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Harnessing and Modelling Wind Power Plant with Permanent Magnet Syncrhonous Generator for Power Generation in Nigeria

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ABSTRACT

Nigeria has tremendous energy resources in the form of abundant gas, water and mineral resources. Yet, it is highly energy deficient. The country is rated first among the oil producing countries in Africa with average of 2.5 million barrel per day, with highest natural gas reserve in Africa of 176 trillion cubic feet. Mathematical modeling of wind turbine system design technology suitable for Nigeria has been developed in this work taking into account wind speed distribution in Nigeria in as much as it is assumed to be the geographical location in this paper. The wind turbine system designed generates three phase current whose rms values ranges from 0.2093 to 2.2996 for relatively low wind speeds ranging from 2m/s to 10m/s. It also generates three phase voltage whose rms values ranges from 35.9097 to 397.850 with electromagnetic power whose steady state value ranges from16.2624 to1945.5 for relatively low wind speeds ranging from 2m/s to 10m/s. These values of the generated current are sufficient for steady electricity generation to power home appliances. The investigation has revealed that wind turbine system design is a tool that can aid further research and development of more efficient turbines for Nigeria. Wind energy generation feasibility and implementation has been achieved in this study showing that even in the tropical regions of Nigeria, wind energy is an economically feasible competition to hydrocarbon combustion generators. The design method and the components used in this paper will not only reduce cost of design but will also reduce the cost of maintenance, thus making it very economical and affordable. It is recommended that since in the northern parts of Nigeria where wind speeds up to 15m/s, wind farms can be built like those in the more developed countries to support the existing grid system. Modern technologies and control techniques can provide power at frequencies steady enough to be synchronized with the grid system.

Keywords: *Nigeria, wind, renewable, turbines.*

INTRODUCTION

Growth and economic development of a nation is dependent on available energy. This has come as a result of the ease of conversion, transmission and distribution of electrical energy and also the advent of digital systems. Most applications of other forms of energy receive electrical energy input to function. This has led to high need of electrical energy which if not met would lead to socio-economic and technological underdevelopment. Electricity has therefore become a sensitive arena that continually attracts global attention and form top agenda on the to-do menu of virtually all governments globally.

The threat it poses to national economic sustainability, development and appreciable growth is conspicuously visible in the way each country of the world seeks and exploit various alternative energy sources of generating electricity in the most economical and environmentally friendly way. Nigeria has tremendous energy resources in the form of abundant gas, water and mineral resources. Yet, it is highly energy deficient. The country is rated first among the oil producing countries in Africa with average of 2.5 million barrel per day, with highest natural gas reserve in Africa of 176 trillion cubic feet. It also has extensive coal resource with inferred reserves estimate ranging from 1.5 billion metric tons to 2.75 billion metric tons (CPE, 2009) and renewable resources such as water, wind and sun energy from which appreciable electricity can be generated. With the abundance of energy resources,

Nigeria need not import energy to achieve sustainable generating capacity. This suffices the targeted economic growth. Nigeria had been able to trace the collapse of her industrial sector, small and medium scale businesses and economic downturn to the inadequate and erratic state of the country's electricity market –several commitments by different government of Nigeria, both financial and human capital, has been thrown behind the power sector in recent years. This paper describes the renewable energy potential in Nigeria. It shows how the current power generation, transmission and distribution system can be enhanced by the introduction of wind turbine generators into the current working grid system. It also entails the design and simulation in MATLAB/SIMULINK environment of wind turbine generator model. Wind energy conversion systems converts kinetic energy of the wind into electricity or other forms of energy. Wind power generation which has experienced a tremendous growth in the past decade has been recognized as an environmentally friendly and economically competitive means of electric power generation. Energy when considered in terms of means of generation is broadly classified into two main groups: renewable and non-renewable resources. Non-Renewable energy is the energy which is taken from the sources that are available on the earth in limited quantity and may go extinct a few years from now. Sources of non-renewable energy exist in the form of fossil fuels, natural gas, oil and coal. Renewable energy on the other hand is generated from energy sources which exist in nature such as sun, wind, rain and tides. They can be generated again and again and as such seem inexhaustible in quantity because it has self-replenishing energy cycle. Technology advancement and the low cost of production have caused more developed countries to harness the energies from these renewable sources. Over the years, the discovery of fossil fuels deposit in Nigeria in large quantity led to the nation's total dependence on non-renewable sources of energy. Despite the abundance of renewable and non-renewable energy resources, the country is still in short supply of electrical power. Only about 40% of the nation's over 140 million populaces have access to electrical grid network. Even the electricity supply to the consumers that are connected to the grid is erratic. Provision of electricity is largely supplemented by private individual through the use of individual electricity generators powered with fossil fuel for the privileged income groups. (Vincent-Akpu I, 2012). Therefore, it is necessary to harness renewable energy potential (such as wind, solar etc.) for reliable power supplyin Nigeria. Continued apprehensions about nuclear power around the world should drive the country into strong demand for wind generation for the health of the populace as well as the economy. The aim of the paper is to design and simulate a 2KVA wind turbine generator which can be used individually to power medium range electrical appliances.it will involve design and simulation of a wind turbine generator in MATLAB environment. This will provide a more cost-effective alternative to hydro-carbon combustion generators and introduce a cheaper solution to grid extension to rural areas currently without electrical power.

REVIEW OF LITERATURE

Currently, with some of the completed integrated power projects, Nigeria national grid comprises of seventeen power generating stations. Presently, of the seventeen (17) active power generating stations, eight of these are owned by federal government (existing) with installed capacity of 6,256MW and of which 2,484MW is available (Omorogiuwa E, and Ogujor A, 2012).The remaining nine (9) are from both the national independent power project (NIPP) and independent power project (IPP) with total designed capacity of 2,809MW, of which 1,336.5MW is available. Thus, the current nation's available electricity generating capacity is about 3,820MW with per capita power capacity of 28.57W and this is grossly inadequate even for domestic consumption.

Current power generation projection by PHCN is 26,561MW. EPSR Act nurtures a wholesome market starting with a single buyer of electricity produced by PHCN and the IPPs for onward sale to the eleven Distribution Companies that would also be offered for sale. Eventually the single model would be discarded for a bilateral contract model with suppliers and buyers free to contract between themselves. The Act focused on the liberalization and Privatization of the sole power provider - PHCN while introducing Independent Power Producers - IPPs. The Act further provide for the establishment of Nigeria Electricity Regulatory Commission (NERC) which is charged with the following: Regulate tariffs and quality service, Oversee the activities of the industry for efficiency, Institutional enforcement of the regulatory regime, Licensing of Generation, Distribution, Transmission and trading companies (Victor Okolobah and Zuhaimy Ismail, 2013)

