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Article

Modeling and Control of Pitch Angle of HAWT Induction Generator in Wind Energy Conversion System

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ABSTRACT

Wind energy is a sustainable and environmentally friendly source of power that has recently been the subject of abundant research aimed at maximizing its practical application. The primary benefit of wind turbine systems is enhancing the turbine's design and performance. Modeling by the graphical user interface of MATLAB provides a clear picture of the wind turbine's efficacy in a real-world scenario. This study investigates a horizontal-axis wind turbine with a variable pitch mechanism. The wind speed and pitch angle were manipulated in MATLAB-Simulink to simulate the turbine. Variables such as wind speed and angle of attack influence the active power output of the turbine. The results indicate that the optimal wind turbine characteristics, including pitch angle and turbine speed, are attained at different wind speeds. Consequently, through the process of simulating and analyzing the outcomes, it is ascertained that the turbine attains its maximum active power output when the pitch angle is optimized.

Keywords: Wind Energy Conversion System (WECS), Modelling, MATLAB/Simulink, Pitch Angle Control, Permanent Magnet Synchronous Generator (PMSG).

1. Introduction

The transformation of the conventional power grid owing to the integration of Renewable Energy Resources (RER) is a significant development on a global scale. Conventional power plants produce electrical energy through the combustion of fossil fuels, including diesel, coal, gasoline, and others. Coal is the preferred option among these because of its sample supply and economical cost compared to alternative fossil fuels. Globally, coal-fired power stations generate approximately forty percent of the electricity supply. On the contrary, coal-fired power facilities contribute to environmental degradation by emitting greenhouse gases into the atmosphere. It has a detrimental impact on global warming and contributes to the rise in sea levels. Furthermore, the expeditious consumption of fossil fuels contributes to their elevated depletion rate. Thus, RER plays a crucial function in generating electricity [1–2].

The rate at which electrical energy is extracted from renewable energy resources is experiencing significant growth due to their inexhaustible availability on the land surface. Furthermore, RER has an exceptionally minimal impact on the environment compared to conventional power facilities. RER is categorized as biomass, solar, wind, hydro, and tidal. On the contrary, solar energy extraction is expanding rapidly due to the technology's low cost per unit installation. The potential energy of solar PV is subject to substantial variation depending on atmospheric conditions, as its operation is predicated on photovoltaic effects [2-3].

A wind turbine is an apparatus designed to harness the mechanical energy of the wind. In turn, the generator facilitates the conversion of mechanical energy to electrical energy. Various horizontal-axis wind turbines exist, including the Savonius and Darrieus turbines. The rotor, an essential element of wind turbines, consists of blades that facilitate wind energy capture. The rotor is linked to the generator, and depending on the design of the wind turbine, a transmission may be positioned in intermediate space. Subsequently, the generator is linked to the electrical grid. The transmission and generator are encased in a nacelle, which serves as the mounting structure for the entire system atop the tower. Simulink is a graphical programming interface based on MATLAB that facilitates real-time simulation of dynamic systems. Simulink comprises an extensive array of functionalities, encompassing mechanical, electrical, and hydraulic systems, among many others. It is feasible to optimize the design by simulating and obtaining real-time results by developing the necessary model. In the simulation, a wind turbine facility is constructed in MATLAB and connected to the virtual electric grid. A statistical analysis test is performed to ascertain the power and coefficient of power corresponding to the experimental equivalent data. Three distinct wind speed levels are selected for the purpose of analyzing the active power output: low, with an average velocity of 5 m/s; medium, with an average velocity of 8 m/s; and high, with an average velocity of 12 m/s [4].

A wind turbine system with a fixed pitch angle is subjected to a simulation to determine the effectiveness of maintaining the fixed pitch angle at varying velocities. The scope of the simulator illustrates the relationship between mechanical power and wind velocity [5]. To maintain a constant power output, installing a horizontal axis wind turbine is analyzed to identify the performance-influencing factors, most notably the influence of pitch angle at consistent speeds. An analysis of the wattage generated in response to the effect of pitch angle is conducted using the properties of the aerofoil blade [6]. Achieving optimal wind energy from atmospheric wind presents a challenge; therefore, the suggested nonlinear predictive control system relies on a discrete prediction model implemented with a significant time step; its efficacy is evaluated compared to an industrial controller. The results demonstrate that the proposed method improved energy extraction efficiency [7].

MATLAB/Simulink is employed to simulate and model a horizontal axis turbine to enhance the performance of a three-bladed configuration within a variable-speed wind turbine system operating at specified velocities. Wind system modeling aims to improve turbine system performance [8]. The investigation entails the modeling and simulation of a 2 MW direct drive wind energy conversion system. In the absence of a transmission, a Permanent Magnet Synchronous Generator (PMSG) that is physically connected to the wind turbine is utilized as the generator. This is referred to as PMSG direct drive wind systems. By disregarding the gearbox, significant reductions in transmission losses occur, leading to an overall enhancement in efficiency [9]. This work demonstrates how to obtain a constant output voltage value using a PI controller. The PI controller is utilized to alter the pitch angle of the blades, which induces a corresponding change in thrust and aids in maintaining a constant voltage. In wind turbines, the PI controller is frequently employed to regulate the pace and trust [10].

A wind system is devised with the capability to authenticate the power captured and torque generated in real time. A permanent magnet synchronous machine is employed in conjunction with a wind turbine that has a fixed pitch. The paper presents a dynamic model of the wind turbine power system [11]. A comparative analysis of the efficiency performance of two minor wind turbine systems that are potentially connected to the grid. Wound rotor induction generators and permanent magnet generators are the two potential grid systems. A method for determining power losses is described, along with an examination of the anticipated efficacy of the system. The efficiency of wound rotor induction generators is discovered to be greater than that of permanent magnet generators [12]. Power is regulated through pitch control when the wind velocity exceeds the rated velocity. The most prevalent method in this context is pitch control, typically accomplished with a PI controller. The pitch-controlled wind turbine, connected to a permanent magnet synchronous generator, is simulated using MATLAB-Simulink [13]. The global energy landscape places significant emphasis on the application of technology-driven approaches and the pivotal role that innovations play in advancing and modernizing emerging energy systems. The primary areas of emphasis are ultra-high voltage infrastructure, large capacity storage, and communication, all of which are crucial in the design process of wind systems [14]. More than fifty distinct analyses are performed on the wind turbines, examining a variety of methodological approaches and assumptions and calculating the energy return on investment about the power rating. This aids comprehension of the conditions more favorable to wind turbines than those favorable to fossil fuels, nuclear power, and solar power generation technologies [15].

