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Study and Analysis of Adaptive PI Control for Pitch Angle on Wind Turbine System

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ABSTRACT

In the current work, a study is proposed using the engineering program MATLAB through computer tests of a simulation model for modifying the tilt angle in wind turbines, with a study of the effect of changing the angle of the wind turbine on the mechanical energy resulting from changing wind speed. Variable wind speeds reduce turbine efficiency; pitch control mitigates this. A PI-based pitch controller adjusts blade angles to maintain optimal λ.20 kW model achieved 15% higher power output at variable speeds. λ (tip-speed ratio) and Cp, λ the ratio of blade tip speed to wind speed, determines turbine efficiency. Unlike prior fixed-speed models, our variable-speed design adapts to turbulent winds via real-time pitch adjustment. This approach aids in stabilizing grid integration for renewable energy systems. While pitch control improves turbine efficiency, existing studies lack real-time adaptive strategies for variable wind speeds. our work optimizes pitch angles dynamically using MATLAB simulations. We propose a data-driven pitch control model for 5 kW and 20 kW turbines, validated under turbulent wind conditions. This study aims to maximize power output by correlating pitch angle (β) and tip-speed ratio (λ) via MATLAB simulations. As a research contribution, the turbine characteristic curve is examined, as changes occur with changes in lambda, and the Cp Max is obtained at the optimal lambda. Assuming that beta is chosen from the curves to determine how it changes and its effect on operation at a given Cp, a given lambda is determined from the curve. Torque can be recognized as the first variable, both mathematically and physically. A change in torque affects speed, and thus affects lambda. Since there is a relationship between turbine speed and wind speed with lambda, turbine speed also depends on mechanical speed. The aim of the study is to design and build a simulation model using a mathematical representation of a wind turbine to study the effect of tilt angle control on handling changes in wind speed. The research contributions include the design of two models: one with a capacity of 5 kW and the other with a capacity of 20 kW. The first model uses a constant speed, while the second uses a variable wind speed. To stabilize the output at rated power, the turbine is angled. Using the wind turbine simulation model and some proposed tests, we can determine the behavior of the system as speed changes.

1. Introduction

Energy production requires various sources, including electricity, a traditional source of energy production, using fossil fuels. As a result of technological advancements, a more advanced method has emerged: the use of renewable energy. Converting energy into electricity requires an efficient system, which prompts researchers in this field to focus their studies on the best systems in terms of efficiency, cost, and lifespan, as well as achieving the objectives of building these systems, such as producing the energy required to cover electrical loads. Maintaining a clean environment is one of the most important factors that encourage the use of clean and environmentally friendly energies in the field of electricity production. Wind energy is one of the clean and environmentally friendly energies and is used as an alternative energy to fuel to produce electrical energy. Wind energy is essentially a variable energy depending on the change in wind speed and is not constant in terms of energy output under normal conditions. This is a problem resulting from the fluctuations in energy production with the change in wind speed. This challenge requires finding solutions to produce stable energy. The relationship is that energy production is linked to wind speed and its percentages may be high or low depending on the size of the system and the size of the change in speed and the resulting fluctuations. In previous studies, some solutions were found to control these fluctuations and control the fluctuation in the production of output power through, for example, the installation of an energy storage system, but this strategy is relatively expensive. Another method is to use the tilt angle control strategy. These strategies include the feed-forward method and the regression method. However, there is a difference in the system parameters, which affects the fact that they do not adapt to the fluctuations in the wind generator in energy production. The ideal solution is to have adaptation according to the process of regulating and adjusting the tilt angle control, which requires specifying reference values as input to the control unit and representing a processing that works to reduce errors. To verify the effectiveness of the system, more than one test case can be set up for comparison and the best one can be selected based on the results of the proposed tests.

Wind turbines are an efficient technology that converts mechanical energy (generated from the kinetic wind) into electrical energy [1]-[3]. Electrical energy obtained from wind power can be used in many areas, making it an important and interesting topic for researchers and a worthy research topic for renewable and clean energy using wind turbines [4]-[6]. Numerous research contributions can be made in the field of wind energy generation, including the development, construction, and design of a dynamic system for moving turbine blades using air, which enhances the ability to meet loads [7]-[9]. This requires the necessary studies and analyses to develop the system. Other contributions include reducing noise resulting from turbine movement and friction by selecting the appropriate shape and size according to models and methods for high-performance functionality using advanced and effective technologies [10]-[12]. Storage systems are important as they can be integrated with generation sources, where systems and units can be installed to store surplus energy to enhance the management and organization of the system's operation in meeting the required load with energy. Energy systems are a focus of attention for researchers, academic institutions, companies, and all relevant sectors, both near and far [13]-[15]. Numerous views have been raised by various stakeholders regarding control methods, as well as conversion devices such as electronic power converters, thermal storage panels, electrical energy storage, and many other areas that could open up broad research areas [16]-[18]. Experts are always thinking about building a highly efficient, reliable, and secure system, in addition to identifying problems and developing solutions by continuously updating the behavior of these systems during real-time operation [19]-[21].

The increased demand for electrical energy in various fields is very costly and environmentally impactful, which requires the use of alternative, environmentally friendly energy sources. The importance of generating and producing energy from multiple sources to meet demand in the appropriate quantities has become a major concern for specialists. One of these sources is the generation of electrical energy from wind energy. Wind turbines are classified according to the axis of rotation into horizontal and vertical, depending on the position of the blades. In horizontal turbines, they are parallel to the direction of wind movement, while in vertical turbines, they are perpendicular to the wind. Another classification is based on the location of the wind farms. Some of these turbines are located in seas and oceans and are called offshore turbines. These turbines operate at a constant speed, while others operate at variable speed. As a result of the advancements and developments in the field of energy technology and electronics, they can be connected to the grid using AC power converters. Variable speed turbines differ from fixed speed turbines in terms of maintenance, control, structure, and cost. There are turbines connected to a synchronous generator, while others are connected to an induction generator. Synchronous generators are more common and widely used than induction generators because they are relatively cheaper, require less maintenance, and are more efficient. Developing a strategy to control the operation of a wind turbine power generation system to improve performance is essential. Variability in wind speed is a significant factor in energy production, and the relationship represents a comparison between the output power and the reference or rated power. To achieve this, the turbine must rotate at the rated speed to obtain that power. Some of the variations that occur during system operation include the wind turbine's rotational speed being less than the rated speed, while others may be greater than or equal to the rated speed. To obtain the required power in the system output and achieve maximum energy, it is possible to follow an appropriate operating strategy to save energy and stabilize the turbine rotation speed using appropriate control units.