For Nigeria to meet up its energy needs, it requires per capital power capacity of 1000W or power generating/handling capacity of 140,000MW as against the current capacity of 3,820MW. Furthermore, on completion of all the present ongoing power projects in Nigeria, its total installed capacity will become 12,054MW which does not provide one tenth of the power generation capacity required for sustainable constant power in the country. This analysis has shown that for steady electrical power to be available in all parts of Nigeria, other measures apart from those currently being taken must be adopted (Vincent-Akpu I, 2012). An important criterion considered in wind energy generation is the availability of sufficient amount of wind power to drive the turbines. Technological experience has shown that on considering other criteria such as turbine blade diameter, vertical height of turbine, wind minimum speed of 3m/s to 4m/s is required to ensure steady voltage and electrical power generation. The technologies for harnessing wind energy have over the years, been tried in the northern parts of the country (Nigeria) mainly for water pumping from open wells in many secondary schools in Sokoto, Kano, Katsina, Bauchi and Plateau States. With the discovery of fossil fuel deposits in Nigeria as well as improvements in fossil fuel energy generation technology has caused the prices of fossil fuels to drop in the following decades and therefore with cheap energy, wind power was not an appealing alternative. Investment in windmills ceased and the infrastructures deteriorated. The existing infrastructure is obsolete, but research into the feasibility of wind power in certain regions has suggested the potential for this type of power generation is high in some regions of Nigeria. However recent feasibility study carried out by various groups has shown high wind energy potential in the country and renewed interest in the technology. A survey was carried out by Fagbenle and Karayiannis (1994) for 18 stations cutting across 6 geopolitical zones from 1979 to 1988. In the report, Fagbenle and Karayiannis specifically mentioned that average wind speeds in Nigeria range from about 2 m/s to about 4 m/s with highest average speeds of about 3.5 m/s and 7.5 m/s in the southern and northern areas respectively. Most recent study by Fadare (2010) applied Artificial Neural Networks (ANN) to predict wind speeds distribution across Nigeria and compared the predicted wind speeds with measurements data from 28 stations that span between 1983 and 2003. This analysis predicted monthly average wind speed ranging from minimum of 0.8 m/s for Ondo (south region) to maximum value of about 13.1 m/s for Kano (north region) with both values occurring in December. The overall average annual wind speed of 4.7 m/s was predicted for Nigeria. (Fadare, 2010).

Finally according to an extensive Federal Government sponsored survey by Lehmeyer International Consultants carried out in 2004, wind energy reserve in Nigeria at 10m height based on data analyzed for ten wind stations cutting across North West, North East, North Central, South East and South West geopolitical zones shows that some sites have wind speeds between 1.0 m/s and 6.3m/s depending on the particular stations, and confirms that Nigeria falls into the moderate wind regime.

Table 2.2 shows data of wind energy resources mapping for ten (10) sites in Nigeria including Sokoto collected from ground measurement carried out between May 2004 and May 2005 by Lehmeyer International. It can be seen from the table that the sites are potential wind farm areas. This is because most wind turbines start generating electricity at wind speeds of around 3-4 meters per second (m/s).(Agbetuyi et al, 2012).

Table2.2. *Lehmeyer Consultants Measurement of Wind Speed at Various Stations*

SITE ID	SITE NAME	Mean Wind Speed at 30m Height (m/s)
Sok 01	Sokoto/Badaga	5.4
Jos 01	Jos Plateau /Kassa	5.2
Gem 01	Gembu/Mambila plateau	5.0
Pan 01	South part of Jos plateau/Pankshin Hotel	5.0
Kan 01	Kano/ Funtua	4.9
Mai 01	Maiduguri/mainokc	4.7
Lag 01	Lagos/ Lekki Beach	4.7
Enu 01	Enugu/Nineth mile corner	4.6
Gum 01	Gombe Station	4.1
Ibi 01	Ibi Meterological Station	3.6

(Wind Energy Potential in Nigeria, 2012)

Wind turbines are of two types depending on the axis of rotation.these include horizontal axis wind turbine (The H.A.W.T) and vertical axis wind turbine (The V.A.W.T)

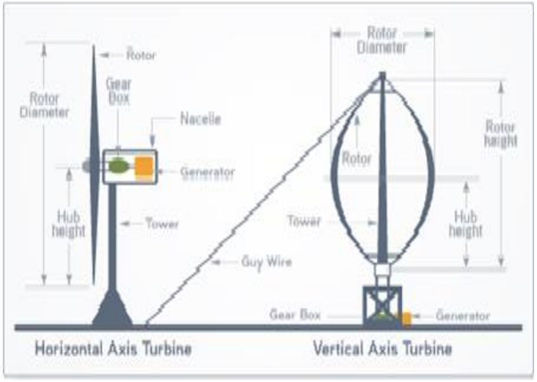

Figure2.1. *wind turbine types Source:http://www. hillcountrywindpower.com/wind-basics.php*

The horizontal axis wind turbine has its rotor's axis of rotation parallel to the ground and the wind stream. They are generally used as commercial grid connected wind turbines built with a propeller type rotor and are mostly made of three or two blades that are designed to catch as much energy as possible from the wind. The blade is designed in a way (air-foiled shape) such that a more pressure point generates at its lower side as the wind passes over it. The difference in pressure between the upper and lower sides of the blade results in an aerodynamic lift. Because the loads are restricted to a centre point, the aerodynamic lift results in a rotary movement about the horizontal axis. The diagram demostrates the effect. (Fahad, 2012).

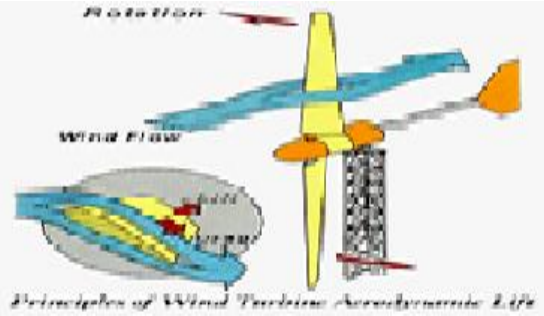

Figure2.2. *Principles of wind turbine aerodynamic control*

Source: *http://www.daviddarling.info/encyclopedia/ H/AE_horizontal-axis_wind_turbine.html*

The HAWT is generally classed to be more efficient and a more reliable type of wind turbine due to its inherently high power coefficient (Bharanikumar et al, 2012). But this only applies to places where the wind is stable and of a relative uniform speed. And because the area of implementationis assumeed to be having low and unsteady winds, the HAWT may not be the best fit.

VAWT rotates about a vertical axis. Through vertically mounted blades a lift is created which causes rotary movement on the turbines. VAWTs are of three types;Darrieus vertical axis wind turbine (having curve shaped blades), Giromill vertical axis wind turbine (having straight blades) and Savonius vertical axis wind turbine (having scoop shaped blades). Savonius vertical axis wind turbine are mostly found in homes and small scale application while darrieus and giromill vertical axis wind turbines are used for large scale production.

Asynchronous Generators

Asynchronous generators generally known as induction generators produce electrical power when their rotor is turned faster than the rated synchronous speed. The figure below shows a cross section of an induction generator that has a squirrel cage type rotor (Fahad, 2012).

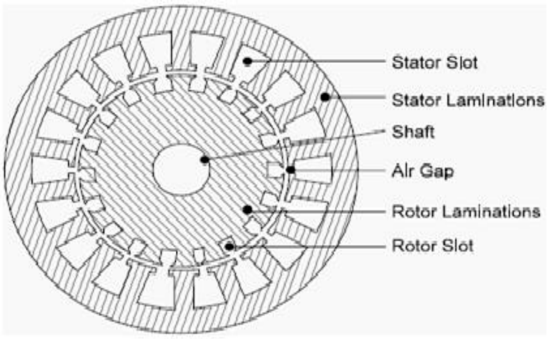

Figure2.3. *Cross-section of asynchronous generator with squirrel cage rotor (http://electrical-engineering-portal.com)*

Synchronous speed is the rate of rotation of the magnetic field on the stator. The speed of the rotor of these generators is made to never match the synchronization speed, hence the name asynchronous. No current will be induced if both speeds match. The stator requires an excitation current initially from a separate electrical source that will help produce the magnetizing flux. The magnetizing flux induces current into the normally short-circuited rotor and their interaction produces voltage at the stator end. The excitation current, its magnitude and frequency is determined by a closed loop control system (Raju et al, 2003). The close loop system adjusts the excitation current so as the generator to give out constant voltage regardless of the variations of speed and load current.

Synchronous Generators

These are generators that operate as synchronous speed hence the name synchronous generators; the speed of the rotors matches the supply frequency of the generators. The figure below shows the cross section of a synchronous generator.

