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Potential of 1kW Horizontal Axis Wind Turbine for Residential Use in North-West Nigeria

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ABSTRACT

The absence of harmful emission in wind energy makes it one of the fastest growing technologies in energy generation industry. The erratic and epileptic state of power in this country should be of a great concern for all and should drive us into strong demand for wind generation. The shortage of electrical power generation in Nigeria requires an alternative that is more economical, reliable and environmentally friendly. The present use of generators as an alternative power supply has not proven reliable due to its high running cost. Therefore, the development of 1kW horizontal axis wind turbine as an alternative power supply for residential use is considered. This paper presents the design and simulation of horizontal axis type wind turbine to generate an approximately output power of 1kW. A mathematical equation was employed to determine the tip speed, rotor blades and generate the output power. All the required parameters needed for the turbine design were simulated using MATLAB/SIMULINK software packages. From the simulation, the validation of results it was deduced that after 25 seconds of blade rotational speed, the wind turbine power output measured was between 1 and 1.5 kW at the wind speed of over 7 meter/second based on synchronous generator speed of 550 revolutions per minute. Conclusively, this output power is suitable to meet the minimum basic electrical load requirements for most residential use in North - West Nigeria.

1. INTRODUCTION

Energy has a major impact on every aspect of our socio-economic life. It plays a vital role in the economic, social and political development of our nation (Slootweg *et al.,* 2001). Despite the abundance of energy resources in Nigeria, the country is still in short supply of electrical power. Only about 40% of the Nigerians have access to grid electricity (Sambo, 2006). Nigeria's electric power generation and grid distribution capacity is currently in the range of 4000 to 4500 MW, which is far short of the required energy demand in the range of 20000 to 25000 MW to support continuous and reliable power flow for residential and industrial uses (Sambo *et al.,* 2014). Wind generation described to be one of the natural and cost effective resources among renewable energy technologies in the universe (Bhola *et al.,* 2009). Wind is a natural phenomenon related to the movement of air masses caused primarily by the differential solar heating of the earth's surface (Sambo, 2005). In a stochastic nature, wind energy cannot be controlled, but can be managed. This is because wind power is available only when the wind speed is above a certain threshold (Brady, 2009). The power company has been unable to cope with the electricity demand that is growing at an average rate of about 7% annually, even with the establishment of National Integrated Power Project (NIPP).

The Director General of Energy commission of Nigeria in a Paper presented at International Association for Energy Economics in Third quarter 2009 lamented that renewable energy resources most especially wind energy have not been integrated to the Nigeria grid (Sambo, 2009). Also, most studies have not placed emphasis on horizontal axis wind turbine power output of about 1kW and below. However, a method for determining the optimum design parameters for horizontal axis wind turbine were developed and tested by Collecutt and Flay (1996). These design parameters were the rotor diameter, rated power and tower height. The optimum values were found to be dependent on site wind regime. The results of the study indicates that only the optimization of the relative combination of rotor diameter and rated power with respect to site mean annual wind speed that afforded significant reduction in energy production cost. This validation confirmed that presently available wind turbines were optimized for mean annual wind speeds in the range 6 to 8 m/s and suggested that for low wind sites the energy production cost may be reduced up to 10% through the optimization of machine rated wind speed fitted for the site. The majority of wind farm sites around the world have annual mean wind speeds of 8m/s (Slootweg *et al.,* 2005).

Collecutt and Flay (1996) stated that the re-optimization of current technology to suit sites with significantly higher mean annual wind speeds might well yield a reduction in energy production cost at such sites. Also for a wind speed of 10 m/s site, a 10% reduction in energy production cost is achievable through the optimization of the rated wind speed of the machine as compared to a site with a wind of 8 m/sec and below. The starting and low wind speed behavior of a small Horizontal Axis Wind Turbine was conducted by Wright and Wood (2004). The studies revealed that in order to extract the maximum possible power, it is important that the blades of small wind turbine start rotating at the lowest possible wind speed. This method of analysis of the low wind speed performance of a small wind turbine has potential as a relatively simple design tool. The simplicity of the generic equations for lifting and dragging has particular appeal and is probably a good starting point for lift and drag approximation for many blades. Their studies indicated that most starting torque is generated near the hub and most power extracting torque comes from the top region so that it should be possible to optimize start-up performance while maintaining good power performance.

