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Performance Evaluation of a Mini Wind Turbine for Electricity Generation in Nigeria

Omorogiuwa Eseosa*, Uchechikwu Woke

Electrical/Electronic Engineering, Faculty of Engineering, University of Port Harcourt, Rivers State, Nigeria.

**Corresponding Author: Omorogiuwa Eseosa, Electrical/Electronic Engineering, Faculty of Engineering, University of Port Harcourt, Rivers State, Nigeria. Email: eseosa.omorogiuwa@uniport.edu.ng*

ABSTRACT

Nigeria with close to 200 million people depends solely on fossil fuel for its power generation. However, due to its unfriendly nature in terms of environmental pollution and damage/havoc to the ecosystem, there is need to search for alternative source of clean energy. Fortunately Nigeria is blessed with abundance of wind energy. This work aim to harness wind energy for power generation. It involves modeling of wind turbine and evaluation of mechanical and electrical power and its coefficient as well as its overall performance for various wind speed data range as obtained from National Meteorological Agency (NIMET) for various parts of Nigeria. it was found that at wind speed less than 3.5m/s, the turbine did not generate power. Tip speed ratio, coefficient of performance, torque, power output while keeping both the blade pitch angle and turbine angular velocity constant were determined. The results obtained showed that mechanical power varies directly with cube of wind speed and electrical power generated at the output is greatly dependent on performance coefficient of wind turbine and does not have linear relationship with wind speed. Moreso, both powers (mechanical and electrical) depends on air density, area swept by the blade and wind speed. It was also observed that for wind turbine whose blade length is 5m, operating at an angular speed of 10rad/s with pitch angle of 5deg is installed in the northern part of Nigeria, it will have maximum power of 7.674kW and a maximum coefficient of performance of 0.284. The wind speed at which this maximum power will occur is 13m/s which is also the cut-out wind speed of the turbine. At wind speed greater than 13 m/s the wind turbine will stand a chance of failure due to stress from the wind. This failure can be averted by using a control mechanism that will shut down the wind turbine at wind speed greater than 13 m/s.

INTRODUCTION

The search for other energy sources (renewable energy) is now necessary. Reason being that fossil fuel is not environmentally friendly coupled with its high cost. It has been speculated that energy from the wind will generate 1.1 trillion Kilowatt-hours of the total 3.3 trillion kilowatt-hours of the predicted renewable energy to be supplied by 2030 (Taufik 2015). Energy from the sun will be prevalent in Arab nations due to the availability of high sun intensity (Taufik 2015). Intense research is ongoing in most countries to know the possibilities of generating high quantity of power from the sun. Again, it has been predicted that wind and sun alone can provide energy sources of economic importance because other sources of renewable energy are very expensive (Chiang *et al*, 2003).

In future, the major sources of renewable energy will come from the sun and wind. Wind turbines that are situated offshore are used to harness the wind speed available offshore and simultaneously reduce environmental pollution. The first people to use wind turbine were the Dutch and its usage has been prevalent since then. So many techniques and devices have been developed to efficiently harness wind energy in recent times. The associated challenges with harnessing wind energy have been reduced to a large extent since the invention of computerized systems.

This is the reason most universities are now offering courses in wind energy systems. Automated systems are now implored to generate large amount of power from wind energy offshore using wind turbines. These wind turbines are durable and can last as long as 20years with little or no maintenance cost even in environments with harsh weather conditions (Van, 2007). Originally vertical axis wind turbines were thought to be preferable because it could move in different directions and also have gears and other ancillaries for generating power situated at the down side of the tower. The turbine had an onion-like shape called "Troposkein curve". The design failed because the rotor was not efficient and it was quite heavy. It also failed due to metal-fatigue issues resulting from much tension in the rotor parts. Nevertheless, the design can still be applied when the power demand is low and can be installed on the roof of buildings. Intense studies have revealed that wind turbines having one blade are the best. This is because all the energy coming from the wind is incident on a single blade. However, the single blade must have a high angular velocity before it can generate sufficient power. But this high blade angular velocity causes too much noise which is not a desirable characteristic for a good offshore wind turbine (TaufikRoniSahroni 2015). This has prompted the elimination of one-bladed design in the wind turbine industry. Gardner in 2009 stated that stall and pitch regulation could be implored to regulate power when the wind speed is high. Speed regulation using stall guarantees rotor steady speed when the wind speed rises. This obviously makes the flow angle to tilt. The blades get stalled hence limits the power to a good level to ensure that no damage is done to the turbine system by the excessive wind speed. Aerodynamicists were initially amazed on learning that stalling could actually be used to limit power because its effect could be fatal and can cause plane crash in flight aerodynamics. Nevertheless, it showed to be in controlling over speeding and its peculiar to wind energy industry.

The narrative of generating power from wind energy off shore is quite new. History has it that the first wind park that was built offshore was in Denmark in 1986 (Taufik, 2015).In most countries, gas turbines use natural gas as means of generating power. The ecological degradation it causes has prompted different nations to search for alternative means of power generation. Several countries are wrecked with the effect of climate changes resulting from gas emission into the atmosphere. These have led to different countries conducting researches in renewable energies which will produce power without damaging the environment. There is enormous quantity of untapped wind energy in Nigeria which could be harnessed to generate electricity especially in the North. This paper considers performance evaluation of a mini wind turbine for electricity generation in Nigeria. The paper is limited to performance evaluation of a 5m three bladed wind turbine, operating at an angular speed of 10 rad/s with a blade pitch angle of 5deg as applicable to Nigerian weather conditions. The objectives include:

- Modeling wind turbine using Matlab Simulink
- Evaluate mechanical power, coefficient of performance and electrical power for the various wind speed range