Researchers are interested in improving performance by adding management and control systems to how wind turbines operate under different scenarios [22]-[24]. Among the research contributions are working on how to manage the pitch and yaw of turbines and how they can adapt through control units that effectively handle system fluctuations and disturbances [25]-[28]. To protect the system structure (wind turbine architecture), it is necessary to study how to maintain the system's health and address and detect faults according to multiple strategies and methods [29]-[31]. Achieving system protection requires the implementation of advanced technologies that enable early detection of faults by installing sensors tuned to appropriate data, and a maintenance schedule is also established [32]-[34]. Therefore, it is necessary to establish a suitable architectural engineering for building the system, in addition to establishing a foundation for building a structural model and a mechanism for assembling its components, and determining the criteria for evaluating the resulting environmental impacts and the expected lifespan of the materials used in building the system, which enhances functional performance [35]-[37]. Among the factors that are included in evaluating performance and expected lifespan, and which also determine the system's life cycle, are the characteristics of the materials used, their manufacturing method, and the function during the system's operation. It is also possible to shed light on the locations and sizes of wind energy systems, in addition to the economic aspect of each system, and whether this system is connected to the grid or not, the possibility of transferring the generated energy, its capabilities, and linking it in a hybrid system with solar energy, etc. [38]-[40].

The current simulation presents a study and analysis of the system behavior using a wind turbine model to generate kinetic or mechanical energy as a primary input, and then generate electrical energy from the wind energy source using the mechanical energy generated by the wind energy source as a secondary input. The study identifies some components, including the structure, blades, pitch and yaw control systems, and the generator. The current simulation includes a turbine model designed using MATLAB that simulates the mechanical, hydraulic, and electrical components of the system, including the generator and other subcomponents such as the frame, blades, and control units.

2. Method

2.1. Wind turbines

A clean environment is a fundamental requirement for all countries around the world to protect humanity from the dangers and problems of global warming, which can result from the excessive use of fossil fuels to generate electricity due to the carbon dioxide released by burning fuels [41]-[43]. Today, the world relies on alternatives to fossil fuels to generate electricity, including renewable, clean, and environmentally friendly energies such as solar and wind. To maximize energy production, appropriate studies and tests are conducted to obtain energy from wind energy sources [44]-[46].

It is essential to select contemporary research topics of interest to institutions and researchers around the world. Renewable energy is a clean and renewable energy source that addresses the problem of global warming caused by greenhouse gas emissions. The researchers in this study present research contributions that include understanding the behavior of wind turbines by designing and building a simulation model with several proposed tests that simulate how electricity is generated from a wind energy source. The components of a horizontal and vertical axis turbine system are identified, along with their advantages and disadvantages, such as the speed of the horizontal or vertical axis turbine, as well as the pitch of the blades and the wind level (medium, low, or high). The kinetic or mechanical energy from the wind is captured and used to generate electrical power. A research contribution is being developed that includes developing a model for a variable-speed horizontal axis power system, according to a strategy that verifies maximum power and highest possible efficiency. The system is tested to adjust the pitch angle appropriately to the turbine's dynamic air capacity. From here, the system's response can be analyzed, and improvements and the benefits of adding them can be identified [47]-[50].

Wind turbines can be identified by their type, for example, a horizontal axis-of-rotation (HAWT) turbine with respect to the ground, approximately parallel to the plane of the air current (i.e., the wind). The rotor shaft is mounted on a horizontal axis. The main rotor shaft is located at the top of the wind turbine tower, and the generator is also located at the top of the tower. To achieve maximum power output, the rotor axis must be aligned with the wind direction. This requires steering and adjusting the rotor using an active yaw motor or tail rotor. Gears connect the generator to the turbine shaft, converting the blades to a faster rotation rate that optimizes the operation and rotation of the generator to produce the required power. These turbines (the horizontal axis) are sensitive to disturbances, such as changes in wind direction, which negatively impact performance. Therefore, it can be argued that there is a need to reorient the wind turbine to the wind direction [51]-[54]. Vertical axis-of-rotation (VAWT) shown in Fig. 1, horizontal axis-of-rotation (HAWT) shown in Fig. 2.

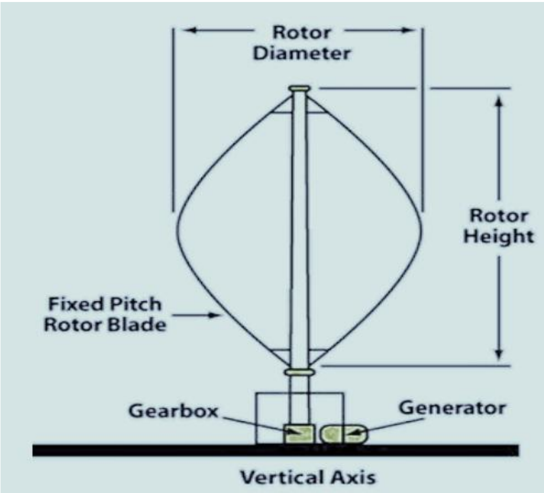

Fig. 1. Vertical axis-of-rotation (VAWT)

The proposed system, which represents a wind energy conversion system to electrical energy, can be simulated under two hypothetical conditions: constant wind speed and variable wind speed. In the first case, the tilt angle is changed and the output power is determined for each test condition. The second test is when the speed is variable. This condition includes system tests with and without a tilt control unit to identify improvements in system performance. The system consists of a horizontal-axis wind turbine with a number of blades that can be moved at a specific tilt as needed, using a tilt mechanism linked to a motor. The system also includes a generator connected to the turbine and a gearbox. The system is connected to the grid using electronic power converters that adjust the voltage and frequency to the specified values. Each system has properties that may include properties related to wind dynamics and their effect on the turbine, such as speed, direction, height, etc., in addition to the turbine dynamics, its diameter, type, material, length, etc. There are also properties related to the electrical generator connected to the turbine, depending on its type, whether inductive or synchronous, such as horsepower, the speed at which the rotor rotates, etc [55]-[57].

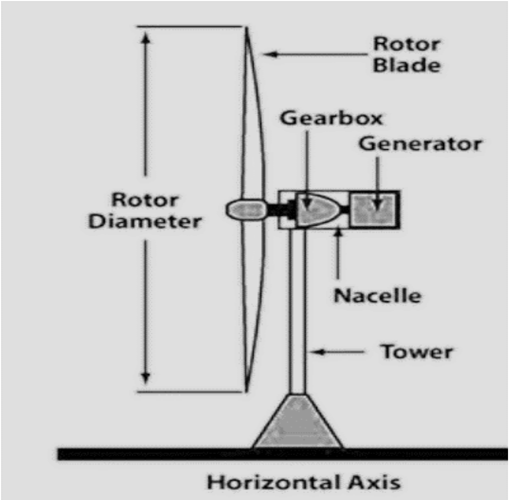

Fig. 2. Horizontal axis-of-rotation (HAWT)

2.2. Modeling System

Building a simulation model to conduct the proposed tests during the simulation process requires establishing a mathematical basis through the relationship between the system components. The system is wind energy that depends on three vectors: area, height, and wind speed. These represent the system input, while providing kinetic or mechanical energy as the system output. This energy is used to produce electrical energy, which can be expressed mathematically by the equations (1)-(5). In modeling System, there are many equations can be writing in this section to show the modeling of wind turbine system include, mechanical output power, performance coefficient. In equation one show the mechanical output power of wind turbine is Pm, Air density is $\rho = 1.225\left(\frac{kg}{m^2}\right)$, the performance coefficient $C_p(\lambda,\beta)$, the tip speed ratio is λ , the blade pitch angle in (degree) is β and the wind speed in m/s is $V\omega^3$ [58], [59].