The design of wind turbine systems should be the subject of research that addresses the difficulties associated with wind energy conversion systems and their grid transmission. It provides novel avenues for investigation into enhancing turbine aerodynamics, generator configuration, and power control systems, thereby facilitating the development of dependable systems [16]. Therefore, the primary objective of this research is to utilize MATLAB-Simulink to model and simulate the wind turbine system that has been designed and analyzed. This study investigates the effect of varying blade pitch angles on the wind turbine's performance at various rotational velocities. It is possible to deduce the graphical solution from the simulation results and optimize the wind turbine's design accordingly. The manuscript is partitioned as follows: The research consists of the following sections: introduction, methodology discussion, simulation presentation in the third section, results presentation in section four, and conclusion in section five.

2. Methodology

The turbine's output is proportional to the wind's velocity and angle of attack. The performance characteristics of a wind turbine, including the torque on the rotor, would alter in response to variations in wind speed. A turbine translates the energy captured from moving air into electrical energy. The following equations describe the power coefficient, air density, and turbine-swept area as variables that influence the captured energy:

$$P_m = \frac{1}{2}\rho A\, C_p(\lambda, \beta) v^3 \qquad (1)$$

The equation represents the power produced by the wind (P_m) in watts. It involves variables such as the density of air (ρ), which is 1.225 (kg/m^3), coefficient of power (C_p), wind velocity (v) in meters per second, and the swept area (A) in square meters.

Scientist Betz proved that the optimal power output of an ideal turbine rotor, with an unlimited number of blades, utilizing wind energy in perfect conditions, is 59.26% (0.5926 times) of the available wind power. The term used to describe this restriction is the Betz limit. Wind turbines are designed with two or three blades for structural and economic reasons. As a result, they are able to harvest around fifty percent (0.5 times) of the available electricity. The definition of the tip speed ratio (TSR) of a wind turbine is:

$$\lambda = \frac{R * \omega}{v} \qquad (2)$$

where ω = The rotor shaft mechanical speed (rad/s) of the wind turbine; R = Radius of the blade (m); v = Air velocity (m/s),

The blade pitch angle β, and TSR are utilized to compute the rotor power coefficient, C_p. The coefficient of rotor power can be computed as:

$$C_p = \text{Extracted power / Power in the wind} = P_{rotor} / P_{wind} \qquad (3)$$

Pitch change mechanisms (Pitch angle control) are incorporated into variable-speed wind turbines to modify the blade pitch angle for a more favorable power coefficient profile by regulating the rotational speed [17].

A. Simulink modelling

The wind turbine facility is represented through the utilization of electrical and mechanical tool sets sourced from Simulink. A turbine with a horizontal axis is chosen and inserted into the empty model. For phasor operation, the induction generator is modified. The phasor type entails modifying the system to connect the stator winding directly to the grid, and the turbine propels the rotor. A turbine is connected to a three-phase transformer consisting of two windings; the transformer outputs are connected to the three inputs of the turbine, as illustrated in Figure 1. At 60 hertz, the frequency of the transformer is configured. The ABC terminals are connected to winding 1 (see Figure 1), while terminals a, b, and c are connected to winding 2. As illustrated in Figure 2, terminal n2 of the three-phase transformer is linked to the Series RLC branch.

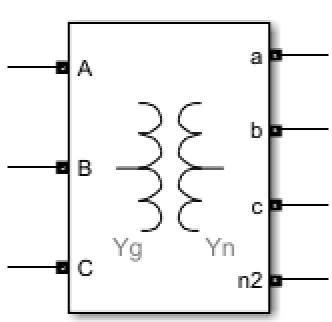

Figure 1. Three-phase transformer

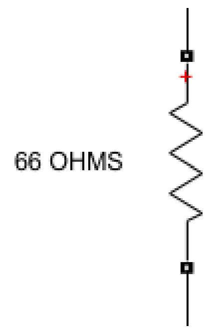

Figure 2. Series RLC branch

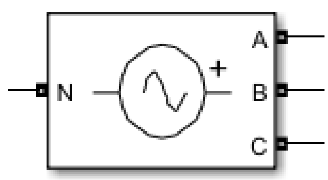

Figure 3. Three-phase programmable voltage source

which is explicitly designated for the resistance R and is connected to the ground at the opposite end of the resistor (Figure 3). An opposite end of a three-phase programmable voltage source is linked to the ground and connected to the transformer. At 25 kV, the voltage is adjusted. The input wind speed is to increase in a stepwise fashion. As a result, the wind speed is input to the turbine via a step function rather than the standard input, and a trip is connected as the turbine's input. The bus connector is connected to the turbine's output, which restricts the occurrence of diagrams to p and q. Every individual output of the bus connector is linked to the gain tools, which amplify the signal before connecting it to the scope and display it to observe the results (Figure 4).

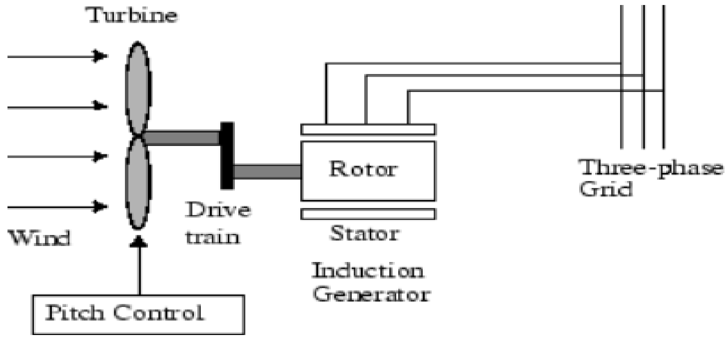

Figure 4. Wind Turbine Induction Generator (Phasor type) [18]

B. Component of wind turbine

The wind turbine is composed of the subsystems illustrated in Figure 5.

- Rotor blades and hub.
- The nacelle comprises the generator, transmission, shafts, and couplings.
- Tower that holds the Nacelle.
- Power converters, switchgear, transformers, and cables comprise an electrical system.

