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# Modelling and Simulation of Wind Turbine

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***Abstract:-*** The modelling of wind turbines based on PMSG is the subject of this research. The mathematical modelling of the turbine at various wind speeds is the main topic of this research. The fundamental circuit equations that control the wind turbines and PMSG's variable speed functioning are used to create the wind turbine model. The wind speed is not constant and it depends on the environmental conditions this variation in the wind speed can be controlled by a pitch angle controller and the desired constant electrical power is generated at operational wind speed. This paper is about the mathematical modelling of wind turbines, and their different characteristics obtained from different parameters. A standalone wind turbine system was modelled and analyzed using MATLAB/Simulink and the outcomes met the design specifications.

***Keywords****: Pitch Angle Control, PMSG, and Wind Turbine.*

## 1. Introduction

At present, variable generation systems like solar, and wind have become the most important and fast-growing. These variable generation sources are variable because their availability and energy production depend on natural conditions which can change through the day and seasons. This variation poses challenges for maintaining a consistent electricity supply. Wind energy has gained popularity recently since it can provide electricity with little harm to the environment and boost economic growth. Nowadays the extraction of power from the wind on a large scale has become a recognized industry, however, Due to a lack of wind turbine (WT) technology, wind power output was insignificant in comparison to conventional plants earlier. However, with recent advancements, wind power has grown exponentially. The amount of wind energy generated globally has reached a shocking milestone in the last ten years in terms of gross power generation. The total installed wind power capacity in the world as of 2023 is estimated to be 1,021 gigawatts (GW).

A stand-alone generation system offers a feasible solution to distributed generation for isolated localities where the grid is unavailable. One practical approach to self-sufficient power generation for isolated localities involves using a wind turbine with a storage battery [1]. Different generators are coupled with the wind turbine like induction generators, doubly-fed induction generators, and synchronous generators are used. A wind power production system is better suited for the permanent magnet synchronous generator (PMSG) because of its high efficiency, low maintenance needs, and capacity to produce electricity at any wind speed.

To run contemporary power systems, which incorporate renewable energy sources, Modeling and simulation are necessary [2]. This work presents comprehensive modelling and simulation experiments conducted on a wind power generating system based on PMSG, considering fluctuations in wind speed [3]. The simulation results demonstrate the wind energy system's dynamic performance. The format of this document is as follows. The overview modelling of the wind turbine is covered in Section II. The simulation studies used to analyze the wind energy system's performance under conditions of variable wind speed are presented in Section III. Section IV ends with a synopsis of the key ideas.

## 2. Modelling of Wind Turbine

The Modeling process involves capturing the dynamic behaviour of various components within the wind turbine system. The wind turbine is typically modelled using aerodynamic equations and mechanical equations to describe the relationship between wind speed and power output [4]. These equations help simulate how the turbine responds to changing wind conditions. The Wind Energy Conversion System is a sophisticated setup with several interrelated parts intended to effectively catch wind energy and convert it into electrical power that can be used. Blades, a pitch system, hub, main shaft bearings, main shaft, nacelle, yaw system, gearbox, mechanical brake, generator, power electronic systems and their control mechanisms, hydraulic and cooling systems, and the supporting tower are some of the essential components of this complex system [5]. The general block diagram of the Wind Energy Conversion Systems (WECS) is shown in Fig. 1[2]

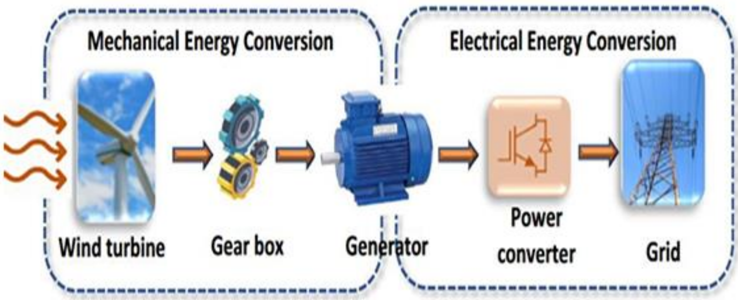


**Figure 1: Layout of WECS**

A wind turbine converts kinetic energy from the wind into mechanical energy, which is then converted into electricity. Here is how a wind turbine works step-by-step:

**A. Wind Capturing**

**Blades**: The turbine has large blades shaped like aeroplane wings to capture wind energy.

The wind flows over the blades, creating a pressure difference (lift force) that makes them rotate.