To study the dynamic properties of air or wind, we examine the amount of energy produced and its relationship to wind speed (v), which is affected by several factors, including the air density (ρ), the area (A) in which it rotates, and the amount of energy produced as motion. This energy is considered mechanical energy that rotates and moves the turbine and can be represented mathematically by Equation (1).

$$P = \frac{1}{2}\rho A C_p v^3 \tag{1}$$

In addition, the system depends on other factors that are also related to the system's operation through its function. These factors include the angle of inclination (β), the power factor, and the tip speed ratio (γ), Cp, which is given by the equation:

$$P_m = 0.5 * C_p(\lambda,\beta) * \rho * A * V^3 \tag{2}$$

$$C_p(\lambda,\beta) = C_1(C_2 * \frac{1}{\gamma} - C_3 * \beta - C_4 * \beta^x - C_5)e^{-C_6\frac{1}{\gamma}} \tag{3}$$

$$\frac{1}{\gamma} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1+\beta^3} \tag{4}$$

$$\lambda = \frac{\omega_m R}{v} \tag{5}$$

$$T_\omega = \frac{P_m}{\omega_m} \tag{6}$$

The first equation represents the mechanical output power, which is symbolized by the symbol PM. The output power can be calculated through the equation depending on variable quantities with a constant of proportionality of (0.5). There is also another constant quantity, which is R, which represents the air density and is considered as a quantity. The variables include wind speed, which is symbolized by the symbol V. While there is another R for the rest of the variables, such as the power factor, which is symbolized by CP, and the area occupied by the system, which gives air energy proportional to it. Where, C1, C2….C6 are constant (C1=0.5, C2=116, C3=0.4, C4=0 that mean x not used, C5=5, C6=21). V is speed of wind (wind speed). ρ is density of air (air density) and it is equal $\rho = 1.225\text{kg}/m^3$. $C_p(\lambda, \beta)$is coefficient of power(power coefficient).A is area of wind turbine(swept area rotor) and R is radius $(A = \pi * R^2)$. Also, $\omega_m$is angel (velocity angular) rotor. By mathematically representing wind turbines, the theoretical value can be obtained using the power factor equation, which is estimated as C_p(λ, β) = 0.593. However, the actual value is almost certainly much lower than the Betz limit, which can be estimated with values ranging from 0.35 to 0.45, which is commonly used and can even be used in the best wind turbine designs. Structural model of wind turbine shown in Fig. 3, wind turbine characteristic curves shown in Fig. 4.

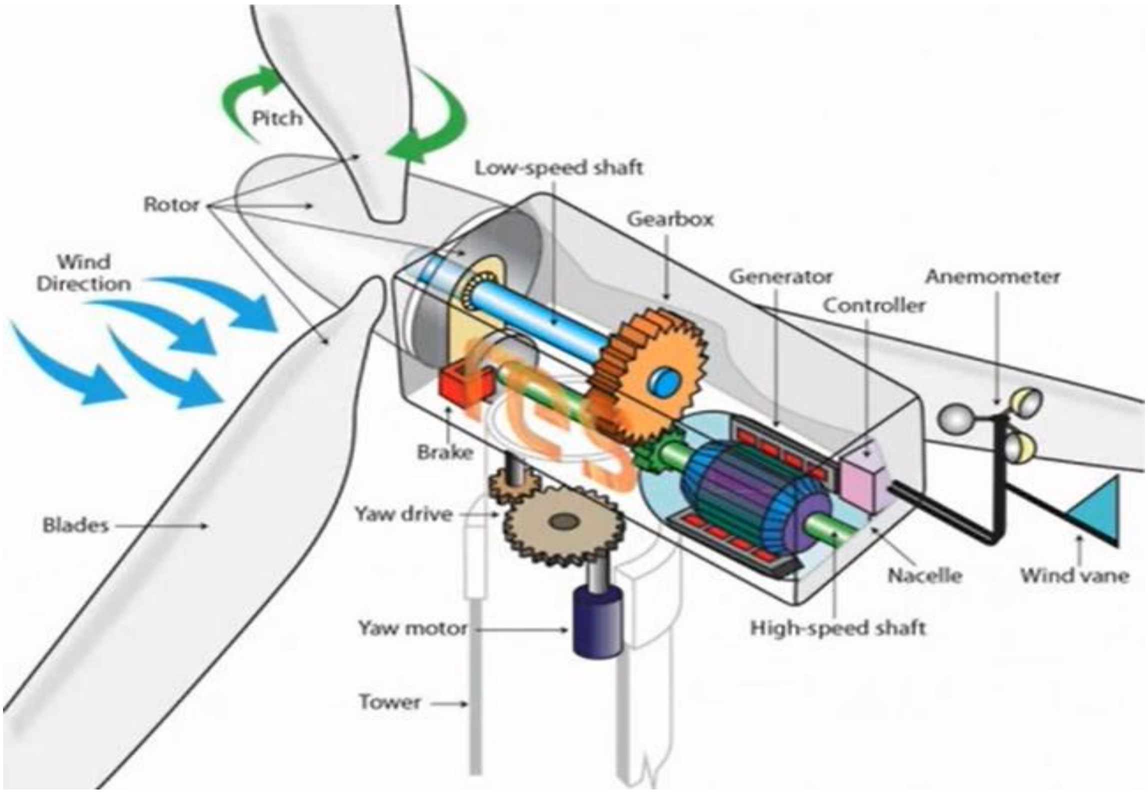

Fig. 3. Structural model of wind turbine

3. Simulation Model and Results

Researchers and academic institutions are interested in developing plans and studies on electrical power generation systems from renewable and environmentally friendly energy sources, including wind and solar energy, among others. Wind energy was chosen as the research focus, presenting one of the most important renewable energies based on research contributions that included the construction and design of a wind energy generation system. The contribution also included identifying potential problems and possible solutions to improve performance and achieve an efficient, reliable, and safe system. Work is underway to develop a simulation model with a conventional control unit design that adjusts the output power represented by the dynamics of air movement regulation to rotate wind turbines, improving performance under operating conditions that include variable speeds and blade tilt to achieve maximum power. To verify the feasibility of an effective model, appropriate measurement criteria were established. The wind energy generation system is introduced by reviewing the system components, the function of each component, and their impact on the system's input and output. Tests are conducted to identify system behavior, analyze change conditions, and identify potential disturbances and how to address them.