In order to address the electricity needs of most residential homes, a residential scaled horizontal axis wind turbine generate power output in watts up to 1 kW is proposed to serve as a backup power supply during power outages. As the demand for more environmentally friendly energy resources grows, energy providers have recognized the importance of wind power and have invested in the development of wind turbine. The prospect of wind energy as a source of alternative power supply is emerging as other sources of energy and power supply are becoming unavailable, epileptic and more expensive. Wind turbines are now being used as the generic term for machine with blades rotation that converts kinetic energy of wind into useful power.

2. METHODOLOGY

This study considered the design and simulation of a horizontal axis wind turbine which are more common and widely available to generate power output of 1 kW to serve as a backup for power supply during power outages. The proposed horizontal axis wind turbine comprises of 3 blades due to its size and tip speed ratio of 5. The turbine is represented by a circular blade disk of area $A = \pi R^2$ where R is the blade radius in (m) as shown in Figure 1. The volume is about to cross the imaginary line in the wind that represent the blade disk. The volume is about to cross the imaginary line (when viewed side on) in the wind that represents the blade disk. The volume of the element is the product of its area, ΔA in m^2 and normal length to the disk, δx, in m. The mass in kg of the turbine is represented as $\rho \Delta A \delta x$ and its kinetic energy (K.E) is defined as

½$\rho\Delta A\delta x U_0^2$. The time taken in sec for this element to cross the blade disk δt and U_0 is the wind speed in m/s is given as $\delta x = U_0\delta t$. The contribution of the elements to the total amount of K.E that passes in δt is symbolized as ΔK.E. Thus, it is given as:

$$\delta(\Delta \mathrm{KE}) = \frac{1}{2}\rho\Delta A U_0 \delta t U_0^2 \quad (1)$$

$$\delta(\mathrm{KE}) = \frac{1}{2}\rho A U_0^3 \delta t \quad (2)$$

The differential equation can now be taken formally to the limit as $\delta t \longrightarrow 0$, to give

$$P = d\,(\mathrm{KE})/dt = 1/2\rho A U_O^3 \quad (3)$$

P is the maximum power that a wind turbine utilized in wattage while $\frac{d}{dt}$ is the time rate change (derivatives) of the energy (Glauert, 1976). Equation (3) verified the fact that the output power of any turbine depends on the cube of the wind speed (Sinha *et al.,* 2010). Furthermore, a turbine cannot capture all the wind that would otherwise pass through the disk, even if it could decelerate this flow to rest, so that finding the K.E in the absence of the blades will overestimate the actual energy capture. Based on Betz limit, equation (3) is practically impossible. Therefore, a fraction of equation (3) suffices.

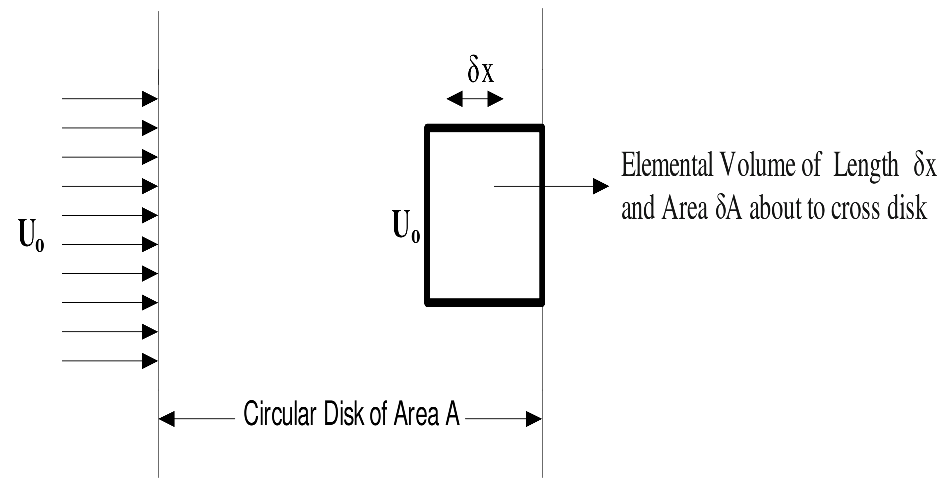

Figure 1: Wind Flow Past a Circular Disk Representing the Blades (Bergey, 1998)