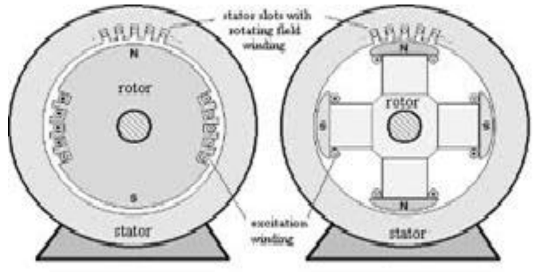

Figure2.4. *Cross section of a synchronous generator*

Source: *http://www.user.tuberlin.de/h.gevrek/ordner/ilse/wind/wind5e.html*

The synchronous generators are the most widely used source of electrical energy in the world. These generators can be used to generate large power ratings of up to a thousand megawatt. The synchronous generator has its rotor mounted on the shaft that is to be driven by a mechanical mover, the rotor being a ferromagnetic material produces a constant magnetic field from a field winding that carries DC current (Hong-Geuk et al, 2007). The number of the field windings could be increased depending on the number of poles required. As the rotor rotates, the magnetic field cuts pass the stationary windings on the stator which is also made of ferromagnetic materials; this action induces voltage into the windings. The electrical frequency of the induced voltage depends on the mechanical speed of the rotor and the number of poles it has. Synchronous generators are constructed with either a salient pole rotor or a wound rotor depending on the type of application. The salient pole rotor generators are mostly for low speeds applications while the wound/cylindrical rotor generators are used for high speed applications (Fahad, 2012).

Wind Parameter Analysis Equations

Wind power

Theoretically, the power in the wind can be computed by using the concepts of kinetics. The wind mill works on the principle of converting kinetic energy of the wind to mechanical energy. The kinetic energy of any particle is equal to half its mass times the square of its velocity,

Kinetic Energy $=\frac{1}{2}mv^2$ (2.1)

Amount of Air passing is given by

m=pAv (2.2)

Where, m = mass of air trans versing, A=area swept by the rotating blades of wind mill type generator, ρ = Density of air, v= velocity of air. Substituting this value of the mass in expression

K.E=½pAv^3 (2.3)

Equation 2.2 indicates that the power available is proportional to air density (1.225 kg/m3) and it is proportional to the intercept area. Since the area is normally circular of diameter D in horizontal axis of the aero turbines then,

A=$\frac{\pi D^2}{4}$ (2.4)

Put this quantity in equation 2.4 then

Available wind power Pa=$\frac{1}{8}\pi D^2 v^3$ (2.5)

Equation 2.5 shows that the power available in the wind is directly proportional to wind velocity and wind blade diameter. The equation would also only hold true in an ideal situation with 100% efficiency of the generator design.

Over the years, experiments and surveys carried out by different groups of people as led to the generation of different mathematical expressions relating wind turbine parameters, environmental conditions and the wind power.

Vertical Extrapolation of Wind Speed

Wind speed near the ground changes with height; this requires an equation that predicts wind speed at any height in terms of the measured speed at another height. The most common expression for the variation of wind speed with height is the power law having the following form.

$$\left(\frac{v1}{v2}\right) = \left(\frac{h1}{h2}\right)^a \quad (2.6)$$

Where $v1$(m/sec) is the actual wind speed recorded at height $h1$(m), and $v2$(m/sec) is the wind speed at the required or extrapolated height $h2$ (m). The exponent a depends on the surface roughness and atmospheric stability numerically it lies in the range (0.05 to 0.5).

Wind Speed Probability Distribution

Wind speed data in time series format is usually arranged in frequency distribution format since it is more convenient for statistical analysis, therefore available time-series data were translated into frequency distribution format. Two of the commonly used functions for fitting measured wind speed probability distribution in a given location over a certain period of time are the Weibull and Rayleigh distributions. Weibull

Wind speed probability density function is given as $v, f_w(v)$during any time interval

$$f_W(v) = \left(\frac{k}{a}\right)\left(\frac{v}{a}\right)^{k-1} e^{-\left(\frac{v}{a}\right)^\wedge k} \qquad (2.7)$$

Where: k(m/s) is the Weibull scaling parameter and a is the dimensionless Weibull parameter.

The Ralyeigh $f_r(v)$ distribution is a special case of the Weibull distribution in which the shape parameter k is assumed to be equal to 2. From Equation (2.7) the probability density functions of Ralyeigh distribution is given as

$$f_r(v) = \left(\frac{2v}{a^2}\right) e^{-\left(\frac{v}{a}\right)^\wedge 2} \qquad (2.8)$$

Wind Power Density Function

Evaluation of wind power per unit area is of fundamental importance in assessing wind power projects; it is well known that power of wind at speed V through the blade sweep area A increases as the cube of its velocity and is given by

$$P_v == \frac{1}{2} pAv^3 \qquad (2.9)$$

Where p(kg/m3) is the mean air density, the value 1.069 kg/m3 is used in this work. This depends on altitude, air pressure and temperature. The expected monthly or annual wind power density per unit area of a site based on a Weibull probability density function can be expressed as follows

$$P_W = \frac{1}{2} pa^3 G\left(1 + \frac{3}{k}\right) \qquad (2.10)$$

Where: G is the gamma function and a is the Weibull scale parameter (m/s) given by:

$$P = \frac{V_m}{G\left(1 + \frac{1}{k}\right)} \qquad (2.11)$$

The two significant parameters k and a, are closely related to the mean value of wind speed V_m. By extracting a from Equation (2-8) and setting k equal to 2, power density for Rayleigh model is found to be

$$P_r = \frac{3}{\pi} pV_m \qquad (2.12)$$

Where

$$V_m = aG\left(1 + \frac{1}{2}\right) \qquad (2.13)$$

The errors in calculating the power densities using the distribution models (Weibull and Rayleigh) in comparison to values of the Probability density distributions derived from measured values can be found using equation 2.14.

$$\text{Error\%} = \frac{P_{w.r} - P_{m.r}}{P_{m.r}} \qquad (2.14)$$

Where $P_{w.r}(W/m^2)$ is the mean power density calculated from either the Weibull or Rayleigh function used in the calculation of the error, and $P_{m.r}(W/m^2)$ is the wind power density for the probability density distribution, derived from measured values which serves as the reference mean power.

DESIGN METHOD

Wind turbine generator system is modeled analogous to an electrical embedded system. It comprises of three masked subsystems which together form the wind turbine generator system. These include wind turbine subsystem, drive train subsystem and permanent magnet synchronous machine all modeled in Matlab/ Simulink environment

Wind Turbine Subsystem

Wind turbine extracts a portion of wind power (P_{wind}) from the swept area of rotor disc and converts it into mechanical power (P_m) as determined in equation 3.1.

$$P_m = \frac{1}{2} . \rho . A . \omega_{wind}{}^3 . C_p \qquad (3.1)$$

Where: ρ is air density (approximately 1.225 kg/m^3), A is swept area of the rotor in (m^2) and ω_{wind} is free wind speed in (m/s).

The power coefficient (C_P< 0.593) can be maximized for a given wind speed by optimally adjusting the values of tip speed ratio and the blade pitch angle.