An example of a five-kilowatt turbine design using the above equations to obtain model parameters, construct and conduct the proposed simulation tests. The parameters include, C1=0.5, C2=116, C3=0.4, C4=0, C5=5, C6=21, $\lambda = 8.1$ $\beta = 0$, R=1.91431, $\lambda i = 11.304$ $\omega_r = 50.775$. Modeling of wind turbine system at Pm=5KW shown in Fig. 5.

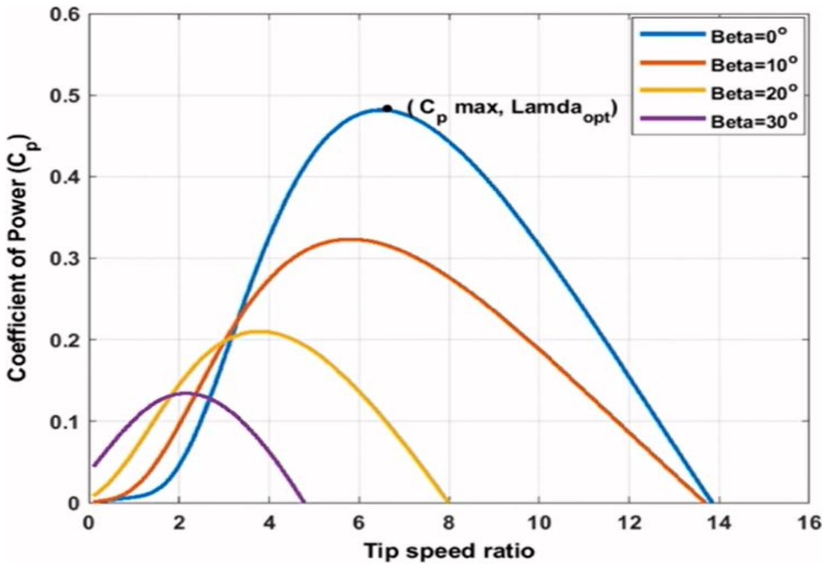

Fig. 4. Wind turbine characteristic curves

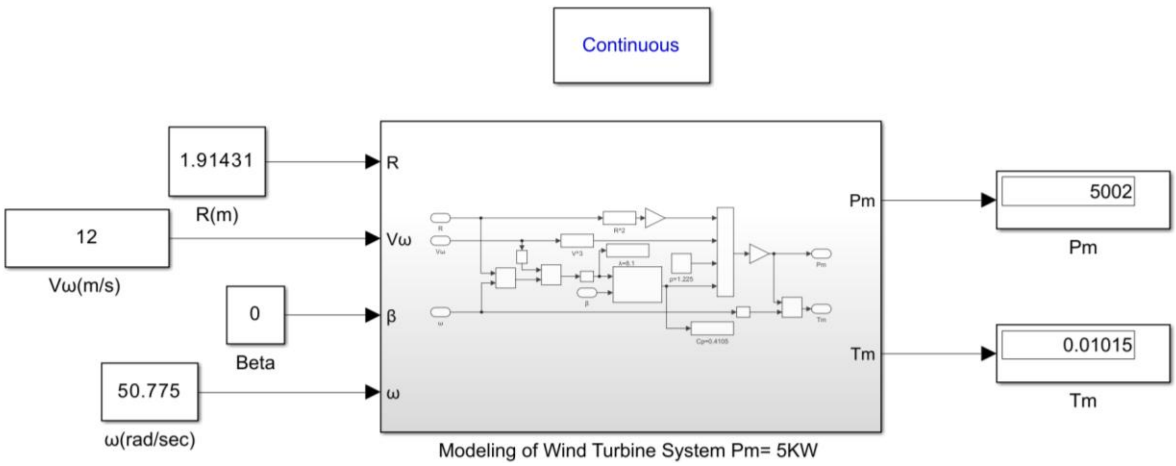

Fig. 5. Modeling of wind turbine system at Pm=5KW

Also another example by using, P=WT, T=P/W, T=20KW/22rps, T=905, Wind speed(m/s) =12, Mechanical output power(w)=20KW, Electrical generator power (VA)=20KVA and Pitch angel (deg)=0. The angle changes with the average wind speed and is between the values first, when β=90, at speed of wind turbine between (0m/s to 3 m/sec). second, when β=0, at speed of wind turbine between (3m/s to 12 m/sec) and third, when β>0, at speed of wind turbine between (12m/s to 25 m/sec). Wind turbine modeling using MATLAB SIMULINK shown in Fig. 6. Modeling of wind

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turbine system at Pm=20KW shown in Fig. 7. Subsystem of modeling of wind turbine system at Pm=20KW shown in Fig. 8. Subsystem of Cp shown in Fig. 9.

