PERFORMANCE EVALUATION OF A MINI PERMANENT MAGNET SYNCHRONOUS GENERATOR (PMSG) FOR WIND ENERGY SYSTEM

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Abstract: In this work, the performance of a 500 W permanent magnet synchronous generator was evaluated in MATLAB /Simulink. The Simulink model consists of a wind turbine, a PMSG, and an AC – DC rectifier. The PMSG input parameter were measured and inputted in the Simulink block while the output results were voltages, currents and power respectively. The PMSG was tested at various wind speed. At the rated wind speed of 11m/s, the output power was 443.2 W.

Keywords: MATLAB/Simulink., PMSG, Variable speed

1. INTRODUCTION

The fuel crisis of the 1970s led to the investigation of alternative energy that is not dependent on fossil fuel [1]. More so, a growing concern arose about emissions from fossil-based energy sources. Wind energy system is among the growing forms of renewable energy. In terms of cost, wind energy system was found to have the lowest capital cost when compared with concentrated solar power (CSP) and photovoltaic (PV) systems [2]. In a study to determine viability of small wind turbine technology with other sources for small scale energy systems, using the levelized cost of energy (LCOE) calculations, wind energy systems was financially better than gasoline generators at wind speed above 4.7 m/s and solar technology at wind speed above 5.5 m/s [3].

The most common generators applied in small wind systems are the Self Excited Induction Generators (SEIG) and the Permanent Magnet Synchronous Generator (PMSG) [4]. A major weakness in the SEIG is that a fixed capacitor alone cannot provide the adequate amount of reactive power needed by the induction generator at all possible speeds and loading conditions [5]. Compared with SEIG, the PMSG offers a higher efficiency due to elimination of rotor conductor losses [6], reduced maintenance due to the absence of brushes and slip ring and variable speed operation for optimum power extraction due to its synchronous operation [7].

The functionality of the PMSG wind turbine has been validated by simulated results obtained from MATLAB/Simulink proposal of a stand-alone wind energy system consisting of a PMSG, rectifier, dc-dc buck converter, battery and load. The output power changes from 202.5 W to 479.8 W at 12 m/s to 16 m/s wind speed [8]. In another study, a small scale grid connected wind energy conversion system comprising of a direct driven PMSG, wind turbine and power electronic interface was modeled in MATLAB/Simulink. At the rated speed of 400 RPM, the output phase voltage and current of the generator were 99 V and 15 A respectively [9].

The objectives of this study is to access the performance of a small permanent magnet generator at different speed and the possibility of its used for a stand – alone wind energy system by applying a DC – DC boost converter to enhanced its application in areas with low wind speed.

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doi.org/10.29081/jesr.v28i3.002

1.1. The wind energy system model

The wind turbine model consists of the rotor blade aerodynamic model and PMSG model. Figure 1 illustrates the stand-alone wind energy system.

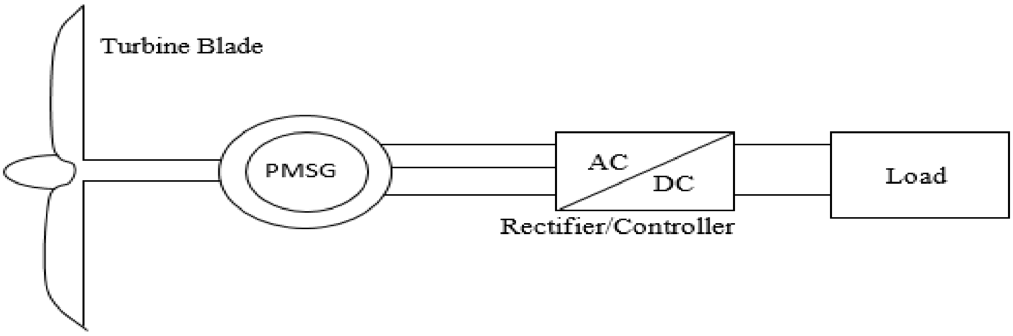

Fig. 1. A stand-alone wind-driven PMSG.

1.1.1. The Rotor blade aerodynamic model

The aerodynamic power of a wind turbine is given by (1) [10]:

$$P_w = \frac{1}{2}\rho A v_w^3, \tag{1}$$

where P_w and V_W are the wind power and wind speed respectively, A is the swept area of the blade and ρ is the density of air. Only a part of the wind power is captured by the turbine blades. Therefore the coefficient of captured wind power C_p also called the Betz Limit [11] and is mathematically expressed as the ratio of the extracted power by the rotor P_R to the power in the wind P_w.

$$C_p = \frac{P_R}{P_w} \tag{2}$$

The power captured by the wind turbine is given by the expression in (3) by substituting for P_w in (2) into (1):

$$P_R = \frac{1}{2} P_w . C_p . \pi . R_T^2 v_w^3 \tag{3}$$

where R_T is the radius of turbine rotor blades.