**Yaw Mechanism**: Ensures the turbine faces the wind by rotating the nacelle (the housing containing key components).

**B. Rotor Movement**

**Rotor**: The blades are attached to a rotor, which spins when the wind blows.

**Tip Speed Ratio**: The rotor speed is optimized to maximize energy capture for a given wind speed.

**C. Gearbox:** Increases the rotational speed of the rotor to match the generator's requirements. Converts the slow rotation of the rotor (10–30 RPM) into a faster rotation (1,000–1,500 RPM).

**D. Generator:** The high-speed shaft drives the generator, converting mechanical energy into electrical energy. Most turbines use either asynchronous (induction) or synchronous generators.

**E. Power Electronics**: Converts raw electricity into grid-compatible electricity (AC or DC as needed).

**F. Grid Integration**

The electricity is transmitted to the power grid or used locally.

The initial stage in modelling turbines in wind energy conversion systems (WECS) is to determine the kinetic energy applied to the turbine. The basic idea underlying wind turbine operation is the transformation of wind energy into mechanical energy, which a generator then converts into electrical energy. The kinetic energy can be found using.

$$E = {}^{1}\!/_{2}\, mv^2$$

E is kinetic energy expressed in joules.

*m* is the mass of the wind or flowing air.

*v* is the wind's speed or velocity.

The equation clearly shows that the mass of the moving air and the square of its velocity are two essential parameters directly related to the kinetic energy within the wind. According to this connection, the wind's kinetic energy increases dramatically as its mass and velocity rise [6]. This basic idea, emphasizes that the more kinetic energy is available, the greater the wind's mass and speed, and this is the foundation of how wind turbines work. This basic idea underpins how wind turbines efficiently capture and transform wind energy into mechanical and electrical power, demonstrating wind's potential as a useful renewable energy source for various uses [7].

The air mass (m), air density (ρ, kg/m³), turbine blade swept area (A, m²), and wind speed (V, m/s) are all important variables that affect how much energy a wind turbine can generate. The energy equation for time (t) needs to be differentiated to determine the power produced by the wind turbine from the wind's kinetic energy. One of the most important measures of wind turbine performance and its ability to effectively transform wind energy into electrical power that can be used is the power generated. The rate of change of energy, or Pwind, is the instantaneous power generated by the wind turbine in a uniform wind field can be expressed as,

$$\text{Pwind} = \frac{dE}{dt}$$

$$= \frac{1}{2} V^2 \frac{dm}{dt}$$

The equation provides the rate at which mass changes.

$$\frac{dm}{dt} = \rho_{air} \text{AV} = \rho_{air} \pi R^2 \text{V}$$

The wind speed and the radius of the turbine blades can be used to calculate the amount of wind power produced by a wind turbine.

The air density is represented by ρ(rho).

A is the turbine blade's swept area, which is usually $\pi R^2$ (assuming a circular swept area).

$$P_{wind} = \frac{1}{2} V_W{}^2 \rho_{air} \text{AV}$$

$$= \frac{1}{8} V_W{}^3 \rho_{air} \pi D^2$$

The 'D' or blade diameter, which represents the size of a wind turbine's blades, has a significant effect on the amount of power it can produce. The power is directly correlated with the wind speed cube. In essence, the amount of power generated can increase significantly and exponentially with even a small increase in wind speed. Also, the maximum quantity of wind power that may be captured is determined by the square of the turbine's intercept area, which is frequently represented by the turbine's swept area.

In practice, the available wind power increases fourfold when the rotor's diameter is doubled. This demonstrates how important rotor size is to effectively capture wind energy. A key component of wind turbine design and performance improvement is larger rotor diameters, which greatly increase the turbine's capacity to harvest wind energy.

Let,

$V_a$ Is the average wind speed through the rotor plane in m/sec.

The upwind speed, expressed in m/sec, is Vu.

The downwind speed is expressed in m/sec as Vd.

