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Modelling and Analysis of a Permanent Magnet Synchronous Reluctance Generator for Wing Energy Conversion System

[1] Khan Farnia, [2] Aboo Bakar Khan, [3*] Mohammed Aslam Husin, [4] Md Tabrez

[1] [2] CSMU Panvel, Navi Mumbai, India
[3] Department of Electrical Engineering, Rajkiya Engineering College Ambedkar Nagar, U.P, India
[4] EEE Department, Motihari College of Engineering, East Champaran, Bihar, India

*Corresponding Author:
Mohammed Aslam Husain
EED, Rajkiya Engineering College Ambedkar Nagar, Uttar Pradesh, India
Email: mahusain87@gmail.com

Abstract: The permanent magnet synchronous reluctance generator (PMSRG) is an innovative electrical machine that combines the benefits of both permanent magnet and reluctance torques. In recent times, the synchronous reluctance generator (PMSRG) has gained significant attention in the industry due to its unique characteristics. This study emphasizes the comprehensive analysis, modeling, and simulation of a PMSRG drive system, highlighting its distinguishing characters in comparison to other generators used in similar applications. By employing dynamic equations, the PMSRG's mathematical base is established, and the d-q transformation strategy is implemented for vector control. Space Vector Pulse Width Modulation (SVPWM) technology is utilized to model and simulate the PMSRG without rotor cage or magnetic material. The MATLAB Simulink environment is employed to simulate and customize the PMSRG model. This simulation takes into account speed variations under different frequencies and load conditions, further enhancing the understanding and potential of the PMSRG in practical applications. Apart from that this analysis also focuses on highlighting the distinctive features of the PMSRG, demonstrating its potential for improved energy conversion efficiency and reduced losses compared to traditional motors. These findings contribute to a better understanding and optimization of PMSRGs, making them a promising option for various industrial and renewable energy applications.
Keywords: Permanent magnet synchronous reluctance generator, synchronous reluctance generator, d-q transformation, Space Vector Pulse, Space Vector Pulse Width Modulation, MATLAB Simulink

1. INTRODUCTION

In the synchronous electric machine, the rotor is energized with direct current while the stator carries Alternating Current (A.C.). Conversely, a direct current (D.C.) machine relies solely on D.C. sources for excitation or acts as a D.C. source itself. In industrial applications, A.C. motors are commonly used if they possess inherent suitability or can be adapted with power electronics devices. However, the growing complexity of industrial processes necessitates greater flexibility in electrical machines regarding specialized characteristics and speed control. The synchronous reluctance generator (SRG) has garnered significant interest owing to its notable benefits, including cost-effectiveness, robustness, high reliability, efficiency, and excellent torque performance. In comparison to the induction motor (IM), the SRM boasts superior power density and efficiency. Furthermore, as it does not rely on expensive rare-earth magnets, the SRM remains insensitive to operating temperatures, resulting in a lower overall cost compared to permanent magnet synchronous motors (PMSMs). Consequently, the SRM holds great potential as a workable alternative to both IMs and PMSMs in various industrial applications. It can be seen in Fig. 1 that the rotor topology of a synchronous reluctance macxhine is different from other ac mahines. This unique rotor topology of SRMs, a high-performance control strategies are necessary for efficient drive operations. The SRM is a three-phase motor driven by a three-phase space vector inverter. Unlike traditional synchronous machines with windings or permanent magnets on the rotor and salient poles, the SRM features a fragmented rotor composed of numerous barriers. To address issues of low torque response and unsuitable power factor, modern SRMs incorporate laminated axially steel in their rotor design—a technology absents in older reluctance motor versions. While the stator-winding layout resembles that of the IM, the SRM's rotor structure is distinct, lacking caged or twisted components and magnetic material. Instead, it comprises optimized, complex laminated obstacles, creating top quadrature axis complement and non-direct axis jealousy, leading to low and high hesitation areas representing the magnetic poles practically [1]–[8].