The Tip-speed (λ) is the ratio of the blade tip speed to the wind speed. It is express as (4) [12].

$$\lambda = \frac{\text{blade tip speed}}{\text{Wind speed}} = \frac{\omega_r R_T}{V_w} \tag{4}$$

where ω_r is the angular speed.

The aerodynamic torque T$_m$ delivered by the wind turbine is given as [12]:

$$T_m = \frac{P_R}{\omega_r} \tag{5}$$

$$\therefore T_m = \frac{0.5P_w C_p \pi R_T^3 v_w^2}{P_w} \tag{6}$$

The power coefficient C_p, represents the relationship between the blade's tip speed ratio λ and the pitch angle β. Based on the turbine characteristics, the generic equation of the power coefficient model in term of the tip speed ratio and pitch angle is given as (7) [13].

$$P_R(\lambda,\beta) = .C_1.(\frac{C_2}{\lambda_i} - C_3\beta - C_4)e^{-\frac{C_5}{\lambda_i}} C_6\lambda. \tag{7}$$

where $\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.008\beta} - \frac{0.035}{\beta^3 + 1}$. The coefficients are: C_1 = 0.5176, C_2 = 116, C_3 = 0.4, C_5 = 21 and C_6 = 0.0068.

1.2. PMSG model

The PMSG 3–Phase stator variable (f_{abcs}) such as voltage, current and flux quantities derived in the stationary abc reference frame can be transformed into the appropriate dq0 rotating reference frame i.e. (f_{dq0s}^r) using Park transforms according to (8) [14] as illustrated in Figure 2.

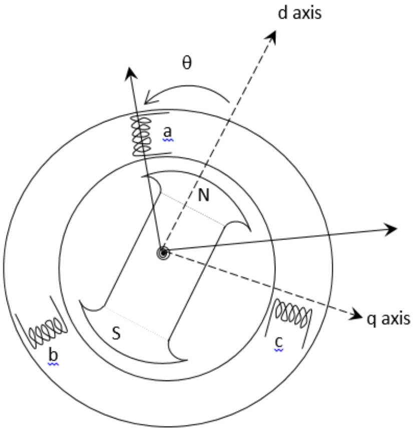

Fig. 2. A 2-pole, 3-phase permanent magnet synchronous machine.

Thus, for the three stator variable,

$$f_{qdos}^r = K_s^r f_{abcs} \tag{8}$$

where $(f_{qdos}^r)^T = [\ f_{qs}^r \quad f_{ds}^r \quad f_{0s}^r\ ]$ and $K_s^r = \frac{2}{3}\begin{bmatrix} \mathrm{Cos}\theta_r & \mathrm{Cos}(\theta_r - \frac{2}{3}\pi) & \mathrm{Cos}(\theta_r + \frac{2}{3}\pi) \\ \mathrm{Sin}\theta_r & \mathrm{Sin}(\theta_r - \frac{2}{3}\pi) & \mathrm{Sin}(\theta_r + \frac{2}{3}\pi) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$.

By transforming the voltage into the appropriate time invariant rotating (dq0) reference frame from their time-variant stationary (abc) reference frame using Park transformation, the quadrature and direct axis voltages V_q and V_d are expressed as (9) and (10)[9].

$$V_q = (r + \frac{d}{dt}L_q)i_q + \omega L_d i_d + \lambda\omega \tag{9}$$

$$V_d = (r + \frac{d}{dt}L_d)i_d - \omega L_q i_q \tag{10}$$

where r is the resistance of the stator windings, i_q, i_d are the q and d axis currents, ω is the angular velocity of the rotor. λ is the flux induced by the permanent magnets on the polyphase windings of the stator. The electromagnetic torque in the rotating reference frame is expressed in equation (11) [9]:

$$T_e = \frac{3}{2}\frac{P}{2}(\lambda i_q + (L_d - L_q) i_d i_q) \tag{11}$$

The dynamic equation relating the mechanical and electrical torques is given in (12) [15].

$$\frac{d^2\theta}{dt^2} = \frac{1}{J}(T_e - F\frac{d\theta}{dt} - T_m) \tag{12}$$

where T_e is the electrical torque described by (11) and T_m is the mechanical torque produced by rotor blades as a result of its rotation and it is described by (6) and F is the rotor's viscous friction.