$P_{wind} = \frac{1}{2}\rho_{air}\pi R^2 V_a V_u^2 - \frac{1}{2}\rho_{air}\pi R^2 V_a V_d^2$

$P_{wind} = \frac{1}{2}\rho_{air}\pi R^2 \left(\frac{V_{u+V_d}}{2}\right)(V_u^2 - V_d^2)$

Let 'k' stand for the downwind to upwind speed ratio, which calculates,

$$P_{wind} = \frac{1}{2}\rho_{air}\pi R^2 \left(\frac{V_u + kV_u}{2}\right)(V_u^2 - k^2 V_d^2)$$

$$= \frac{1}{2}\rho_{air}\pi R^2 V_u^3 = \frac{1}{2}\rho_{air}\pi R^2 V_u^3 C_p(\lambda, \beta)$$

$$P_{wind} = \frac{1}{2}\rho_{air} A V^3 C_p(\lambda, \beta)$$

The total wind power incident on the turbine is multiplied by the constants in the expression ½((1+k) (1-k2)). The power produced by this multiplication can be transformed into power that the generator can use. A constant known as the power coefficient indicates the proportion of wind energy that the turbine's rotor can absorb. A sophisticated nonlinear function that takes airfoil drag and other characteristics into account is one of the many elements that affect how efficiently wind energy is captured and converted into electricity. The key variables that affect the wind turbine's maximum power output are the blade pitch angle (β) and tip speed ratio (λ), both of which are measured in degrees.

The power characteristic curve, which depicts the two operating modes for wind turbines parking mode and operating mode is shown in Figure 2 [3]. The cut-in, rated, and cut-out wind speed statistics are necessary to characterize or identify these modes. The highest wind speed at which a wind turbine starts its function is known as the cut-in speed.

The wind turbine switches to parking mode and shuts down below this threshold. The maximum wind speed at which a wind turbine can function without suffering damage is the cut-out speed. The wind turbine must stop and switch to parking mode when this threshold is exceeded. The wind speed at which a wind turbine runs and generates its stated power is known as its rated speed. Even if wind speed rises, a wind turbine's output power remains constant until the cut-out speed.

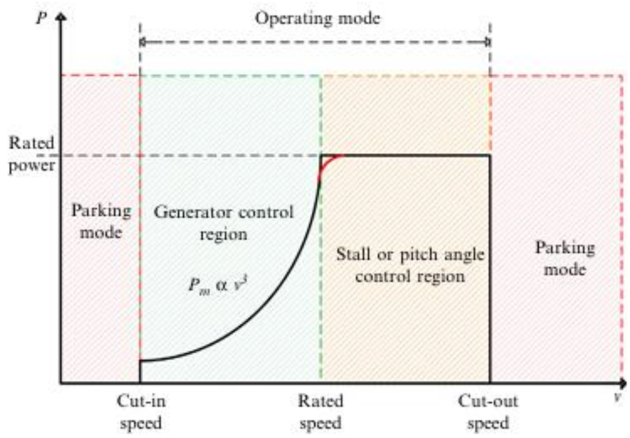


**Figure 2: The wind turbine power characteristic curve**.

In addition, there are two sections to the operating mode: the generator control region and the stall or pitch angle control zone. Starting at the cut-in wind speed, the generator control region rises to the rated wind speed. The primary benefit of this field is the direct relationship between mechanical power and cubic wind speed. The stall or pitch angle control area is between the rated windspeed and the cutout windspeed. The cubic wind speed is no longer proportional to the mechanical power in this area. Wind turbine damage must be avoided by increasing wind speed.

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Pitch Angle Controller: An essential part of mechanical power management is the aerodynamic control system. By altering the blade angle at revolutions over the maximum generator speed, the pitch angle controller in Figure 3 aims to keep the generator from overloading at high wind speeds. When the wind speed is below the nominal value, the ideal angle is nearly zero; as the wind speed increases, the ideal angle rises. It significantly affects both the turbine torque value and the performance coefficient.

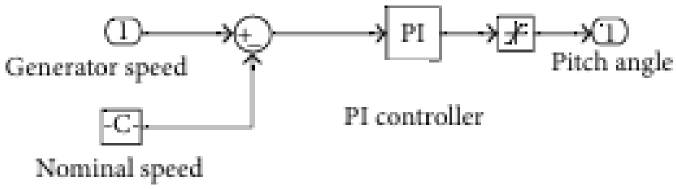


**Figure 3: Pitch Angle Controller.**

The Tip Speed Ratio (TSR), which establishes how well the wind turbine can capture power, is a crucial factor in wind generator efficiency. The turbine produces less power when it rotates too quickly because it inhibits the airflow across the blades. On the other hand, excessive airflow through the turbine causes it to revolve too slowly, which likewise lowers power output. TSR is a crucial factor in wind turbine design and operation since it quantifies the correlation between the incoming wind speed and the tip speed of the rotor blades. There is an optimal TSR for each wind turbine rotor that allows it to efficiently capture the maximum amount of wind energy.

$$\lambda = \frac{R\omega_t}{\mathrm{Vw}}$$

Where $\omega_t$ Represents the rotor or turbine speed in rad/sec.

