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Modeling of a Vertical Axis Wind Turbine with Permanent Magnet Synchronous Generator for Nigeria

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ABSTRACT

The performances of a vertical axis wind turbine (VAWT) with permanent magnet synchronous generator (PMSG) under low and unsteady wind speed is investigated and Modelled in this paper. The ever increasing demand for electrical energy has led to the continuous search for the most readily available means of providing electricity. Wind turbine is an alternative source of electricity. To implement a wind turbine, careful and extensive investigation is required since different environments or geographical locations call for different wind speed. Nigeria is a typical example of locations with low and unsteady wind speed. The wind turbine system consists of three main parts; the wind speed, the turbine and the generator. A three phase PMSG is chosen in this work due to its higher efficiency and less need for maintenance when compared to other types of generators. It does not require rotor windings which imply a reduction of weight and cost. These elements and entire idea of this work have been modelled and simulated using MATLAB/ SIMULINK. Results obtained showed good system performance. The methodology used in this work, if fully implemented, will not only reduce the cost of design but will also reduce the cost of maintenance, making it economical and affordable.

Keywords: *Wind speed, Vertical Axis Wind Turbine (VAWT), Permanent Magnetic Synchronous Generator (PMSG), Matlab/ Simuiink*

1. INTRODUCTION

In the development of any economy, electricity is very important and this has led to the continuous search for the most readily available means of providing electricity. An alternative source of electricity is the Wind turbine. A wind turbine is a rotary device that extracts energy from the wind. The wind turbine converts kinetic energy from the wind, also called wind energy, into mechanical energy. If the mechanical energy is used to produce electricity, the device may be called wind turbine or wind power plant.

Wind as a natural resource is used in the production of electricity in wind turbines. The basics of this system employs the electromagnetic principle where the energy of the wind is used to turn turbines which then move magnets past stationary coils of wire known as the stator. AC electricity is produced as the magnets pass the stator (Bharanikuma et al, 2012). For a typical horizontal vertical axis wind turbine (HAWT) to run and generate power, a wind speed of at least 5m/s is required (Bharanikuma et al, 2012).The VAWT on the other hand is appropriate for such regions due to its ability to capture wind energy from any direction. Also, its way of design makes it possible to us magnetic suspension made of neodymium magnets (the strongest type of permanent magnet made from an alloy of neodymium, iron, and boron).Magnetic suspension is a near frictionless substitute for the conventional ball bearing system found in HAWTs used to offer rotational support to the rotor of the VAWT with little to no maintenance problem and consequently, reduces the cost of maintenance of the wind turbine (Heier, 1998). This will greatly reduce start-up wind speed of the Vertical Axis Wind Turbine.

The objective of this project was to model and investigate the responses of a vertical axis wind turbine with permanent magnet synchronous generator designed with neodymium magnetic suspension (magnetic suspension with zero friction) which generates more current and acquire sufficient amount of power for electricity generation under low and unsteady wind speed. The method used for the design and analysis of the proposed wind turbine system model in this paper is divided into three steps. The first step is modelling the dynamic equations of the wind turbine system. The second step is designing the wind turbine system model using the dynamic equations using Matlab/Simulink. The final step is carrying out the analysis of the designed wind turbine system under low and unsteady wind speed.

2. RELATED WORKS

Adigun et al (2010), in their project, carried out a study on the generation of electricity using a wind turbine. An analysis was carried out on a horizontal axis wind turbine designed for the environmental conditions of the University of Port Harcourt, Nigeria. The maximum power achievable was 322W at a wind speed of 10m/s from the result of analysis. This shows that a vertical axis wind turbine is more suitable for regions with low wind speed like Nigeria since it can attain a power range of 322W at a lower wind speed (5m/s to 6m/s).

Javier (2011), in his project, designed a small-scale vertical axis wind turbine rotor with solid wood as a construction material. “The aerodynamic analysis is performed implementing a momentum based model on a mathematical computer program. The results obtained indicate that wood is a suitable material for rotor construction and a further development of the computer algorithm is needed in order to improve the flow conditions simulation”. The blade aerodynamic analysis is a very important aspect of a wind turbines performance and should always be carried out before any design of a wind turbine system.

Sina and Mahyar (2011), in their paper studied maximum power control of wind turbine using permanent magnet synchronous generator connected with two back to back voltage source converters to grid. In this paper; “The machine currents are controlled by indirect vector control method. In this method, generator side converter controls the maximum excitation (air gap flux) by machine's d-axis current and controls generator torque by machine's q-axis current. Permanent magnet synchronous generator speed is controlled by tip speed ratio upon the wind speed variations to generate the maximum output power. Grid side converter regulates the DC link voltage and injective active power by d-axis current and regulates the injective reactive power by q-axis current using simple control method”. The P-Q Simulation results in the paper depicts that the proposed method operates properly. The control of a wind turbine working with varying speed using a converter model is very important when connecting the turbine to a grid. It should have a maximum power point tracking (MPPT) functionality to extract more power from wind.