1.3. The rectifier and DC-DC Boost circuit model

The rectifier converts the generated AC to DC. The DC output voltage equation of the three phase bridge rectifier in the model is presented in equation (13) [16].

$$V_{DC} = \frac{3\sqrt{3}}{\pi} V_m \tag{13}$$

where V_{DC} is the rectifier's output DC Voltage and V_m is the peak value of the AC Voltage of the PMSG or input voltage of the rectifier.

The DC-DC boost converter increases the output voltage to a higher level. It consists of an inductor, a capacitor, a diode and a power MOSFET. When the MOSFET is switched ON, the input current increases and energy is stored in the inductor. When the MOSFET is switched OFF, the stored current in the inductor flows through the diode to the capacitor and load. The current in the inductor then decreases until the MOSFET is switched ON for another cycle or period T. The capacitor limits the voltage ripple and provides a continuous DC current to the load when the diode is switched OFF and the MOSFET is switched ON. The cycle or switch ON time is equivalent to (1-D)T [16, 17]. A Pulse Width Modulation (PWM) signal performs the switching operation of the MOSFET at an appropriate duty cycle as shown in equation (14) [17].

$$\frac{V_{out}}{V_{in}} = \frac{1}{(1-D)} \tag{14}$$

where D is the duty cycle.

If a stable output voltage is desired irrespective of changes in the input voltage or load current, a close loop control system can be incorporated.

2. METHODS

The MATLAB/Simulink model is shown in Figure 3. The PMSG is coupled to the rotor of the wind turbine. As the blades rotates, the mechanical torque produced by the rotation of the blades, produces an electromagnetic torque in the PMSG. The output AC electrical power of the PMSG is rectified through a DC rectifier. For experimental purpose, a pure resistive load of 1.5Ω was selected for the load test. The PMSG was tested over a range of rotating speed in emulation of the varying rotation speed in the PMSG that would have been produce by wind energy. In order to study the variation of the generated voltage with the speed, the controller was left in an open loop configuration.

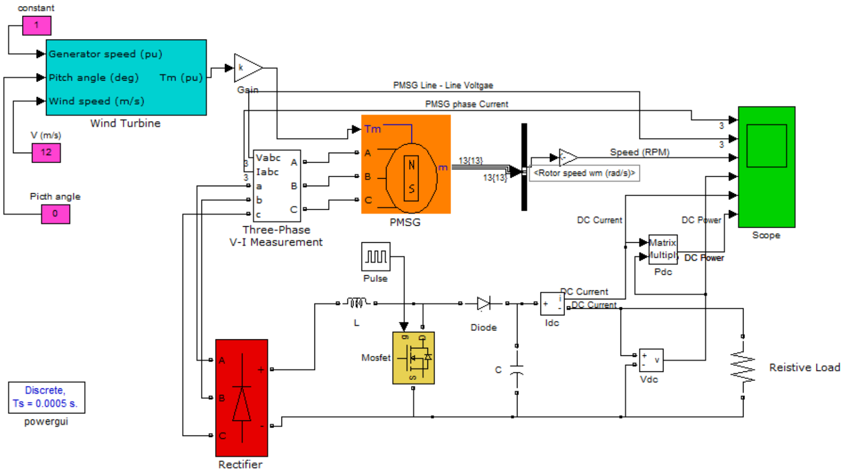

Fig. 3. Simulink model of the wind driven PMSG.

The input parameters of the PMSG under evaluation are presented in Table 1. The output results of the PMSG are voltage, current, rotor speed, load voltage, load current and power respectively.

Table 1. Simulink input parameter.

Parameter	Value
Wind Turbine Nominal Mechanical Power	780 W
Rated Electrical Power	500 W
Number of pole Pairs (P)	4
Flux Linkage	0. 151 V.s
Resistance/phase (R)	0.657Ω
Inductance on d-axis (L_d)	1.64×10^{-3}H
Inductance on q-axis (L_q)	1.64×10^{-3}H
Moment of Inertial (J)	1.183×10^{-3}Kgm^2
Friction Factor (F)	0.001142

3. RESULTS AND DISCUSSION

The measured output of the PMSG voltage, current, rotor speed, load and power were obtained at a wind speed of 3 – 11 m/s. The results are presented in Table 2.

Table 2. PMSG Output parameters at wind speed of 3- 11 m/s.