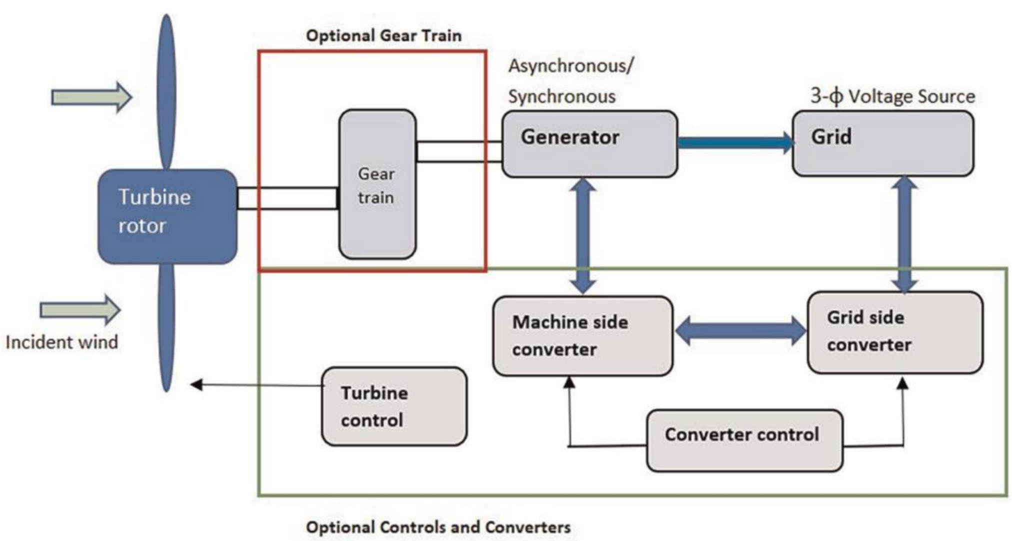

Figure 5. Modern Wind Turbine diagram

3. Simulation

A. Power equation simulation:

The model (Figure 6) has been constructed to illustrate the impact of the variables (equations 1 and 2) on the power output of a wind turbine. Figures 7, 8, and 9 depict the corresponding output results. The Simulink model applies to a diverse array of wind turbines. The proposed wind turbine's specifications are detailed in Table 1. Any value may be modified by adjusting the setting values of the blocks [19, 20].

Table 1 Characteristics of the wind turbine.

Diameter of the Rotor	52 m
Swept Area	2.125 m^2

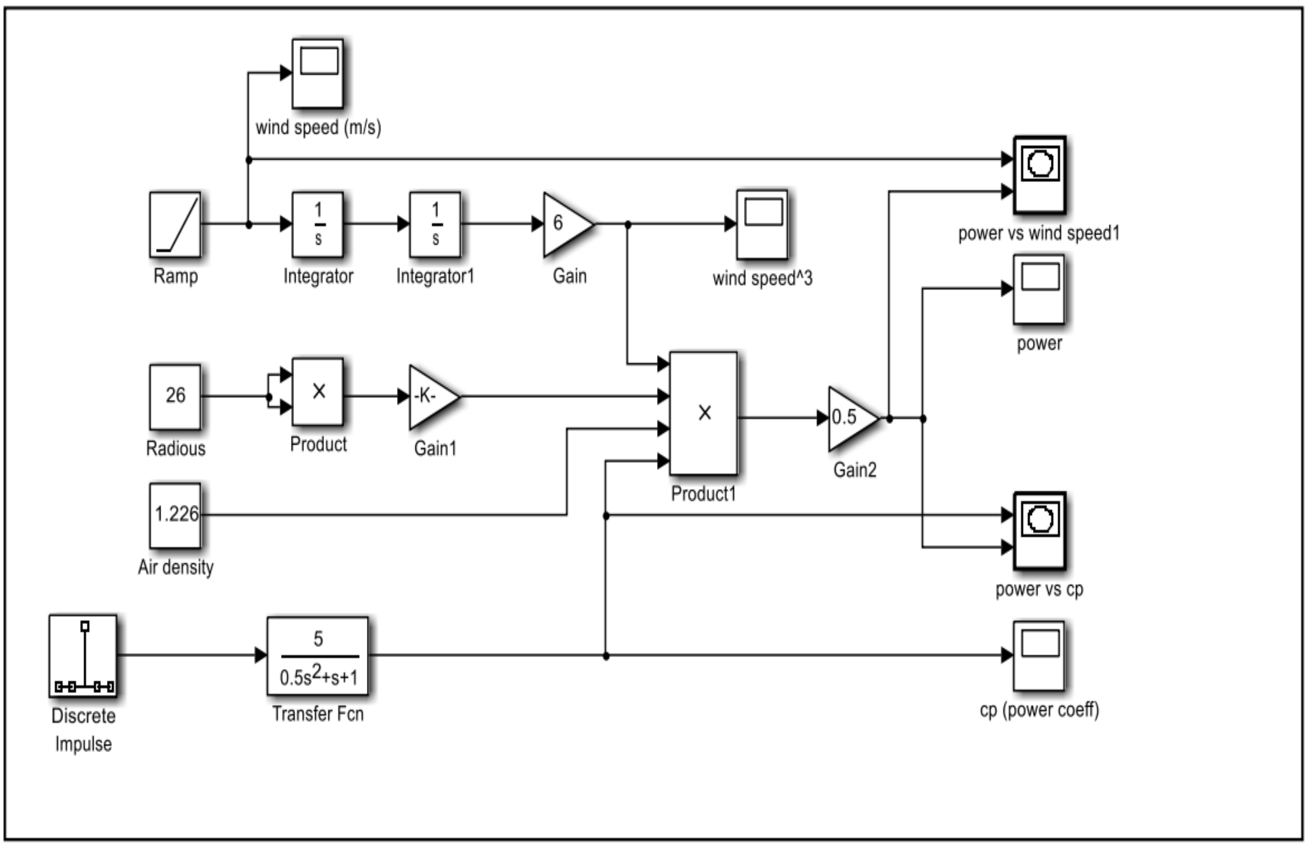

Figure 6. Simulink model for equations 1 and 2.

B. Wind turbine plant modeling:

The wind power plant illustrated in Figure 6 was constructed using MATLAB-Simulink in accordance with the block diagram. The system involves a wind turbine with a variable value of 1.5 MW, which is connected to a three-phase transformer with a capacity of 400 KVA and an electric source of 25 KV. Active and reactive power is assessed across various wind velocities and blade pitch angles. The correlation between turbine speed, which is contingent upon wind speed, and turbine output power is depicted in Figures 9, 10, and 11, showcasing different wind speeds and blade pitch angles. An advantage of MATLAB-Simulink is the capacity to easily modify these values by adjusting the parameters of the system parts [23-25].

