood/glass/epoxy
Type of rotor air brake	Full blade
Blade profiles	NACA4412
Chord length	0.12 m

Table 2: Varied Parameters

ANGLE OF ATTACK	WIND SPEED	PITCH ANGLE	SPEED OF ROTOR	POWER GENERATED
3.00	2.00	2.00	500	0
6.00	4.00	4.00	560	1.00
9.00	8.00	8.00	620	2.50

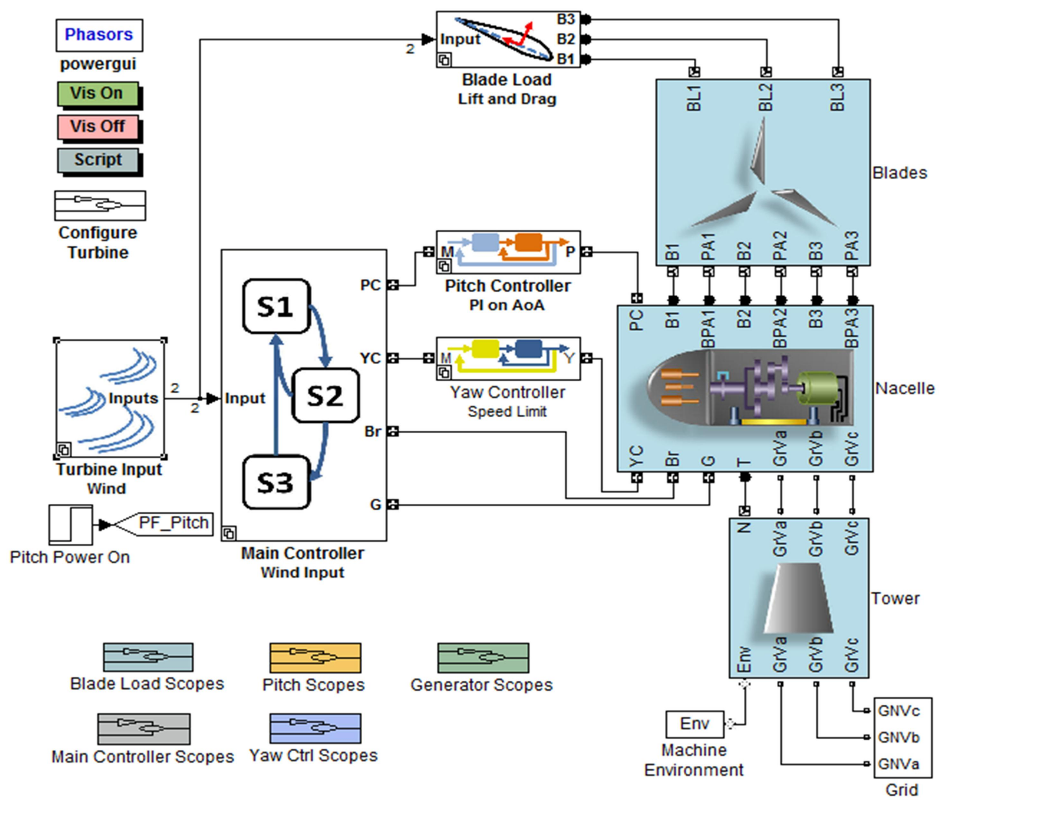

Fig. 2: Wind Turbine Model [8]

5. RESULTS

When the simulation started, a virtual 3-Dimensional wind turbine comes up. This was used to observe the wind turbine. When the wind started blowing against the blades of the wind turbine, it took 8-9 seconds for the blades to pitch. Pitching of the blades is when the blades turn to the direction of the wind. During this time duration, the actual wind speed was 3 -3.5 m/s. As the wind speed increases, the blades continue to spin, thereby generating useful power. The wind speed may get to its maximum or it may reduce, this is observed from the wind speed graph. The simulation time T = 79.9951 sec and the offset time = 0 as shown on the graphs generated to show the results of the simulation.