Wind Speed (m/s)	Rotor Speed (RPM)	PMSG Voltage (V)	PMSG current (A)	PMSG Power (VA)	Load Power (W)
3.0	145.2	10.0	4.2	42.0	35.4
4.0	177.2	10.8	5.1	55.3	41.9
5.0	219.8	15.2	7.1	107.9	94.5
6.0	273.9	16.1	8.7	139.0	111.6
7.0	301.4	17.8	9.7	172.9	142.4
8.0	334.2	22.5	9.6	216.8	243.6
9.0	411.0	22.8	10.6	240.7	247.7
10.0	426.0	26.5	14.6	387.0	338.2
11.0	484.1	29.9	16.9	506.2	443.2
12.0	552.2	31.3	17.7	554.7	492.7

The rated wind speed of the wind energy system is 11m/s. The PMSG results for rotor speed, voltage, current and load power obtained in Simulink at the rated wind speed is shown in Figure 4.

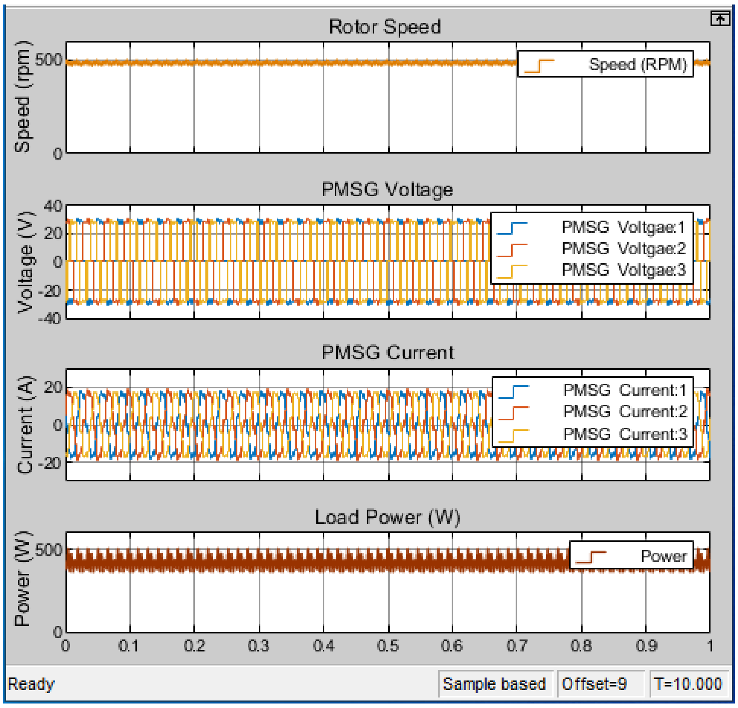

Fig. 4. Simulink results for the PMSG Rotor Speed, Voltage, Current and load Power at Wind Speed of 11 m/s.

The range of generated load voltage was between 10 – 31 V, while the currents ranged was 4.2 – 17.7 and the load power ranged was from 35.4 – 492.7 W at wind speed of 3 m/s – 12 m/s and rotor speed of 145.2 – 552.2 rev/min. The fluctuations in the AC currents can be attributed to the harmonics produce in the PMSG. At the rated wind speed, the efficiency is given as:

$$\eta = \frac{\text{Output Power}}{\text{Intput Power}} \times 100 \tag{14}$$

where, η is the efficiency, the input power is the rated power of the PMSG given as 500W and the output power at 11 m/s given as 443.2 W.

Therefore, the efficiency of the PMSG from equation (14) is 88.6 %

However the theoretical overall efficiency for the wind system at the rated input or turbine power of 780W and a load output power of 443.2W is 56.7 % which is below 59.3 % or 16/27 limit (Bertz constant) for wind turbine systems [18]. In practice, the system's overall efficiency will be much lesser.

4. CONCLUSION

The performance of a 500W PMSG has been evaluated in MATLAB/Simulink and the variation of the output power with the wind speed was highlighted. The variable nature of wind flow produced fluctuations in the generated power. In practice, the rectified output power of the generator must be enhance with a feedback control system in the DC – DC controller along with an inverter system for greater efficiency and stable output voltage.

The simulated results show that rated output power was 443.2 W at the rotational speed of 484.1 rpm corresponding to a wind speed of 11 m/s. The generated output power represented a PMSG efficiency of 88.6 % and a wind energy system efficiency of 56.7 %

Acknowledgement: This research was funded by the Tertiary Education Trust Fund (TETFUND) Nigeria, research fund grant 2016 batch 9.

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