3. DESIGN METHODOLOGY

WIND TURBINE: The wind turbine model is known as the aerodynamic model extracts power from the wind in the form of kinetic energy and then converts it into mechanical energy that is fed to the generator through a shaft. The aerodynamic power is given by the relation below (Ahmad et al, 2006).

$$P_m = \frac{1}{2} C_{p(\lambda)} \rho A U_w^{3} \quad (1)$$

Where,

ρ is the air density which is given by 1.225 kg/m^3 at normal temperature

U_w is the wind speed in meter per second (ms^{-1})

C_p is the power coefficient of the wind turbine

λ is the tip-speed ratio

A is the wind turbine swept area= $2RL$ (m^2)

R is the wind turbine rotor radius (m) and L is the length of the blade (m)

We shall use a generic equation of C_p as proposed by Heier (1998). The equation is expressed below as

$$C_p(\lambda, \vartheta) = 0.22\left(\frac{116}{\lambda_i} - 0.4\vartheta - 5\right) e^{-\frac{12.5}{\lambda_i}} + 0.0068\lambda_i \quad (2)$$

And

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\vartheta} - \frac{0.035}{1+\vartheta^3} \quad (3)$$

Where, ϑ is the pitch angle.

The relationship between of Coefficient of power and Tip-speed ratio is given below.

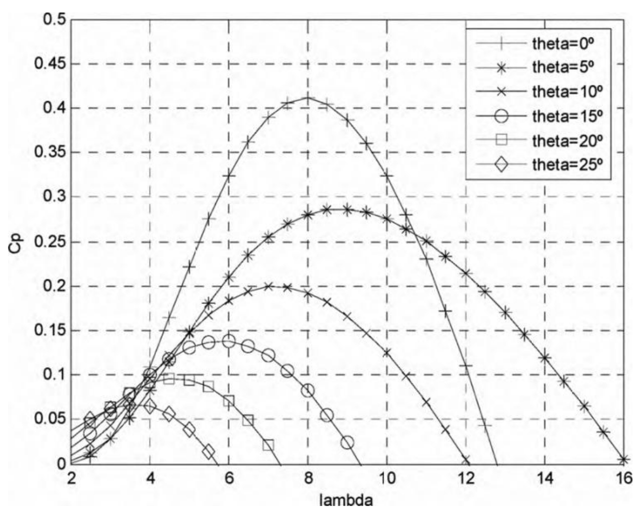


Figure 1: The graph of Coefficient of power (Cp) versus Tip-speed ratio (lambda)

The relationship between the tip-speed ratio λ and the rotor angular speed ω_m (*rads*$^{-1}$) is given as

$$\omega_m = \frac{\lambda U_w}{R} \quad (4)$$

Where R is the wind turbine rotor radius in meters (m)

The relationship between the mechanical torque T_m and the mechanical power P_m is given by the equation below (Ahmad et al, 2006):

$$T_m = \frac{P_m}{\omega_m} \quad (5)$$

By subsisting P_m from (1) and ω_m from (4) into (5), the mechanical torque T_m is given as

$$T_m = \frac{1}{2} C_t \rho A R U_w^{2} \quad (6)$$

Where C_t is the torque coefficient and is given below as

$$C_t = \frac{C_p}{\lambda} \tag{7}$$

Swing equation is the basic mathematical relation describing how the rotor of a synchronous machine will move (swing) when there is an unbalance between mechanical power fed into the machine and the electrical power extracted from it. The differential equation describing the swing is given below (Pranamita and Aiswarya, 2009):

$$J\frac{d^2\theta_m}{dt^2} = J\frac{d\omega_m}{dt} = T_a = T_m - T_e \tag{8}$$

Where,

$J =$ total moment of inertia of the rotor mass *(kgm*^{2})
T_m and $T_e =$ mechanical and electromagnetic torque (*Nm*)
$\omega_m = \frac{d\theta_m}{dt} =$ rotor angular speed (*rads*$^{-1}$)
$\theta_m =$ mechanical angular position of the rotor (*rad*)

THREE PHASE PERMANENT MAGNET SYNCHRONOUS GENERATOR: PMSG has been considered as the system which makes it possible to produce electricity from the mechanical energy obtained from the wind. The analysis of the PMSG is done using the dq rotating reference frame. The transformation between the dq rotating reference frame and the abc three phase frame is maintained by park transformation and park's inverse transformation given below (Ece, 2004).

$$\begin{bmatrix} f_q \\ f_d \\ f_0 \end{bmatrix} = [T_{qd0}] \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \tag{9}$$

And

$$\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} = [T_{qd0}]^{-1} \begin{bmatrix} f_q \\ f_d \\ f_0 \end{bmatrix} \tag{10}$$

