Chapter

Modeling and Simulation of a 10 kW Wind Energy in the Coastal Area of Southern Nigeria: Case of Ogoja

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Abstract

This research demonstrates a model of a wind energy conversion system that operates at different wind speed, with results simulated in MATLAB SIMULINK. The wind turbine system is made up of three parts or subsystems namely the aerodynamic, mechanical and electrical blocks. The system is designed by modeling differential equations for each block and then simulated in SIMULINK environment. The Squirrel Case Induction Generator, horizontal axis wind turbine system with complexities of all three parts of the wind turbine model were analyzed using the mathematical equations, with each block modeled and designed separately, then all three blocks joined together to give the complete unit. Wind speed data from Ogoja community in southern part of Nigeria was used to test the simulation performance. The system simulation was tested and worked satisfactorily, with different wind speed giving proportionate mechanical torque and turbine speed. This model therefore demonstrates that wind energy could be extracted in the region even at varying wind speed.

Keywords: modeling, simulation, wind energy, Southern Nigeria, coastal area, Ogoja

1. Introduction

Demand for renewable energy has been increasingly justified over the last couple of years as world powers turn to clean, green energy while overdependence on fossil fuel generation is still prominent in developing countries. Nevertheless, there is an expectation that renewable energy sources will play a wider role over the next two decades in energy with wind energy projected to contribute 1.1 trillion - kilowatt-hours (kWh) of a total of close to 4 trillion kWh of renewable energy expected to be generated by year 2030. Furthermore, research suggests that solar and wind energy are currently the most likely to provide economically affordable alternate energy sources, because other renewable energy sources like tidal remain costly and inefficient [1]. It is obvious that wind and solar energy studies will be the center of future renewable engineering efforts. Solar energy is becoming more dominant especially in the Arab world where their massive deserts have already seen investigations into the possibility of generating solar energy with enough capacity to power entire countries. With wind energy however, developing offshore wind turbines fit for tackling the substantially higher wind speeds accessible offshore while avoiding the issues of horizon and noise pollution is the way to go. In Ogoja community of southern Nigeria, the average wind speed is seen in this research to be good enough for a horizontal axis wind turbine using a Squirrel Cage Induction Generator due to its seeming advantages as detailed in later sections. Modern offshore wind energy systems are now faced with expectations of generating highly efficient, network frequency electricity in an autonomous and programmed manner and for 20 or more years consistently and continuously with little or no maintenance requirements in some of the harshest environments in the world. This constitutes the challenges encountered by wind energy engineers today [2].

2. Problem statement

Natural gas is being used in gas turbines as a means of power generation in most countries, majority of which are in Africa. The effects of these fuels in the atmosphere led to the need for green energy, a clean and sustainable alternate source of energy generation. Different countries are facing devastating effects from the climate change, stormy rain, hurricane, great flood, etc., leading to different countries conducting research in renewable energy sources which will produce power without damaging the environment. Wind energy is abundant on the Earth and has a low or no impact in environmental pollution. The energy is generated naturally from wind; hence fuel needed for wind turbines is free and occurs every day. This study shows a wind energy system modeled and runs at various wind speeds, similar to wind speeds found in some parts of the world.

3. Aim and objectives of study

The aim of the project is to design with the aid of mathematical modeling a wind energy conversion system that will produce energy at varying speed and test results using simulations. The following are the objectives:

- Model a wind energy conversion system by using mathematical equations.
- Simulate the system design using MATLAB SIMULINK Software, version R2017a.
- Test to see the effects of varying wind speeds.
- Simulate the aerodynamic, mechanical and electrical component design.

4. Wind energy

Wind energy is the indirect form of solar energy which is always being replenished by the sun [4]. The energy conversion occurs when electrical power or electricity is generated using the abundant natural resource wind. A wind turbine is an energy conversion device that changes the wind's kinetic energy into electrical energy. The operation of wind turbines makes use of the turning of two or three propeller-like blades around a rotor by wind. The rotor is attached to the main shaft, which turns a generator to create electricity [5]. The quantitative measurement of accessible wind energy at any point is called the wind power density (WPD). It is calculated as available mean power per square meter of area swept by a turbine with SI unit of watt per square meter. This indicates how much extractable energy on site.

Wind turbines are fabricated in two axis types (vertical and horizontal) and in a wide variety. The smallest types of wind turbines are used as a means of charging battery units used for generation of back-up power. Larger turbines are used to generate power for domestic use. Wind power can be classified as:

- Utility scale wind systems; wind systems that generate power larger than 100 kilowatts (kW) to provide power to a grid system.
- Distributed or small wind systems, which uses wind turbines of 100 kW or lower than that to power directly a home, farm, etc.
- Offshore wind systems, are turbines mounted on water bodies around the world. Depending on speed of wind in that area, they can be used to power whole communities.

4.1 Wind energy in Nigeria

Wind energy is of course, one of the cheapest renewable sources per unit of energy produced, as well its technologies is one of the fastest rising technologies in energy generation industry across the world, yet not so much in Nigeria and Sub-Saharan Africa. It has been suggested that a network of land based 2.5 MW wind turbines can generate over 40 times the current electricity consumption in the world [5]. In Nigeria, renewable energy sources have been restricted to solar energy this is because wind energy is not considered viable due to low wind speeds in most parts of the country. Wind speed is generally considered moderate in the south with the exception of coastal areas and offshore. On the other hand, in the hilly regions of the north, it is strongest [6].

An analysis of wind energy potential in Kano State, Nigeria was done by [7], based on wind data taken for 21 years at a height of 10 m. The data was statistically tested using Weibull probability density function. Results showed an expected average wind speed ranging from 6.5 to 9 m/s, good enough to drive a wind conversion system with wind power estimations as high as 12 MWh/m^2. Five practical wind turbines where also analyzed with the data, giving positive results and economic viability of wind power in Kano State. Refs. [8, 9] noted the viability of renewable energy in Nigeria, the advantages and challenges and as well stated that the high cost of power supply and carbon emission reduction could be realized with the use of renewable sources energy.

In another article on wind energy potential in selected south western states, the investigation surveyed wind energy capability often chosen sites in the south western region of Nigeria and carried out a cost benefit analysis at those sites. Wind speed data at 10 m height gotten from the Nigerian Meteorological Agency was utilized to classify the sites wind profiles for electricity generation. The result demonstrated that sites in Lagos and Oyo States were suited for generation at a substantial scale with average wind speeds. Enough power can be generated with several small turbines connected together. The result demonstrated that the region's wind profiles and qualities are reasonable enough for wind power generation. Average wind speeds from 1.9 to 5.3 m/s are predominant, while the most likely wind speed ranged between 1.9 and 6.2 m/s, with the maximum energy conveying speeds between 2.2 and 8.6 m/s across all the stations [7].

Ref. [10, 11] conducted a research and reported on the wind energy reserve in Nigeria at 10 m (or 40 m) height based on data analysis on 10 wind stations across the North West, North East, North Central, South East and South West geopolitical zones. The research showed some promise, with some sites having wind regime between 3.6 and 5.1 m/s, therefore confirming that Nigeria falls into the moderate wind regime according to the Beaufort scale. Along these lines it can be inferred that the sites are potential wind farm areas. This is because most wind turbines start generating electricity at wind speeds of around 3–4 m/s, known in wind generation as the cut in speed. The report also suggested that Nigerian shoreline areas from Lagos State through Ondo, Delta, Rivers, Bayelsa to Akwa-Ibom States also showed promising potentials for harvesting moderate wind energy throughout the year. Coastal regions constitute majority of oil and gas activities in the country, with these activities causing environmental degradation while some of these communities are also cut off from the electricity grid hence leading to a quest for alternate energy sources.

4.2 History of wind energy for wind farms

Arrays of large turbines, called wind farms, are utilized to generate power as a means of reducing fossil power generation in developed countries. By the start of the twentieth century in Denmark, there were already in subsistence some 2500 windmills used to drive mechanical loads like grinding mills and water pumps with an estimated total peak power in the region of 30 MW. By 1910 there were electric generators ranging in power from 5 to 25 kW driven by wind and in use in the United States. During World War I, windmill engineers in the United States were manufacturing 100,000 small-scale farm windmills yearly, mostly used as water pumps [12]. One of the very first modern design horizontal-axis wind generators was used in the Soviet Union by 1931. It was a 100 kW generator placed on a 30-m tall tower and connected to the Nation's 6.3 kV electricity distribution system. It was accounted for to have had a yearly capacity factor of about 32%, which shares close similarity to the efficiency exhibited by current wind machines [12]. As stated earlier, turbine blades can spin about a horizontal or a vertical axis, with horizontal axis rotation being older and more popular. They can also come with blades or be bladeless. Vertical axis wind turbines are not used as much because they produce less power [3].