In this study, optimal choice of C_P for a given wind speed is determined. According to Betz’s law, no wind turbine can capture more than 59.3% of wind kinetic energy. Betz’s coefficient (also called power coefficient C_P) of a wind turbine is the ratio of maximum power obtained from the wind to total power available in the wind and it is equal to 0.593. This implies that the best C_p most likely to be obtained in a wind turbine is 0.593 but in practice this value will be further whittled down due to further losses (Adigun et al, 2010). Factors that will affect turbine efficiency include gravitational stress, air density and so on. The ratio between the tip speed ratio ƛand the rotor angular speed $w_m(rads^{-1})$ is given as

$$ƛ = \frac{w_m R}{U_w} \qquad (3.2)$$

Thus,

$$w_m = \frac{ƛU_w}{R} \qquad (3.3)$$

Where R is wind turbine radius in meters (m), U_w is wind speed in m/s. The relationship between mechanical torque T_m and mechanical power P_m is given in the equation 3.4 (Ahmad et al,2006):

$$T_m = \frac{P_m}{w_m} \tag{3.4}$$

By combining equations 3.1 and 3.4 mechanical Torque T_m is given as

$$T_m = \frac{1}{2} C_t pARU_w{}^2 \tag{3.5}$$

Where C_t is the torque coefficient and it is as shown in equation 3.6

$$C_t = \frac{C_p}{\lambda} \tag{3.6}$$

From equations 3.1 and 3.5 it can be seen that the mechanical power is proportional to the cube of wind speed, while the mechanical torque is proportional to square of wind speed.

Thus the turbine's operation is at its peak in tracking mode, but the mechanical torque delivered is not at its highest. The wind turbine subsystem was built using dynamic model equations developed (3.1-3.6). The model design was done using Matlab/Simulink and masked after the system blocks were set in order to ease assigning of variables. These variables include wind turbine swept area A, air density p and radius of turbine R. The masked system of the wind turbine has one output (mechanical torqueT_m), and two inputs (wind speed U_w and the angular speed w_m of the generator). Figure 3.1 shows the masked model of the wind turbine system.

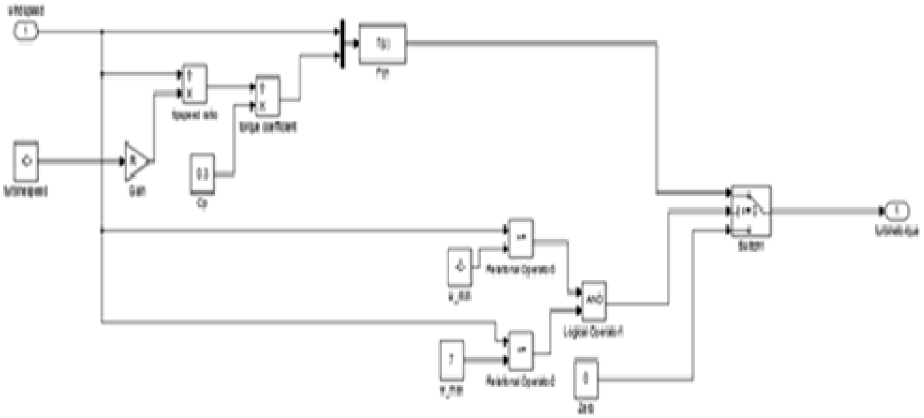

Figure3.1. *Wind turbine subsystem Matlab model*

Drive Train Subsystem

The second subsystem in the wind power plant system is the drive train. This ensures transmission of mechanical torque from the turbine to the generator. The drive train is a mechanical system that basically shows the interconnection of both the turbine and generator rotors by a shaft. It also shows the actions of the frictional damping and stiffness due to inertia which impedes rotational acceleration while the gear box amplifies the speed of rotation. In magnitude, the effect of the gear box is represented as gear box ratio which is a ratio of rotor speed to turbine speed. Depending on the level of accuracy required in a drive train model, four drive train models exist. These include six, three, two and one mass models.

Starting from the six-mass model of a wind turbine drive train, the three, two and one mass models are derived by making the proper assumptions, lumping together some parameters of interconnecting systems and neglecting limiting parameters.

Two Mass Model

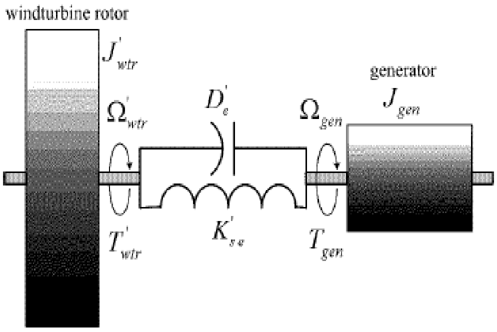

Figure3.2. *Two mass drive train system (VlastimilSantin, 2011).*

The equations representing the two-mass model are shown in 3.7 and 3.8 respectively.

$$T_{wtr} = J_{wtr} * \frac{d\Omega_{wtr}}{dt} + D_e * \left(\Omega_{wtr} - \frac{\Omega_{gen}}{k_p}\right) + k_e\left(\theta_{tur} - \frac{\theta_{gen}}{k_p}\right) \tag{3.7}$$

$$-T_{gen}k_p{}^2 = J_{gen}k^2{}_p * \frac{d\Omega_{gen}}{d_t} - D_e * \left(\Omega_{wtr}k_p - \Omega_{gen}\right) - k_e * \left(\theta_{tur}k_p - \theta_{gen}\right) \tag{3.8}$$

Where J_{wtr}= moment of inertia of turbine, J_{gen}=generator moment of inertia,k_e =shaft stiffness, b_e=shaft damping coefficient,k_p=gear ratio,Ω_{wtr}=wind turbine speed,Ω_{gen}=generator speed,θ_{gen}=generator rotor angular displacement, θ_{tur}=turbine rotor angular displacement, T_{wtr}=turbine torque,T_{gen}=generator torque

The modeling and implementation of the sub-system in Matlab/Simulink is shown in figure 3.3.

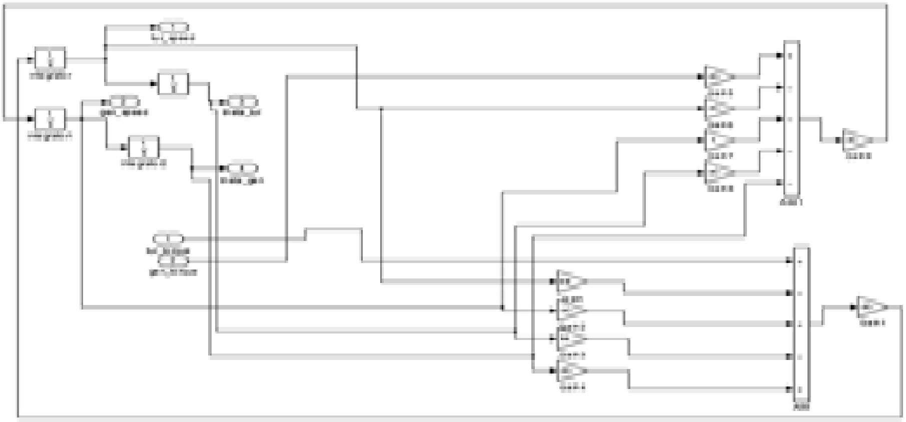

Figure3.3. *Two mass drive train system Matlab model*

One Mass Model

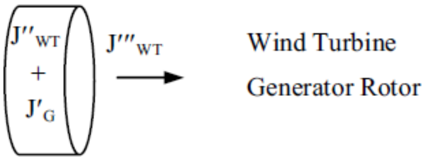

Figure3.4. *One mass drive train system (Mayeen et al, 2009).*

In the one mass model, all types of wind turbine drive components are lumped together and it is assumed to work as a single rotating mass. The dynamic behavior can be represented by the following differential equations (3.9-3.11) respectively.

$$T_{gen} - T_{wtr}'^{.} = J_{ech}\frac{d\Omega_{gen}}{d_t} \qquad (3.9)$$

Where

$$J_{ech} = J_{gen} + \frac{J_{wtr}}{{k_p}^2} \qquad (3.10)$$

$$T_{wtr}'^{.} = \frac{T_{wtr}}{{k_p}^2} \qquad (3.11)$$

This model forms the second subsystem of the design. The implementation of this subsystem is Matlab/Simulink is shown in figure 3.5