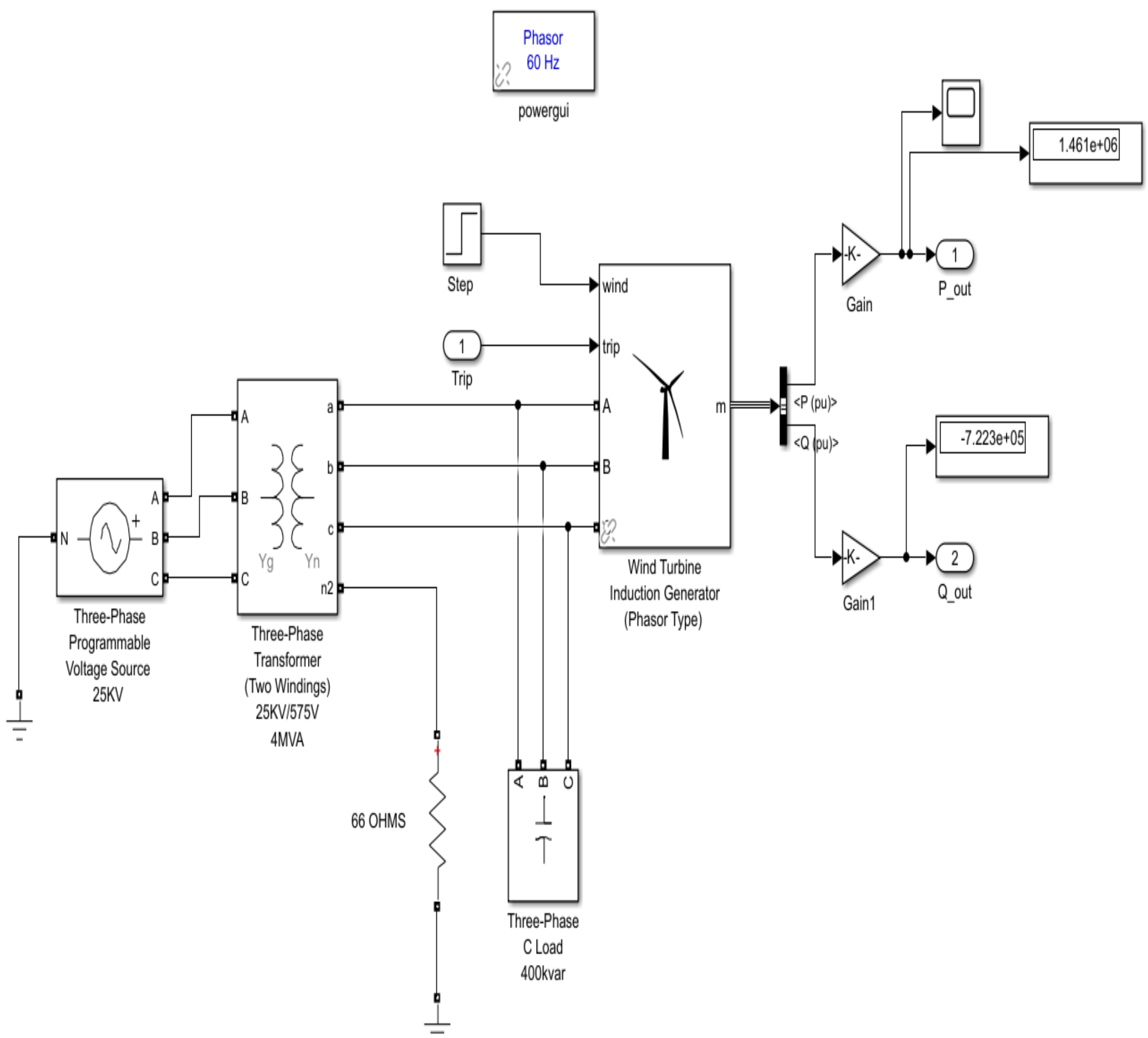

Figure 7. Power plant wind turbine.

C. Pitch angle control system

The pitch angle is characterized as the degree of opposition between the blade and the airflow. Altering the pitch angle results in a corresponding modification of the wind's angle of attack. This can be achieved by modifying the wind turbine parameters block in MATLAB-Simulink, as illustrated in Figure 8. For instance, the turbine generates maximum power at a pitch angle of zero and a wind speed of 12 meters per second, as depicted in Figure 12. However, when the pitch angle is reduced to 5 and 10, respectively, for an equivalent wind speed, the output power diminishes. This observation underscores the influence of pitch angle. Therefore, evaluating the pitch angle value for optimal wind speed is essential to get maximum power, as it changes automatically with high or low wind speed. Position control is utilized to do this, with the wind turbine's set point being determined by the optimal pitch angle value. This position control system adjusts its pitch angle in response to the wind speed. When wind speed is high, the pitch angle drops; when wind speed is low, the pitch angle increases. The goal is to sustain a consistent velocity, maximize the power generated, and guarantee the durability of the blades [26-28].

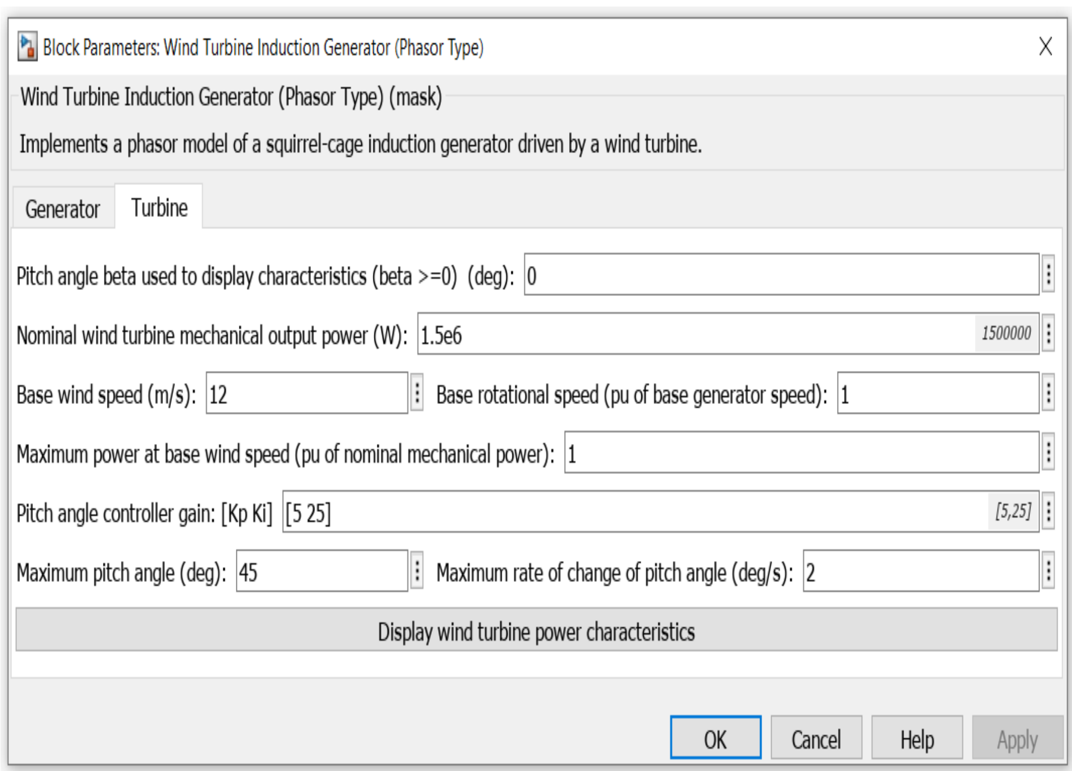

Figure 8. The wind turbine parameters setting block.