An essential component of wind turbine functioning is the change in the power coefficient (Cp) to tip speed ratio (λ) with varying blade pitch angle (β) values. Given a range of tip speed ratios, the graph in Figure 4 illustrates how the power coefficient Cp changes with various blade pitch angles.

At a specific tip speed ratio, a wind turbine's aerodynamic efficiency reaches its maximum. A key metric is the tip speed ratio (λ), which is the ratio of the wind turbine blade tips' speed to the wind speed. This ratio significantly impacts how efficiently wind energy can be converted into mechanical or electrical energy. The tip speed ratio needs to be appropriately calibrated to optimise the turbine's power conversion efficiency, a crucial aspect of wind energy usage.


**Figure 4: Wind turbine power coefficients Cp as a function of λ and β.**

## 3. Simulation Circuits and Waveforms

The system design that is offered includes a wind turbine that produces 20 kW of mechanical power under fluctuating wind conditions. Table 1 shows all of the system's essential parts and specifications [8].

### a. Wind speed

The subsequent blocks, as illustrated in Figure 5, mimic the wind speed for the simulation. Between t=0 and t=100 seconds, the wind speed will increase from 0 to 20 meters per second. The wind turbine will go into parking mode below the cut-in speed and above the cut-out speed, meaning that no electricity will be generated. Maximum power may be achieved because the wind speed will stay constant in the operational region.

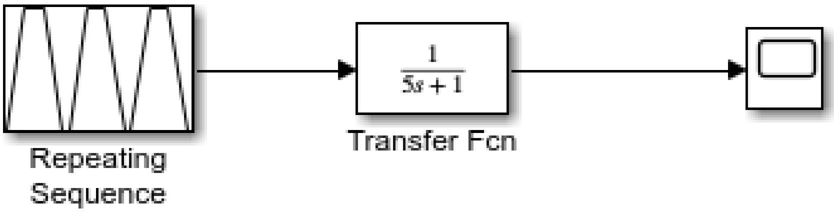


**Figure 5: Wind Speed Simulation.**

### b. Wind turbine

Mechanical energy is transformed into electrical energy by the PMSM, and the resulting energy is then supplied to the local load. To analyze this topology, MATLAB/simscape has been used to simulate it. The wind turbine's Simulink model is displayed in Figure 6. The kinetic energy is transformed into mechanical power by the wind turbine. Wind speed and generated mechanical power are displayed in Figure 7. The mechanical power generated is controlled by the pitch angle and wind speed. When the rotor speed surpasses the cut-in speed, the generator torque controller begins to generate torque. Torque is a function of generator speed when the generator power is below the rated power.

To maximize power, the torque parameters are selected. To maintain the rated power when the power is equal to the rated power, the generator torque varies according to the rotor speed. The Switch block switching criterion uses a blade pitch sensor to display the rated power threshold. The collective blade pitch controller increases the blade pitch once the rated power is reached. Once the rated turbine speed is attained, the collective blade pitch controller starts modifying the blade pitch.

The turbine speed is maintained at its rated value by the controller, a PI controller. The integral and proportional coefficients are scheduled by the blade pitch. Without taking inertial dynamics into account, blade pitch instantly complies with controller commands. The blade rotor is dynamically adjusted by the collective blade pitch controller. The wind turbine's output is maintained by the generator and pitch controllers. The mechanical power is acquired and then fed into the PMSM, which converts it to electrical power, which is then fed into the load. The power system uses reactive compensation to reduce imbalance and regulate voltage.

**Table 1: The parameters of PMSM wind turbine.**

| Component | Specification |
|---|---|
| **Parameters of the Turbine** | |
| **Rotor blade diameter** | 198m |
| **The radius of the rotor blade** | 99m |
| **Air density** | 1.225kg/m$^3$ |
| **Tip speed ratio** | 8.3 |

| Component | Specification |
|---|---|
| **PMSM** | |
| **P rated power** | 15MW |
| **stator d-axis inductance** | 39.5µH |
| **stator q-axis inductance** | 39.5µH |
| **stator resistance per phase** | 0.0008Ω |
| **permanent magnet flux** | 4wb (sinusoidal flux distribution.) |
| **No of poles** | 2 |
| **Frequency** | 50Hz |
| **Reactive Compensation** | |
| **Capacitance** | 400µF |
| **Load** | |
| **Rated Voltage** | 440V |
| **Real Power** | 75kW |
| **Inductive Reactive Power** | 100VA |
| **Capacitive Reactive Power** | -100VA |