Where f can be current (***I***), voltage (***V***) or flux (λ)

$$[T_{qd0}(\theta_e)] = \frac{2}{3}\begin{bmatrix} \cos\theta_e & \cos\left(\theta_e - \frac{2\pi}{3}\right) & \cos\left(\theta_e + \frac{2\pi}{3}\right) \\ -\sin\theta_e & -\sin\left(\theta_e - \frac{2\pi}{3}\right) & -\sin\left(\theta_e + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{11}$$

And

$$[T_{qd0}(\theta_e)]^{-1} = \begin{bmatrix} \cos\theta_e & -\sin\theta_e & 1 \\ \cos\left(\theta_e - \frac{2\pi}{3}\right) & -\sin\left(\theta_e - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta_e + \frac{2\pi}{3}\right) & -\sin\left(\theta_e + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \tag{12}$$

The dynamic electrical model equation for a PMSG in the dq reference frame is given below (Yin et al, 2007):

$$\frac{di_d}{dt} = \frac{1}{L_{ds}+L_{ls}}\left(-R_s i_d + \omega_e\left(L_{qs} + L_{ls}\right)i_q + V_d\right) \tag{13}$$

$$\frac{di_q}{dt} = \frac{1}{L_{qs}+L_{ls}}\left(-R_s i_q - \omega_e[(L_{ds} + L_{ls})i_d + \lambda_o] + V_q\right) \tag{14}$$

Where,

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

$$\omega_e = p\,\omega_m \tag{15}$$

Where p is the number of pole pairs of the generator and ω_m is the rotor angular speed (*rads*$^{-1}$)

Substituting $L_d = L_{ds} + L_{ls}$ and $L_q = L_{qs} + L_{ls}$ into eqs. (13) and (14), we have

$$\frac{di_d}{dt} = -\frac{R_s i_d}{L_d} + \frac{\omega_e L_q i_q}{L_d} + \frac{V_d}{L_d} \tag{16}$$

$$\frac{di_q}{dt} = -\frac{R_s i_q}{L_q} - \frac{\omega_e L_d i_d}{L_q} - \frac{\omega_e \lambda_o}{L_q} + \frac{V_q}{L_q} \tag{17}$$

If we assume that $L_d = L_q = L$, for surface mounted PMSG, eqs. (16) and (17) becomes

$$\frac{di_d}{dt} = -\frac{R_s i_d}{L} + \omega_e i_q + \frac{V_d}{L} \tag{18}$$

$$\frac{di_q}{dt} = -\frac{R_s i_q}{L} - \omega_e\left(i_d + \frac{\lambda_o}{L}\right) + \frac{V_q}{L} \tag{19}$$

The equivalent circuit for both d and q-axis derived from eqs. (18) and (19) are given below (Rolan et al, 2009):

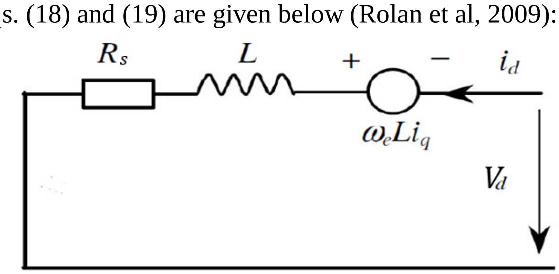


Figure 2: d–axis equivalent circuit

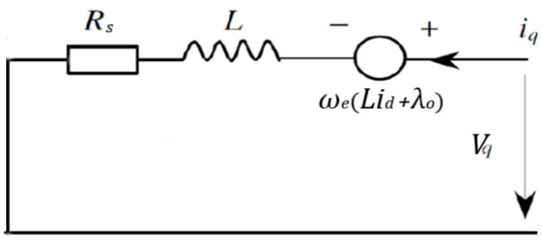


Figure 3: q–axis equivalent circuit

To complete the dynamic model of the PMSG, the mechanical equation is needed, and it is described by the electromagnetic torque equation given below (Rolan et al, 2009):

$$T_e = 1.5 p i_q \lambda_o \tag{20}$$

Where p is the number of pole pairs of the generator.

The relationship between the electrical frequency f_e (measured in hertz) and mechanical angular speed of the generator ω_m is given below:

$$f_e = \frac{p\omega_m}{2\pi} \tag{21}$$

Where,

ω_m =Rotor angular speed = $N \times \frac{2\pi}{60}$ (*rads*$^{-1}$)
p = Number of pole pairs of the generator
N =Mechanical angular speed of the generator in revolution per minute (*rpm*)

The relationship between flux and generate voltage of the PMSG is given below (Saifur and Manisa, 2010):

$$E_s = \frac{6}{\sqrt{2}} p \lambda_o \omega_m \tag{22}$$

Where,

E_s is the stator voltage (*Vrms/phase*)
p is the number of pole pairs of the generator
λ_o is the magnetic flux (*Wb*)

4. SIMULINK MODEL OF THE SYSTEM

The wind turbine model is shown in the figure below.

