Pitch Blade Control Prototype Design for Vertical Axis Wind Power Plant

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ABSTRACT

One alternative energy that is easy and can be used is wind. This energy is utilized through wind turbines which have two general types, namely horizontal and vertical axis wind turbines. This wind turbine can move by utilizing the energy available in the wind to rotate the turbine. The problem with wind turbines is self-starting is difficult to achieve. This can be caused by several factors, such as slow wind speed and erratic wind direction. In addition, wind turbines also have low-efficiency values. Therefore, our contribution to this research is to design a blade controller on a vertical axis wind turbine. This blade control is designed by utilizing the pitch angle by using actuators that are applied to each blade based on the Proportional, Integral & Derivative (PID) algorithm. The PID algorithm is used to find the appropriate pitch angle value on a vertical axis wind turbine. The effect of the pitch angle on the wind turbine serves to maintain the mechanical power value by the available power in the wind. This research was conducted using a simulation method (MATLAB). In this study, it was found that this wind energy conversion simulation produces maximum mechanical power when the wind speed varies is 1723 Watt and when the wind speed is 7 m/s, mechanical power achieved is 362.595 Watt.

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1. INTRODUCTION

At this time, energy sources in Indonesia and the world are decreasing. This is explained by the Ministry of Energy and Mineral Resources, the Directorate General of New Renewable Energy and Energy Conservation (EBTKE). With energy consumption increasing by 7%, so energy is becoming increasingly less and difficult to obtain. On the other hand, this energy consumption is not directly proportional to the sufficient supply of energy which results in energy dependence on fossil energy. The use of fossil energy has several disadvantages, such as being able to produce Greenhouse Gases (GHG) in the earth's atmosphere, which causes global climate change. An alternative solution to meet energy needs and reduce climate change is the use of New and Renewable Energy (EBT). One alternative energy that is easy and can be used is wind. Wind potential in Indonesia is quite high, with wind speeds in some parts of Indonesia ranging from 2-12 meters/second, strong enough to drive wind turbine blades. The wind speed in Riau province in 2022 is in the range of 4 m/s and 5 m/s at night. This allows the use of wind to meet the continuously increasing demand for electrical energy so that the use of fossil fuels can be reduced [1][2][3].

The wind turbine is one type of generator that can convert wind energy into electrical energy [4]. There are two types of wind turbines based on the blade axis, namely the Horizontal Axis Wind Turbine (HAWT) [5] and the vertical axis wind turbine (VAWT) [6]. HAWT is the most common type of turbine. This turbine design is based on a propeller and is placed on a high ground level. The potential power generated by this turbine depends on the blade area used [7]. However, due to the relatively large size of the turbine, the blade often experiences alternating loads on each rotation. In addition, the turbine generator is also located around the blade, so maintenance of the turbine tends to be difficult. A vertical axis wind turbine has the generator located close to the blades above the ground to facilitate maintenance and repair of this type of turbine [8][9][10]. VAWT also has a blade rotation load that tends to be lower than HAWT, so the life of VAWT is longer than HAWT [11][12][13]. The VAWT wind turbine can also receive wind from various directions, and the construction can be lighter and bulkier. Therefore, VAWT turbine technology can be used for alternative wind energy conversion technologies. In addition to the advantages of VAWT already mentioned, VAWT allows the use of lightweight construction materials, and the construction of VAWT is much simpler than HAWT [14]. The generator used in the VAWT can be placed above ground level so that the size of the generator used does not need to be minimized because the swept area of the turbine is not disturbed by the generator [15][16].

Previously, research on the design of vertical axis wind turbines had been carried out by Pranit Nagare, Arnav Nair, Rammohan Shettigar, and Pratibha Kale under the title "Vertical Axis Wind Turbine," which was carried out in 2015. In a research journal published, it was stated to overcome the problem of self-starting on the Darrieus type wind turbine and the problem of the Savonius type turbine speed. It is necessary to develop the blade that will be used. Therefore, a study was made on blade modeling that combines the Darrieus type and the Sovanius type [17]. Lixun Zhang, Yue Pei, Yingbin Liang, Fengyue Zhang, Yong Wang, Jingjia Meng, and Haoran Wang conducted a study entitled "Design and Implementation of Straight-bladed Vertical Axis Wind Turbine with Collective Pitch Control" in 2015. This study aims to overcome the self-starting problem in Darrieus-type wind turbines using collective pitch control (CPC). The resulting prototype is able to increase the coefficient of power and efficiency up to 16% by using four blades. To increase the power coefficient and efficiency, less blade usage is recommended due to the lack of dynamic movement [18].