The design for the optimal wind turbine for one location cannot be in-line with the design for optimal wind turbine for another location because the wind speed distribution varies. For this design, a location with a wind speed ranging from 6 - 11 m/s was chosen. The location should be an open space where there will be no disturbance of wind velocity and direction. The wind turbine blades were designed according to the selected wind turbine power. The wind turbine system generation encompasses the wind, wind blades, turbine, generator, controller, power grid and loads as shown in Figure 2. The controller controls the density of the wind in kg/m^3 to maintain output voltage of the generator supply to the power grid for voltage distribution. Hau, (2006) stated that the useful related equations in wind turbine system are the power output, tip speed ratio and wind blades speed as in the equations 4 and 5.

$$\lambda = \frac{\omega R}{V} \quad (4)$$

$$B = \frac{80}{\lambda^2} \quad (5)$$

Where: λ is the tip speed ratio in m/s; ω is the angular speed in rad/s; V is the wind speed in m/s^2; R is the length of rotor blade in m; B is the number of the blade.

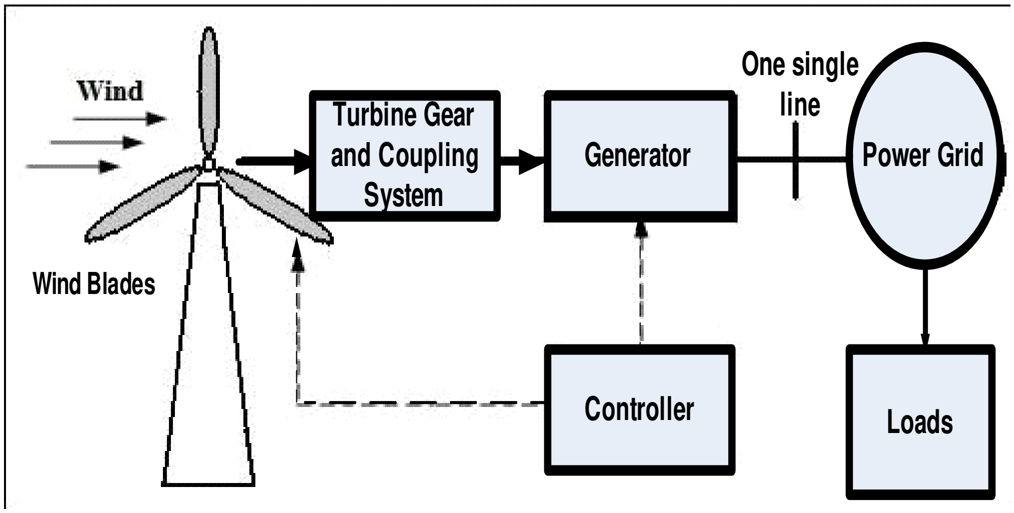

Figure 2: Model for a Wind Turbine System Generation

The total power generated depends upon the ability of aerofoil to extract it. The output power will be calculated using Bernoulli's analytical formula method. The coefficient of lift and drag play major role to decide the power extracted by a wind turbine. Coefficient of lift and coefficient of drag over aerofoil were selected according to the pressure distribution over the aerofoil surface at 1.1 and 0.03 respectively. Total diameter of swept area was taken to be 2.52 m, the blade length was 1.2 m and hub diameter was 0.12 m. When drawing an equilateral triangle over the circle of 12 cm, equation 6 was used.