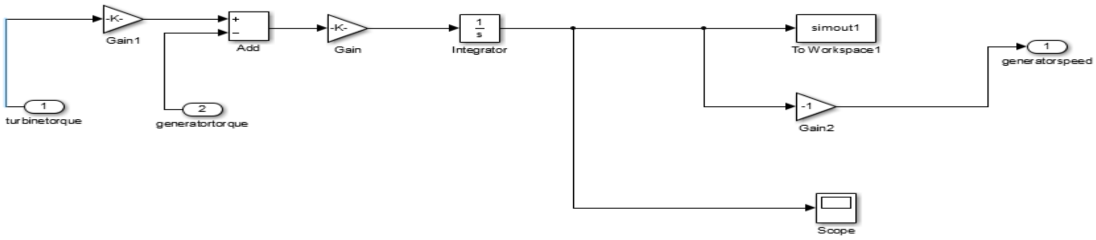

Figure3.5. *One mass drive train Matlab system*

3 Φ Permanent Magnet Synchronous Generator (PMSG) Sub System

Permanent magnet synchronous generator (PMSG) has been considered as the system which makes it possible to produce electricity from mechanical energy obtained from the wind. The stator of PMSG used consist of cylindrical laminated core with slots containing delta connected three phase winding. PMSG block receives mechanical torque as input and produces electrical current as output. Hence, there must be an electro-mechanical phenomenon combining the electrical and mechanical systems. This phenomenon is best described by swing equation.

The swing equation is the basic mathematical relation describing how the rotor of a synchronous machine will move (swing) when there is an imbalance between mechanical power fed into the machine and the electrical power fed into the machine and the electrical power extracted from it. Considering a synchronous generator with electromagnetic Torque T_e running synchronous speed ω_m, i.e. mechanical angular speed of the rotor;

- During normal operation, mechanical torque T_m(Nm) is equal to electromagnetic torque. T_e(Nm) (i.e. $T_m = T_e$).
- Disturbance will result to an accelerating/ decelerating torque T_a

$$T_a = T_m - T_e \qquad (3.12)$$

Where, $T_a > 0$ for accelerating torque and $T_a < 0$ for decelerating torque. The differential equation describing the rotor dynamics is given in equation 3.13-3.15 (Pranamita and Aiswarya, 2009):

$$J\frac{d^2\theta_m}{dt^2} = T_a = T_m - T_e \qquad (3.13)$$

Where: J is the total moment of inertia of the rotor mass (kgm^2),θ_m is rotor mechanical angular position (rad)

$$J\frac{d\omega_m}{dt} = T_a = T_m - T_e \qquad (3.14)$$

Where,

$\omega_m = \frac{d\theta_m}{dt}$ and $\frac{d\omega_m}{dt} = \frac{d^2\theta_m}{dt^2}$,$\theta_e = \rho\theta_m =$ electrical angle (elect.rad),$\omega_e = \frac{d\theta_e}{dt} = p\omega_m =$ electrical rotating speed $(rads^{-1})$

p= Number of pole pairs.

$$T_e = 1.5p\left(\left(L_d - L_q\right)i_d i_q + i_q\lambda_0\right) \qquad (3.15)$$

Assuming inductances on d and q axis are equal (i.e.$L_d = L_q$), the electromagnetic torque can be expressed as

$$T_e = 1.5p(i_d i_q + i_q\lambda_0) \qquad (3.16)$$

Electrical analysis of three phase PMSG was done using equivalent circuit that has been derived from the two-phase synchronous reference frame (dq reference), in which the q-axis is with respect to the direction of rotation (Yin *et al*,2007). The transformation between dq rotating reference frame and abc three phase frame is maintained by the expressions known as Park's transformation equation.

PARK'S TRANSFORMATION (ELECTRICAL ANALYSIS)

Park's transformation is a phase transformation (coordinate transformation) between the three physical phases or coordinates that are convenient for the analysis of synchronous machines. This transformation is also known as the dq transformation. The Park's transformation equation is given in the form:

$$\begin{bmatrix} f_q \\ f_d \\ f_0 \end{bmatrix} = \left[T_{qdo}\right]\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \qquad (3.17)$$

Where f can be current (I), voltage (V) or flux (λ),T_{qdo} is given by (Ece,2004) as

$$[T_{qdo}(\theta_e)]= \frac{2}{3}\begin{bmatrix} \cos\theta_e & \cos(\theta_e - \frac{2\pi}{3}) & \cos(\theta_e + \frac{2\pi}{3}) \\ -sin\theta_e & -\sin(\theta_e - \frac{2\pi}{3}) & -\sin(\theta_e + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \qquad (3.18)$$

Where θ_e is electrical angle.

After analysis under Park's transformation d-q reference frames, it would be necessary to convert back to three phase system for a more definitive result. The inverse Park's transformation is used in transforming vector components from dq reference frames to abc frames. The inverse Park's transformation is given in equation 3.19 (Ece, 2004).

$$[T_{qdo}(\theta_e)]^{-1} = \begin{bmatrix} cos\theta_e & -\sin\theta_e & 1 \\ \cos(\theta_e - \frac{2\pi}{3}) & -\sin(\theta_e - \frac{2\pi}{3}) & 1 \\ \cos(\theta_e + \frac{2\pi}{3}) & -\sin(\theta_e + \frac{2\pi}{3}) & 1 \end{bmatrix} \qquad (3.19)$$

Where θ_e is the electrical angle. Thus, the inverse Park's transformation equation is given in the form:

$$\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} = [T_{qdo}(\theta_e)]^{-1}\begin{bmatrix} f_q \\ f_d \\ f_0 \end{bmatrix} \qquad (3.20)$$

Where f can be equivalently be expressed as current (I), voltage (V) or flux (λ). The dynamic electrical model equation for PMSG in dq reference frame is given in equation 3.21 (Yin *et al*, 2007)

$$\frac{di_d}{dt} = \frac{1}{L_{ds}+L_{ls}}\left(-R_s i_d + \omega_e\left(L_{qs} + L_{ls}\right)i_q + V_d\right) \qquad (3.21)$$

$$\frac{di_q}{dt} = \frac{1}{L_{qs}+L_{ls}}\left(-R_s i_q - \omega_e[(L_{ds} + L_{ls})i_d + \lambda_0] + V_q\right. \qquad (3.22)$$

Where:R_s is stator resistance (Ω),L_d and L_q are inductances of the generator on d and q-axis (H),L_{ld} and L_{lq} are leakage inductances of the generator d and q-axis (H),λ_0 is permanent magnetic flux (Wb),ω_e is electrical rotating speed $(rads^{-1})$,i_d and i_q are currents flowing through the d and q-axis (A),V_d and V_q are voltages across the load in the d and q-axis (V)

Using equations 3.14, 3.18, 3.21, 3.22, 3.19 and 3.16, PMSG model is implemented in Matlab/Simulink environment and it is shown in figure 3.7. For this work however, an inbuilt

Permanent Magnet Synchronous Machine in MATLAB SIMULINK library was used. To enable the machine to run as a generator, the input to the machine was negated thus indicating that it was not to run in motor mode. This model forms the third subsystem of the design.