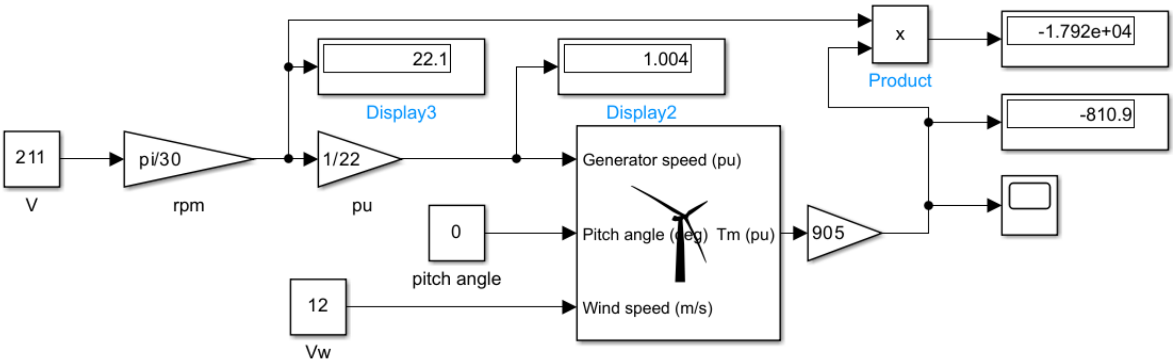


Fig. 6. Wind turbine modeling using MATLAB SIMULINK

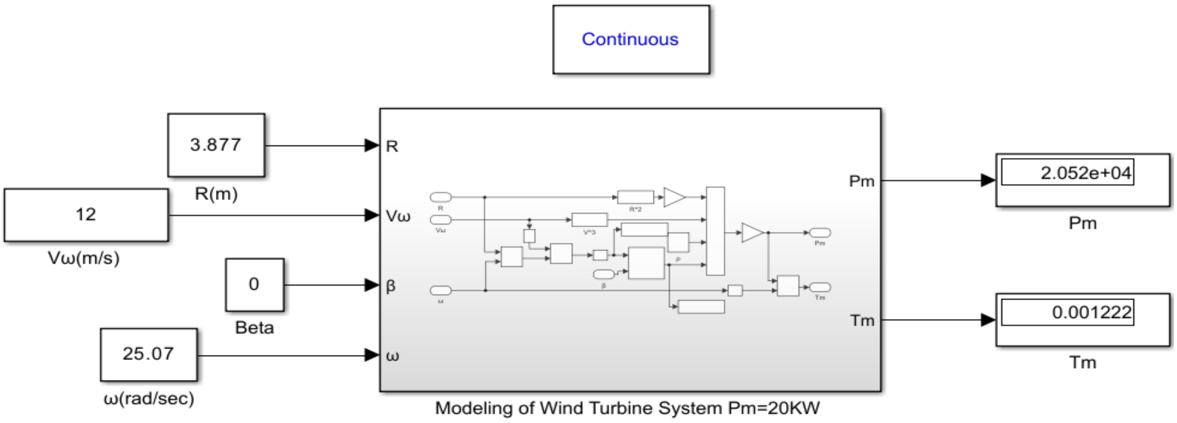


Fig. 7. Modeling of wind turbine system at Pm=20KW

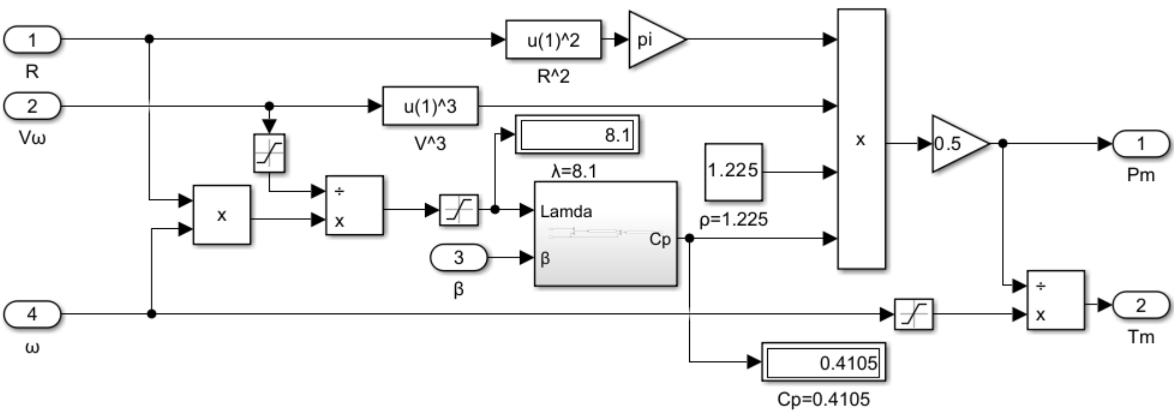


Fig. 8. Subsystem of modeling of wind turbine system at Pm=20KW

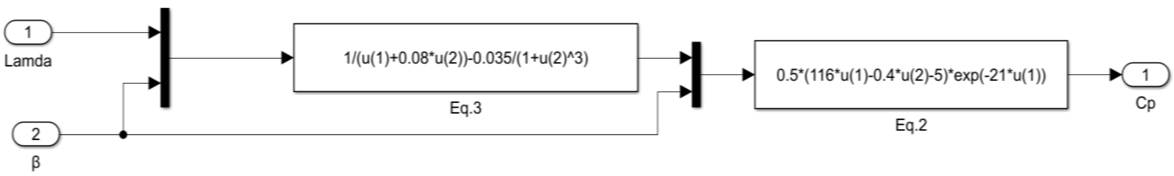
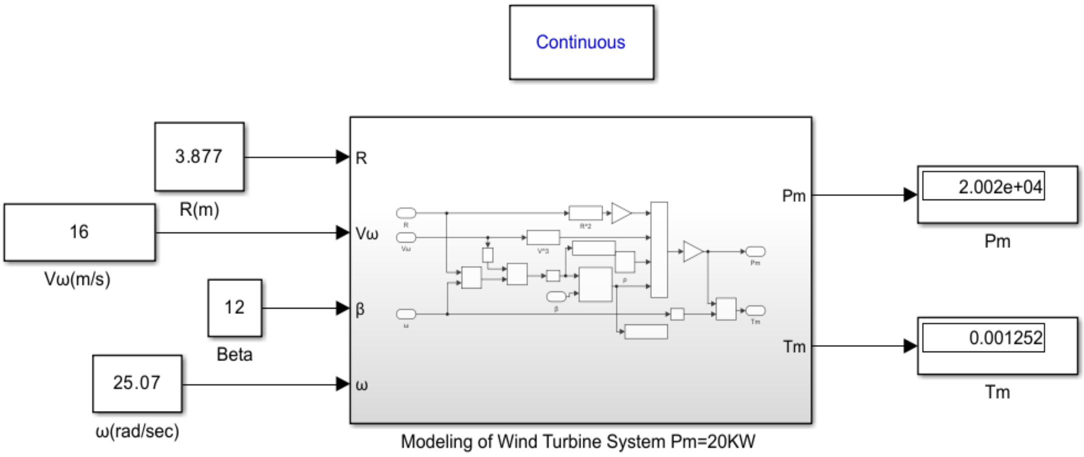
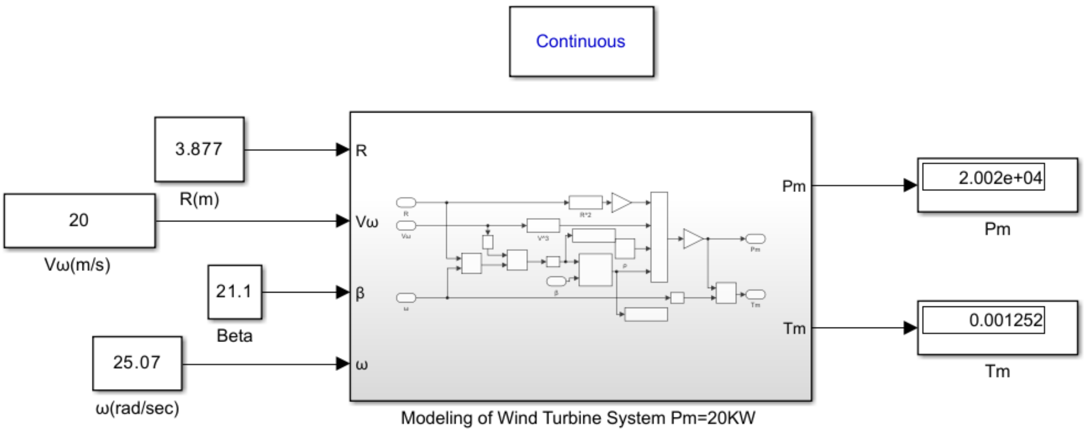