$$r = \frac{a}{2\sqrt{3}} \tag{6}$$

Given that, r = 12 cm, a = 0.4156 m

Tip chord b length is taken as 50% of root chord length a

$$b = 0.5 \times 0.4156 = 0.2078 \text{ m}$$

Chord length at a point will be a function of distance of that point from root of the blade (Burton *et al.,* 2001). That means chord length will decrease linearly from 0.4156 m at root to the 0.2078 m at tip while average chord length will be 0.3119 m. Relation between chord length and distance of the point from root is

$$C = 0.09362r + 0.4156$$

To calculate the tangential velocity at blade tip, the tip speed ratio is selected and this is taken to be 5. The formula for tip speed ratio is given in equation (4). Given that the tip speed ratio is 5 and the wind speed is 4 m/s. Thus, the tangential velocity at the blade tip will be 20 m/s. The angular velocity of the shaft ω in rev/s is given as;

$$\omega = \theta_v \text{ x 1rev/s}$$
$$\omega = 20\text{rev/s}$$

From equation (1) using a tip speed ratio 5, Relative velocity of the wind is given as;

$$w = \sqrt{u^2 + v^2} \tag{7}$$

From equation (1), tangential velocity is given by ω R in relation to the wind speed, then

$$w = \sqrt{400r^2 + 16}$$

Angle formed between direction of relative wind velocity and plane rotation of rotor (β). Formula for β is

$$\beta = \tan^{-1}\frac{u}{v}$$

$$\beta = 78.6°$$

Two types of forces on rotor are useful force (f_θ) tangential to the tip of the blade and axial force (f_x) axial to the shaft.

$$f_x = L\sin\beta + D\cos\beta \qquad (8)$$

$$f_\theta = L\cos\beta \qquad (9)$$

The total power output generated from the turbine is achieved thus below;

$$P = 0.08\int^{1.1}(\rho \times v \times r \times (v^2 + \omega^2.r) \times ((0.09362 \times r) + 0.4156))\,d\omega$$

Thus, $\rho = 1.2$ kg/m^3, v = 4 m/s, r = 1.2 m, P = 897 W

For the purpose of this study, the design employs a wind turbine of cut-in rated and cut-out wind speeds of 8m/s and 20 m/s respectively. The wind turbine model equations were used to produce the simulink model is as shown in Figure 3. Where ρ is the air density in kg/m^3; V is the wind speed in m/s; r is the length of the blade in m; P is the output power of the turbine in W.