REVIEW OF PREVIOUS WORKS

(Mohd*et al*, 2015) simulated and analyzed grid connected wind energy with MATLAB/ Simulink. The system was a wind turbine driven by permanent magnet synchronous generator and connected to the grid system. The efficiency of permanent magnet synchronous generator (PMSG) is high and it is used most times because of this quality. The project was simulated in a grid system. Differential equations were used to design pitch controller, turbine, shaft and electrical unit of a three-blade wind turbine using MATLAB SIMULINK. Phase angle and voltage, active power, line current and rotor speed were the output obtained. (Pavankumar Reddy and VenuGopala, 2015) modeled and simulated hybrid wind solar energy using MPPT. The major idea behind this project is to control the direct current (DC) to the DC booster converter using maximum power point tracking controller. The performance of this system was analyzed using MATLAB/ SIMULINK. (Nagendra*et al*, 2017) simulated and modeled a turbine attached with a permanent magnet synchronous generator under grid connected system. Their research was aimed at modeling and simulating wind mill connected to the grid with MALAB/ SIMULINK.

The scope of the research was to evaluate the performance from a permanent magnet synchronous generator coupled with the turbine. Two variable speeds were used to conduct the performance test and the active power, reactive power, current and voltage waveforms of the inverter were plotted with SIMULINK. (Suman Nath and Somnath Rana, 2017) modeled and simulated wind energy Based Power System using MATLAB, the objective of their research was to test and design14.9kVA power system capacity which operated at 440V, 20m/s base wind speed. An induction generator was used and the design was simulated in MATLAB SIMULINK. The different components of wind energy system which includes generator, controller system, wind turbines, rectifier, inverter, load and other equipment including transformers, grid value and equations were used for the design steps and modeling of the system in MATLAB simulation environment. (FuratAbdal and Mohammed Abdulla, 2010) carried out simulation of Wind-Turbine Speed Control by MATLAB. The paper considers the frequency of a self-excited induction generator (SEIG) rotated by the wind turbine and supply static load. The principles of wind energy conversion were presented. Linearization and dynamic modeling of wind turbine are derived.

The speed control system consisting of actuator models, speed controllers, and the turbine liberalized mode lis simulated using MATLAB /SIMULINK. (Rasel Sarkar *et al*, 2015), The mathematical model and simulation of wind turbine of induction generators was presented by this paper for the modeling consideration of the drive train, asynchronous or induction generators (IG). The dynamic simulation, the presented model and the simulation results run in MATLAB/SIMULINK. This paper also modeled the pitch angle observation and the variable wind speed. (Omijeh*et al*, 2013) Modeling of a vertical axis wind turbine with permanent magnet synchronous generator for Nigeria. This paper evaluates and models the behavior of a vertical axis wind turbine (VAWT) with permanent magnet synchronous generator (PMSG) under low and unsteady wind speed.

There are three main parts which constitute the wind turbine system, the parts are the generator, the turbine and the wind speed. A three phase PMSG was used in this paper because it presents higher efficiency and needs little or no maintenance compared to other generator types. Rotor windings are not needed in PMSG making it less robust and cost effective. These elements and entire idea of this work was modeled and simulated using MATLAB/ SIMULINK. (IntissarMoussa*et al*, 2015). In this paper, the machinery application of the system algorithms for control of wind turbines with DC machines that are emulator based was considered. The analysis and discussion of data performed with Simulink and XSG (Xilinx system generator) which shows the implementation of the application. Algorithms are implemented on FPGA (Virtex-5LX50T) with the help of XSG. (Sachin*et al* 2012) the execution of the pitch control of turbines was carried out on MATLAB/SIMULINK. The paper shows that a constant voltage can be obtained even when the turbine does not operate at constant speed. The controller is used in achieving this by continually changing the blades' pitch angle. The torque of the turbine is regulated using pitch control. PI controllers are used in conventional pitch control. Matlab-Simulink was used to simulate the speed control system. The simulation results show that the controller faultlessly regulates the pitch angle of the blades to get the desired output power. (Mohammed *et al*, 2014) The research presents modeling and performance characteristics of a standalone wind system in MATLAB/ SIMULINK environment.

The wind turbine simulation was designed with basic equations that characterize the operation of wind turbines. A permanent magnet synchronous generator (PMG) with a variable speed of operation was used in this work. Power electronic devices control the rotation of the wind turbine because the speed is variable. The voltage in the output of the PMSG is made constant using a rectifier and the rectified voltage scaled down to a value usable by the battery and the connected DC loads using a DC/DC bulk converter. The bulk converter is configured to tap the maximum power of the wind turbine. First of all, modeling of a wind turbine has been properly done and the characteristics obtained using different variables. Again a modeled and analyzed standalone wind turbine system has been achieved. The usefulness of this paper is that it models, simulates and studies the effect of change in wind speed of a standalone system.

METHODOLOGY

Wind speed data for Nigeria was obtained from National Meteorological Agency (NIMET). A MATLAB Simulink model is designed using the wind turbine equations. Wind speeds were simulated in Simulink model and the corresponding mechanical power, coefficient of performance and electric power were evaluated. Figure 3.1 shows the flow chart of the model used for the study.