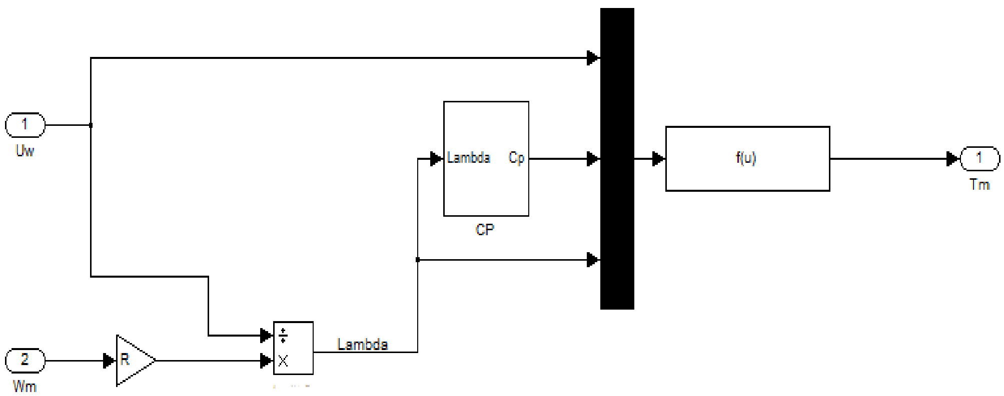


Figure 4: Wind turbine model

The internal architecture of the Cp block in the wind turbine model in figure 4 is shown below.

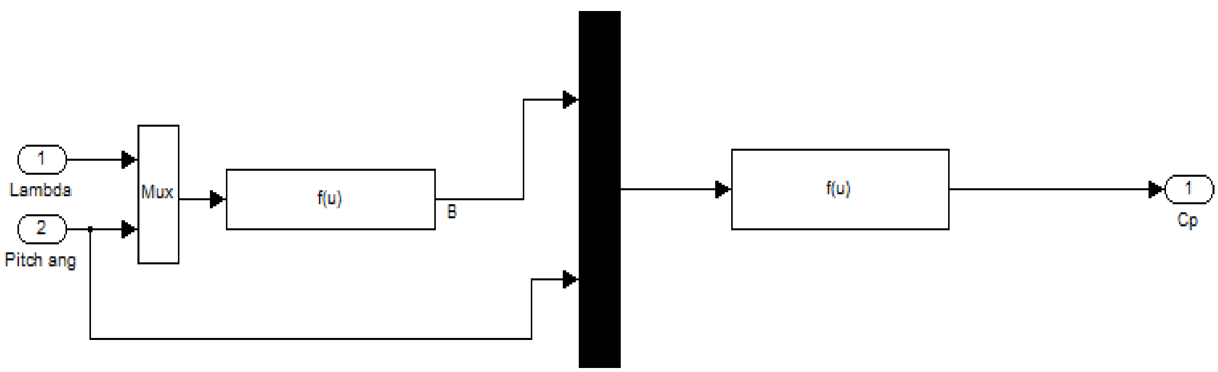


Figure 5: Coefficient of power, Cp calculation Model

The three phase PMSG model is shown in the figure below.