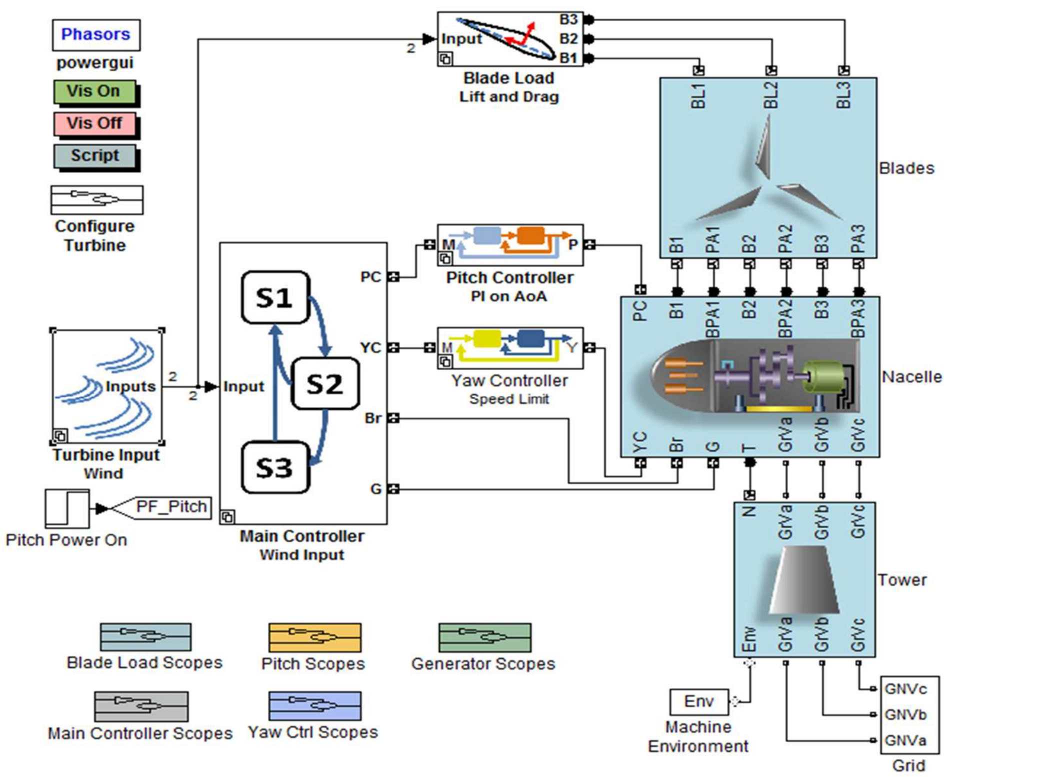

Figure 3: Simulink Model for Wind Turbine System (Mathworks, 2012)

Equations (1) to (9) were coded using MATLAB SIMULINK packages. All the required parameters such as blades, environment gear, generator, main controller, Nacelle pitch controller and Yaw actuator instruments were considered respectively. Table 1 indicated the generator parameter used for the simulation.

Table 1: Generator Simulation Parameters

Specification	**Values**
Rated power	1 Kw
Rated current IN	50 A
Synchronous rotation speed n0	550 rpm
Rotation speed at rated power	560 rpm
Slip at rated power Ns	0.0170
Voltage	20 V
Frequency F	50Hz

3. RESULTS AND DISCUSSION

The performance of the wind turbine speed and the output power generated from the simulation was deduced from the graph shown in Figures 3 and 4 respectively. When the wind started blowing against the blades of the turbines, it took 8 - 9 seconds for the blade to pitch. During this duration, the actual wind speed recorded was 3 - 4 meter per seconds. No useful power was generated from the wind turbine generator at this wind speed. The blades just began to pitch at this time of the simulation. After the blades have fully pitched at the 13th second, the blades continued to rotate and the generator speed continued to increase. After 25 seconds, the blades were at the peak rotation and the power output measured was 1.2 kW at a wind speed of over 8 m/s. The blades pitched at the pitch angle 60° when it turned in the direction of the wind. The speed of the generator in revolution per minute, (rpm) when it produced this output power was 550 rpm.

Figure 3 indicated the time taken along the horizontal axis measured in seconds (s) and the wind speed along the vertical axis measured in meters per seconds (m/s). It can be observed that between time 0 s and 5 s, the wind speed was less than or equal to 2 m/s and from 5 s the speed started to increase gradually. At 10 s the speed was approximately 5.1 m/s and at 20 s the speed was approximately 10.5 m/s. After 25 s the wind speed began to decrease, the blades tend to reach the maximum peak rotation and the generator speed continued to increase beyond the pre-set value of the output power. Figure 4 shows the power generated when the wind blows against the blades of the turbine. The blades of the turbine have to spin for a while to generate enough revolution per minute to power the generator and then produce useful output power in Watts. The wind has to blow against the blades for about 25 – 26 seconds before power is generated. The power output generated is between 1 and 1.5 kW.