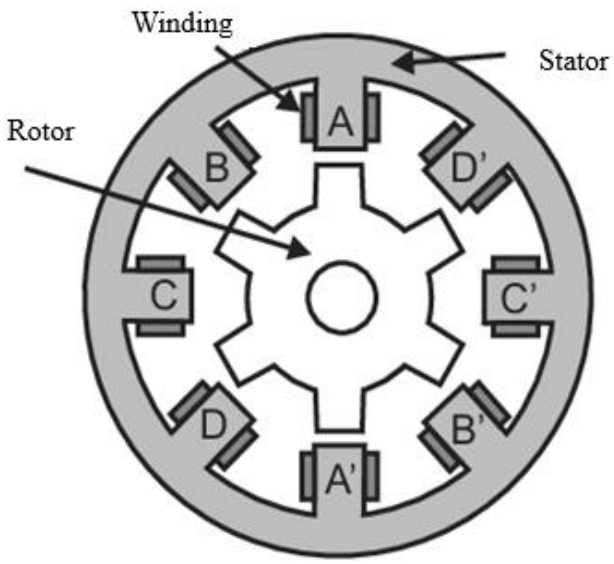

Fig. 1. Internal View of SRM

The SRM is a synchronous machine with a rotor structure lacking winding or magnet material, making it skillfully constructed and straightforward. Compared to other reluctance motors, it exhibits distinctive properties like low torque average, higher torque pulsation, and low power factor. SRG operates based on the synchronous reluctance effect, where the rotor aligns with the rotating magnetic field. SRG also utilizes a rotor with a combination of permanent magnets and reluctance saliency, enhancing torque density and efficiency. Offers improved efficiency and reduced losses compared to traditional induction generators, requires vector control strategies like d-q transformation for precise control and optimal performance. It's suitable for various industrial applications, electric vehicles, and renewable energy systems. The switched reluctance (SR) generator offers a straightforward and robust design, comprising only a magnetic core and windings. This simplicity makes it an ideal choice for ultrahigh-speed applications, such as micro-gas-turbine generation. Additionally, its flexible shape and small moment of inertia render it suitable for low-speed applications like small-scale wind-turbines and micro-hydroelectric power generation. However, the SR generator faces a challenge due to its complicated generation system, requiring both an exciting circuit and a position sensor. To address these concerns, we have turned our attention to a permanent magnet reluctance generator (PMRG). This generator shares a similar structure with the SR generator but incorporates permanent magnets in the stator yoke. As a result, it eliminates the need for an exciting circuit and a position sensor, making the proposed PMRG's system simpler and more efficient compared to the SR generator. The table 1 provides a general comparison between PMSRGs and Permanent Magnet Machines [1].

Table 1. Comparison of PMSRG and permanent magnet machines

Reference	Criteria	PMSRG	Permanent Magnet Machines
[3], [4]	Operating Principle	Utilizes a combination of permanent magnets and reluctance saliency on the rotor to produce torque. Output voltage is trapezoidal.	Employs permanent magnets to create a constant magnetic field for, motors and generators. Output voltage is sinusoidal

[9]	Efficiency	Offers improved efficiency and reduced losses compared to traditional induction generators.	Provides high efficiency due to the use of permanent magnets, minimizing energy losses.
[1], [2]	Construction	Consists of a rotor with a combination of permanent magnets and reluctance saliency, and a wound stator.	Can be found in various configurations, such as permanent magnet motors, generators, and other electrical machines.
[10]–[15]	Control Strategies	Requires scalar control such as DTC and vector control strategies like d-q transformation for precise control and optimal performance.	Control strategies depend on the specific application and type of permanent magnet machine. Commonly used control techniques include field-oriented control (FOC) and sensor-less control.
[16]–[19]	Application Areas	Industrial applications, electric vehicles, and renewable energy systems.	Electric vehicles, industrial automation, and renewable energy systems, among others.
[9], [20]	Advantages	offers high torque density and efficiency. Offers lower cost	Offers excellent power density, high torque capability, and enhanced control options. Costlier than PMSRG.
[21], [22]	Key Features	Precise control options due to d-q transformation and enhanced energy conversion efficiency.	Enhanced performance and energy efficiency due to permanent magnets' presence.