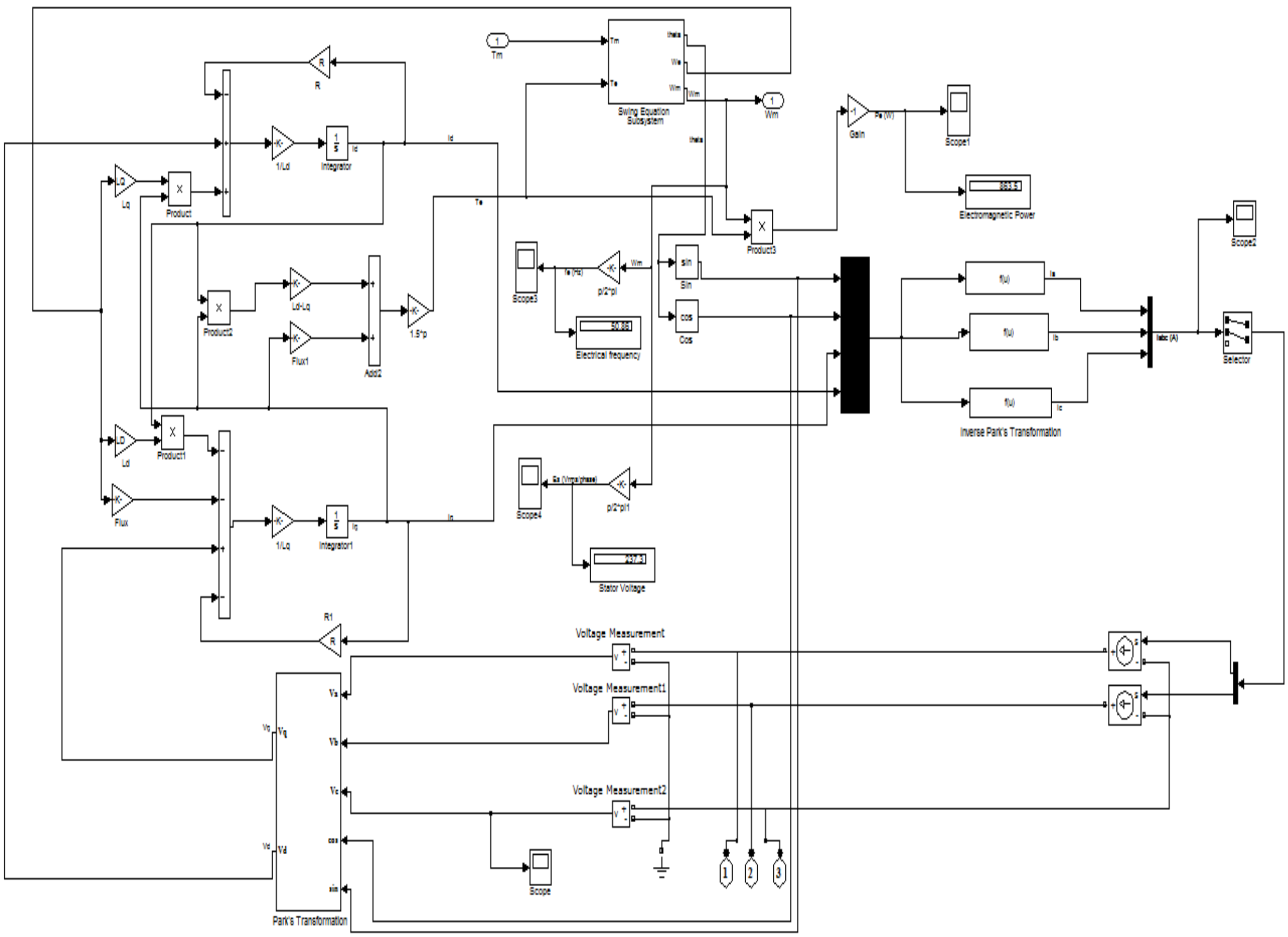


Figure 6: Three phase PMSG model

The internal architecture of the swing equation block in the three phase PMSG model in figure 6 is shown below.

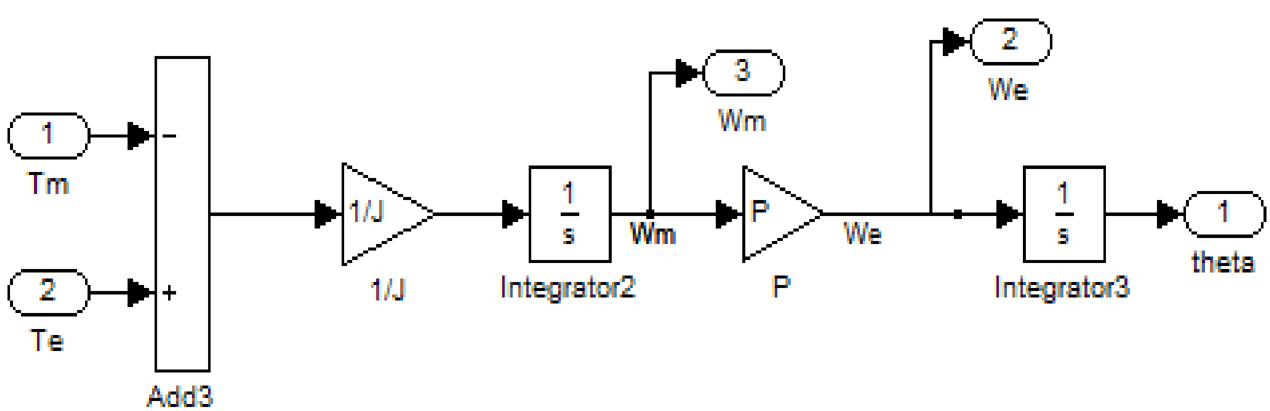


Figure 7: Swing equation Model

The internal architecture of the Park's transformation block which is also in the three phase PMSG model in figure 6 is shown below.