Flow Chart for the Design

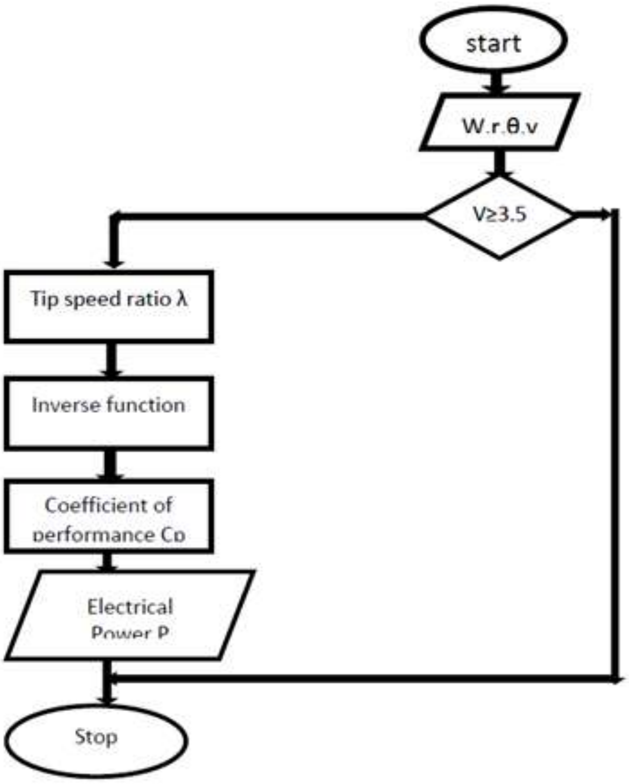

Fig3.1: *Flow chart of the model*

Most wind turbines start generating power from 3.5 m/s wind speed. A reference wind speed of 3.5 m/s isused in this work. At wind speeds less than 3.5 m/s, the turbine does not generate any power. However, from wind speeds of 3.5m/s the turbine starts generating. The tip speed ratio, coefficient of performance and electrical power were computed and simulated using MATLAB/ SIMULINK model for the varying wind speeds using equations 3.1-3.54. In this work, the blade pitch angle and angular velocity of the turbine are kept constant. The coefficient of performance, power output and torque were evaluated from the design and analysis made. Data obtained from NIMET is shown in table 3.1

Table 3.1: *Wind speed data from NIMET*

Month	Ikeja		Port Harcourt		Jos		Kano		Ilorin	
	mean speed (m/s)	STD (m/s)	Mean Speed (m/s)	STD (m/s)	Mean Speed (m/s)	STD(m/s)	Mean Speed (m/s)	STD(m/s)	Mean Speed (m/s)	STD(m/s)
Jan	10.9	1.5	4.9	2.8	13.8	5.3	12.2	4.1	4.2	1.5
Feb	10.4	1.4	5.8	3.4	14.7	5	12.4	4.4	4.5	1.1
Mar	11.9	1.4	5.8	2.8	14.8	4.4	12.1	3.9	5.2	1.1
April	11.7	1.7	5.8	2.9	14	3.9	11.5	3.4	5.4	1.6
May	9.8	1.2	5.6	2.9	12.2	4.4	11.2	3.2	5.2	1.2
June	10.6	4.9	5.6	2.9	12.5	3.9	11.6	3.5	4.8	1
July	12	3.3	6.2	3.5	12.1	3.8	11.2	3.5	4.9	1.2
Aug	11.8	1.7	6.5	3.2	11.7	4.4	9.9	3.3	4.9	1.4
Sept	11.6	1.6	5.8	2.7	11.4	3.9	8.9	2.9	3.9	0.9
Oct	8.9	0.5	4.9	3.5	13.5	4.4	9.1	2.9	3.8	0.9
Nov	8.9	0.9	4.1	2.6	15.6	4.9	11.1	3.1	3.5	1
Dec	9.2	1.2	4.6	2.7	14.5	4.1	11.6	3.4	3.6	1.2

Block Diagram for the Model

The input parameters are the blade pitch angle, angular velocity, wind speed, air density and the turbine blade length. The tip speed ratio, coefficient of performance, electrical power and turbine Torque were computed

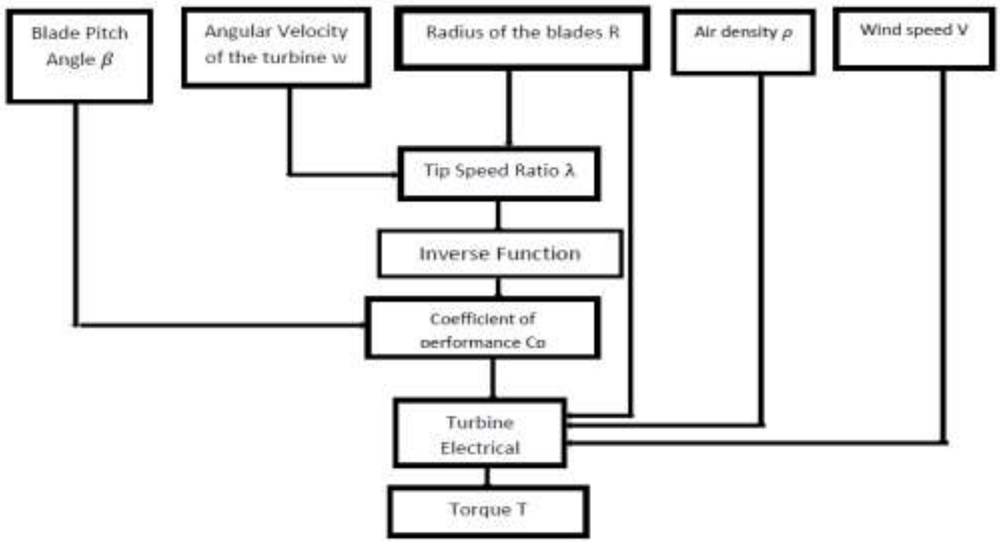

Fig3.2. *Block diagram of the model*

Energy Conversion in Wind Turbines

The three stages of energy conversion that takes place in wind turbines are displayed in figure 3.3. Kinetic energy from the wind is transformed to mechanical energy and then into electrical energy. The block diagram in figure 3.3 shows a simple energy conversion process for the wind turbine.