Fig. 3 is the graph generated from the simulation which shows the wind speed variation with respect to the time duration the wind blows against the wind turbine blades. The time axis is measured in seconds (s) and the speed axis is measured in meters per seconds (m/s). It was observed that at time t = 0 s, the wind speed was not recorded. It is until the wind has blown against the blades for 10 s or more that wind speed was recorded. As the wind continues to blow against the blades, the wind speed continue to increase. This is shown by the yellow line in the graph which constantly increases. After a while, the wind speed begins to decrease, this is also shown by the decreasing slope of the curve.

Figures 4-6 are the graphswhich show the power outputswhen the required parameters were varied above and below the actual values. The blades of the turbine spun for a while to generate enough RPM to power the generator and then produce useful output power in Watts. From the figures,the wind has blown against the blades for about 25 – 26 seconds before power is generated. Table 2 showed how the required parameters were varied.

6. DISCUSSIONS

The daily measured time series wind speed data for Abeokuta, Nigeria have been analyzed statistically based on Weibull probability distribution function. The yearly Weibull probability distribution parameters, mean wind speeds and wind energy density availability for the location have been determined. Based on the analysis, the yearly average wind speed was about 4 m/s at a height of 15m. The power generated based on this site is adequate for residential purposes such as battery charging, lighting and other electrical load within the generated power output. Hence, some homeowners who do not have access to the grid can chose to use wind turbines which is environmental friendly and save on energy costs. Energy has been and will still be the main stay of an economy. It is one of the most important factors of National development. As energy demands around the world increase, the need for a renewable energy sources that will not harm the environment has increased. Therefore, there is need for wind energy adaptation.

7. CONCLUSION

The daily measured time series wind speed data for Abeokuta, Nigeria have been analyzed statistically based on Weibull probability distribution function. The yearly Weibull probability distribution parameters, mean wind speeds and wind energy density availability for the location have been determined. Based on the analysis, the yearly average wind speed was about 4 m/s at a height of 15m. The results showed that the average exploitable wind power density between 4 W/m^2 and 14.97 W/m^2 was realizable. This paper demonstrated a practical selection method for determining the optimum blade design parameters, that is, design wind speed, tip speed ratio, lift and drag forces and attack angle. The design wind speed was considered carefully for the wind turbine. If the design wind speed is too low, the wind turbine rotor cannot achieve expected rotor power output for the whole operating wind speed range. If the design wind speed is too high, the wind turbine rotor exceeds the rated power. This could damage the wind turbine, a furling system would turn the rotor away from the direct wind force. From the simulation, power output of 1 kW was generated at a wind speed of 4 m/s. This is suitable for many communities which are off the national grid line, as well as alternative for the urban population that experiences erratic supply power situations to power their minimum electrical load requirements. The performance of the wind turbine was evaluated by varying the required parameters for the simulation and the results were compared. With parameters above the actual parameter settings, the power output was 2.5 kW. The simulation results showed that increased parameters guarantees good performance.