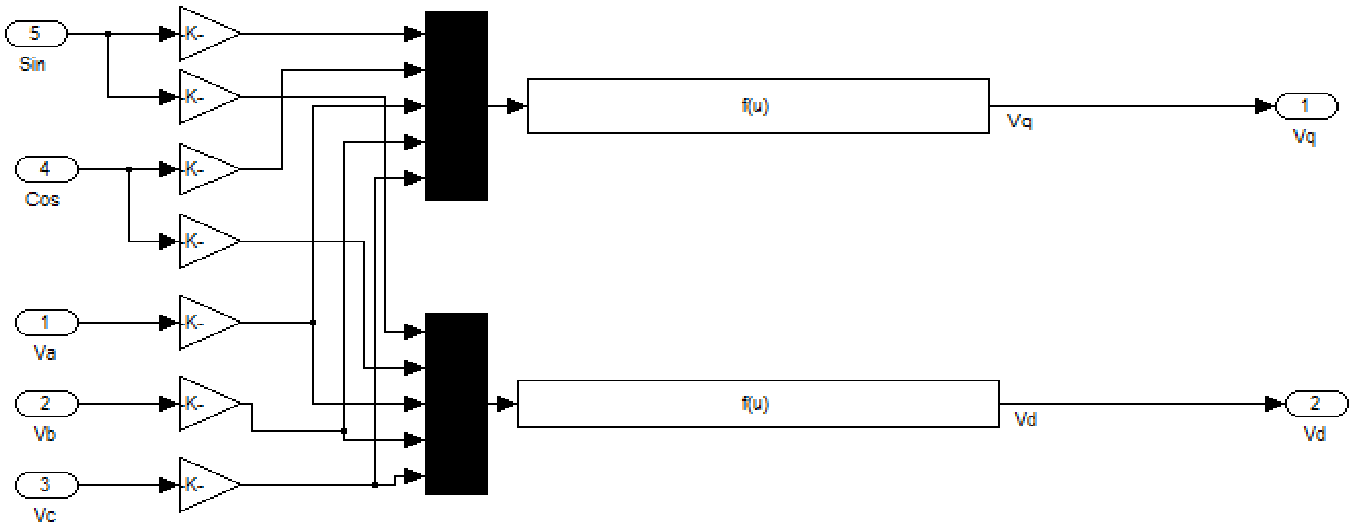


Figure 8: Park's transformation Model

The parameters used in the design of the wind turbine model and the three phase PMSG model are shown in the tables below.

Table 1: Wind turbine parameters

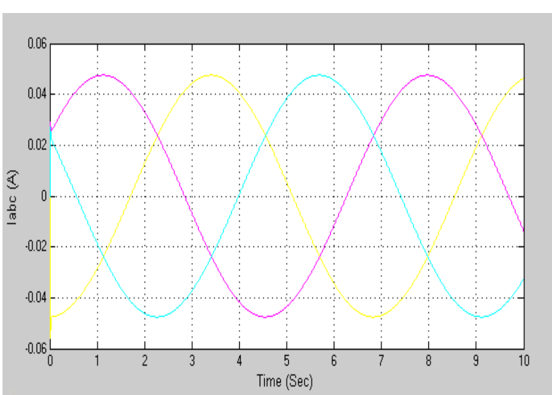
Parameter	Symbol	Value and Units
Wind turbine rotor radius	R	1.25 m
Length of blade	L	2.5 m
Swept area of wind turbine	A	6.25 m^2
Air density	ρ	1.225 kg/m^3
Pitch angle	ϑ	0

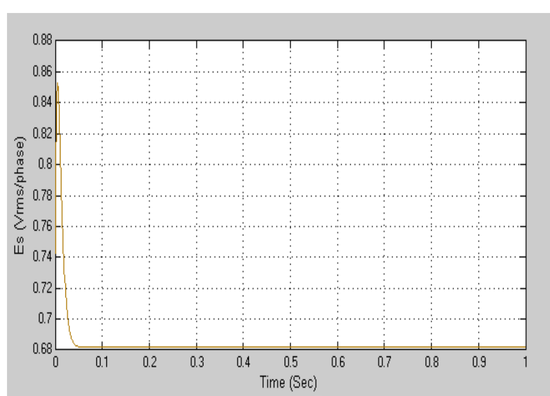
Table 2: Three phase PMSG parameters

Parameter	Symbol	Value and Units
Stator resistance	Rs	2.875 Ω
Inductance on d-axis	Ld	0.0085 H
Inductance on q-axis	Lq	0.0085 H
Permanent magnet flux	λ_o	0.175 Wb
Pole pairs	P	2
Moment of inertia	J	0.0008 Kgm^2

5. RESULTS

The simulation result graphs are shown below.





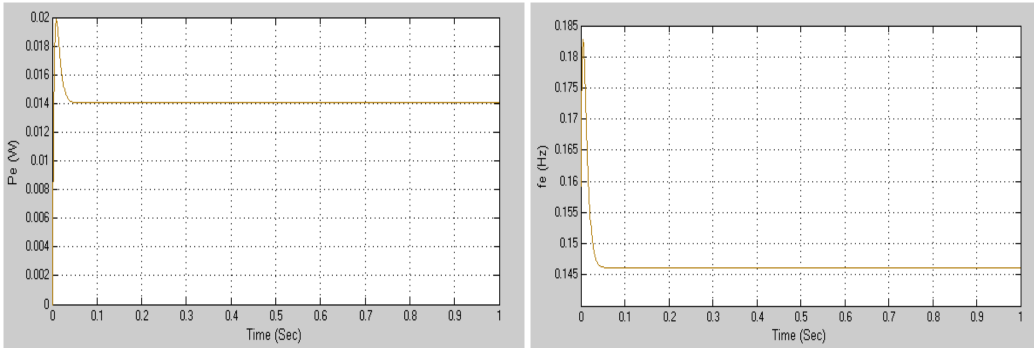


Figure 9: Graph of the three phase current, the voltage, the electromagnetic power and the electrical frequency at a wind speed of 1m/s