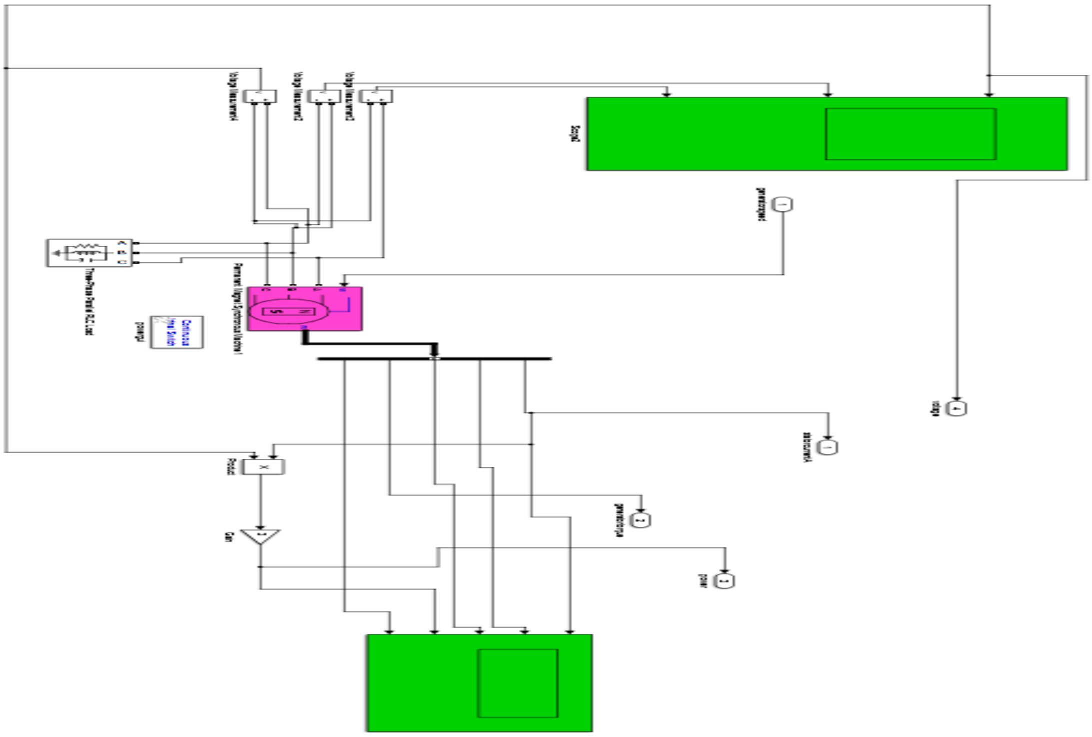

Figure3.7. *PMSG subsystem Matlab model*

A 3ϕ RLC load is connected to the PMSG in parallel. Voltage measurement blocks are connected across the load point terminals and the output voltage of the generator is measured. Stator current per phase is measured from the PMSG block output segment as shown in figure 3.9 while the model of wind turbine closed loop system is shown in Figure 3.9. The three-phase electromagnetic power output of the generator is then computed. $P = 3I_LV_L$ (3.23)

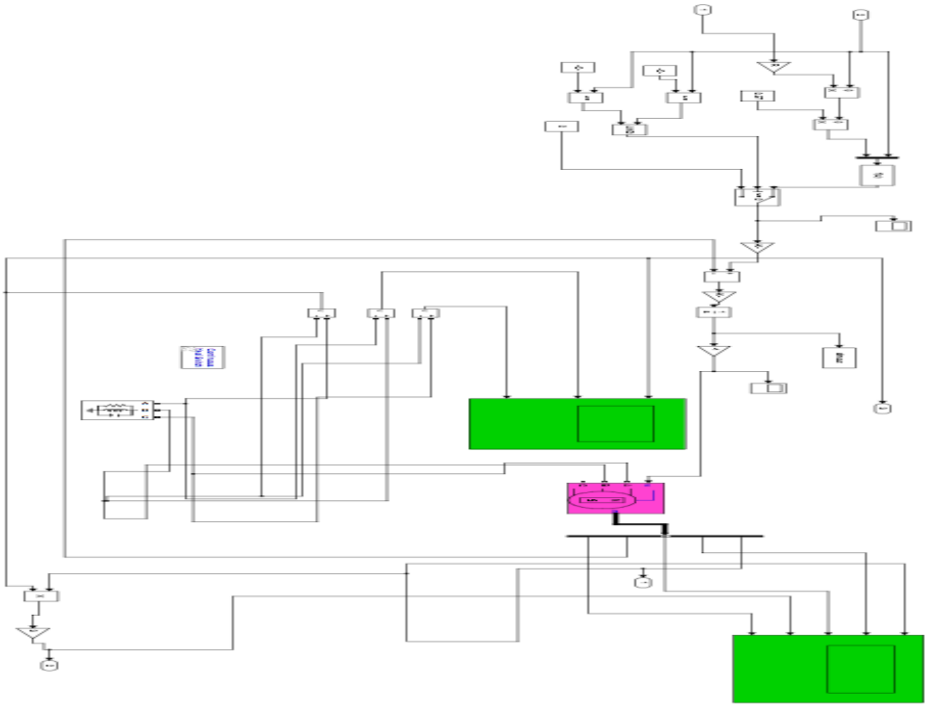

Figure3.8. *Wind turbine generator matlab model*

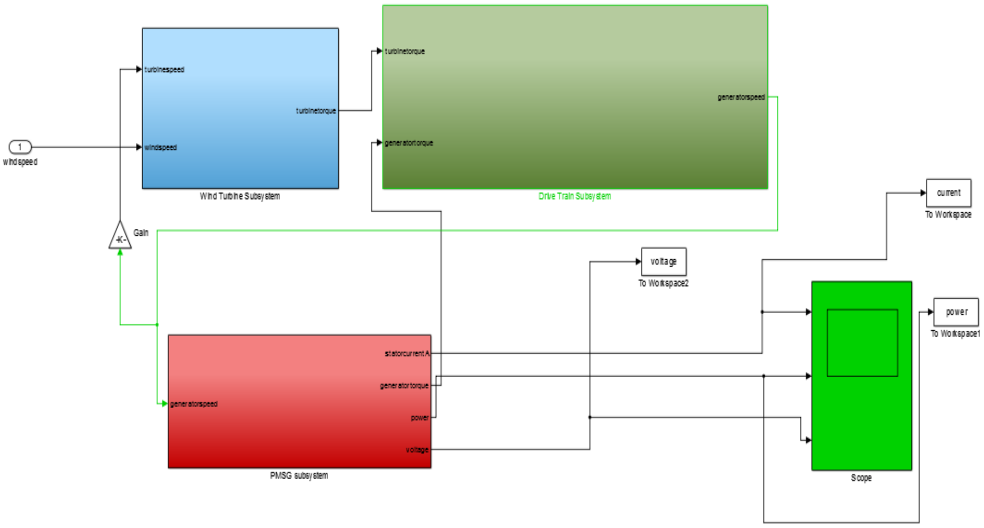

Figure3.9. *Wind turbine closed loop system Matlab model*.

Wind turbine parameters, drive train parameters and PMSG parameters are shown in the Table 3.1.

Table3.1.*Modeling Parameters*

Symbol(unit)(Unit)	**Quantity**	**Value**	**Symbol (unit)(Unit)**	**Quantity**	**Value**
Cp(-)	Power Coefficient	0.57	**jtur(kgm^2)**	Turbine Inertia	0.75
R(m)	Blade Radius	1.5	**Rs(ohm**	Stator Phase Resistance	0.425
P(kg/m^3)	Air Density	1.225	**Lq(H)**	Inductance	0.000835
A(m^2)	Blade Interaction Area	7.071	**Ld(H)**	Inductance	0.000835
w_min(m/s)	Minimum wind speed	2	**M.F (V.s)**	Magnetic Flux	1.0825
w_max(m/s)	Maximum wind speed	10	**(V_peak l-l/krpm)**	Voltage Constant	392.6876
kp(-)	Gear Ratio	8	**(N.m-A_peak)**	Torque Constant	3.2475
jgen(kgm^2)	Generator Inertia	0.23	**P**	Pole pairs	2
			ϕ	Power Factor	1

RESULTS AND DISCUSSION

The results are in form of dynamic simulations of currents and voltages of stator as well as for three phase electromagnetic power. The results are analyzed for various wind speeds achievable in Nigeria. Appendix C shows the average wind speed distribution in Nigeria. The wind turbine setup works in a close loop manner which means that change in any parameter or block within the model will affect the system's response in all parts. The simulation is run for 50 seconds which allows for adequate time to observe the transient and steady state of the output voltage, stator current and power of the generator. Using the scope block in the MATLAB Simulink library, these quantities are observed in real time.