Fig3.3. *Energy conversion in Wind turbine*

Design Analysis

MATLAB/SIMULINK is used to show how wind speed varies with mechanical energy and electrical energy. The relationship between the coefficient of performance and the wind speed was also examined. The mechanical power varies linearly with the cube of the wind speed

Power Equation of Wind Turbines

From the investigation, mechanical power varies directly with the cube of wind speed. This means if the wind speed is doubled, mechanical power increases by eight times of its original value. However, this does not apply to electric power generated at the turbine output. Electrical power generated at the output is greatly dependent on the performance coefficient of wind turbine and it does not have linear relationship with wind speed. This means increasing the wind speed does not entail an increase in the performance coefficient and electrical power of the turbine at all times. In fact, in cases of high wind speed values the performance coefficient drops (this depends on the configuration of wind turbine). The wind speed at which the coefficient of turbine performance starts dropping varies in different turbine designs and it is called the *designed wind speed*. Both wind turbine electrical and mechanical power depends on the density of air ρ in kg/m^3, area swept by the blades of the turbine A in m^{2}and the wind speed V in m/s. However, the density of air and blade area is always constant. This implies the mechanical power trapped by the blades depend solely on the speed of the wind, whereas the electrical power is dependent on the speed of the wind and the turbine performance coefficient. The mechanical power trapped by the blades of any wind turbine is written in the equation 3.1

$$P = \frac{1}{2} \times v^3 \times A \times \rho \qquad 3.1$$

Where: P = Mechanical power watts (W), V= Wind velocity in m/s, A= Area of the swept by the blades m^2, ρ= Density of air in kg/m^3

Recall that area A of any object performing circular motion is given as

$$A = \pi r^2 \qquad 3.2$$

Where: r=radius of the rotating blades in m

Substituting equation 3.2 into 3.1, the mechanical power becomes

$$P = \frac{1}{2} \times v^3 \times \pi \times r^2 \qquad 3.3$$

Mechanical power trapped by the blades of any wind turbine is shown in equation 3.4.

$$P = \frac{22}{14} \times v^3 \times r^2 \quad 3.4$$

Tip Speed Ratio

This is referred to as the ratio of wind speed at the blade tip to input wind speed and its written mathematical in equation 3.5

$$\lambda = \frac{v_{TIP}}{v_{WIND}} = \frac{w \times r}{v} \quad 3.5$$

Where:

w= angular velocity of the rotor (rad/s), r= Blade radius (m), V = Wind velocity (m/s)

Blade Pitch Angle

Most turbines are designed with more than one blade. In recent times turbines are majorly designed using three blades so that enormous energy can be trapped at the same time controlling excess speed in other to avert sudden break down. This paper did not consider speed control of wind turbines. Pitch angle simply means the position of the blades in air for maximum energy capture. Figure 3.4 shows variable pitch angle system of wind turbine. In this paper, the blade pitch angle θ is set to 5 degrees.

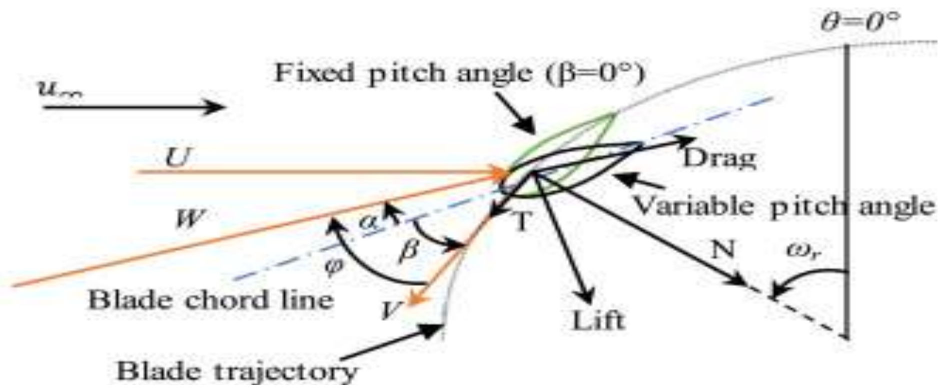

Fig3.4. *Variable pitch angle system of a wind turbine (Source: Jasmin Martinez 2017)*

Coefficient of Performance (Power Coefficient)

Not all the mechanical power trapped by turbine blades is used to generate electrical power in the turbine output. Some of the wind energy is lost in the rotor due to friction. The coefficient of performance is a parameter used to ascertain the quantity of wind energy that was converted to electricity by the generator. It is a dimensionless quantity represented by Cp and its given as the ratio of the blade mechanical power that was transformed to electricity to the initial wind power into the system. Mathematically its expression is written as shown in equation 3.6.

$$Cp = \frac{Power\ extracted\ by\ the\ turbine}{Power\ input\ to\ the\ turbine} \quad 3.6$$

The performance coefficient depends on the tip speed ratio and blades pitch angle. The equation connecting performance coefficient Cp, tip speed ratio λ and blade pitch angle θ is as shown in equation 3.7

$$Cp = 0.5\left(\frac{116}{\beta} - 4\theta - 5\right)e^{-\frac{21}{\beta}} \quad 3.7$$

Where,

$$\frac{1}{\beta} = \frac{1}{\lambda + 0.08\theta} - \frac{0.035}{\theta^3 + 1} \quad 3.8$$

Substituting the expression λ=wr/v and the values of θ=5deg, w=10m and r=5m into equations 3.8 and 3.7 gives the relationship between the performance coefficient of wind turbine and wind speed.

$$Cp = \frac{56.542V - 175.806}{50 + 0.4V} e^{-\frac{20.998V - 0.292}{50 + 0.4V}} \quad 3.9$$

Equations 3.7 and 3.8 apply to all types of wind turbines. However equation 3.9 only applies to the model designed due to the choice of parameters θ, w and r, which might not be the same for other wind turbine designers.

The parameters include the following.

θ = blade pitch angle (degrees), λ = tip speed ratio of the blades in (rad), v = wind speed in (m/s)

Betz Law

Betz law states that the coefficient of performance of any wind turbine cannot exceed 0.593. This is called Betz limit. No matter how good a wind turbine design may be, its efficiency cannot exceed 59.3%. Performance coefficient of most practical wind turbines lies between 0.3 to 0.5.