5. Types of wind turbine

Considering how the turbine spins, two kinds of wind turbines can be defined. The mechanism is the same only the direction of the spin differs. Wind turbines that rotates along its vertical axis is the vertical axis wind turbines (VAWT), while the ones that spins about a horizontal axis is the horizontal axis wind turbines (HAWT).

5.1 Horizontal axis wind turbines

The horizontal axis wind turbine (HAWT) is a turbine whose rotor rotational axis is parallel to the ground and wind stream [13]. Its primary rotor shaft and electrical generator are at the pinnacle of the tower and must be faced directly to the wind. Micro turbines are directed by a wind vane, with larger turbines utilizing a wind sensor coupled with a servomotor. The gear box is located in the drive train and is used to convert the slow blade movement into much quicker rotation capable

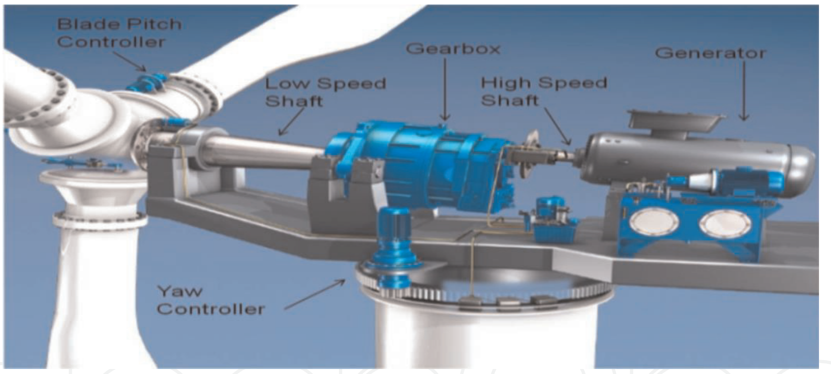

Figure 1.
A horizontal axis wind turbines [30].

of enough energy to drive an electrical generator [14]. Most HAWTs are either two or three blades, but the number of blades has no limit, it depends solely on the designer. HAWT could also be classified as upwind and downwind turbine. In Ref. [15] it is stated that a gear system is used for stepping up the speed of the generator, although designs may likewise utilize an annular generator. Some designs operate at fixed speed, but variable speed turbines have better efficiency and employ a power converter to communicate with the transmission system. All turbines come with protective lineaments for damage limitation during turbulence. In such turbulence the system is also controlled by feathering the blades into the wind hence stalling them, and brought to a halt with the aid of brakes (**Figure 1**).

5.2 Vertical axis wind turbine (VAWT)

The main rotor shaft of this type of turbines are arranged vertically, hence the name. The major advantage of this arrangement is the turbine does not need to follow the direction of the wind to exhibit high efficiency, which is advantageous in sites with highly variable wind directions. Also advantageous is its ability to be mounted on a building because it is much less steerable. The drivetrain and electrical machine can also be positioned close to the ground with the aid of a direct drive from the rotor arrangement to the ground-based gearbox, enhancing availability for repairs. Energy efficiency over time is still poor, a severe drawback. Key disadvantages also include the relatively low rotational speed with the consequence being increased torque with a proportional increase in cost of the drive train, reduced power coefficient, pulsating mechanical torque, and modeling difficulties for accurate wind flow studies leading to issues of rotors design analyses prior to fabrication [16].

6. Efficiency of the wind turbine system

The conservation of mass demands that the measure of air in and out of a turbine must be equivalent. Consequently, Betz's Law defines maximum achievable wind power drawn by a wind turbine as 16/27 (59.3%) of the aggregate kinetic energy of the air entering the turbine. The best hypothetical power yield of a wind turbine is therefore 16/27 times the kinetic energy of the air entering the turbine effective area (**Figure 2**).

$$P = \frac{16}{27} \times \frac{1}{2} \times \rho \times v^3 \times A = \frac{8}{27} \times \rho \times v^3 \times A \quad (1)$$

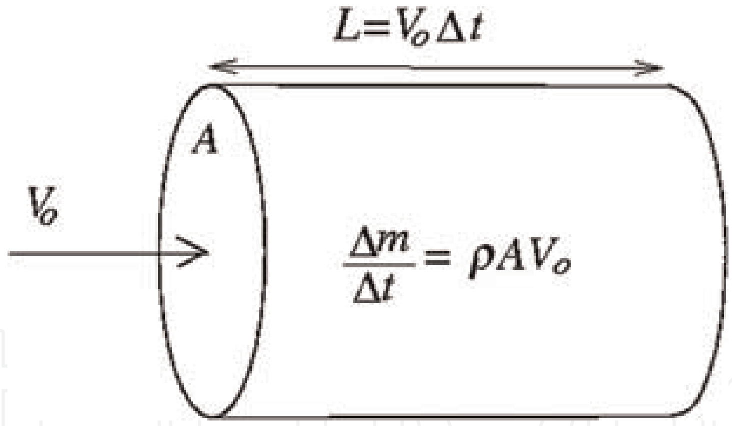

Figure 2.
The air flow through area A [36].

where ρ is the density of air, A is effective area of disk, v is wind velocity, and P is power.

The power accessible from the wind is directly proportional to the cube of the speed of the wind. Meaning if the speed of the wind is doubled then the output power from the turbine is given eight times. Therefore, wind turbine designs have to take this into account by ensuring designs can support higher wind loads than those from which they can generate electricity, in order to prevent them from damage. Wind turbines approach maximum efficiency at wind speeds between 12 and 15 m/s. Over this wind speed, the power yield of the rotor must be controlled to diminish main thrusts on the rotor blades and in addition the load on the general wind turbine system [17].

As wind energy is free, wind-to-rotor efficiency, losses in the generator and power electronics are the major factors that affect the final cost of wind power generation. To keep parts from corroding, extracted power is fixed above rated operating speed as theoretical power increments at the cube of wind speed, which reduces the efficiency. Turbine efficiency can diminish somewhat after some time because of wear. Examination of 3128 wind turbines 10 years or older in Denmark demonstrated that half of them did not diminish in efficiency, while the other observed a decrease of 1.2% per year [18]. Vertical turbine efficiency is lower than their horizontal counterparts.

7. Review of previous works

A journal article on the feasibility of a simple small wind turbine with variable speed regulation [19] was looked at. The objective of the research was to suggest and evaluate a Very Small Wind Turbine (VSWT) with a Squirrel-Cage Induction Generator (SCIG) that can contend favorably with VSWTs connected to the grid with respect to cost and relative ease. To assess the dynamic response of the system other different wind speeds, two tests were made. The results were gotten from real life scenarios not computer simulations and showed the drop in performance with regards to its nominal value was about 75%, when working at 50% of the nominal power which is reasonable enough. In summary, the VSWT and its intended control algorithm is feasible for controlling direct-shaft grid-connected VSWTs.

A paper on control of active and reactive power of a wind energy conversion system with variable speed [20] details a design of wind energy conversion system with different speed employing a three-phase SCIG driven by a HAWT. A static VAR compensator is suggested and linked with the SCIG terminals so as to run the system parameters.

Pitch angle control was utilized in controlling the mechanical power and the system was simulated using SIMULINK software. From the simulation results, the response of the suggested system offers quick recovery faced with different dynamic system disturbances with the controller boosting power thereby improving system efficiency.

A Research by the Czech Technical University studied the need for gearless wind turbines is looked into due to positives such as reliability, and reduction in downtime due to less moving parts. The design simulation was carried out using MATLAB SIMULINK. Results showed the wind turbine had the ability to sustain an electric-power scheme. The system allowed for the independent control of both reactive and active power, suggesting that the gearless design is suitable for turbines with variable speed [21].

In a paper on the transient response of Doubly Fed Induction Generator using an accurate model [22], the transient execution of various models of DFIG considering saturation impact was looked at and a few parameters that influence rotor overcurrent due to voltage sag was simulated. The findings from the paper include the importance of consideration of saturation effect on transients but less so for steady state analysis. Also, the rotor speed of saturated model reaching steady state value quicker than unsaturated model.