Elie Antar, Amne El Cheikh, and Michel Elkhoury conducted a study entitled "A Dynamic Rotor Vertical-Axis Wind Turbine with a Blade Transitioning Capability" in 2019. This study discusses the transition from the blade from the Savonius type in the start phase to the Darrieus type by increasing the Tip speed ratio (TSR). This research was conducted so that the maximum power coefficient can be achieved by setting the TSR at a certain location [19]. Liang Ying-bin, Zhang Li-xun, Li Er-xiao, and Zhang Feng-Yue have conducted research entitled "Blade Pitch Control of Straight-Bladed Vertical Axis Wind Turbine" in 2016. In this study, a collective pitch control test was conducted on the VAWT, resulting in an increase in turbine power and can reduce damage to the blade at high wind speeds [18].

Our contribution in this study is to control the pitch blade on the Vertical Axis Wind Turbine (VAWT) using the PID method so that the desired angle on the turbine is achieved faster and produces optimal power. In addition, by using the PID method, the efficiency level of the turbine can reach a high value compared to other methods and can overcome the problem of self-starting on the Darrieus type VAWT, which is one of the turbine's weaknesses [20].

2. METHOD

The research method in this paper uses an approach by comparing the power produced by the turbine (Pm) and the power available in the wind (Pw) on the vertical axis of the wind turbine. Vertical axis wind turbine selection is based on the reason that vertical axis wind turbines can receive wind from various directions so that the wind turbine can rotate more easily. The main components in this system are Arduino, servo motor, optocoupler, and anemometer. The flowchart of the method can be seen in Fig. 1.

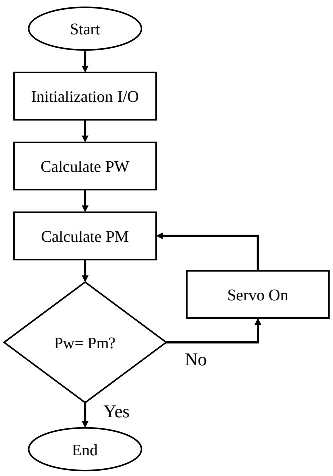

Fig. 1. System Block Diagram

Based on Fig. 1. the first process to do is initialize I/O. The inputs used in this system are wind speed, wind turbine rotational speed, and blade pitch angle. The anemometer is used as a wind speed sensor, and the optocoupler as a speed sensor will also read the speed of the wind turbine [21][22]. The first step is to initialize I/O. The inputs used in this system are wind speed, wind turbine rotational speed, and blade pitch angle. After that, the next process is to read wind speed, wind turbine rotational speed, and blade pitch angle on Darrieus type VAWT. The next stage is to calculate the available power in the wind through the wind speed sensor, namely the anemometer, and calculate the mechanical power obtained by the wind turbine through the wind turbine rotational speed sensor, namely the optocoupler. If the mechanical power is equal to the available power in the wind, the actuator will maintain the blade pitch angle [23] when this condition is reached and if this condition has not been reached, the controller will instruct the actuator to change the blade pitch angle by sending a number of clock signals.

2.1. Blade Design

Specifications of the wind turbine can be determined by receiving wind data at the place where the wind turbine will be installed. The wind data will explain the available wind power potential so that the appropriate size and dimensions of the wind turbine can be determined. The average wind speed in Riau province is 0.76 m/s. Based on this wind data, the blade height (*H)* and radius of the wind turbine (*R*) can be calculated using the following equation based on [24].

$$p = 0.5 \times \rho \times A \times V^3 \tag{1}$$

$$\mathrm{A} = 2\pi\mathrm{RH} \tag{2}$$

$$\frac{D}{H} = 1.2 \tag{3}$$

Furthermore, to determine the chord length (*c*) of the blade, the calculation is carried out using the TSR value. The optimal TSR value of a vertical axis wind turbine with 3 blades is around 1.6. From the TSR value, it can be determined that the solidity of the graph is 0.444 [25].

$$c = \frac{\sigma R}{N} \tag{4}$$

After the calculation is done, the blade design can be described through Solidwork with 3 blades placed at a calculated radius [5]. Fig. 2 shows a blade design with a blade length of 0.515 m and a chord length of 0.05 m.