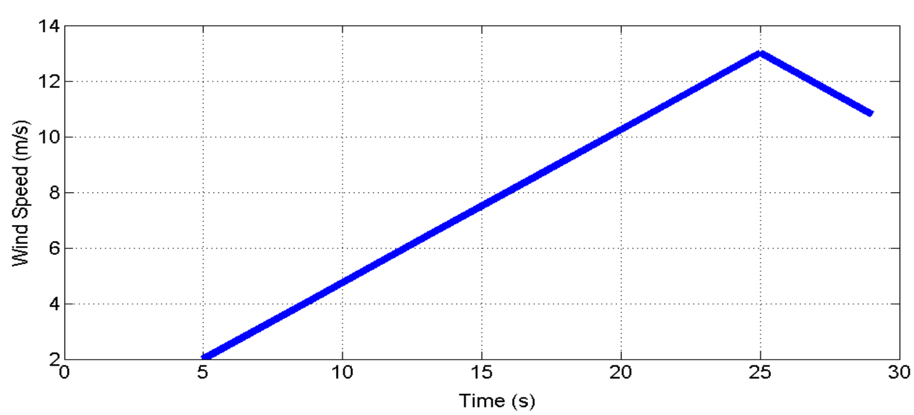

Figure 3: The Graph of Wind Speed at 25 second

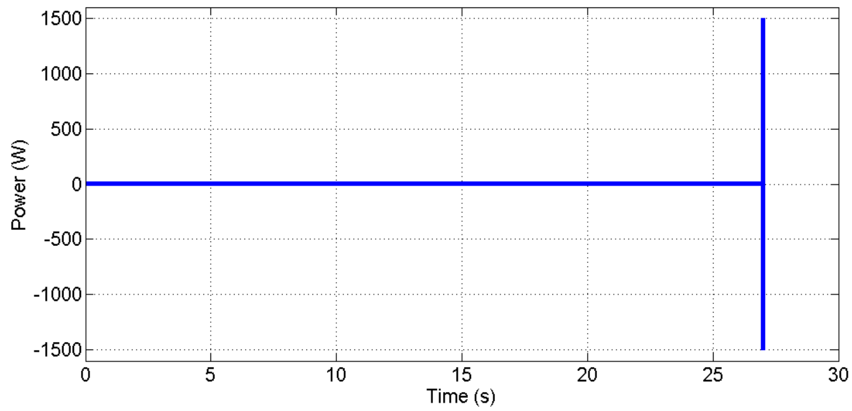

Figure 4: The Graph of Power Generated at 1.5kW

This experiment considered some major cities and communities in North-West, Nigeria. These include Kano, Katsina, Zamfara and Sokoto States. The mean wind speed profile characteristics of these cities were reported to be between 6.0 and 11 m/s at 10m blade diameter all year round (Fagbenle, 2012; Ajayi *et al.,* 2011; Ajayi *et al.,* 2011). The power generated based on these sites was adequate for residential purposes such as lighting, entertainment, fan, and other light electrical load within the generated power output. The total cost of developing a 1 kW wind turbine at present in Nigeria economy is about Two Hundred Thousand Naira Only, (₦200,000) which is approximately to Five Hundred and Twenty US Dollar ($520). Therefore cost of electricity in kilowatt unit of energy per hour (1kWh) in Nigeria is ₦62.33, thus 1kWh is equal to 1000W of electricity used in 1 hour. Considering the national minimum wage in the country at Thirty Thousand Naira, equivalent of 78 US Dollar and the purchasing power ability of the population of the informal sector of the targeted economy, the installation of 1 kW turbine power is very feasible and workable.

Because of the importance of the energy sector to Nigerian economy and a major drive for growth in addition to its micro economic importance to reduce poverty, improving productivity and enhancing general quality of life of Nigerian people, Bank of Industry in partnership with United Nation Development Programmed have a project, called Renewable Energy Business Financing for promotion of the Development of Renewable Energy Technology through a planned payback period for interested user. The installation can readily deliver the required energy for residential use in North West Nigeria. This will cater for power loss during the peak hour periods at night. However, the sites wind speed can generate more capacity up to MW of electrical power if the required number of wind mills are installed.

4. CONCLUSION

The design and implementation of 1kW horizontal axis wind turbine for residential use in North-West Nigeria was achieved in this work using the requirement components such as the blades, pitch angle, turbine gear system, generator, main controller, Nacelle pitch controller and Yaw actuator instruments. The Betz limit was incorporated to monitor the output power of the generator on limiting factor or efficiency of 0.59. From the simulation result, the power output of over 1 - 1.5kW was generated at a wind speed of 8m/s. Thus, the power generated will be suitable as an alternative supply for many urban and rural areas that experiences erratic and epileptic power problems in the study area. The system is void of greenhouse emission which makes it less hazardous to the health of inhabitants in the installation locality and it is economically viable as an alternative to the local populace that are unconnected to the national grid. Therefore, the system can supply energy for accessing information when desired and a pointer for achieving the Sustainable Development Goals in Nigeria.

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