A detailed model of fixed speed wind turbine (FSWT) stability studies with stator transient was addressed in a PhD work by [23]. The addition of the stator current transient permit a precise speed divergence forecast. A model for stability of power system analysis like Doubly-Fed Induction Generator (DFIG) wind turbine was also suggested in the same work including the stator flux transient. By doing so, the analysis of Fault Ride-Through (FRT) is done. However, such representation gives rise to difficulties when looking into the implementation of the positive sequence fundamental frequency simulation tools, as a result of small time-step prerequisite and inconsistency with normal power system parts.

A model of DFIG wind turbine was introduced in [24], the stator transient was not considered at normal operation. However, the use of a current controller still demands high simulation resolution.

A basic model of a DFIG wind turbine, compatible with the natural frequency representation was projected by [25]. Both stator and rotor flux dynamics were neglected in the model. This model is comparable to a steady state representation, while the controller of the rotor current is assumed to be instantaneous. Therefore, iteration process which is not favorable in the implementation model is required to solve algebraic loops between the grid model and the generator model.

With the introduction of time lags representing current control delays, algebraic loops can be avoided [26]. Nevertheless, it is assumed that the maximum power tracking (MPT) in this model is directly proportional to the arriving wind speed, although in common practice, the generator speed or the generator output power drives the MPT.

Miller et al. [27] presented another DFIG simplified model. According to this model, the generator is simply modeled as a current source that is controlled; hence the rotor parameters are omitted. This proposed simplified model did not take into account the limiters of rotor current and the FRT schemes are not clearly modeled.

Demonstrations of detailed FSWT models for power system are presented in [28]. In this paper, the generators are modeled thoroughly. They need very small time-step therefore complicating the execution in a standardized fundamental frequency simulator. Ref. [29] proposed a simplified model of an FSWT model.

In a power system network comprising different generation unit, there is bound to be frequency stabilization and control issues. In the work of [31] the frequency responses of the grid power system network and other variables of the grid connected wind during the period of grid dynamics show improved performance as shown in the simulation results.

8. Variable speed and fixed speed wind turbines

The difference between the variable speed and fixed speed wind turbines is whether the rotor is designed to run at different speed or constrained to move at a particular speed. Early wind turbine designs generally operated at constant speed. In this type, the rotor speed does not change regardless of wind speed changes. A converter of power electronic frequency is needed in order to link the variable-frequency output of the wind turbine to the constant electrical system frequency. Power electronics required for different speed wind turbines may be more costly, but they make up for the higher costs by spending more time than fixed turbines working at optimum aerodynamic efficiency [33]. A graph of the performance coefficient versus the tip speed ratio shows this difference clearly. Tip speed ratio is known as the ratio between the angular velocity of the blade tips of a turbine and the wind velocity as shown in Eq. (7). In wind turbine with fixed speed, ω is constant, corresponding to a specific wind speed. Hence for any other speed from the wind, the turbine efficiency is reduced.

The aim of the wind turbine with variable speed is to always run at optimal efficiency, with tip speed ratio consistency, corresponding to the maximum performance coefficient, by adapting the velocity of the blades to variations of wind speed. Therefore, wind turbines with variable speed designs are ideal for efficient power generation, regardless of the wind speed. Then again, as a result of the fixed speed operation for constant speed turbines, any variations in the speed of the wind are communicated as instabilities in the mechanical torque and then as instabilities in the electrical power grid [17]. This as well as an increased energy capture capability of the variable speed turbine makes the power electronics cost effective [33]. Therefore, wind turbines with variable-speed are more preferable.

9. Methodology

This section introduces the model of the wind turbine while analyzing all three blocks. The equations used in the design model for each block are derived and analyzed as well. The wind energy conversion system modeling is reduced into three subsystems which are the aerodynamics block, mechanical block, and the electrical block as shown in the block diagram in **Figure 3**.

The aerodynamics block is responsible for the extraction of power from the wind in the form of kinetic energy necessary to propel the blades. The mechanical block then converts this kinetic energy into mechanical energy used to drive the generator which in turn is turned into electrical energy by the electrical block.

The modeled wind turbine system is designed and simulated with the MATLAB SIMULINK software. The simulation model diagram showing all three subsystems is shown in **Figure 4**.

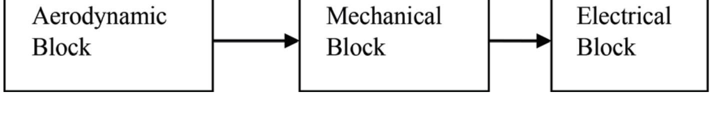

Figure 3.
Block diagram of the conversion system model.

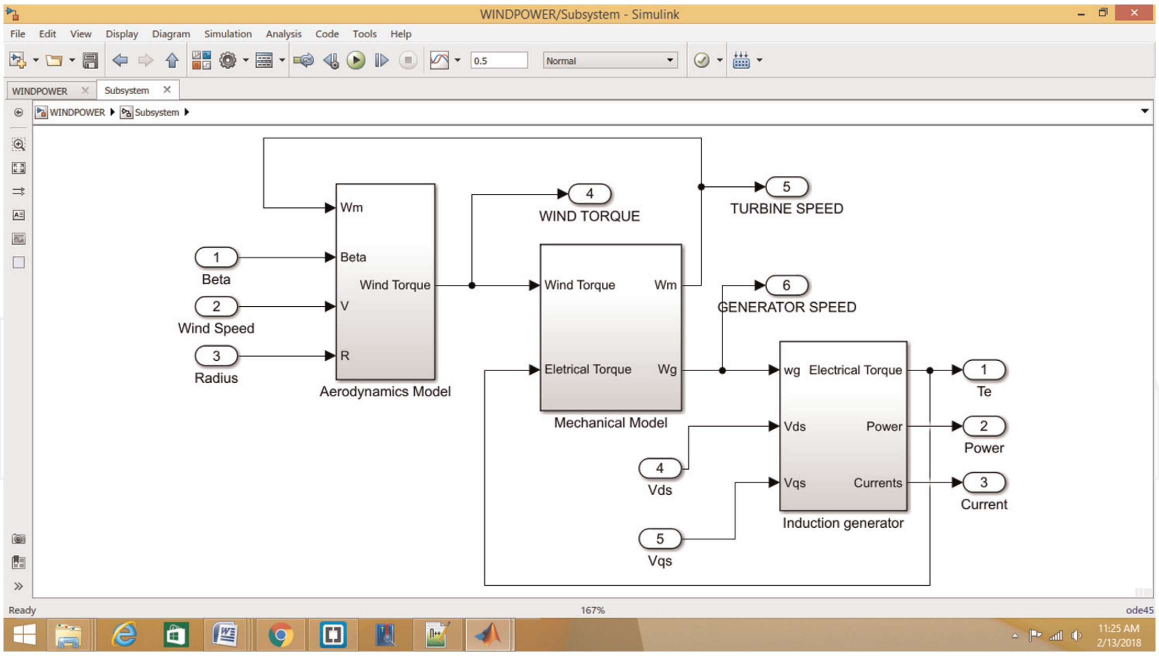

Figure 4.
Simulation schematic diagram of the wind turbine model.

10. Aerodynamic subsystem modeling

The wind turbine blades and its interaction with the wind make up the aerodynamic subsystem to be modeled. The aerodynamic modeling block diagram is shown in **Figure 5**.

The blades of a wind turbine rotate due to kinetic energy from the wind which is defined by the wind speed. An object with mass (m) which moves at velocity (v) has kinetic energy in the air given by [17] as:

$$E = \frac{1}{2} \times m \times v^2 \tag{2}$$

The power contained in the moving blades assuming constant velocity is equal to the differential of this kinetic energy with respect to time as given in (Eq. (3)).

$$P_w = \frac{dE}{dt} = \frac{1}{2} \times m \times v^2 \tag{3}$$

where m represents the mass flow rate per second.

When the air crosses the area "A" brushed by blades of the rotor, the power in air can be calculated with (Eq. (4)).

$$P_w = \frac{1}{2} \times v^3 \times A \times \rho \tag{4}$$

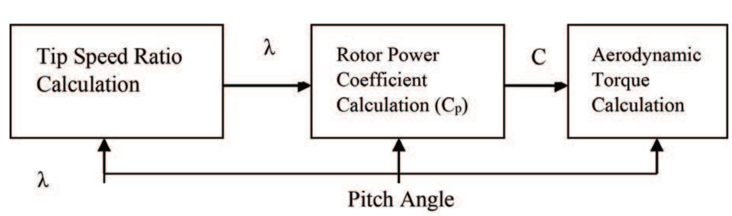

Figure 5.
Block diagram of the aerodynamic model.