The graphs above in figure 9 explain the start-up wind speed, which is the speed at which the rotor and blade assembly begins to rotate. The start-up wind speed of the wind turbine system designed in this work is 1m/s during simulation. it can be observed that at a wind speed of 1m/s, the three phase current has a peak value of 0.0475A, the voltage has a steady state value of 0.6819Vrms/phase, the electromagnetic power has a steady state value of 0.01404W and the electrical frequency has a steady state value of 0.1461Hz. The steady state of the voltage, the electromagnetic power and the electrical frequency is attained, after a transient lasting for approximately 0.1 seconds. These values are too small to generate usable power. Hence, the wind turbine system can not generate electricity at this wind speed.

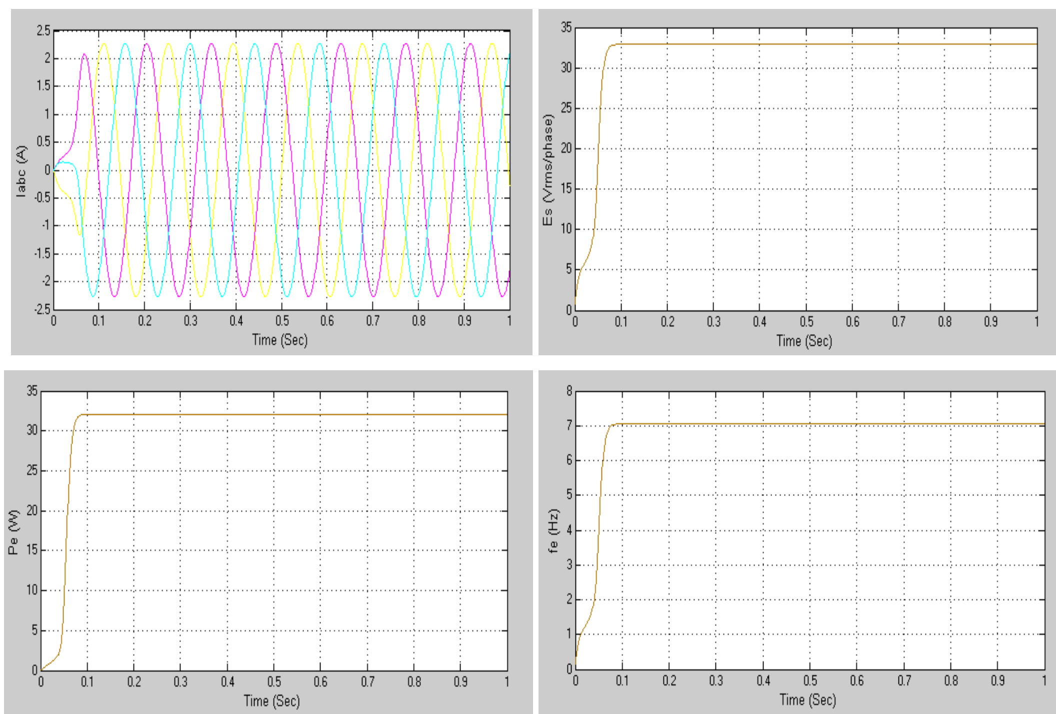


Figure 10: Graph of the Three Phase Current, The Voltage, The Electromagnetic Power and The Electrical frequency at a Wind speed of 3m/s

The graphs above in figure 10 explain the cut-in wind speed, which is the minimum wind speed at which the wind turbine will generate usable power. The cut-in wind speed of the wind turbine system designed in this work is 3m/s during simulation. It can be observed that at a wind speed of 3m/s, the three phase current has a peak value of 2.27A, the voltage has a steady state value of 32.9Vrms/phase, the electromagnetic power has a steady state value of 32.08W and the electrical frequency has a steady state value of 7.051Hz. The steady state of the voltage, the electromagnetic power and the electrical frequency is attained, after a transient lasting for approximately 0.1 seconds. The wind turbine system starts generating electricity at this wind speed.