Mathematical prove of Betz's Limit

In Figure 3.5, the wind speed passing through the turbine rotor is denoted as v. The value of this speed upstream is denoted as v_w while its value downstream is given as v_2

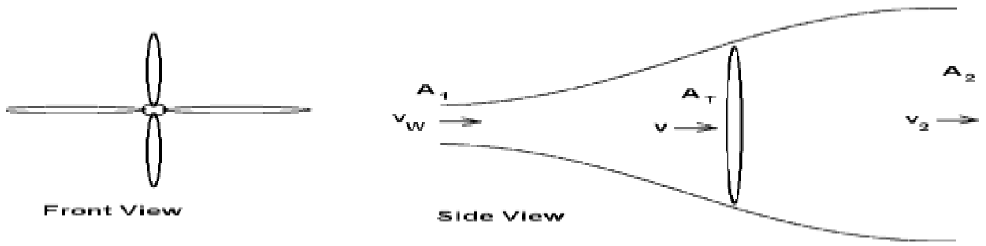

Fig3.5. *Wind turbine profile illustrating the path of airflow (Source: Arcadii and Campbell 2016)*

Since air cannot be compressed, the mass flow rate of air (kg/s), $\dot{m}$, remains constant and can be expressed as

$$\dot{m} = \rho A_1 v_w = \rho A_T v = \rho A_2 v_2 \quad 3.10$$

Where

ρ = The density of air (kg/m^3),A_1= The cross-sectional area of the wind approaching the turbine (m^2),$\dot{m}$ = The mass flow rate (kg/s),A_2= The cross-sectional area of the air stream after the turbine (m^2),A_T = The area of the turbine (m^2),v_w= The upstream wind speed (m/s), v = The air velocity at the turbine blades (m/s),v_2= The velocity of the downstream air after it has passed the turbine (m/s). This expression in equation 3.10 shows that the mass flow rate is constant on both the upstream and downstream side of turbine. From basic kinematics, the force that acts on a body of mass 'm', and acceleration 'a' is given by equation 3.11

$$F = ma \quad 3.11$$

$$= m\frac{dv}{dt} \quad 3.12$$

$$= \dot{m}\Delta v \quad 3.13$$

$$= \dot{m}\,(v_w - v_2\,) \quad 3.14$$

Substituting equations 3.10 into 3.14 give

$$F = \rho A_T v.\,(v_w - v_2) \quad 3.15$$

The incremental work done in the wind stream is in equation 3.16

$$dE = Fdx \quad 3.16$$

The power developed in the wind stream is obtained by taking the derivative of equation 3.16 with respect to time.

$$P = \frac{dE}{dt} = F\frac{dx}{dt} \quad 3.17$$

But$\frac{dx}{dt} = v$, substituting this into equation 3.17 givespower developed as a function of turbine velocity blades and the force, thus

$$P = Fv \quad 3.18$$

Substituting equations 3.15 into 3.18 gives equation 3.19

$$P = \rho A_T v^2.\,(v_w - v_2) \quad 3.19$$

Power is also expressed as shown in equation 3.20

$$P = \frac{\Delta E}{\Delta t} \quad 3.20$$

$$P = \frac{\frac{1}{2}m\,v_w^2 - \frac{1}{2}m\,v_2^2}{\Delta t} \quad 3.21$$

$$P = \frac{1}{2}\dot{m}.\,(v_w^2 - v_2^2) \quad 3.22$$

Substituting equations 3.10 into 3.22 gives equation 3.23

$$P = \frac{1}{2}\rho A_T v(v_w^2 - v_2^2) \quad 3.23$$

Equating equations 3.19 to equation 3.23

$$\rho A_T v^2.\,(v_w - v_2) = \frac{1}{2}\rho A_T v(v_w^2 - v_2^2) \quad 3.24$$

$$\rho A_T v^2.\,(v_w - v_2) = \frac{1}{2}\rho A_T v(v_w - v_2)(v_w + v_2 \quad 3.25$$

$$v = \frac{1}{2}(v_w + v_2) \quad 3.26$$

This suggests that the wind speed at the rotor could be taken as the average of the upstream and downstream wind speed. Substituting this expression for rotor wind speed into equation 3.15 and equation 3.19, will give the expressions for force and power in terms of the upstream and downstream wind speeds

$$F = \frac{1}{2}\rho A_T\,(v_w - v_2)\,(v_w + v_2) \quad 3.27$$

$$F = \frac{1}{2}\rho A_T(v_w^2 - v_2^2\,) \quad 3.28$$

$$P = \frac{1}{4}\rho A_T(v_w + v_2)^2(v_w - v_2) \quad 3.29$$

$$P = \frac{1}{4}\rho A_T(v_w^2 - v_2^2)(v_w + v_2) \quad 3.30$$

$$P = \frac{1}{4}\rho A_T(v_w^3 - v_w v_2^2 + v_w^2 v_2 - v_2^3\,) \quad 3.31$$

$$P = \frac{1}{4}\rho A_T v_w^3[1 - (\frac{v_2}{v_w})^2 + \left(\frac{v_2}{v_w}\right) - (\frac{v_2}{v_w})^3] \quad 3.32$$