ρ = the density of air.

Density of air can be conveyed as a component of the turbine's rise above sea level (H) as shown in Equation (5).

$$\rho = \rho_0 - 1.194 \times 10^{-4} \times H \tag{5}$$

where ρ_0 = 1.225 kg/m^3 which is the air density at sea level at temperature T = 298 K. The power extracted from wind is defined as [32],

$$P_{BLADE} = Cp(\lambda, \beta) \times P_w = Cp(\lambda, \beta) \times \frac{1}{2} \times v^3 \times A \times \rho \tag{6}$$

Cp = 0.593 (Betz law). The rotor power coefficient is a function of both the tip speed ratio "λ" and the blade pitch angle "β" (in degrees). The blade pitch angle is characterized as the angle between the blade cross-area and the plane of rotation. It alludes to changing the attack angle to best suited angles to adjust the rotation speed of the blades hence adjusting generated power.

Tip speed ratio is defined in Eq. (7),

$$\lambda = \frac{w_m \times R}{v} \tag{7}$$

w_m is angular velocity of the rotor, R blade radius, and "w_m*R" is the blade tip speed. The rotor torque is therefore defined as,

$$\mathrm{T_w} = \frac{P_{BLADE}}{w_m} = \frac{Cp(\lambda, \beta) \times \frac{1}{2} \times v^3 \times A \times \rho}{w_m} \tag{8}$$

And, A, the area covered by the blade

$$A = \pi \times R^2 \tag{9}$$

Substitute Eq. (9) into Eq. (8), giving Eq. (10).

$$\mathrm{T_w} = \frac{P_{BLADE}}{w_m} = \frac{Cp(\lambda, \beta) \times \frac{1}{2} \times v^3 \times \pi \times R^2 \times \rho}{w_m} \tag{10}$$

The power coefficient Cp can be expressed as shown in Eq. (11).

$$Cp(\lambda, \beta) = c_1 \times \left(c_2 \times \frac{1}{y} - c_3 \times \beta - c_4 \times \beta^x - c_5 \right) \times e^{\frac{-c_6}{y}} \tag{11}$$

where gamma "y" is given as [32],

$$\frac{1}{y} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1 + \beta^3} \tag{12}$$

where $c1$–$c6$ are the aerodynamic coefficients given as $c1$ is 0.5176; $c2$ is 116; $c3$ is 0.4; $c4$ is 5; $c5$ is 21; and $c6$ is 0.0068.

The simulation schematic of the aerodynamic modeling is shown in **Figure 6**.

The equations used are (Eq. (7)) for the Lambda, the beta is the pitch angle for the wind turbine blades. The gamma function block uses (Eq. (11)), the power coefficient is modeled using (Eq. (11)) and the wind torque is modeled using (Eq. (10)).

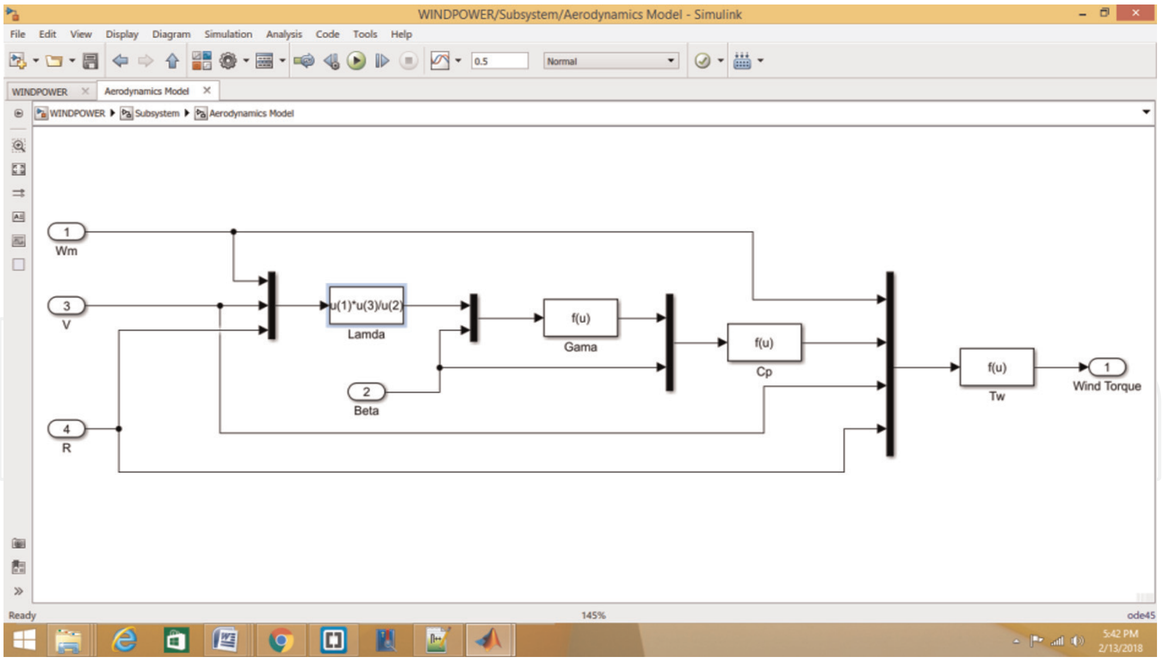

Figure 6.
Simulation schematic diagram of the aerodynamic block.

11. Mechanical subsystem modeling

The wind turbine mechanical subsystem is known as the drive train. It comprises of a blade pitching component, a hub with blades, a rotor shaft and a gearbox (**Figure 7**).

The mechanical model of the wind turbine will be modeled based on two lumped masses assumptions: the gear box mass and the wind wheel mass.

The induction generator equation of motion as given [35] is defined as:

$$H_g \times \frac{dW_g}{dt} = T_e + \frac{T_m}{n} \tag{13}$$

where T_e is Electromagnetic torque, T_m is Mechanical torque, T_w is wind torque.

Since the wind turbine shaft and generator are linked utilizing a gearbox, the shaft of the turbine is not viewed as stiff. Hence there will be movement in the shaft. The equation of motion of the drive train shaft is computed as

$$H_m \times \frac{dW_m}{dt} = T_w - T_m \tag{14}$$

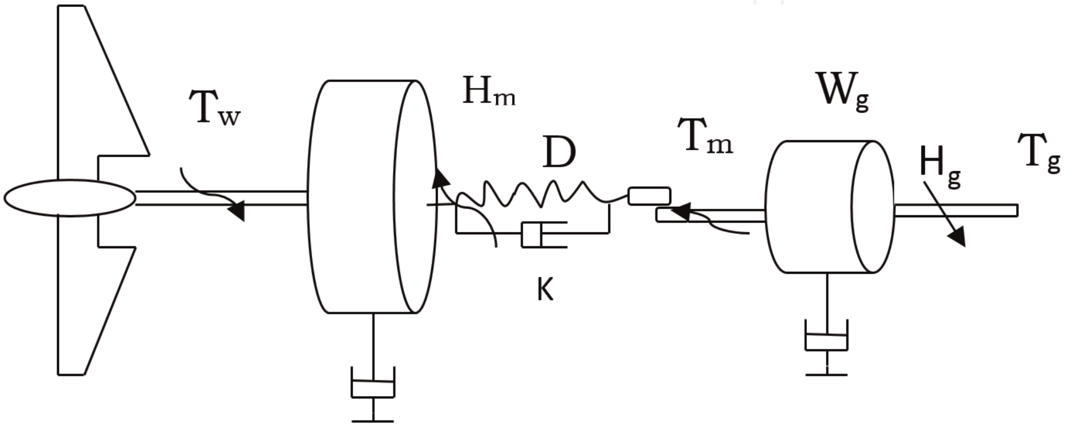

Figure 7.
Mechanical subsystem of a wind turbine.