Modelling is a crucial part for a system to visualize, analyse, predict and design the system. So this manuscript will address the following research questions in this paper.

- ✓ How can PMSRGs be modeled accurately and efficiently for wing energy conversion systems?
- ✓ What are the key design considerations for PMSRGs for wing energy conversion systems?
- ✓ How can PMSRGs be integrated with the wing structure in a way that maximizes their performance?

The manuscript is expected to make the following contributions:

- ✓ A new and improved model of a PMSRG for wing energy conversion systems.
- ✓ Design guidelines for PMSRGs for wing energy conversion systems.
- ✓ A methodology for integrating PMSRGs with the wind energy conversion system.

The manuscript is organized into following manner. Section 1 is all about introduction that includes background information, problem statement and expected outcomes. Section 2 discusses Methedology with different subsections. Section 3 presents results and discussions. The manuscript is finally concluded in section 4.

2. METHOD

The mathematical model of a synchronous reluctance generator describes the relationships between the electrical and magnetic quantities within the machine. This model is essential for analyzing and predicting the generator's performance under different operating conditions [2]. In this section mathematical modelling of synchronous reluctance generator is given. Based on the modelling, a MATLAB/SIMULINK modelled is developed to study the its performance in wind energy conversion system. The key elements in the mathematical modelling is descibed as below.

1. Stator and Rotor Windings: The stator of the synchronous reluctance generator has three-phase windings, while the rotor typically has squirrel cage windings. The winding configurations are represented by the stator and rotor current equations.

2. Magnetic Flux Linkages: The magnetic flux linkages between the stator and rotor are described by the flux linkage equations, which account for the magnetic interactions between the stator and rotor windings.
3. Electromagnetic Torque: The electromagnetic torque developed by the generator is a function of the current flowing through the stator and rotor windings and the magnetic reluctance between the stator and rotor.
4. Rotor Angle: The rotor angle represents the angular position of the rotor with respect to the stator. It is a critical parameter in the generator's operation and is used to describe the generator's transient and steady-state behavior.
5. Synchronous Reactance: The synchronous reactance represents the generator's electrical reactance, which is influenced by the magnetic reluctance and the inductances of the stator and rotor windings.
6. *d-q* Transformation: The d-q transformation is a mathematical technique used to simplify the analysis of the generator by transforming the three-phase quantities into two-phase direct-axis (d-axis) and quadrature-axis (q-axis) quantities.
7. Governing Equations: The mathematical model comprises a set of differential equations that describe the dynamic behavior of the synchronous reluctance generator. These equations relate the stator and rotor currents, flux linkages, electromagnetic torque, and mechanical speed.

The mathematical model can be simulated using numerical methods, to study the generator's performance under various operating conditions, it provides insights into the generator's efficiency, power output, and stability, making it a valuable tool for design, control, and optimization of synchronous reluctance generators [4], [23].

2.2 Mathematical Modelling of a Switched Reluctance Machine

2.2.1 Stator Voltage Equations (d-axis and q-axis)

The stator voltage equations for the d-axis and q-axis of a synchronous reluctance generator are derived based on the d-q transformation technique. In the d-q transformation, the three-phase stator voltages (V_a, V_b, V_c) are transformed into two-phase quantities: V_d (direct-axis) and V_q (quadrature-axis). The *d-q* transformation is used to simplify the analysis of the generator's electrical behavior [14], [15], [22], [23][.

The stator voltage equations in the d-axis and q-axis are as follows:

2.2.2 d-axis voltage equation:

$$V_d = R_s \times I_d + \omega_e \times L_q \times I_q + E_{fd} \quad (1)$$

Where:

V_d is the stator voltage in the d-axis.