To simplify equation 3.32 let

$$b = \frac{v_2}{v_w} \quad 3.33$$

$$P = \frac{1}{4}\rho A_T v_w^3(1 - b^2 + b - b^3) \quad 3.34$$

Equation 3.34 shows that the power extracted by the turbine is a function of the ratio of the upstream and downstream wind speed $\frac{v_2}{v_w}$ and proportional to the cube of the upstream wind speed v_w^3 . Considering the rate of change of kinetic energy from the wind passing through an equivalent area in the absence of a turbine. With this, the maximum efficiency of an ideal wind turbine is determined. The kinetic energy of the wind is defined as:

$$E = \frac{1}{2}mv^2 \qquad 3.35$$

Hence the power becomes

$$P = \frac{dE}{dt} = \frac{d}{dt}\left(\frac{1}{2}mv^2\right) \qquad 3.36$$

Differentiating equation 3.36 implicitly

$$P = \frac{1}{2}\frac{d}{dt}(mv^2) = \frac{1}{2}\left(2mv\frac{dv}{dt} + v^2\frac{dm}{dt}\right) \qquad 3.37$$

In the absence of turbine, the wind velocity is constant, i.e $v_w = v_2$, this means $\frac{dv}{dt} = 0$, and equation 3.37 becomes

$$P_{total} = \frac{1}{2}v_w^2\frac{dm}{dt} = \frac{1}{2}v_w^2\dot{m} \qquad 3.40$$

Substituting equations 3.10 into 3.40,

$$P_{total} = \frac{1}{2}\rho A_T v_w^2 \qquad 3.41$$

Efficiency of wind turbine or coefficient of performance of wind turbine is defined as:

$$C_P = \frac{Power\ extracted\ by\ the\ wind\ turbine}{Total\ power\ input} \quad \text{Thus}$$

$$C_P = \frac{\frac{1}{4}\rho A_T v_w^3(1-b^2+b-b^3)}{\frac{1}{2}\rho A_T v_w^2} \qquad 3.42$$

$$C_P = \frac{1}{2}(1-b^2 + b - b^3) \qquad 3.43$$

To determine the maximum coefficient of performance of wind turbine, the derivative of equation 3.43 with respect to b is taken and then equated to zero, thus

$$\frac{dC_P}{db} = \frac{1}{2}\frac{d}{db}(1-b^2 + b - b^3) = \frac{1}{2}(-2b + 1 -$$
$$3b2=12(1+b)(1-3b) \qquad 3.44$$

By substituting equation 3.33 into 3.44 gives

$$\frac{1}{2}\left(1 + \frac{v_2}{v_w}\right)\left(1 - 3\frac{v_2}{v_w}\right) = 0 \qquad 3.45$$

Two solutions are present which are:

$$\left(1 + \frac{v_2}{v_w}\right) = 0, \Rightarrow v_w = -v_2 \qquad 3.46$$

This does not apply practically because upstream wind speed cannot be in opposite direction to downstream wind speed.

Considering the second solution, thus

$$\left(1 - 3\frac{v_2}{v_w}\right) = 0, \Rightarrow v_w = 3v_2 = v_w \Rightarrow v_2 = \frac{1}{3}v_w \qquad 3.47$$

This is a more practical solution. it implies that at maximum coefficient of performance, downstream wind speed is one-third upstream wind speed. To determine the maximum efficiency, equation 3.47 will be substituted into equation 3.33 thus

$$b = \frac{v_2}{v_w} = \frac{\frac{1}{3}v_w}{v_w} = \frac{1}{3} \qquad 3.48$$

Substituting equation 3.48 into 3.43 gives the value for maximum efficiency or coefficient of performance of wind turbine system

$$C_P = \frac{1}{2}(1-b^2 + b - b^3) = \frac{1}{2}\left(1 - \frac{1}{9} + \frac{1}{3} -\right.$$
$$127=1627=59.26\% \sim 60\% \qquad 3.49$$

The value in equation 3.49 is called Betz's limit

Therefore, power extracted by any kind of wind turbine at any specified wind speed is given as:

$$P_E = \frac{1}{4}\rho A_T v_w^3(1-b^2 + b - b^3) = \frac{1}{2}\rho A_T v_w^3 C_P \qquad 3.50$$

Equation 3.50 is the expression used to compute electric power generated by wind turbine and it applies to all types of wind turbine.

The expression for blade length at maximum coefficient of performance or maximum efficiency is given as;

$$r = \sqrt{\frac{2P_E}{\rho\pi v_w^3 C_P}} \qquad 3.51$$

Electrical Power Equation of Wind Turbine

Electrical power in wind turbine is never equal to mechanical power and its always lower than mechanical power for all cases of wind speed. This is because electrical power generated depends on the coefficient of performance of the wind turbine system. Thus the equation that determines the electrical power of wind turbines is shown in equation 3.52

$$P_E = \mathrm{Cp} \times \frac{1}{2} \times \mathrm{v}^3 \times \mathrm{A} \times \rho \qquad 3.52$$

This can be further modified as

$$P_E = \frac{22}{14} \times \mathrm{Cp} \times \mathrm{v}^3 \times \mathrm{r}^2 \times \rho \qquad 3.53$$

The output torque developed in the wind turbine is given by

$$\mathrm{T} = \frac{P_E}{w} \qquad 3.54$$

Where:

C_p = Coefficient of performance of wind turbine, Pe = Electrical power generated in W ,T= Output torque in Nm.

Parameters Used for the Simulation

Table 3.2 shows the parameters used for the simulation of the model.

Table3.2. *Parameters used for model simulation.*

Parameters used	Value
Air density ρ	1.225 kg/m^3
Wind Speed V	Varied
Blade pitch angle	5
Blade radius	5m
Angular velocity of turbine w	10 rad/s

RESULTS AND DISCUSSION

Simulink Model

This model was designed using equations 3.1-3.54. The input parameters are wind speed, angular velocity, pitch angle and blade radius. Of these parameters only the wind speed is varied, while the others are kept constant. Varying wind speeds values are fed into the model and the tip speed ratio, coefficient of performance and electrical power are computed.