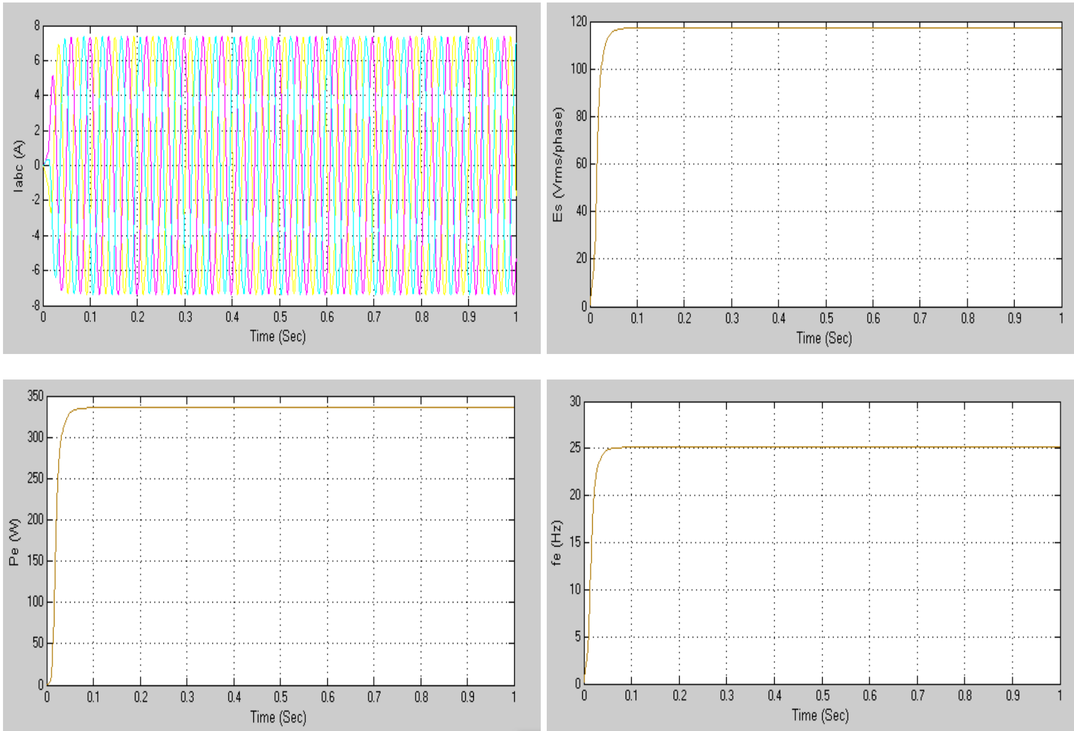


Figure 11: Graph of the Three Phase Current, The Voltage, The Electromagnetic Power and The Electrical frequency at a Wind speed of 6m/s

The graphs above in figure 11 explain the mean wind speed which is also known as the average wind speed. In Nigeria, the daily, monthly and yearly average wind speed measurement can be misleading since the pattern of wind flow is irregular. We are taking the mean wind speed to be 6m/s during simulation. At this wind speed, the wind turbine system will function effectively in majority part of Nigeria since it is assumed to be the overall average wind speed of the country. It can be observed that at a wind speed of 6m/s, the three phase current has a peak value of 7.35A, the voltage has a steady state value of 117.2Vrms/phase, the electromagnetic power has a steady state value of 335.6W and the electrical frequency has a steady state value of 25.12Hz. The steady state of the voltage, the electromagnetic power and the electrical frequency is attained, after a transient lasting for approximately 0.1 seconds. The wind turbine system works effectively at this wind speed.

The table below summarizes the simulation results. These values were deduced from the graphs above for the various wind speeds.

Table 3: Simulation Results of the Designed Wind Turbine System

Wind Speed (Measured in m/s)	Three Phase Current (Peak value measured in Ampere)	Voltage (Steady state value measured in Vrms/phase)	Electromagnetic Power (Steady state value measured in Watt)	Electrical Frequency (Steady state value measured in Hertz)
1	0.0475	0.6819	0.01404	0.1461
3	2.27	32.9	32.08	7.051
6	7.35	117.2	335.6	25.12

6. CONCLUSION

Nigeria is assumed to be the geographical location of the wind turbine system. It is noted that the vertical axis wind turbine designed in this work is a small-scale wind turbine and can only be used to power electrical appliances (loads) with power ratings equivalent to the generated electromagnetic power which depends on the wind speed.

The wind turbine system designed in this work generates three phase current whose peak value ranges from 2.27A to 7.35A for a relatively low wind speed range of 3m/s to 6m/s (the cut-in wind speed to the mean wind speed). These values of the generated current are sufficient for electricity generation under low and unsteady wind speed. It also generates voltages whose steady state values ranges from 32.9Vrms/phase to 117.2Vrms/phase for a relatively low wind speed range of 3m/s to 6m/s. These values are sufficient for electricity generation.

The electromagnetic power generated from this design has steady state values, ranging from 32.08W to 335.6W for a relatively low wind speed range of 3m/s to 6m/s. These values are also sufficient for electricity generation.

The methodology used in this work, if fully implemented, will not only reduce the cost of design but will also reduce the cost of maintenance, making it economical and affordable.

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