Fig. 9. Subsystem of Cp

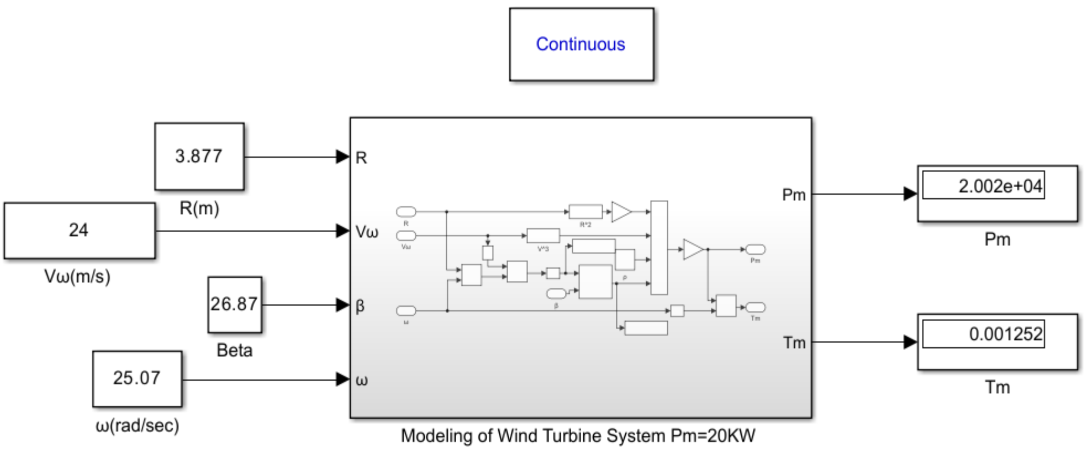
After reviewing the simulation system, it is suggested to verify the possibility of adjusting the system output to the specified power with the effect of changing the speed and adjusting the angle to obtain the same output power. Using a wind power system that gives a mechanical output of five kilowatts and another system of twenty kilowatts, with changing the wind speed and adjusting the turbine tilt at an appropriate angle, gives the specified output. From the test results it was verified that the specified output can be generated with changing wind speed by adjusting the angle. Modeling of wind turbine system at Pm=20KW with virable speed shown in Fig. 10.



a. When Vw=16 and beta=12



b. When Vw=20 and beta=21.1



c. When Vw=24 and beta=26.87

Fig. 10. Modeling of wind turbine system at Pm=20KW with virable speed

Modeling of wind turbine system without PI controller Pm=20KW with different speed that show the response in Fig. 7 and Fig. 10. Fig. 7 show the value of Pm, Tm at Vw equal 12 m/s Beta equal zero. Fig. 10 a show the value of Pm, Tm at Vw equal 16 m/s Beta equal 12. Fig. 10 b show

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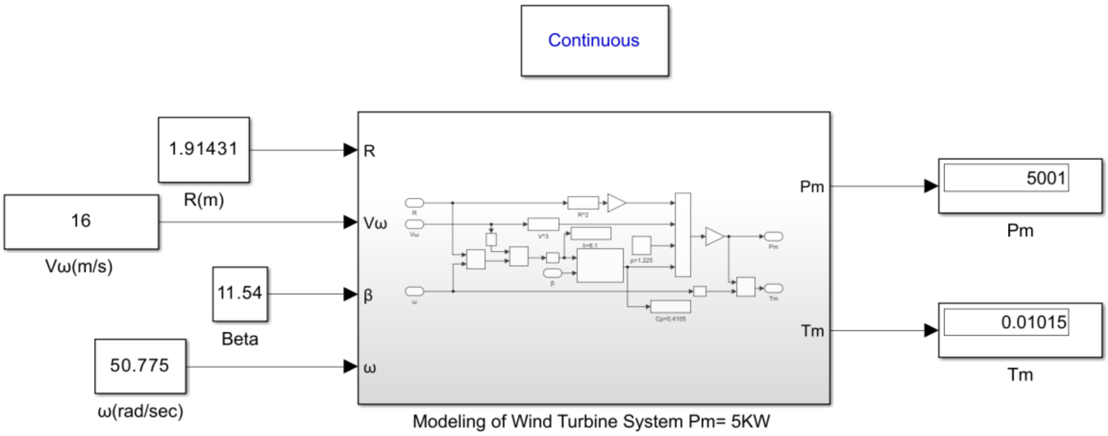
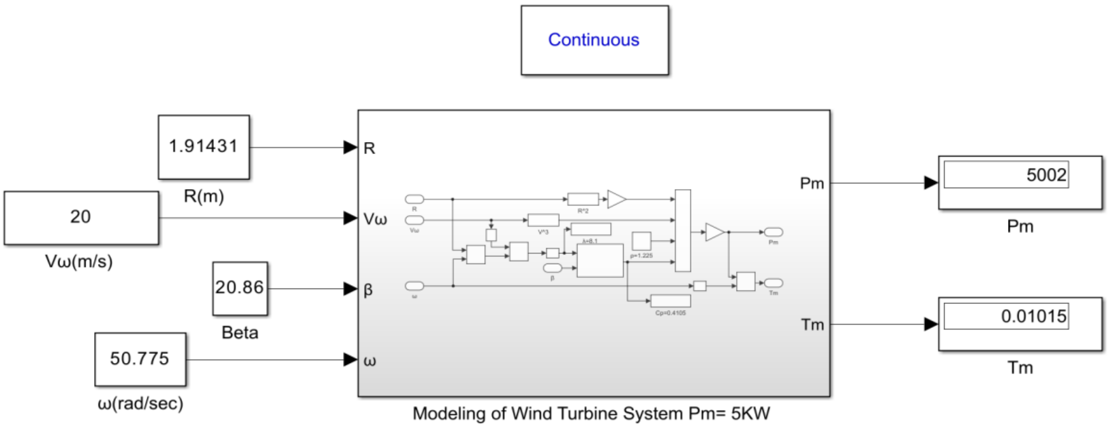
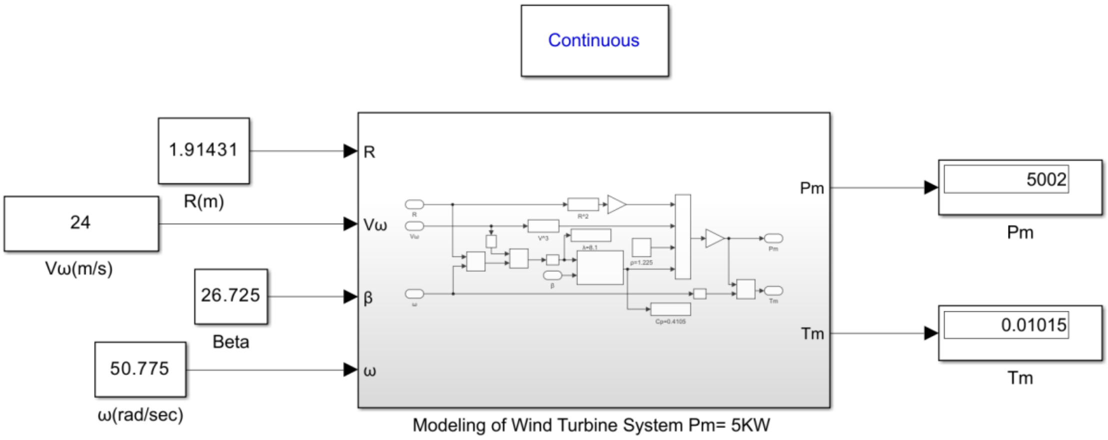
the value of Pm, Tm at Vw equal 20 m/s Beta equal 21.1. Fig. 10 c show the value of Pm, Tm at Vw equal 24 m/s Beta equal 26.87. Modeling of wind turbine system without PI controller Pm=5KW with different speed that show the response in Fig. 11. Fig. 11 a show the value of Pm, Tm at Vw equal 16 m/s Beta equal 11.54. Fig. 11 b show the value of Pm, Tm at Vw equal 20 m/s Beta equal 20.86. Fig. 11 c show the value of Pm, Tm at Vw equal 24 m/s Beta equal 26.725.