4. Results and discussions

A. Power equation simulation:

The results indicate that the wind speed varies with time, as depicted in Figure 9. Due to the variability in wind speed in actuality, the curve exhibits nonlinearity. The wind speed can be calculated by integrating the Ramp function twice, as illustrated in the upper portion of Figure 6. Multiplying the result by 6 yields the wind speed ^3 and the power and power coefficient. Consideration must be given to the local conditions when designing a sweep area in order to extract the maximum amount of power feasible from a wind turbine. Figures 10 and 11 demonstrate that the output power is directly related to the tip speed ratio and wind speed, as outlined in Equation 2. The blade pitch angle determines the tip speed ratio. The turbine's power rises proportionally with the wind speed until it reaches a specific limit. At this point, it lowers because of activating a safety control system in the turbine's nacelle.

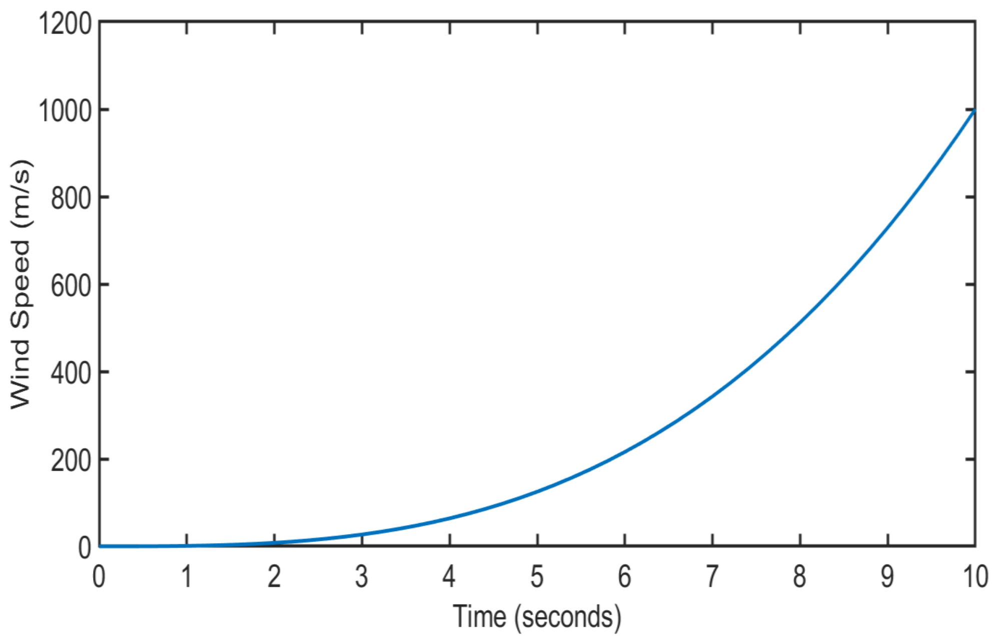

Figure 9. Wind speed m/s simulation

The extent of the blade's sweep greatly influences its effectiveness. The amount of power generated by wind is directly proportional to the size of the rotor's diameter. The effectiveness of wind turbines is greatly influenced by air density. Furthermore, the amount of wind power that can be harnessed is directly correlated with the density of the air. When the air density increases, the power increases, and vice versa. The density of air is also contingent upon the temperature and pressure of the air. The relationship is directly proportional to air pressure and inversely proportional to temperature. Simultaneously, as the altitude rises, temperature and pressure exhibit an inverse relationship [29-31].