## 4. Result Analysis and Conclusion

MATLAB/Simulink is used to give the simulation study of the wind power generation system during operating speed. The information in Table 1 is used to calculate the model for the 20 MW system. The total system working conditions improve with increasing wind speed, which raises operating electrical power and voltage/current parameters correspondingly. The system parameters are monitored while the model runs for 100 seconds. Figure 8 shows the wind energy system's startup procedure and steady-state reaction. From 0 to 20 m/s, the wind speed increases gradually. At cut-in speed (10 m/s), the turbine begins to run.

The wind speed remains constant at the operating region (20m/s) by using pitch angle control. The power generated at the operating region at the rated speed remains constant until the turbine reaches cutout speed. The turbine enters into parking mode gradually power generation reduces. The maximum power is generated at the rated wind speed. The wind power generation's reaction oscillates during startup and stabilizes at the operating region, producing 20MW of mechanical power.

It is evident from the findings obtained in Figure 9 that the PMSG production linearly responds to wind speed. At operational wind speeds, the generated AC voltage reaches a stable value of 5 KV, with an RMS value of 200V. The current RMS value is 20A, which increases to 3KA and stabilizes at operating wind speeds. From 5kW to 15 MW, the electrical power P grows. The power generated was progressively decreased to 1680W at both operating windspeeds and cutout speed.

### Conclusion

Utilizing wind energy effectively can increase renewable energy sources' capacity factor, enhance their ability to produce power, and help make electricity production more economical. The mathematical modelling of wind turbines and their different characteristics are obtained from different parameters considered. A standalone wind turbine system was modelled and analyzed using MATLAB/Simulink and the outcomes met the design specifications. It is seen that the wind speed is not constant and it depends on the environmental conditions this

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variation in the wind speed can be controlled by a pitch angle controller and the desired constant electrical power is generated at operational wind speed.