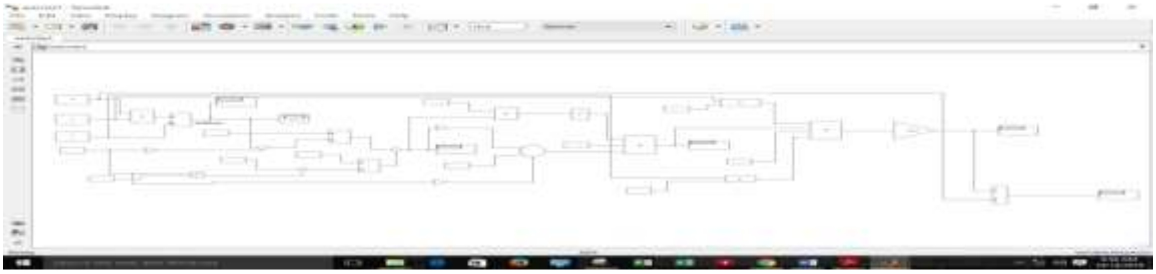

Fig4.1. *MATLAB/Simulink Model*

Wind Speed Variation with Mechanical Power

A plot of mechanical power developed in the turbine blades within wind speed range of 3.5 m/s to 13 m/s is a curve emanating from the origin of the plot. The table of values used for the plot is given in table 4.1.This plot shows that mechanical power developed in the turbine blades increases as wind speed increases. The graph is shown in fig 4.4.

Table4.1. *Wind Velocity and Mechanical Power*

Wind Velocity (m/s)	Mechanical Power (KW)	Wind Velocity (m/s)	Mechanical Power (KW)
0	0	8.5	29.5
3.5	2.063	9.5	41.2
4.5	4.385	10.5	55.7
5.5	8.007	11.5	73.2
6.5	13.22	12.5	94
7.5	20.3	13.5	118

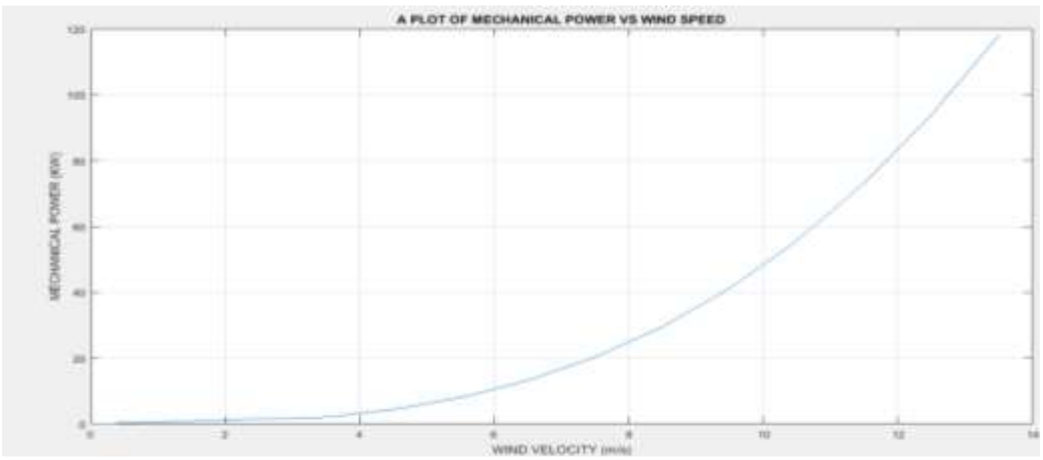

Fig4.2. *A plot of Mechanical Power Versus wind speed*

As long as the wind speed increases, the mechanical power keeps increasing, but this not the case for the electrical power because its value depends on the wind velocity and the coefficient of performance of the turbine. If the mechanical power developed in the blades of the turbine is plotted against the cube of the wind speed. The nature of the graph is as shown in fig 4.5.

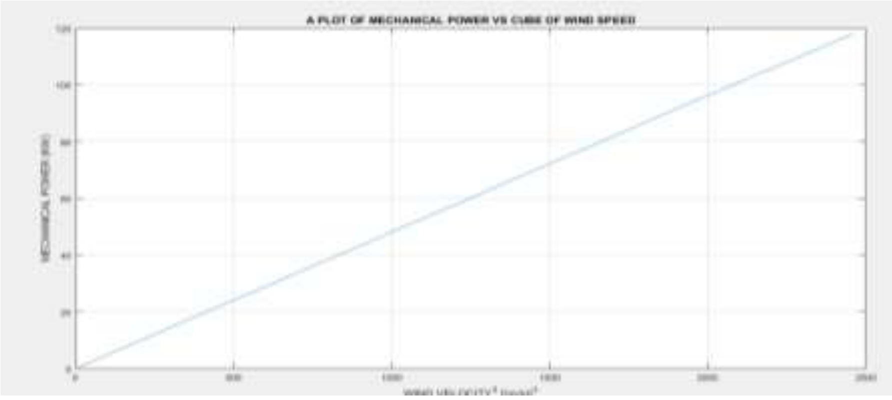

Fig4.3. *A plot of Mechanical Power VS Cube of wind speed*

This is a straight line graph passing through the origin. This graph proves equation 3.4. It shows the linear relationship that exists between the mechanical power in the blades and the cube of the wind speed.