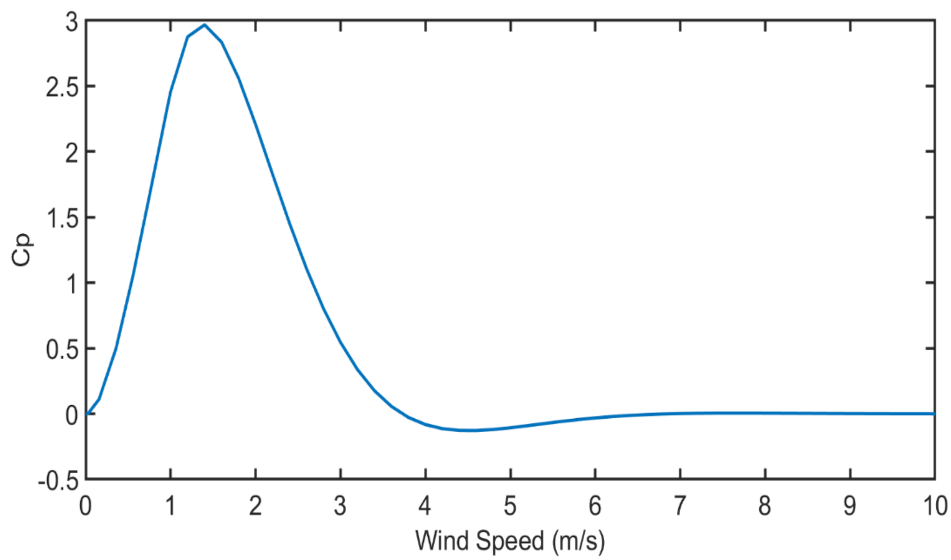

Figure 10. The correlation between wind speed and C_p

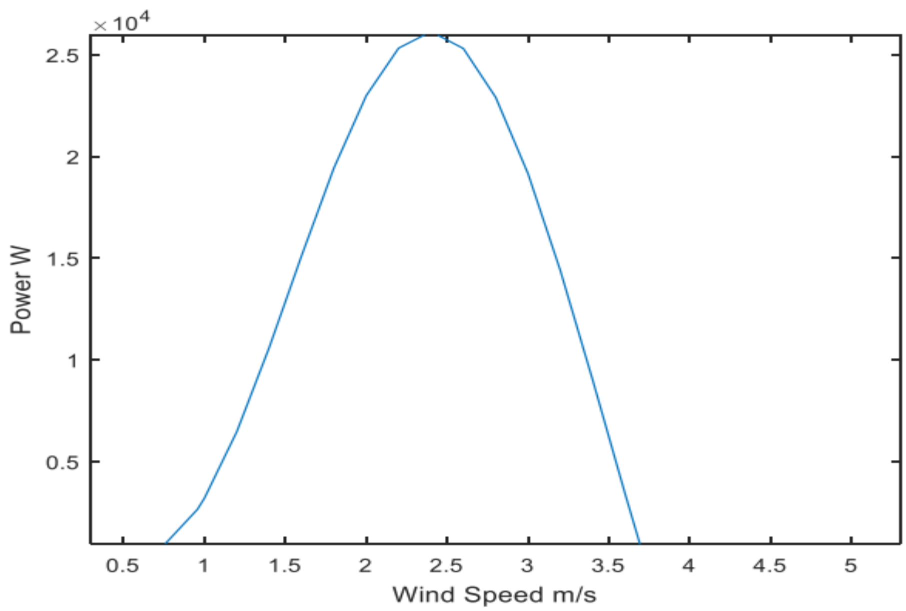

Figure 11. The correlation between wind speed and power.

B. Wind turbine plant and pitch angle control simulation:

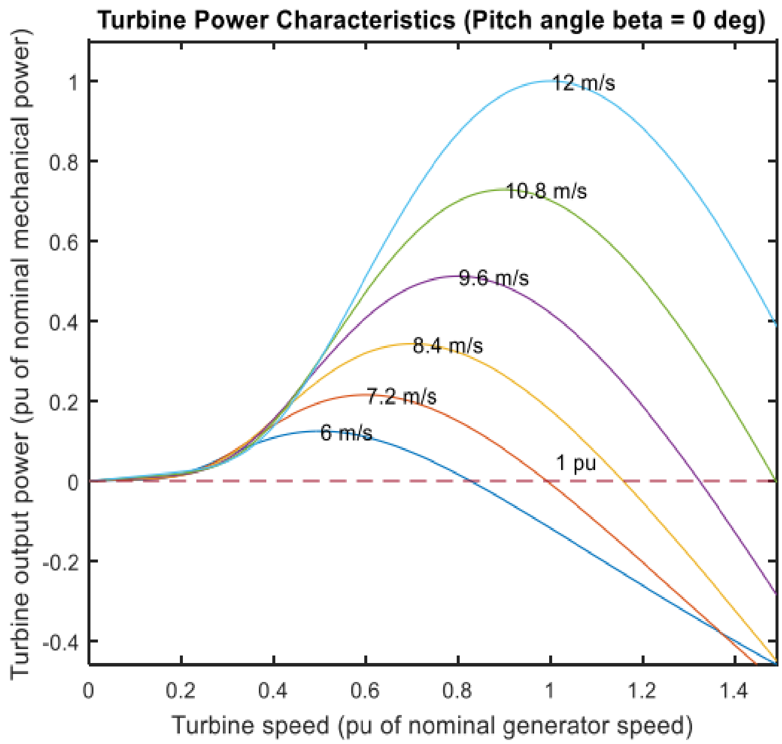

Figure 12. Relationship between turbine speed and output power under zero pitch angle.

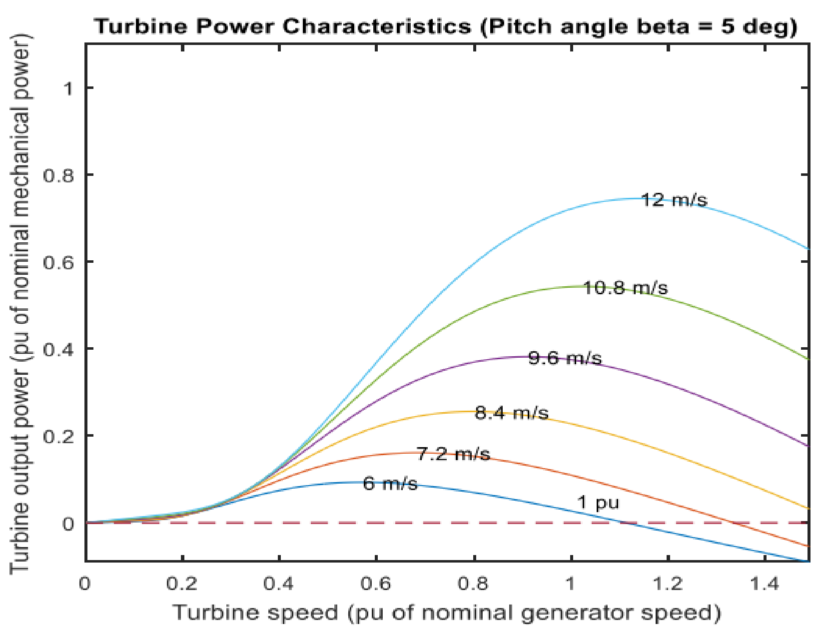

Figure 13. Relationship between turbine speed and output power for pitch angle equal 5.

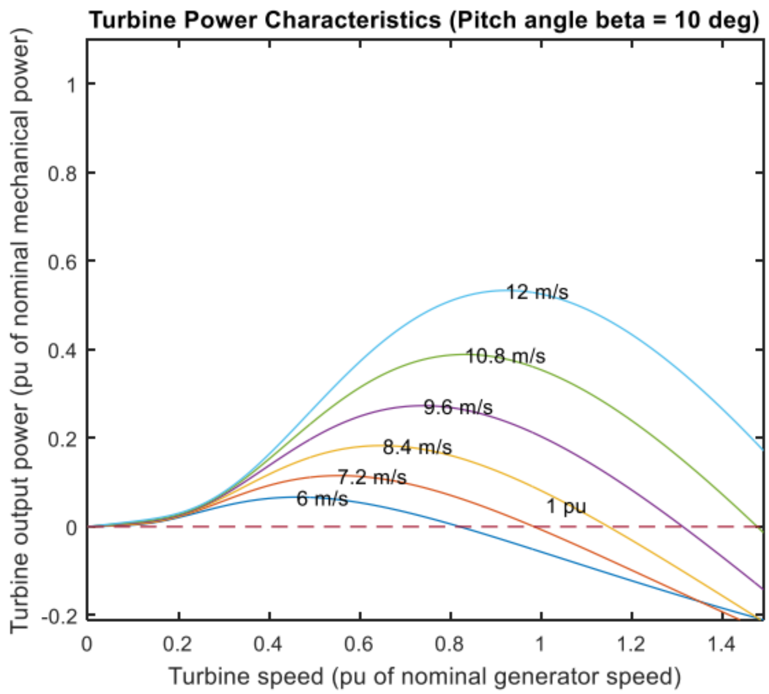

Figure 14. The relationship between turbine speed and output power for pitch angle equal to 10.