a. When Vw=16 and beta=11.54



b. When Vw=20 and beta=20.86



c. When Vw=24 and beta=12

Fig. 11. Modeling of wind turbine system at Pm=5KW with virable speed

Modeling of wind Turbine system (WTS) with PI Controller at variable wind speed that show in Fig. 12, Fig. 13, Fig. 14, Fig. 15, Fig. 16. In Fig. 12 show the modeling WTS at Pm equal 20KW. In Fig. 13 show the modeling PI controller. In Fig. 14 show the Response of wind speed for wind

Turbine system (WTS) with PI Controller at variable wind speed. In Fig. 15 show the Response of output Power for wind Turbine system (WTS) with PI Controller at variable wind speed. In Fig. 16 show the Response of output Torque for wind Turbine system (WTS) with PI Controller at variable wind speed.

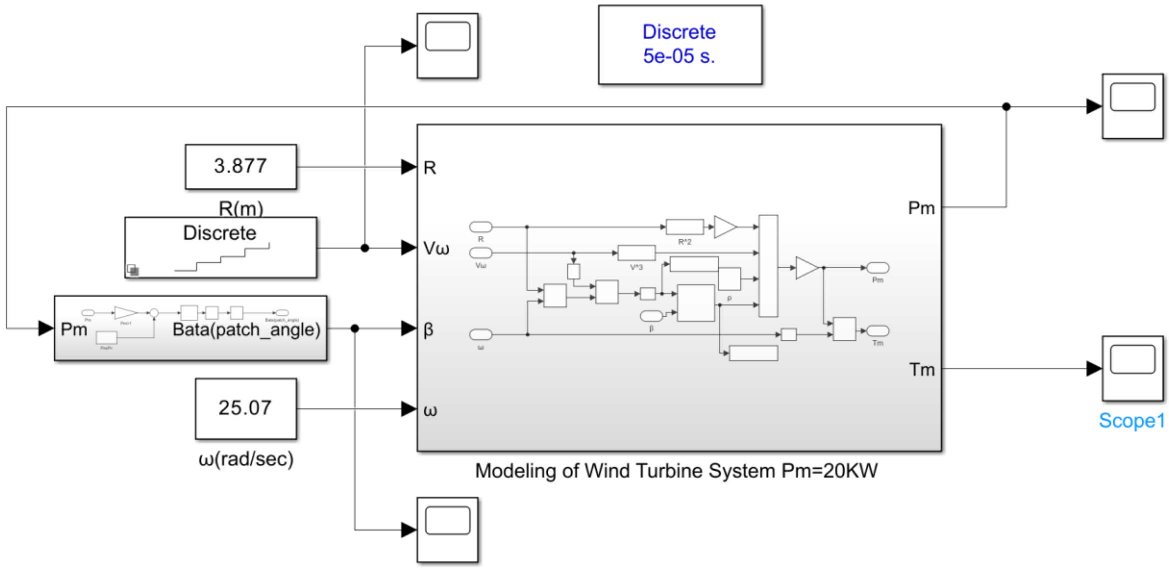


Fig. 12. Modeling of wind turbine system (WTS) with PI controller at variable wind speed