R_s is the stator resistance.

I_d is the stator current in the d-axis.

ω_e is the electrical angular velocity (rad/s) of the generator.

L_q is the quadrature-axis inductance.

I_q is the stator current in the q-axis.

E_{fd} is the d-axis back EMF induced in the generator due to magnetic flux variations.

q-axis voltage equation:

$$V_q = R_s \times I_q - \omega_e \times L_d \times I_d + E_{fq} \quad (2)$$

Where:

V_q is the stator voltage in the q-axis.

R_s is the stator resistance.

I_q is the stator current in the q-axis.

ω_e is the electrical angular velocity (rad/s) of the generator.

L_d is the direct-axis inductance.

I_d is the stator current in the d-axis.

E_{fq} is the q-axis electromotive force (back EMF) induced in the generator due to magnetic flux variations.

In these equations, the back EMF terms (E_{fd} and E_{fq}) account for the effects of magnetic flux linkages and the generator's electromechanical coupling.

2.2.3 Electromagnetic Torque Equation

$T_{em} = (3/2) \times P \times (\psi_d \times I_q - \psi_q \times I_d)$ (3)

Where:

T_{em} is the electromagnetic torque produced by the motor.

P is the number of pole pairs in the motor.

ψ_d and ψ_q are the d-axis and q-axis flux linkages, respectively.

2.2.4 Rotor Speed Equation:

The rotor speed equation for a synchronous reluctance generator is given by:

$N_r = (2 \times f \times P_p) / P$ (4)

Where:

N_r is the rotor speed of the synchronous reluctance generator (in revolutions per minute, RPM).

f is the electrical frequency of the generator (Hz).

P_p is the number of pole pairs in the generator (number of pole pairs = number of poles / 2).

P is the number of poles in the generator.

2.2.5 Rotor Flux Linkage Equations

The rotor flux linkage equations for a synchronous reluctance generator are as follows:

d-axis rotor flux linkage equation:

$\Psi_{rd} = L_{ld} \times I_d + \Psi_m$ (5)

q-axis rotor flux linkage equation:

$\Psi_{rq} = L_{lq} * I_q$ (6)

Where:

Ψ_{rd} is the d-axis rotor flux linkage (in Weber, Wb).

Ψ_{rq} is the q-axis rotor flux linkage (in Weber, Wb).

L_{ld} is the direct-axis rotor inductance (in Henry, H).

L_{lq} is the quadrature-axis rotor inductance (in Henry, H).

I_d is the stator current in the d-axis (in Amperes, A).

I_q is the stator current in the q-axis (in Amperes, A).

Ψ_m is the permanent magnet flux linkage in the rotor (in Weber, Wb).

The stator voltage equations, along with the flux linkage equations and electromagnetic torque equation constitute the mathematical model of the synchronous reluctance generator. These equations are used in simulations and control strategies to analyze and optimize the generator's performance under various operating conditions [16].

2.3 MATLAB Simulation

MATLAB simulation for a permanent magnet synchronous reluctance generator (PMSRG) is essential to comprehensively analyze, design, and optimize the generator's performance under various operating conditions. MATLAB simulations allow for sensitivity analysis of key design parameters, such as magnet strength, stator and rotor geometries, and winding configurations. Understanding these sensitivities aids in the design process to achieve desired performance characteristics. MATLAB simulations provide a platform for developing, implementing, and testing control algorithms. Overall, MATLAB simulation of SRMs is essential for understanding their behavior, optimizing their design and control, and facilitating their integration into various industrial and renewable energy applications. It offers a cost-effective and efficient way to analyze and develop Synchronous Reluctance Motors, leading to improved performance and increased adoption of this technology [20]–[23].