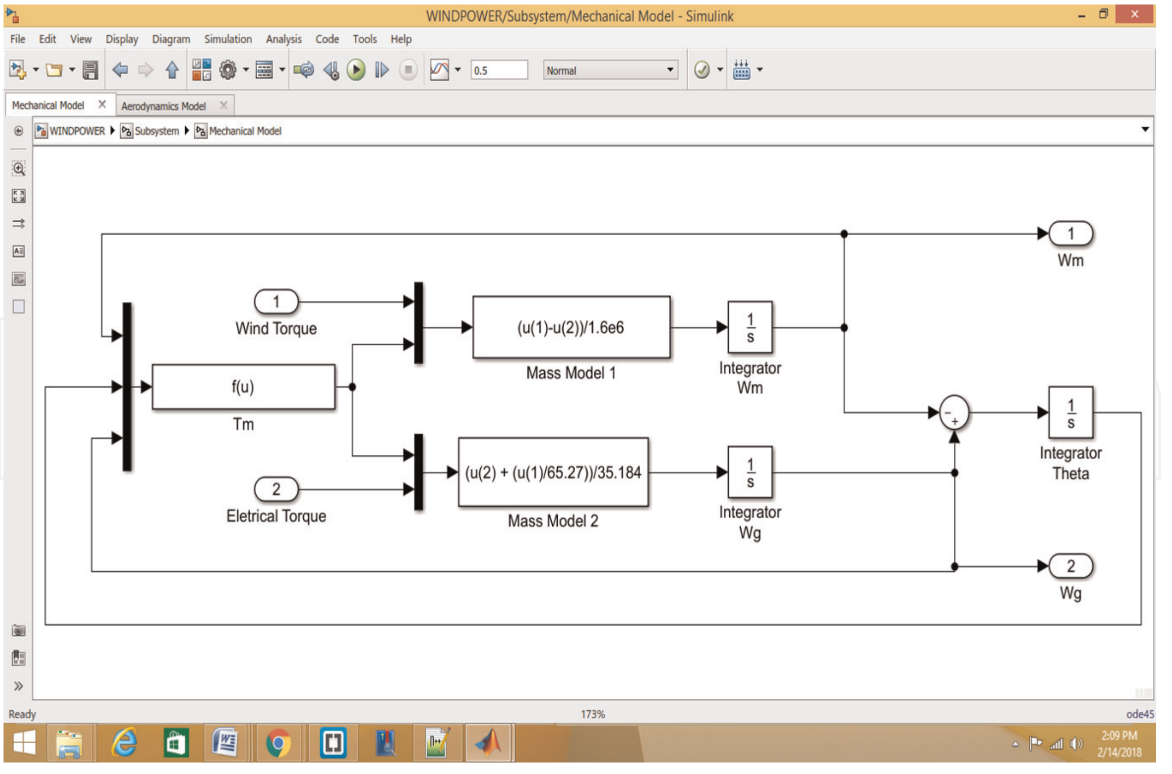

Figure 8.
Simulation schematic diagram of the mechanical model.

T_m is given by

$$T_m = K \times \frac{\theta}{n} + D \times \frac{W_g - W_m}{n} \tag{15}$$

$$\frac{d\theta}{dt} = W_g - W_m \tag{16}$$

where, n is the gear ratio; θ is the angle between the turbine rotor and the generator rotor; W_m is the speed of the turbine; W_g is the speed of the generator; H_m is the turbine inertia constant; H_g is the generator inertia constant; K is drive train stiffness; and D is damping constant [35] (**Figure 8**).

12. Generator model

An induction generator (asynchronous generator) is used in this model. This is because of its high reliability and low maintenance compared to synchronous generators. The power captured by the drive train of the turbine is converted to electrical power which takes the form of an alternating current. The induction generator has three-phase stator armature windings (AS, BS, CS) and three-phase rotor windings (AR, BR, CR). The external stationary part is known as the stator and the rotor the internal rotating part of the generator. The rotor is placed on bearings fixed to the stator. At the point when the wind torque exerted on the rotor is enough to drive it beyond synchronous speed, there is electrical energy generated.

When modeling the induction machine the following assumptions are made as described by the mathematical modeling of induction generator for power systems principles.

- When streaming toward the network, the stator currents are positive.
- The real and reactive powers are positive.
- The stator and rotor windings are as far as the mutual effect with the rotor is concerned, are set sinusoidally along the air-gap.
- The stator openings show no considerable differences of the rotor inductances with rotor position.
- The rotor openings show no considerable variations of the stator inductances with rotor position.
- Magnetic hysteresis can be neglected as well as saturation effects.
- The stator and rotor windings are symmetrical.
- Also neglected is the capacitance of all the windings.

In order to simulate the induction generator in SIMULINK; the three-phase supply is converted into a two-phase supply using the help of "Parks Transformation Matrix" where the flux linkage is taking as a staple variable. After conversion, both phases are called d-axis and q-axis. The conversion process is not covered here. When performing power system dynamic studies of induction generator, two models exist;

- A complete model which comprises of electromagnetic transients both in the rotor and the stator circuits, it contains four electromagnetic variables. This is known as the fifth order model.
- The simplified model neglects the stator transients which contains two electromagnetic state variables. This is also known as the third order model.

12.1 Model including stator transients

The modeling of the asynchronous generator can be done by finding an equation that relates V_{ds}, V_{qs}, the stator direct and quadrature axis voltages, to I_{ds}, I_{qs}, the stator direct and quadrature axis currents. The 0dq reference outline model takes positive currents while rotating at synchronous speed and can be represented using the below equations [34].

- **Magnetic fluxes**

$$\varphi_{ds} = X_s \times I_{ds} + X_m \times I_{qr} \tag{17}$$

$$\varphi_{qs} = X_s \times I_{qs} + X_m \times I_{qr} \tag{18}$$

$$\varphi_{dr} = X_r \times I_{dr} + X_m \times I_{ds} \tag{19}$$

$$\varphi_{qr} = X_r \times I_{qr} + X_m \times I_{qrs} \tag{20}$$

- **Voltages**

$$V_{ds} = -R_s \times I_{ds} + w_s \times \varphi_{qs} - \frac{d\varphi_{ds}}{dt} \tag{21}$$

$$V_{qs} = -R_s \times I_{qs} - w_s \times \varphi_{ds} - \frac{d\varphi_{ds}}{dt} \tag{22}$$

$$V_{dr} = 0 = -R_r \times I_{dr} + w_s \times s \times \varphi_{qr} - \frac{d\varphi_{dr}}{dt} \tag{23}$$

$$V_{qr} = 0 = -R_r \times I_{qr} + w_s \times s \times \varphi_{dr} - \frac{d\varphi_{qr}}{dt} \tag{24}$$

Here, the sub-indexes (s, r) represent the rotor and stator quantities and the sub-indexes (d, q) represent the d- and q-axis in the synchronous rotating reference. The rotor voltages V_{dr} and V_{qr} are equated to zero because current is fed into the stator. The variable ϕ represents the magnetic linkage flux, w_s represent the synchronous rotor speed and w_g represent the generator rotor speed. The slip of the rotor "s" is given as

$$s = \frac{w_s - w_g}{w_s} \tag{25}$$

The electrical parameters R_s, X_s, X_m, R_r and X_r represent the stator resistance and reactance, mutual reactance and rotor resistance and reactance, respectively.

The electrical torque is given as

$$T_e = \varphi_{qr} \times I_{dr} - \varphi_{dr} \times I_{qr} \tag{26}$$

The power generated by the wind turbine is expressed as

$$P = P_{active} + Q_{reactive} \tag{27}$$

$$P_{active} = V_{ds} \times I_{ds} + V_{qs} \times I_{qs} \tag{28}$$

$$Q_{reactive} = V_{qs} \times I_{ds} - V_{ds} \times I_{qs} \tag{29}$$

12.2 Model neglecting stator transients

Neglecting the stator transients reduces the overall order of the model and increases the size of the system that can be simulated. In this model, the rate of change of stator flux linkage is dismissed. The terms $d\phi_{ds}/dt$ and $d\phi_{qs}/dt$ in Eqs. (21) and (22) will be neglected. Eqs. (17)–(29) are used in the modeling of the induction generator subsystem. The simulation schematic is shown in **Figure 9**.

The model is designed using attributes of steady-state power of a turbine. There is infinite drive train stiffness and friction factor and turbine inertia are joined to the turbine. Eq. (30) gives the output power of the turbine,

$$P_m = C_p \times (\lambda, \beta) \times \frac{\rho A}{2} \times v_{wind}^3 \tag{30}$$

where, P_m is mechanical output power (W).

The mechanical power in per unit is expressed in Equation (31).

$$P_{m\_pu} = k_p \times C_{p\_pu} \times v_{wind\_pu'}^3 \tag{31}$$

where pu is per unit.