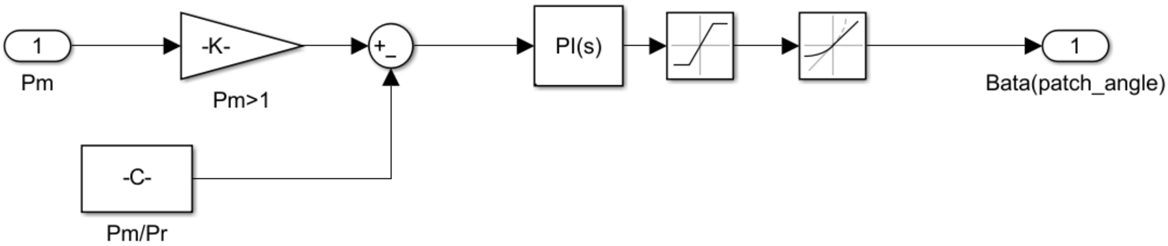


Fig. 13. Modeling of PI Controller at variable wind speed

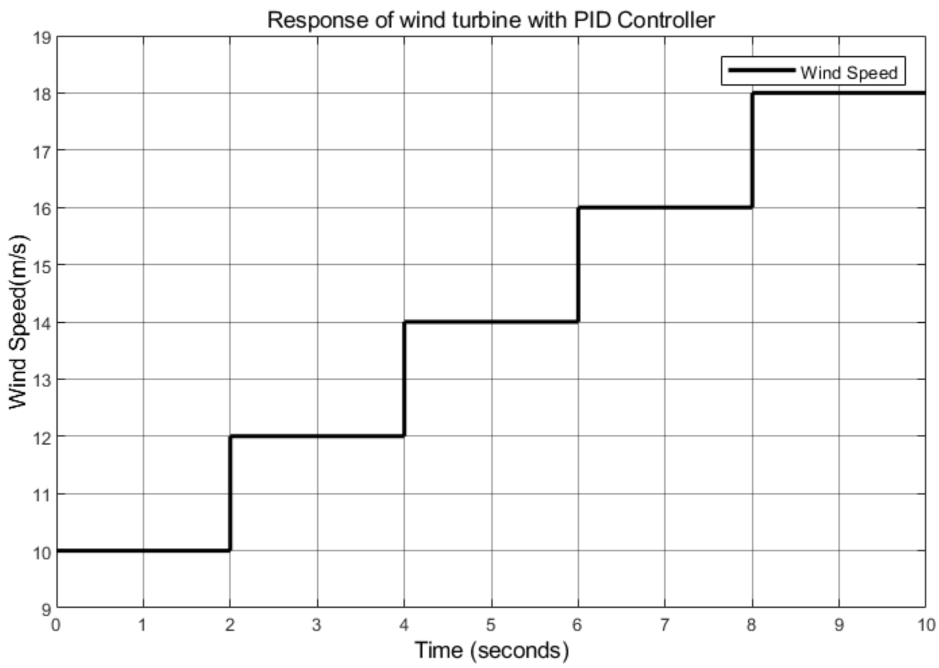


Fig. 14. Response of wind speed for wind turbine system (WTS) with PI Controller at variable wind speed

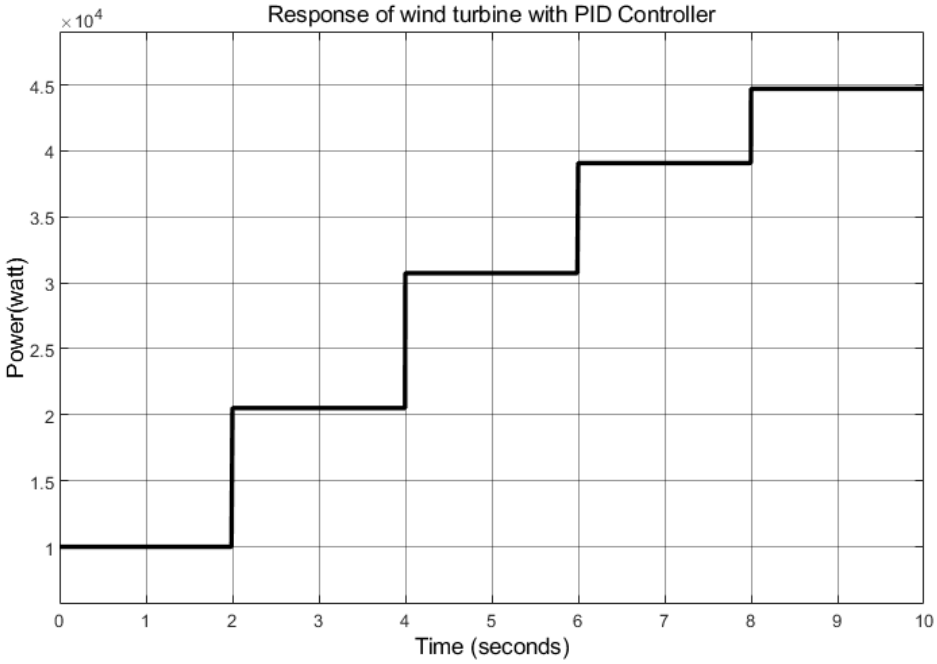


Fig. 15. Response of output power for wind turbine system (WTS) with PI Controller at variable wind speed

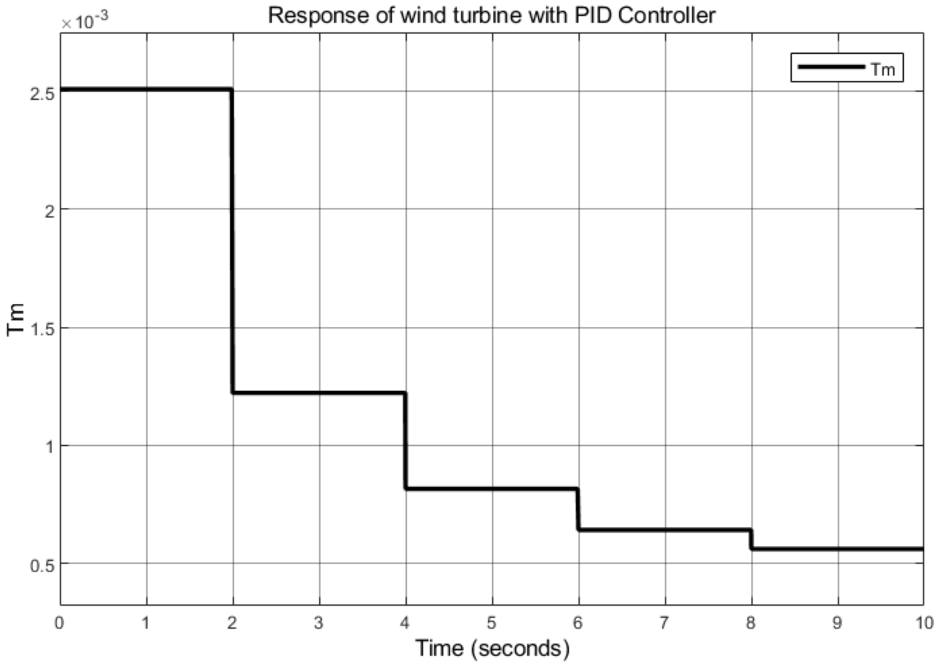


Fig. 16. Response of output torqe for wind turbine system (WTS) with PI Controller at variable wind speed

4. Conclusion

The study was conducted by constructing and designing a simulation model for a wind turbine with an output capacity of 5 kW and another model with an output capacity of 20 kW. Tests were conducted to achieve the research contributions and objectives of studying the effect of wind speed and changing the tilt angle on adjusting the system output to the specified value. The feasibility of studying the effect of changing the turbine tilt angle on adjusting the output power to the specified value with changing wind speed was verified. A model of a wind turbine-based power generation system is being developed. The system can be described and modeled as a wind turbine-generator system, comprising a generator output (Pg) and a system output, with a reference value (P), which is the specified value at which the system operates in steady state, producing the required output to cover the loads according to the system design. The system output error is the difference between the actual output produced by the generator and the set output required to use the system. The tilt angle β is a factor affecting the power output of a generator connected to a wind turbine. Therefore, it is preferable to select and position the turbine to suit the angle that provides the best power output by developing a control strategy (tilt angle). The tilt angle β can be controlled by moving the blades using an electric motor to smooth the system output. The design of an advanced system that handles changes in air density (ρ=1.225 kg/m^3) or turbulence makes it suitable and feasible for real-world application. Furthermore, the addition of a controller improves performance and is important in the design of wind turbines or renewable energy systems, demonstrating the importance of the study and its potential contributions to this field.

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