Table 2. PMSRG design parameters

Sr.no	Parameter	Value	Unit
1	X_1	[-6.6250,0,0,-3.5333]	-
2	X_2	[0,1.8750, -0.5333,0]	-
3	X_{ch}	[0,-0.2000,0, 0.2000]	-
4	Y_1	[-625,0,0,0, -333.3333,0]	-
5	Y_2	[0,0,0,0,0,333.3333]	-
6	L_{ch}	0.2	mH
7	L_d	1.6	mH
8	L_q	0.3	mH
9	R_{ch}	10	Ω
10	J	0.02	Kgm^2

2.4 Simulink Model working

The direct and quadrature axis voltages have been formulated to represent the PMSRG model design [22]. The voltage equations of the PMSRG have been implemented in a Matlab/Simulink environment block, as shown in Fig. 2. The direct and quadrature axis voltages serve as inputs to the PMSRG block system, and the simulation results depict both the voltage and current characteristics. The parameters used in PMSRG design are shown in the Table.2

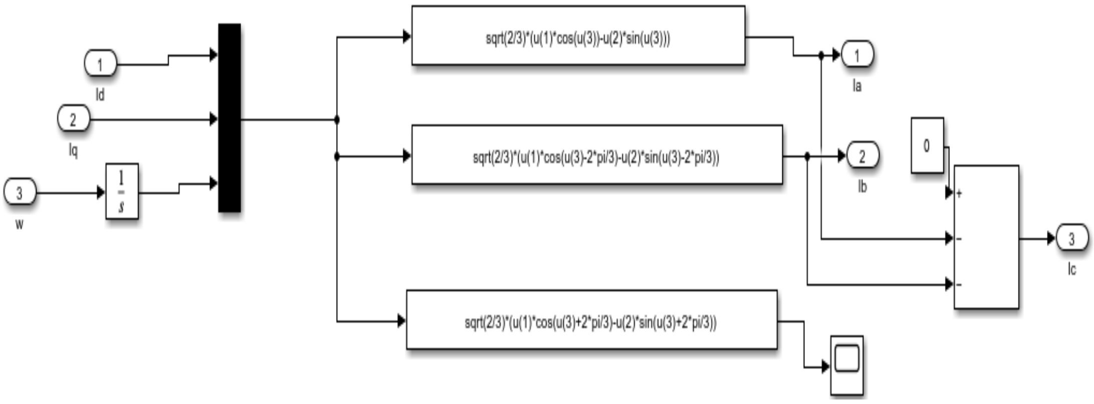

Fig. 2. *Park Inverse Block*

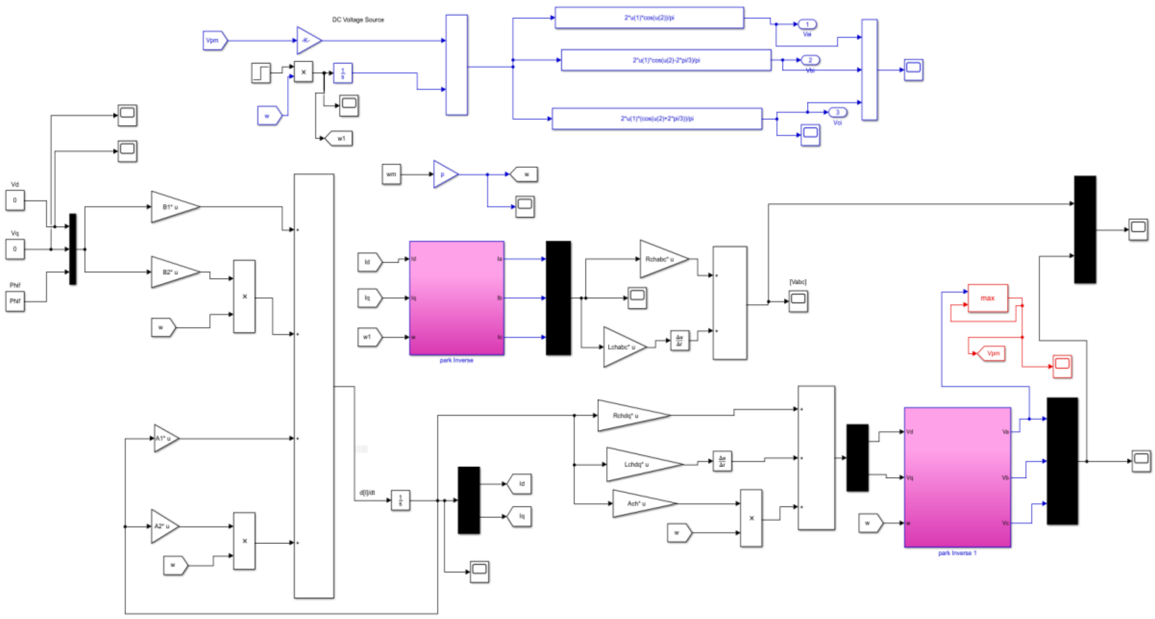

Fig. 3. PMSRG Block Model Simulation

The given input comprises V_d, V_q, and V_{d1}, Phif. These inputs are directed to a Mux block, where inputs with the same data type and complexity are combined into a simulated vector. The outcome of the Mux block is denoted as |B|, which results from the summation of B1 and ωB2. Similarly, |A| is the combination of A1 and ωA2.

$|B| = B1 + \omega B2$ (7)

$|A| = A1 + \omega A2$ (8)

The sum of equations 7 and 8 gives dI/dt, leading to the determination of Id and Iq. When the Park Inverse block Fig.3 is provided with I_d and I_q inputs, it performs the inverse transformation from the d-q reference frame back to the original abc reference frame. This transformation is essential in electric machine control, particularly in applications like Permanent Magnet Synchronous Motors (PMSMs) and generators.In the d-q reference frame, I_d represents the direct-axis current component, and I_q represents the quadrature-axis current component. These components are defined based on the rotor position and the stator currents in the original abc reference frame. The d-q transformation is used to simplify the control of the machine, as it decouples the torque-producing (d-axis) and magnetizing (q-axis) components of current.The Park Inverse