13. Case study

Wind speed attributes are considered stronger in coastal areas and offshore as stated in Section 2 above. This study utilized data from Ogoja community in Cross

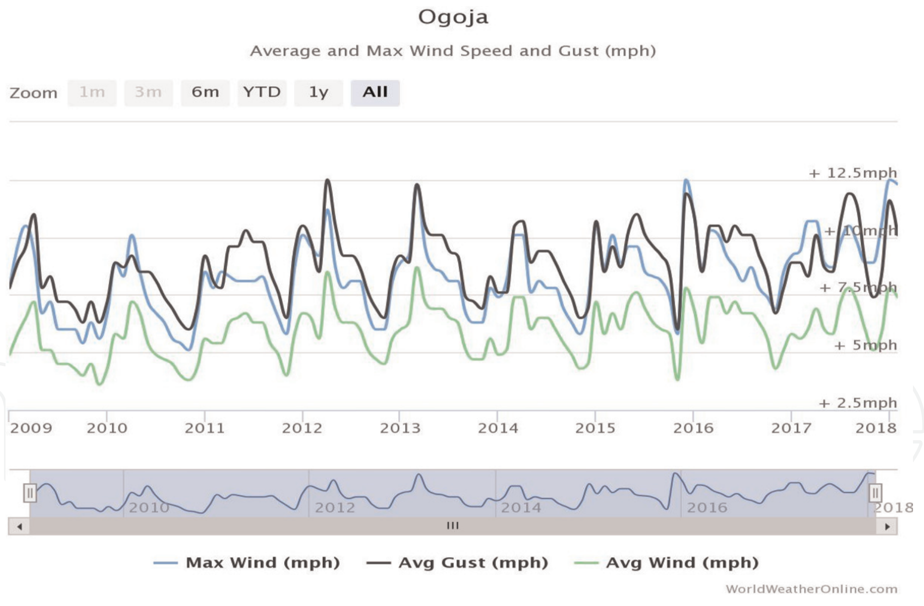

Figure 10.
Average wind speed in Ogoja.

River State (N6.67, E8.48). Monthly data averages on wind speed, temperature and humidity for the last 9 years (January 2009–December 2018) measured at a height of 10 m was gotten from the World Weather Center and presented in **Figure 10** and **Tables 1** and **2**.

14. Simulation result

At rated wind speed of 3.2 m/s (**Table 1**) the relationship between power and the speed of turbine is shown in **Figure 13**. The results of the simulation are as

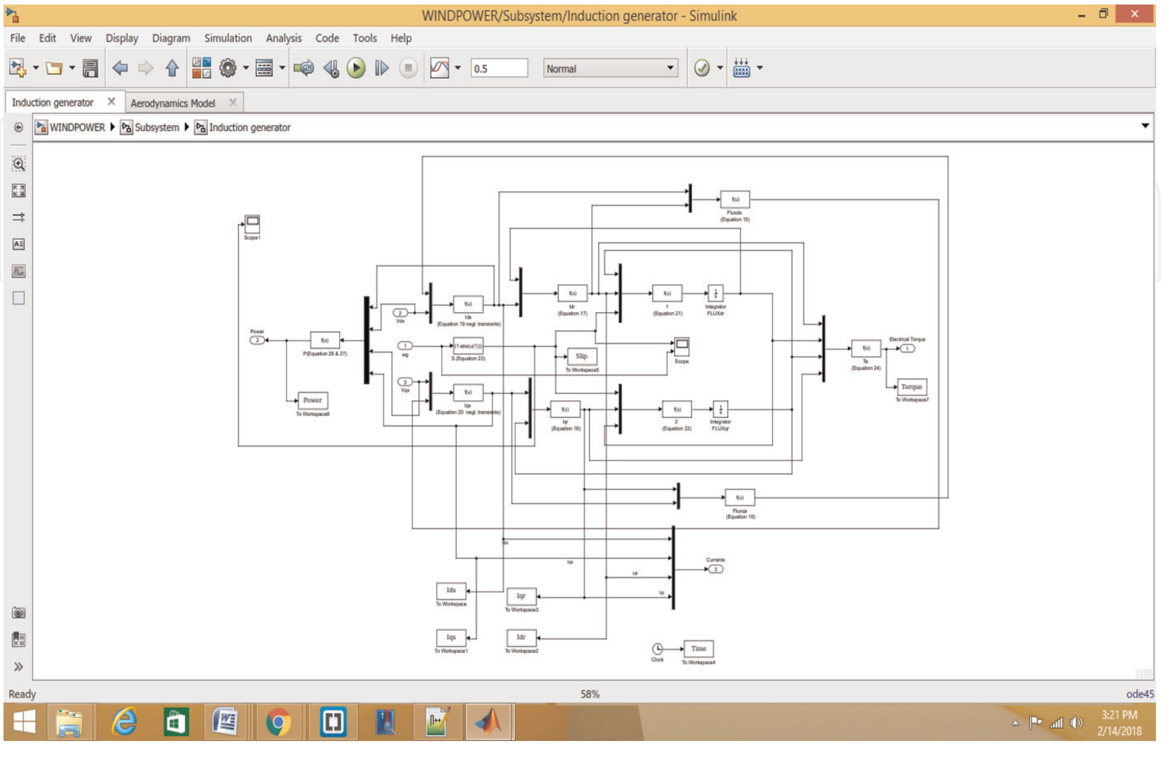

Figure 9.
Simulation schematic diagram of the induction generator subsystem.

Month	(Jan-Dec)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Average
Wind speed	(m/s)	2.9	3.4	3.7	3.6	3.3	3.3	3.5	3.6	3.1	2.8	2.6	2.6	3.2
Temperature	(°C)	32	32	33	32	31	28	28	27	29	30	31	31	30.3
Humidity	(%)	33	47	55	77	65	75	78	83	82	71	46	31	61.9

Courtesy: www.worldweatheronline.com.

Table 1.
Meteorological data for Ogoja community 2009–2018.

Parameters	Air density (p)	Gear ratio (n)	Aerodynamic coefficients $c1$–$c6$	Damping (D)	Stiffness (K)	Rotor inertia (H_m)	Generator inertia (H_g)	Stator resistance (X_s)	Stator reactance (X_s)	Mutual reactance (X_m)	Rotor resistance (R_s)	Rotor reactance (X_r)	Synchronous speed (w_s)	Pitch angle
Value	1.225 kg/m^3	65.27	$c1$ = 0.5176, $c2$ = 116, $c3$ = 0.4, $c4$ = 5, $c5$ = 21, $c6$ = 0.0068	1.00E+06	6.00E+07	1.60E +06	35.184	0.0121	0.0742	2.7626	0.008	0.1761	1	0

Table 2.
Parameters used in the simulation.

shown in the readings captured from the scopes in the simulation model (**Figures 11** and **12**).

Figures 13–16 shows different wind torques and the mechanical torque at 1 and 3.2 m/s is shown on the scopes. It is seen that an increase in speed of wind also leads to an increase in mechanical torque and in the same direction as the wind torque (**Figures 17** and **18**).

From the graphs of the turbine speed and the generator speed, the generator moves in the reverse direction of the wind torque shows that the induction machine is used in the generator mode so it tends to negative. The turbine speed starts increasing gradually as the system generates power, it moves in the positive

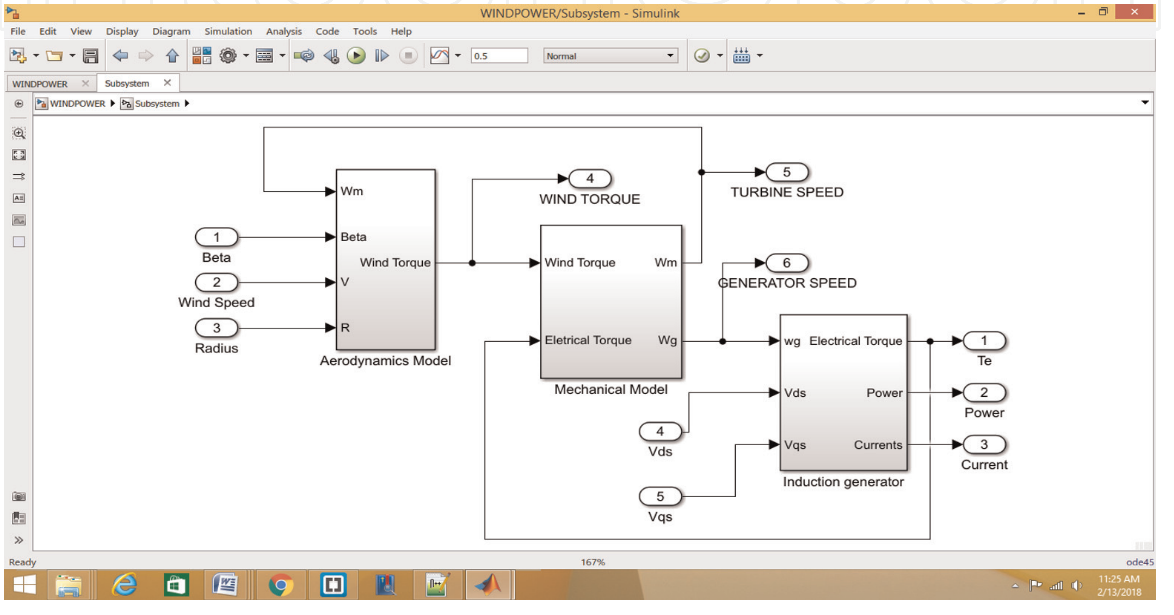

Figure 11.
Simulation schematic diagram of the wind energy conversion system.