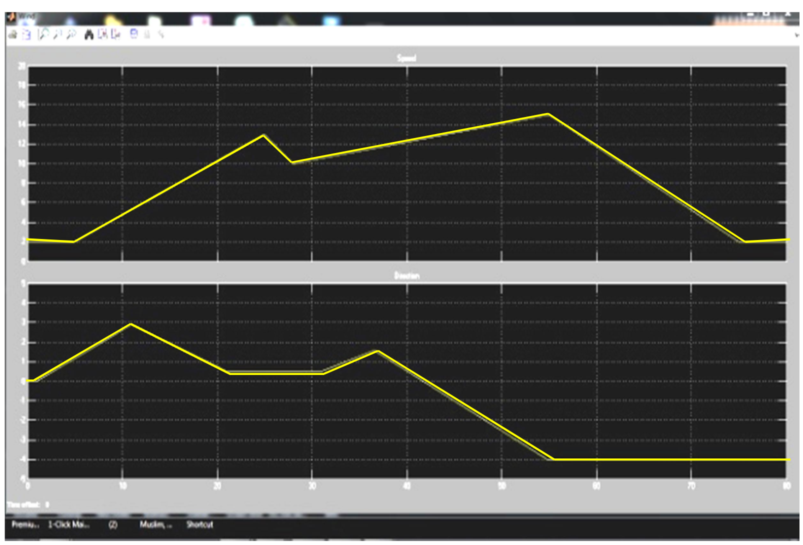

Figure 3: Graph of Wind Speed

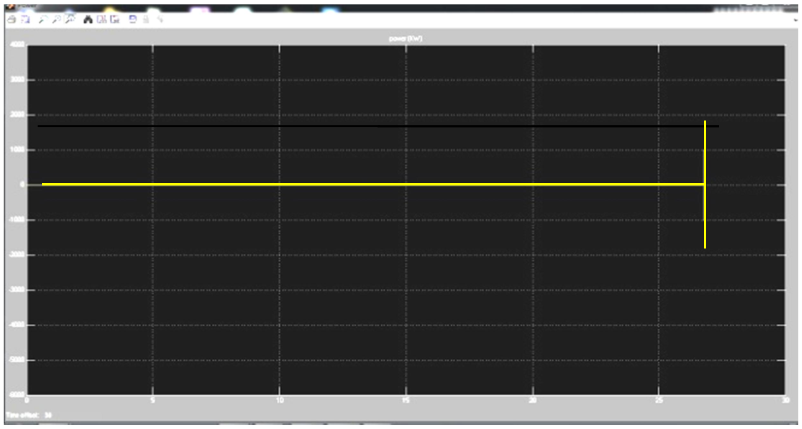

Figure 4: Graph of output power with actual required parameters

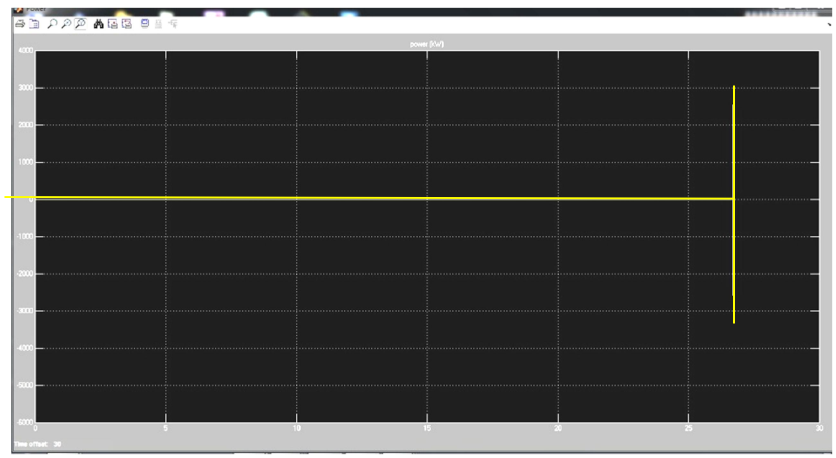

Figure 5: Graph of Power output for increased required parameters

Figure 6: Graph of Power output for decreased required parameters

8. REFERENCES

Electrical power in Nigeria-overview. www.mbendi.com/indy/powr/af/ng/p005.htm Retrieved on 13/01/2014

D.Y.C Leung et.al. "Design Optimization of a Cost-Effective Micro Wind Turbine". Proceedings of the World Congress on Engineering, Vol. II, London, U.K. (2010)

B.K Gupta, Weibull Parameters for Annual and Monthly Wind Speed Distributions for Five Locations in India, *Solar Energy*. **37**, 469-477. (2000)

Emrah Kulunk. " Aerodynamics of Wind Turbines". Fundamental and Advanced Topics in Wind Power. ISBN 978-953-307-508-2, In Tech, available from: http://www.intechopen.com/books/fundamental-and-advanced-topics-in-wind-power/aerodynamics-of-wind-turbine. (2011)

Lakshmi N. Sankar, "Blade Element Theory" Wind Engineering Module 4.1 (2001)

Arvind S.R. et.al, "Design and Analysis of Horizontal Axis Wind Turbine Rotor". International Journal of Engineering Science and Technology. Vol. 3 No. 11. (2011)

Tony Burton, David Sharpe, Nick Jenkins and Ervin Bossanyi, "Wind Energy Handbook". John Wiley and Sons Ltd. (2001)

Mathworks, Inc. Matlab. Wind turbine model, V 7.2, (2011). www.mathworks.com/windturbinemodel/