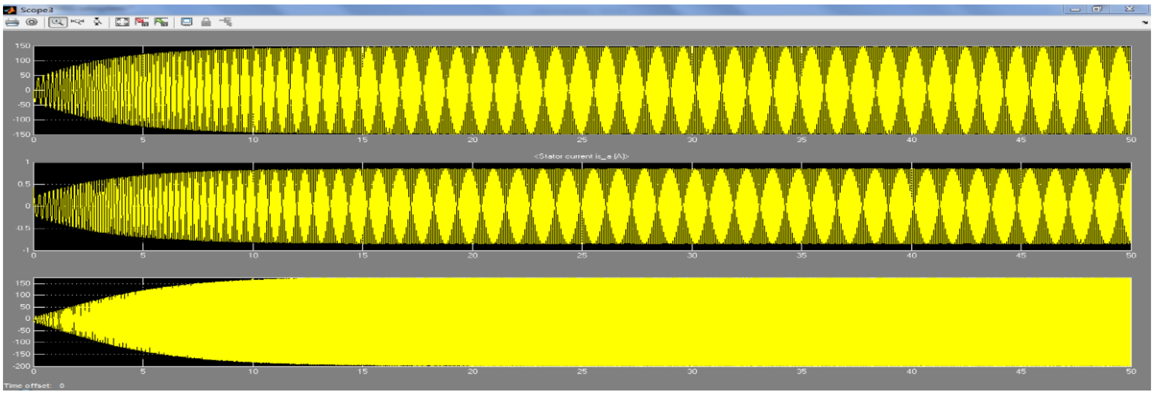

Fig4.2. *Scope Block Simulation Results*

The minimum wind speed is the speed available in Nigeria and from the investigation it is expected to be 2m/s. The results of the simulation at this wind speed are shown in figure 4.3.

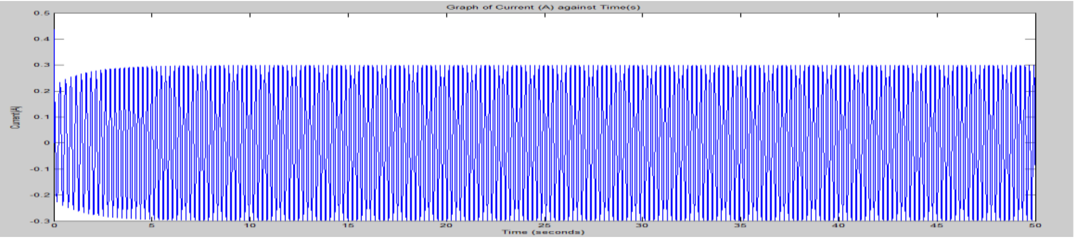

Fig4.3. *Graph of Stator Current (A) against time(s)*

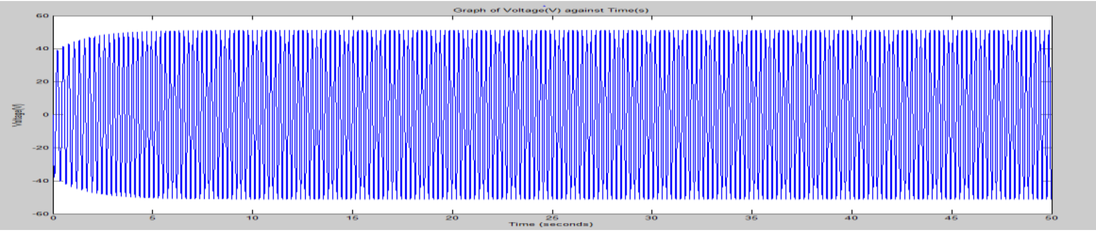

Fig4.4. Graph of Voltage (V) against time(s)

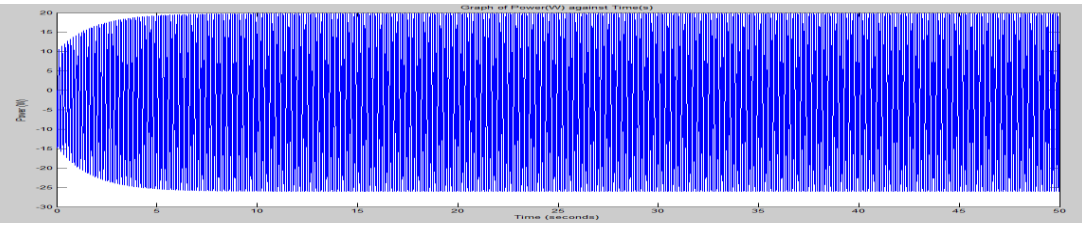

Fig4.5. Graph of Power (W) against time(s)

The mean wind speed is the average wind speed available in the geographical location of the area under study.

From the research, mean wind speed available in Nigeria is 6m/s. the simulation results at this speed is shown in figure 4.6.

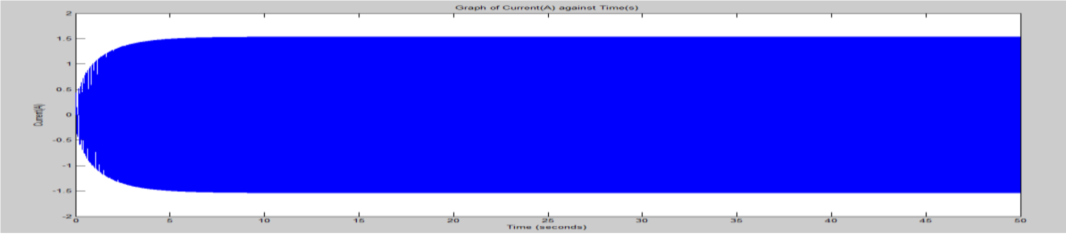

Fig4.6. *Graph of Stator Current(A) against time(s)*

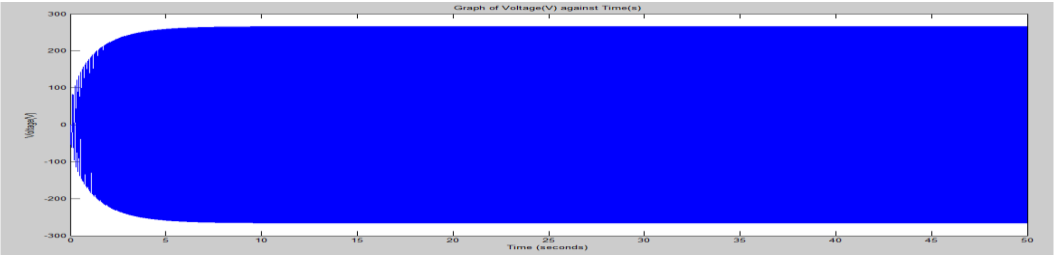

Fig4.7. *Graph of Voltage (V) against time(s)*

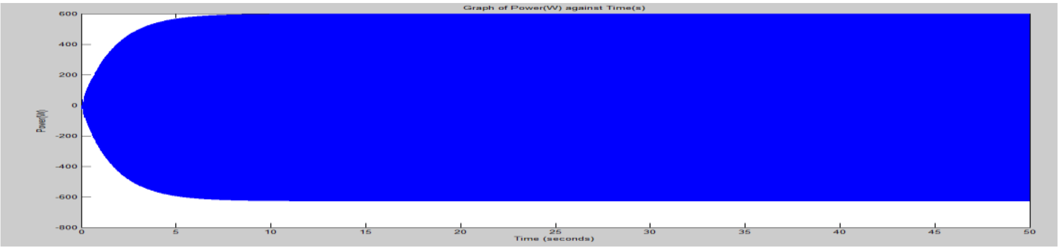

Fig4.8. *Graph of Power(W) against time(s)*

MAXIMUM WIND SPEED

The maximum wind speed expected in the geographical location of this work from the research is expected to be 10m/s. The simulation results at this wind speed are shown in figures 4.9-4.11;