block takes I_d and I_q as inputs and also requires the rotor angle (θ) or angular speed (ω) as input. It then performs the inverse Park transformation by calculating the abc currents based on I_d, I_q, and the provided rotor angle or speed. These currents are then fed back to the control system for further processing or to control the machine's operation.Current is subsequently combined with Rchabc and Lchabc. In MATLAB Simulink, you can establish the relationship between Lchabc and the rate of change of current (Ldi/dt). The relationship can be expressed as follows:

$L_{chabc} = V_{abc} / (di/dt)$ (9)

Where:

L_{chabc} represents the inductance in the Clarke transformation reference frame.

V_{abc} signifies the voltage across the inductor.

(di/dt) denotes the rate of change of current.

3. RESULTS AND DISCUSSION

This study introduces a mathematical model for PMSRG in a wind energy generation system. This study shows that when the load on a wind turbine is varied, it directly affects the torque requirements and the overall operation of the wind turbine. The study employs simulations conducted in MATLAB®/SIMULINK™. The simulation results are presented and described in Fig 4, 5 & 6. The torque produced by the generator is proportional to the electrical current flowing through its stator windings and the strength of the magnetic field as given in equation 3. As the wind speed increases, more torque is produced, resulting in an increase in rotational speed and power output.

$$P_e = T_{em} \times \omega_r \qquad (10)$$

Where:

P_e is the electrical power output (in W).

T_{em} is the electromagnetic torque (in Nm). Tem can be found by equation 3.

ω_r is the rotor speed (in rad/s).

This relationship is crucial for optimizing the performance of a PMSRG in a wind energy system, ensuring efficient energy conversion from the wind into electrical power.

In summary, as the wind speed increases and more torque is generated by the wind turbine, the PMSRG's rotor speed also increases, leading to higher power output. Conversely, when the wind speed decreases, the torque, rotor speed, and power output decrease as well.