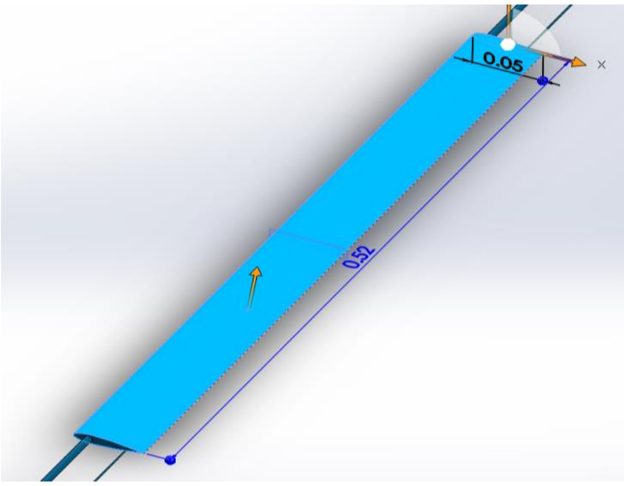

Fig. 2. Blade Shape in Solidworks

2.2. Determination of mechanical power

Mechanical power is the output power obtained by the wind turbine. Mechanical power is the product of the torque multiplied by the speed of the wind turbine [7]. To get the torque, the calculation is carried out using the following equations.

The amount of power extracted from the wind is directly dependent on the tip speed ratio, which can be defined as the ratio between the tangential speed at the blade tip (ω) and the actual wind speed [26]. Tip speed ratio can be formulated as follows:

$$\lambda = \frac{R \times \omega}{V} \tag{5}$$

Betz's law states that wind turbines can only capture the maximum kinetic energy of 59.3% in the wind [27]. The maximum power coefficient that can be achieved by the wind turbine is 59.3% which is known as the Benz coefficient. The axial induction factor (a) is also known as the fractional decrease in wind speed between the free flow and the rotor plane [24].

$$\boldsymbol{a} = \frac{\boldsymbol{V} - \boldsymbol{V_a}}{\boldsymbol{V}} \tag{6}$$

$$a = \frac{Nc}{2\pi R}\frac{R\omega}{V}\sin\theta \tag{7}$$

Analysis based on the force on the wind turbine blades is a very important method because the actual efficiency of the wind turbine is unknown. The blade shape parameter is the only information about the efficiency of the wind turbine blades but this information does not cover the overall efficiency of the wind turbine. The force acting on the blade (W) is calculated according to the azimuth angle (θ), turbine rotation speed, and wind speed [4].

$$V_t = R\omega + V_a\cos\theta \tag{8}$$

$$V_n = V_a\sin\theta \tag{9}$$

$$W = \sqrt{V_t^2 + V_n^2} \tag{10}$$

The angle of attack (α) is the angle of inclination of the blade about the wind trajectory. The angle of attack affects the rotor speed and the TSR ratio of the turbine. For example, a high angle of attack can result in a large sweep area resulting in a slower speed than the same turbine with a lower angle of attack [28].

$$\alpha = \tan^{-1}\left[\frac{\sin\theta}{\left(\frac{R\omega}{V} + \cos\theta\right)}\right] \tag{11}$$

To improve the performance of the vertical axis wind turbine, a variable pitch blade technique is applied by changing the angle of attack [13].

$$\beta = \alpha - \varphi \tag{12}$$

By increasing the pitch angle, the lift coefficient (CL) and drag coefficient (CD) of the system can be improved at some blade positions. The lifting force of the blade on the wind turbine has the potential to produce positive torque. This positive torque makes the wind turbine spin. Before calculating the torque, it is necessary to calculate the tangential force first, namely the force experienced by the rotor [24].

$$\boldsymbol{C_t = C_l \sin\alpha - C_d \cos\alpha} \tag{13}$$

$$F_t = \frac{1}{2}C_t\rho c H W^2 \tag{14}$$

Since the tangential force is only at a single azimuth position, it is important to calculate values at all positions before finding the torque. The component of the average tangential force (F_{tavg}) takes into account all positions [24].