Power can be defined as the rate at which energy flows past a specific location in an electric circuit. Energy storage components utilized in alternating current (AC) circuits, including inductors and capacitors, may induce periodic reversals in the direction of energy flow. Active power, also referred to as real power, denotes the proportion of power that results in a net transfer of energy in a single direction throughout an entire cycle of the AC waveform. This study investigates the impact of varying wind speed on active power output, assuming a constant pitch angle. The process can be executed within the wind turbine parameters block, as illustrated in Figure 8. As illustrated in Figure 15, since the output power of the wind turbine is dependent on wind speed, the output power varies as the wind speed does. As previously described, the wind turbine developed in this study achieves a maximum power of 1.5 MW at 12 m/sec or higher wind speeds. This power is maintained despite lower wind speeds due to the pitch angle position control mechanism, which increases the output power by adjusting the pitch angle to a specific value to induce a higher rotational speed of the fan and decrease it at lower wind speeds [24].

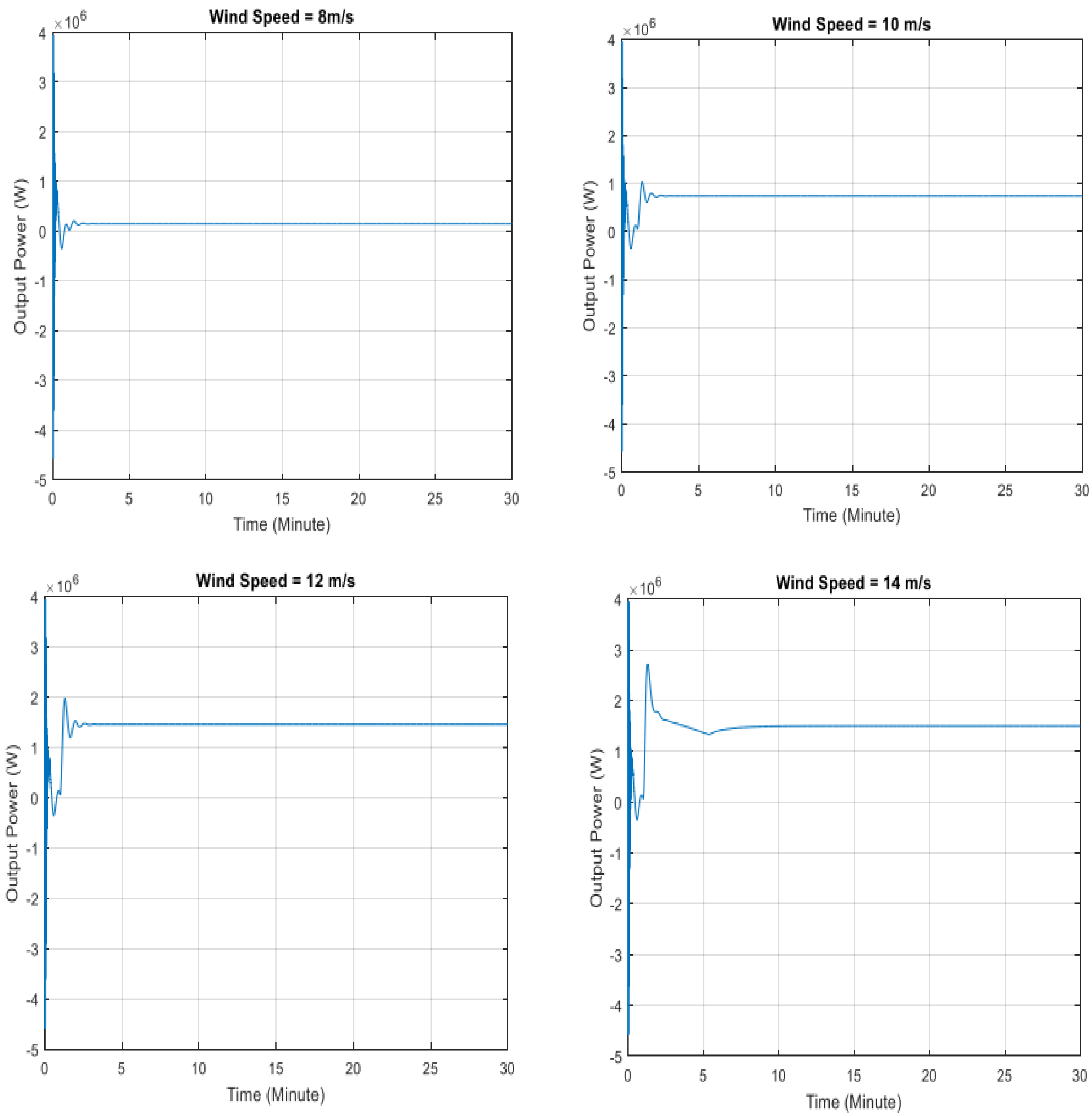

Figure 15. Wind turbine output power for different wind speeds.

Determine the effect of wind speed variation on the output active power by combining all the curves in Figure 15 into a single curve in Figure 16.

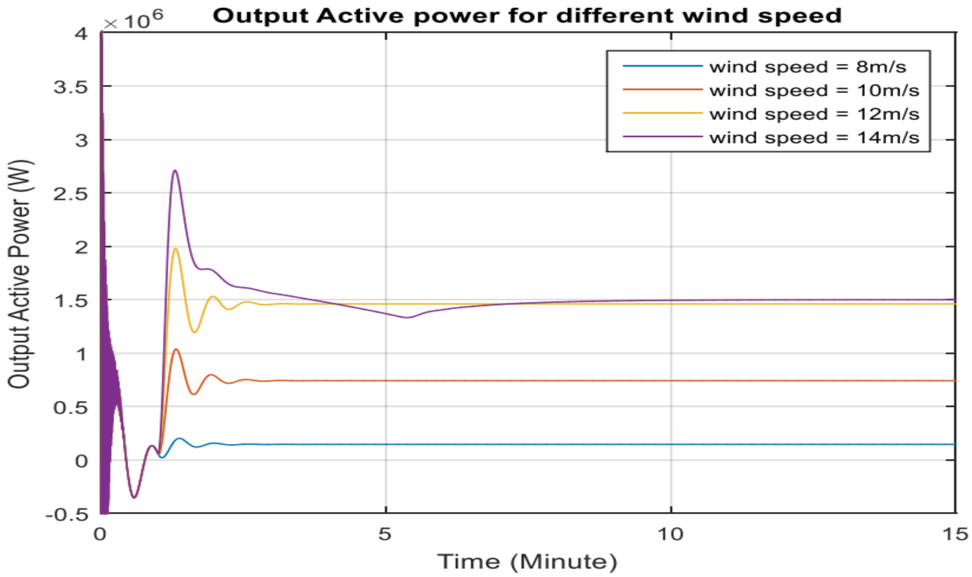

Figure 16. Wind turbine active power.