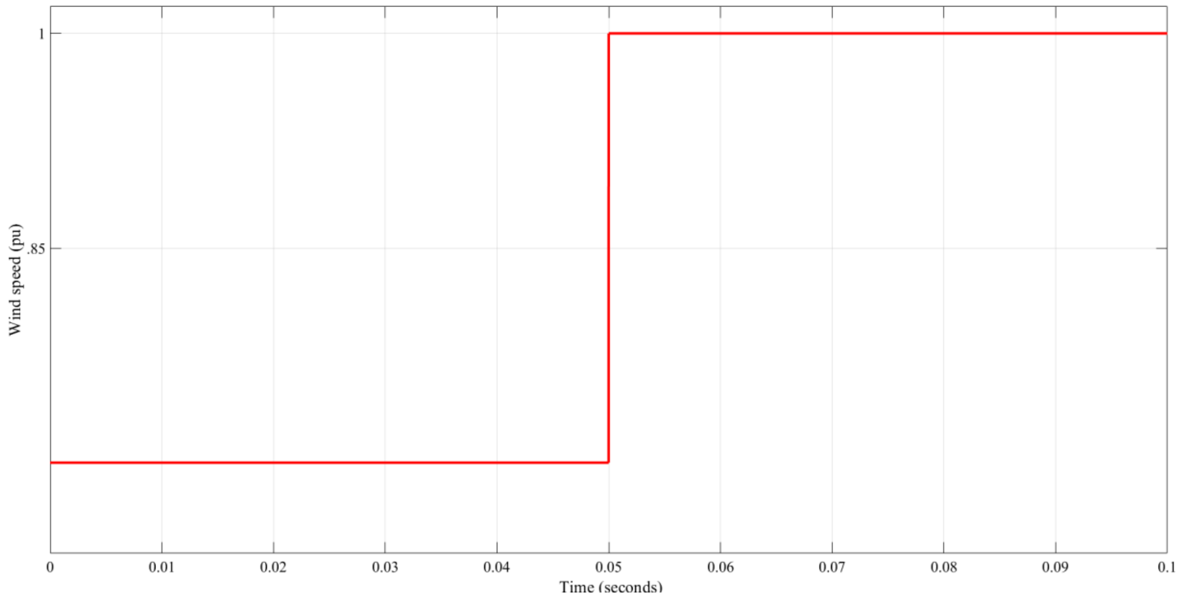

Fig. 4. Wind speed and its variation with time

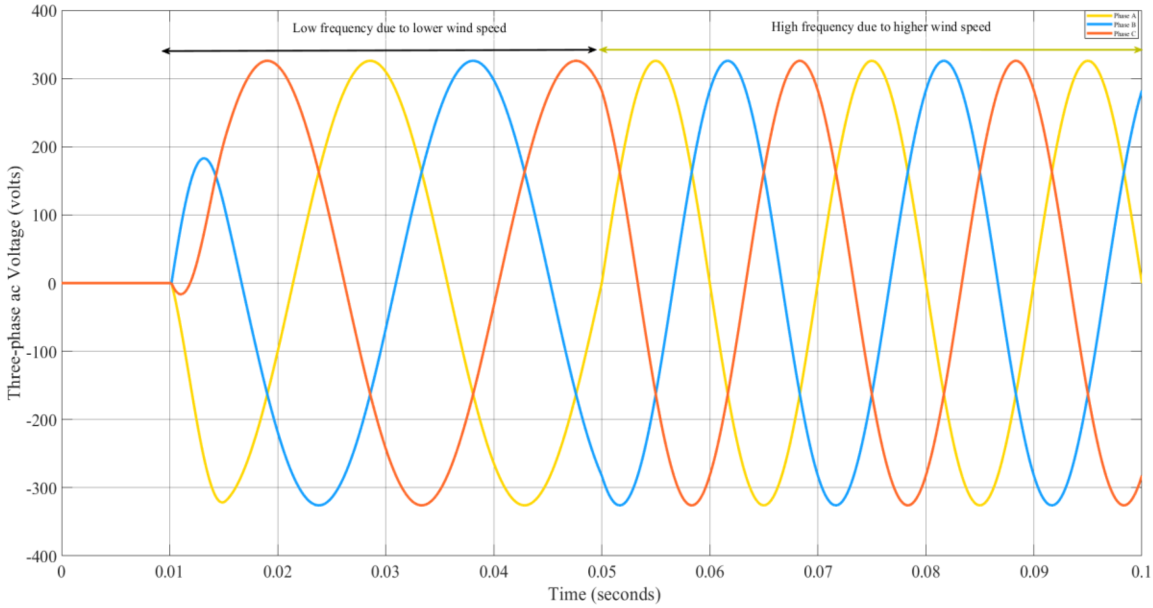

Fig. 5. Output voltage responding to change in wind speed

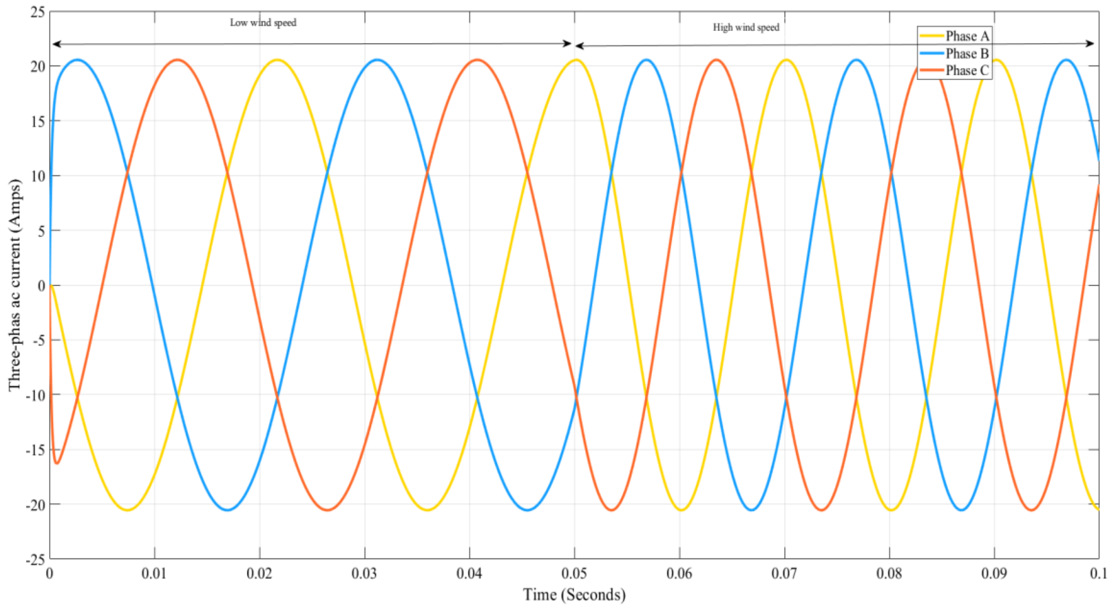

Fig. 6. Output current responding to change in current

4. CONCLUSIONS

The manuscript has made a significant contribution to the field of wing energy conversion systems. The new PMSRG model is more accurate and efficient than previous models, and the design guidelines and integration methodology will help engineers to design and integrate PMSRGs into wing energy conversion systems in a way that maximizes their performance. In conclusion, this manuscript has addressed the research questions mentioned in introduction section of this manuscript and come-up with-A new and improved model of a PMSRG for wing energy conversion systems.

- ✓ A new and improved model of a PMSRG for wing energy conversion systems.
- ✓ Design guidelines for PMSRGs for wing energy conversion systems.
- ✓ A methodology for integrating PMSRGs with the wind energy conversion system.

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