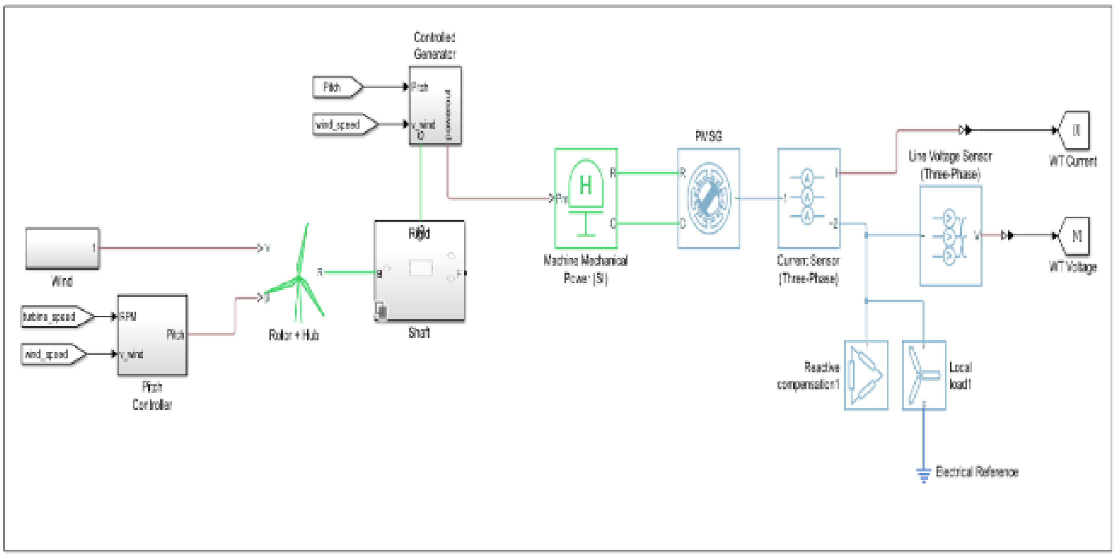


**Figure 6. MATLAB/Simulink model of the wind energy system.**

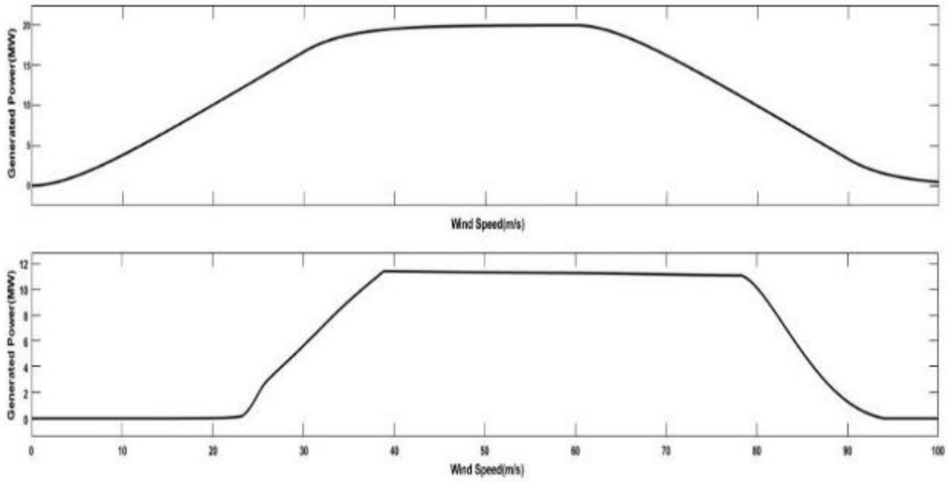


**Figure 7: Wind Speed and Generated Mechanical Power.**

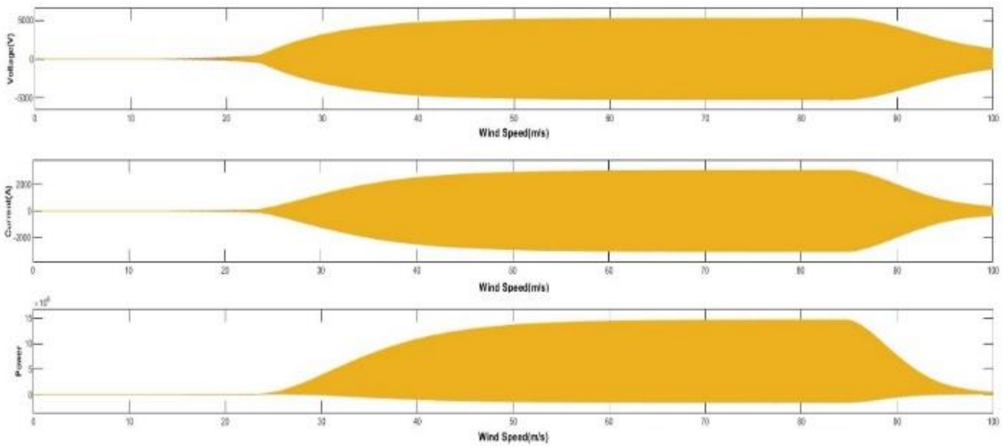


**Figure 8: The waveforms of Voltage, Current, and Power of PMSG.**

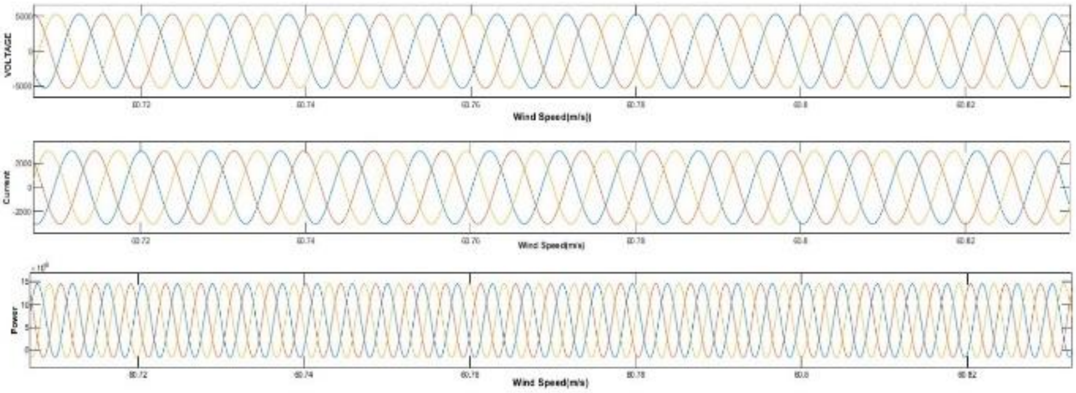


**Figure 9: The waveforms of the phase Voltage, Current, and Power of PMSG.**

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