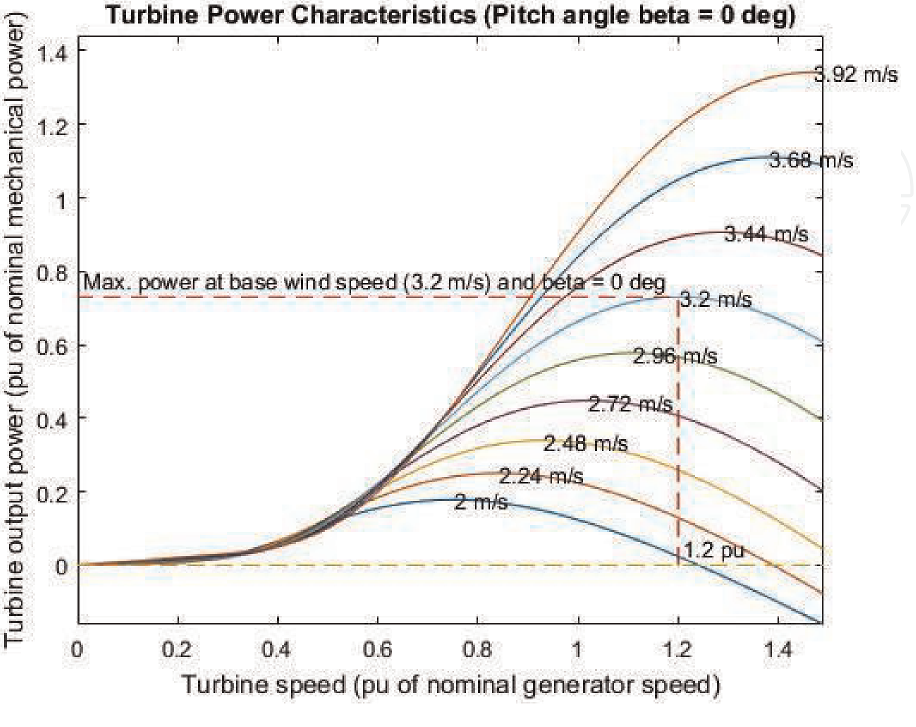

Figure 12.
Relationship between wind speed and output power for the wind turbine.

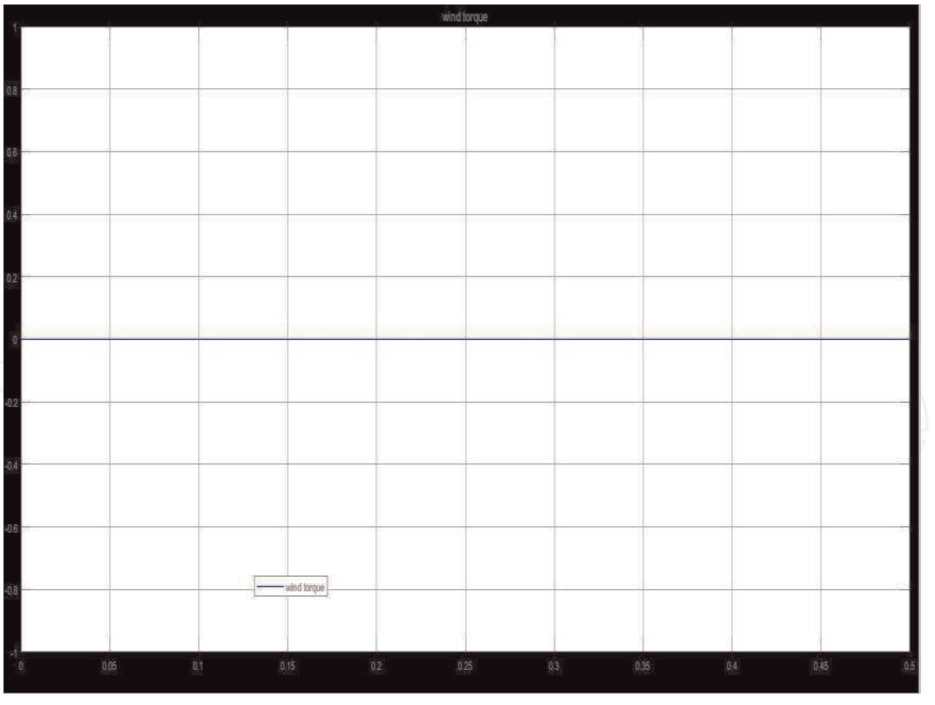

Figure 13.
Wind torque @ 0 m/s.

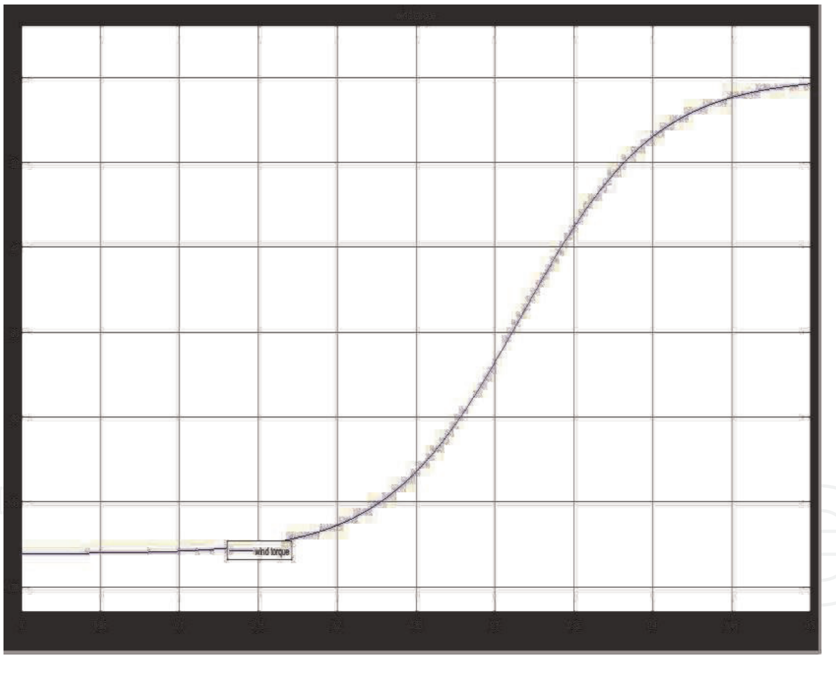

Figure 14.
Wind torque @ 1 m/s.

direction. The higher the speed, the more power that will be generated. Hence the generator speed is proportional to the turbine speed. The speed from the wind is not sufficient to move the turbine blades until around 0.35 s when the speed starts progressing gradually, leading to a proportional decrease in generator speed (**Figure 19**).

The turbine generates fluctuating values of electrical power peaking at about 80 W at 0.25 s in the simulation. These results are gotten at rated wind speed of 3.2 m/s and zero pitch angle.