Determination of Rated Wind Speed and Rated Power of the Wind Turbine

A MATLAB/SIMULINK model was designed to examine the characteristic of wind speed with turbine output power. The model was developed using equations 3.1-3.14. The Simulink model was used to generate a table of turbine output power (electrical power) corresponding to varied wind speed and the table is as shown in Fig 4.4

Table4.2. *Wind speeds and Electrical Power*

Wind speed (m/s)	Electrical power (KW)	Wind speed (m/s)	Electrical power (KW)
3.5	0.215	9	6.46
4	0.596	10	7.158
5	1.655	11	7.575
6	2.951	12	7.734
7	4.281	13	7.674
8	5.485		

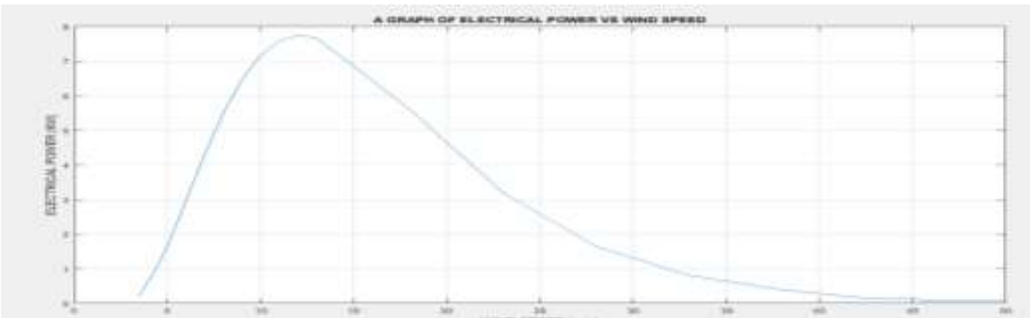

Fig4.4. *Plot of Electrical Power VS wind speed*

The values of power and velocities are used to plot the graph in fig 4.6

From the figure, it is shown that electrical power increases from 3.5m/s, which is the minimum speed at which power generation starts.

This iaalso known as ***cut-in wind speed***. The power gets to a maximum of 7.674kW at a speed 13m/s. This is also known as ***cut-out wind speed or rated wind speed***. This peak power is the rated turbine power in this case 7.674KW. The power starts decreasing from a speed of 14m/s until it comes to zero. This entails that the maximum speed the wind turbine can withstand is 13m/s. At speeds greater than this, the wind turbine is at the risk of breakdown. Certain control mechanisms need to be implored to automatically shut down the turbine at wind speed greater than 13m/s to avoid turbine failure due to tensile stress from high wind.

Determination of Maximum Coefficient of Performance (Efficiency) and Design of Turbine Wind Speed

A plot of coefficient of performance of wind turbine versus wind speed is as shown in figure 4.5. From the plot, the coefficient of turbine performance initially rises as the wind speed also rises. It keeps increasing until it gets to maximum value of 0.284 at a speed of 6m/s then begins to decrease. The wind speed at which the wind turbine attains maximum coefficient of performance (efficiency) is called ***designed wind*** speed and in this case it is 6m/s. It decreases to a certain value and remains almost constant between speeds of 12.5 m/s to 25 m/s. The design wind speed and the cut out wind speeds are always given in the manufacturer's manual.

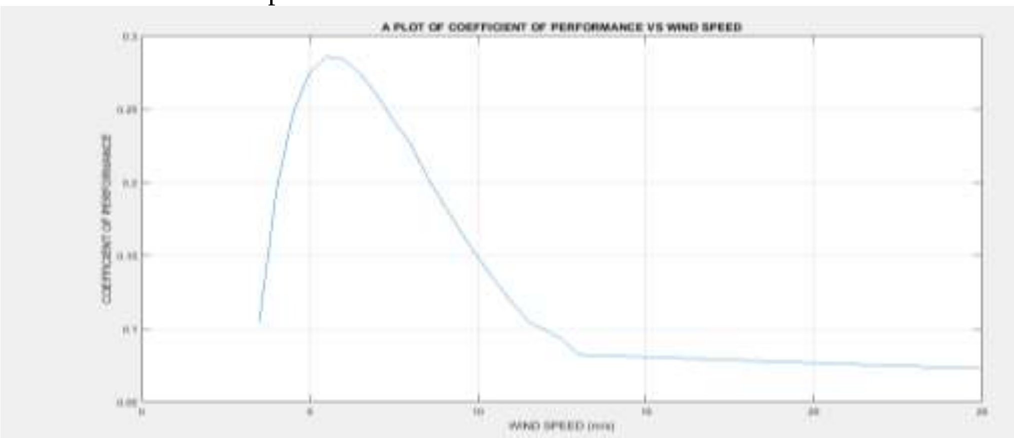

Fig4.5. *Plot of coefficient of performance Versus wind speed*

This plot is in accordance with equation 3.9 which takes the form of y= xe^{-x}.The maximum coefficient of performance of turbine is 0.284 at a design wind speed of 6m/s which is not bad for a turbine operating at an angular speed of 10 rad/s with blade length of 5m. The coefficient of performance can be increased by using a higher angular speed and also making the blade length longer. However, the wind speed obtainable in the area must be considered before these changes can be made.

Conclusion

The huge environmental challenges posed by gas turbines and other non-renewable energy systems can be solved by wind turbine systems which have little or no impact on the environment. Enormous power can be generated using wind turbine in Nigeria especially in the North where wind speed is high. This paper considers performance evaluation of wind turbine for electricity generation in Nigeria. Wind speed data was obtained from NIMET. The results of the simulation show that if a wind turbine whose blade length is 5m, operating at an angular speed of 10rad/s with a pitch angle of 5deg is installed in Nigeria, it will have maximum power of 7.674kW and a maximum coefficient of performance of 0.284. The wind speed at which this maximum power will occur is 13m/s which is also the *cut-out wind speed* of the turbine. At wind speed greater than 13 m/s the wind turbine will stand a chance of failure due to stress from the wind. This failure can be averted by using a control mechanism that will shut down the wind turbine at wind speed greater than 13 m/s.

Recommendations

From the results of the research work, the following recommendations are made:

- Young engineers in Nigeria should pick up interest in the study of wind energy systems as it has a high propensity to solve the power problems in some areas with high wind density with little or no maintenance cost.
- Nigeria government should pay attention to the potentials of wind energy systems by giving necessary support to students intending to pick a research on wind energy systems
- That courses on wind system should be inculcated into engineering undergraduate curriculum

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