Furthermore, this study involved measuring reactive power to obtain comprehensive insights into wind turbines. Reactive power, which returns to the source with each cycle, is the proportion of power generated by stored energy in wind turbines (Figure 16). The reactive power profiles for wind speeds varying in magnitude are illustrated. Figure 17 concludes with a screenshot of the MATLAB-Simulink scope display, illustrating the proposed wind turbine's output curve [24].

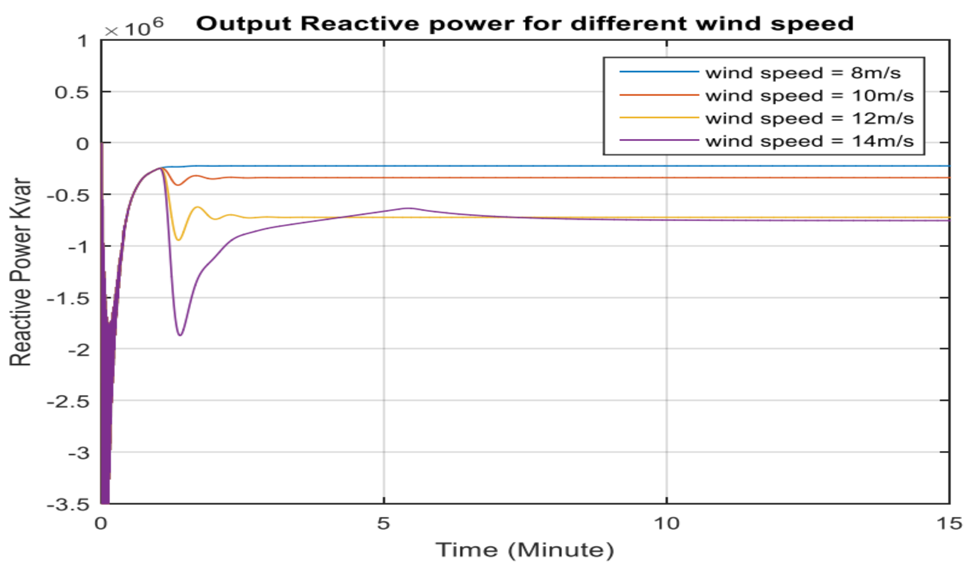

Figure 17. Wind turbine reactive power.

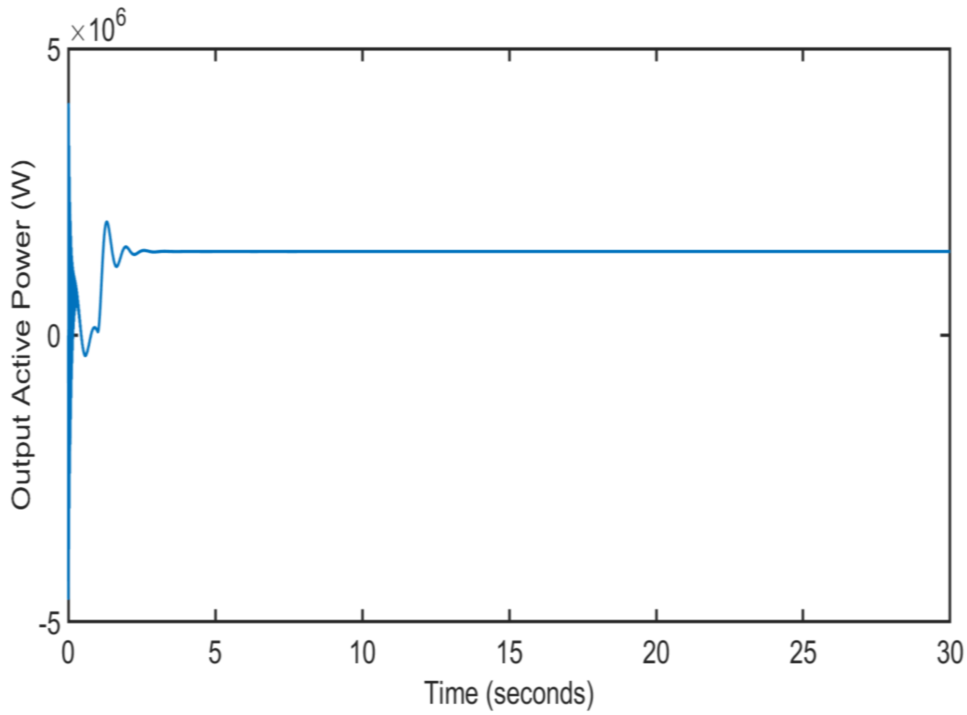

Figure 18. Scope display of the MATLAB-Simulink.

5. Conclusion

In this paper, applying wind energy to generate electricity is significant to the electricity market. Effective utilization of wind energy has the potential to improve the capacity factor of renewable power generation, thereby contributing to cost-effective electricity production. During the fabrication or installation of wind turbines, numerous parameters are considered, including air density, wind speed, and the power coefficient as a function of blade tip speed and pitch angle. This investigation involved using MATLAB/Simulink to model and simulate a wind turbine generator. The model developed in this research is readily comprehensible. The work demonstrated the incorporation of the developed wind turbine model into the public electrical infrastructure. Once the model was constructed, it was used to determine its utility; it was required to analyze its behavior when integrated into the entire power system. A variety of wind speed levels were considered, including low with a mean value of 8 m/s, medium with a mean value of 10–12 m/s, and high with a mean value of 14 m/s. These enabled the monitoring and predicting of the system's active and reactive power output. In future work, the authors tend to verify the proposed work experimentally and apply artificial neural networks to the PC of wind turbines.

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- **Conflict of Interest**

The authors declare no conflict of interest.

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