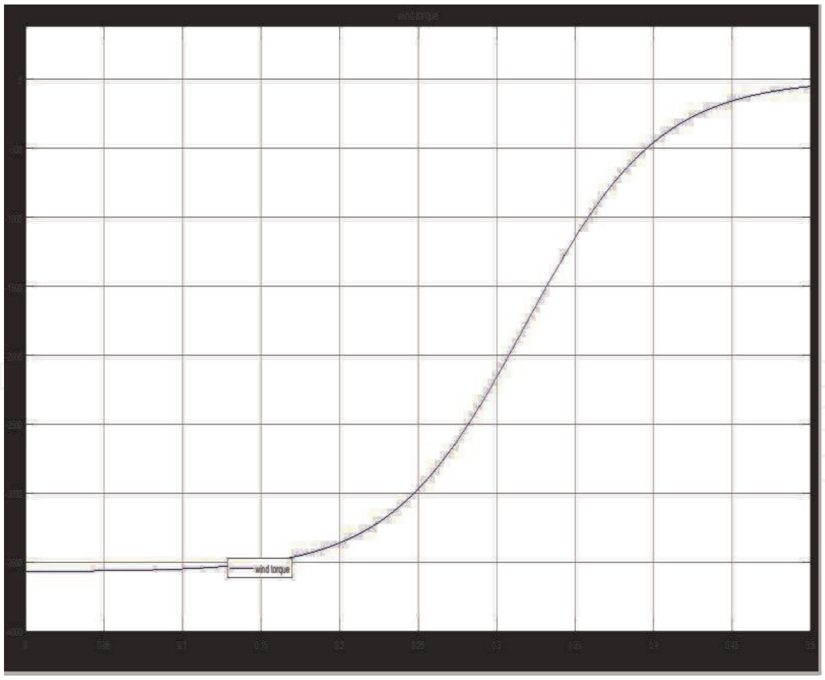

Figure 15.
Wind torque @ 3.2 m/s.

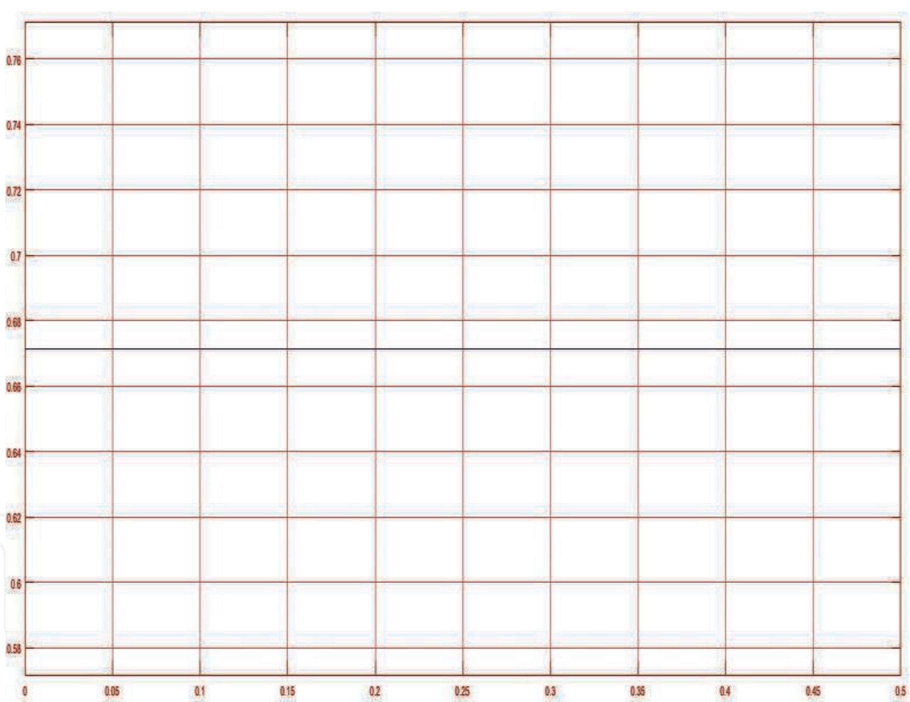

Figure 16.
Mechanical torque @ 3.2 m/s.

15. Conclusion

With shortage of energy supply prominent in most developing countries especially in Africa, the need for clean and self-replenishing alternative energy supply cannot be over emphasized. A wind energy conversion system with different wind speed, made up of the blades, drive train and SCIG was modeled for Ogoja community in the southern part of Nigeria as presented. The output power, turbine speed and torque were simulated in MATLAB SIMULINK environment

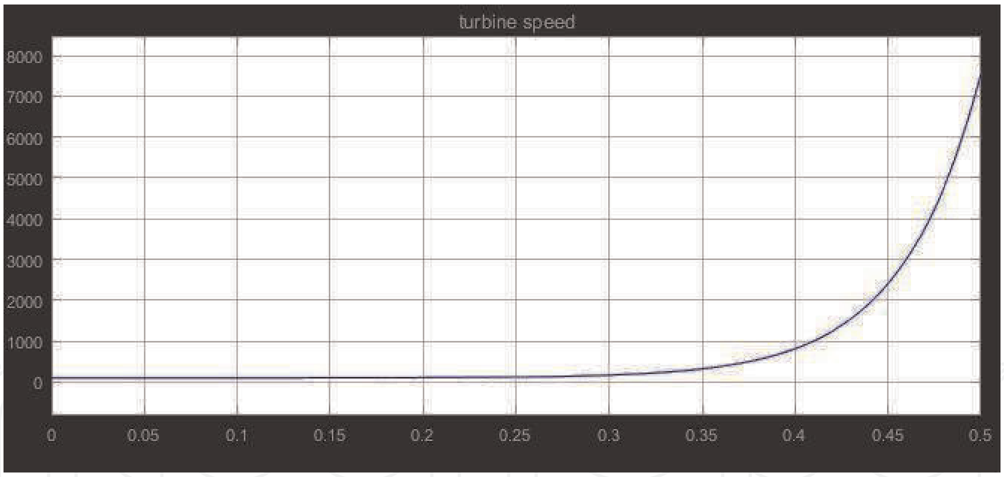

Figure 17.
Turbine speed.

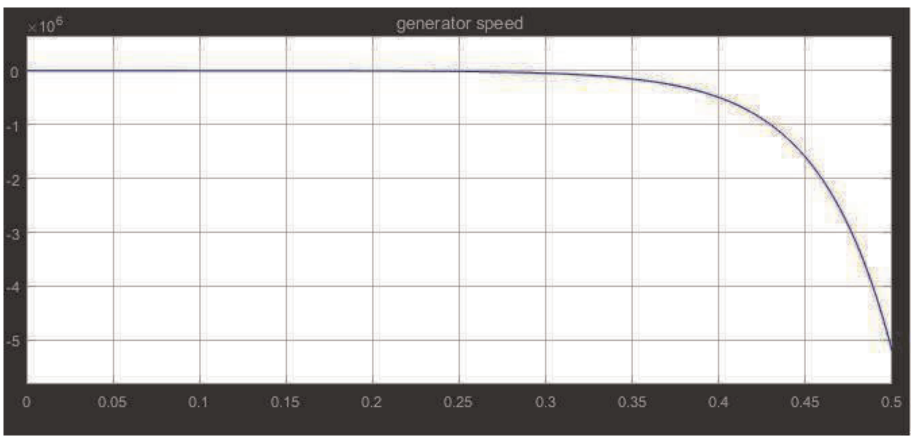

Figure 18.
Generator speed.

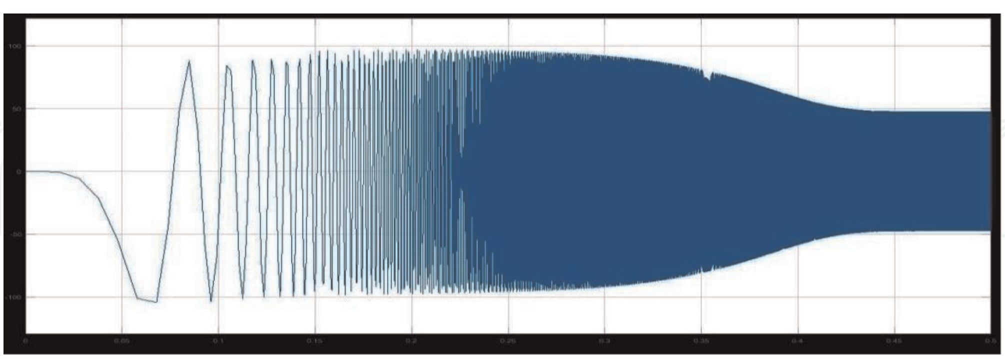

Figure 19.
Electrical power.

successfully. Tests were carried out on the system and showed that turbine speed and wind speed are proportional to power response when simulated. The generated power increases with the turbine speed, making the model useful as wind energy is generated at different wind spend, and this has been able to unveil that even at different wind speed, wind energy potential is available in the coastal area of southern Nigeria. This energy could be used for distributed generation for these communities isolated from the grid.

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