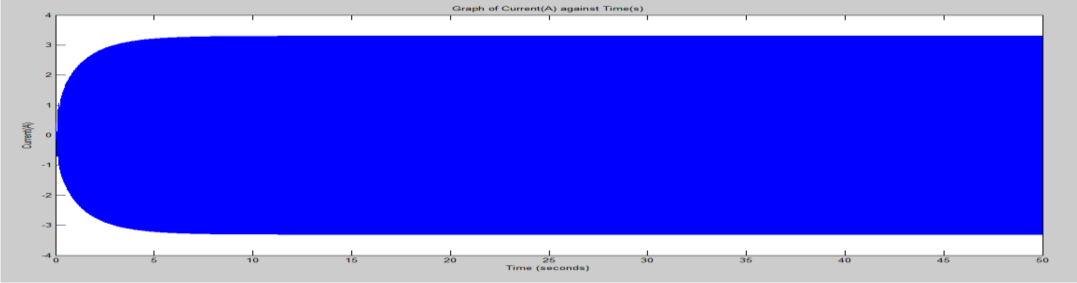

Fig4.9. *Graph of stator Current(A) against time(s)*

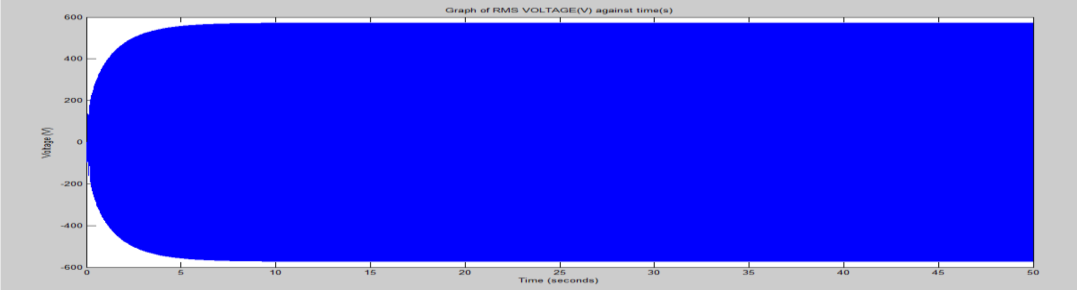

Fig4.10. *Graph of Voltage (V) against time(s)*

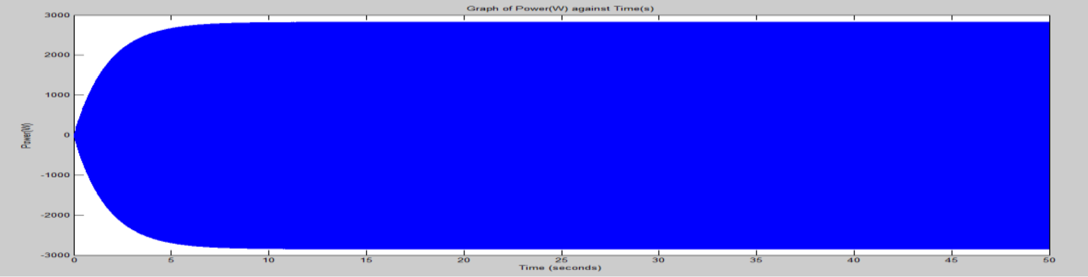

Fig4.11. *Graph of Power (W) against time(s)*

Table4.2. *Simulations Results (Rms)*

Wind Speed(m/s)	Current(A)	Voltage(V)	Power(W)
2	0.2093	35.9097	16.2624
4	0.5822	100.7472	125.6270
6	1.0678	184.9240	422.5444
8	1.6435	284.6739	1000.9
10	2.2966	397.850	1945.5

Results shown in table 4.2 indicated that as wind speed increases, voltage as well as output power increases as analysis were done for various wind speed ranging from 2m/s to 10m/s. Furthermore, from the research findings in the course of the investigation, the following were deduced:

- Nigeria is one of the geographical locations with low and unsteady wind speed. The average wind speed distribution of Nigeria, which can be very difficult to deduce due to the irregular pattern of wind flow has been deduced to be 6m/s but this wind speed is still low for an efficient operation of a wind turbine.
- Horizontal axis wind turbine will not be suitable for operation in Nigeria. It requires a high and steady wind speed due to its orientation and nature of design and hence cannot generate sufficient amount of current, voltage and power for electricity generation under low and unsteady wind speed.
- A vertical axis wind turbine will be more suitable and efficient for Nigeria. It can generate sufficient amount of current, voltage and power for electricity generation under low and unsteady wind speed due to its orientation and nature of design.

CONCLUSION AND RECOMMENDATION

Embarking on this project became a necessity because of the following reasons: slow pace of economic growth of the nation due to lack of electricity, majority of the country's population is not connected to the grid network, high production cost as a result of fossil fuel purchasing, generator sets are unfriendly to the environment as it constitute noise as well as noise pollution in form of carbon mono-oxide and also contribute to the depletion of the ozone layer. The objective of this project is to research, model and investigate the responses of a wind turbine with permanent magnet synchronous generator which generates a sufficient amount of current, voltage and power for electricity generation under low and unsteady wind speed. At the end of this project, the following goals have been met;

- The wind turbine system designed in paper generates three phase current whose rms values ranges from 0.2093 to 2.2996 for relatively low wind speeds ranging from 2m/s to 10m/s. These values of the generated current are sufficient for steady electricity generation.
- The wind turbine system designed generates three phase voltage whose rms values ranges from 35.9097 to 397.850 for relatively low wind speeds ranging from 2m/s to 10m/s. These values of the generated current are sufficient for steady electricity generation.
- The wind turbine system designed in this generates electromagnetic power whose steady state value ranges from16.2624 to1945.5 for wind speeds ranging from 2m/s to 10m/s. These values of electromagnetic power are sufficient for powering in house appliances.

RECOMMENDATION

Although wind turbine system design in this paper is a useful power generator, by implementing the following recommendation, the system could be transformed into one of the most versatile and efficient power generators available.

- Various methods and ways of minimizing cogging torque in the permanent magnet synchronous generator for enhanced performance must be applied.
- A suitable control mechanism for the wind turbine system to detect cut-in and cut-out wind speeds and carry out the necessary actions during these wind speeds is recommended. The most popular of the various techniques available is the pitch control technique which turns the blades towards the wind or away from incoming wind in cases of wind speeds approaching cut in or cut out speeds respectively.

An appropriate interfacing converter between the three phase PMSG of the wind turbine system and the grid. The interfacing converter rectifies the input AC (the output of three phase PMSG) with variable voltage and frequency, adjusts voltage levels and inverts DC voltage into AC with grid

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- A battery bank can be incorporated for the storage of energy which could be used when the turbine is not generating usable power. Additionally, it should have maximum power point tracking (MPPT) functionality to extract more power from wind.

For use of small-scale wind turbines in homes, an electronic control system, pitch angle control, 3 phase bridge diode rectifier, boost converter system, battery bank and inverter can be incorporated

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