$$F_{tavg} = \frac{1}{2\pi}\int_0^{2\pi} F_t(\theta)d\theta \tag{15}$$

The force in the above equation is the force experienced by only one blade. To calculate the average torque of a turbine with a number of blades N and a radius r, the torque equation becomes [24]:

$$\tau = NF_{tavg}r \tag{16}$$

2.3. Pitch Blade Control System Design

The blade pitch control system (Fig. 3) functions to change the blade angle position, namely the angle of attack, so that the blade position can be perpendicular to the wind so that the blade receives greater wind power. This angle is obtained based on the comparison between the power obtained by the wind turbine, namely, based on the speed of the wind turbine and the power available by the wind. If the wind turbine power produced is less than the available power in the wind, the actuator will increase the pitch angle on the blade, and vice versa. If the wind turbine power is more than the available power in the wind, the actuator will reduce the pitch angle on the blade. The variable (e) represents the tracking error, the deviation between the desired wind power plant (Pv) and the actual wind power plant (Pw) from the controlled target. This error signal will be sent to the PID controller, and the controller computes both the derivative and the integral of this error signal. The PWM signal to the Servo motor is equal to the proportional gain (Kp) times the magnitude of the error plus the integral gain (Ki) times the integral of the error plus the derivative gain (Kd) times the derivative of the error. This PWM signal is sent to the servo motor, and the new pitch angle (ß) is obtained. The new pitch angle affected the actual wind power plant, and then the actual power is fed back and compared to the reference to find the new error signal. The controller takes this new error signal and computes its derivative and its integral again, ad infinitum. Our contribution is to design a PID-based blade pitch control system so that maximum power available in the wind is achieved.

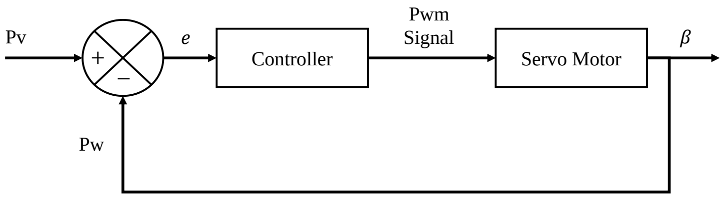

Fig. 3. Blade Pitch Control System

The controller used is a PID controller. Pv is used as a reference power [29] and inputs to the blade pitch controller. The output generated by the controller is a pitch angle that will make the blade produce a certain slope that is perpendicular to the wind direction, and this angle is channeled to the actuator, namely the servo motor. The resulting mechanical power value is inputted again until the desired pitch angle is reached. After all components and systems have been arranged, then the entire vertical axis wind power generation system is implemented to SIMULINK in the MATLAB application. The calculation of torque is carried out through the formula in [24]. Then, the results of the formula will be used on a vertical axis wind turbine designed on SIMSCAPE MULTIBODY, which is a subsystem of Simulink [30].

3. RESULTS AND DISCUSSION

This wind energy conversion simulation test is done by adding a pitch controller in it and adjusting the angle of the blade. This pitch controller will change the pitch angle according to the target power, namely the available wind power. This pitch controller will compare the value of the mechanical power of the wind turbine and the target power. If the target power has not been achieved, the controller will instruct the wind turbine to increase the pitch angle and vice versa. If the mechanical power has exceeded the target power, the controller will instruct the wind turbine to reduce the pitch angle.

3.1. Testing with a Constant Wind Speed of 7 m/s

Testing with a wind speed of 7 m/s was chosen according to the construction designed on the VAWT. A wind speed of 7 m/s is the middle speed between the minimum speed (3 m/s) and the maximum speed (12 m/s). The resulting simulation contains components from the Simscape Multibody library, which can represent the wind turbine physically, and the output from the wind turbine in the Simscape multibody will be recalculated through the system built-in Simulink.

In Fig. 4, it is known that the value of the turbine speed produced is 118.4025 rad/s. With the turbine rotational speed, a torque of 3.0500 N.m is generated and a mechanical power of 362.5950 watts. So that it produces a power coefficient of 1.7261, in Fig. 4, it can be seen that the system reaches a stable state faster than an uncontrolled wind turbine at the same wind speed.

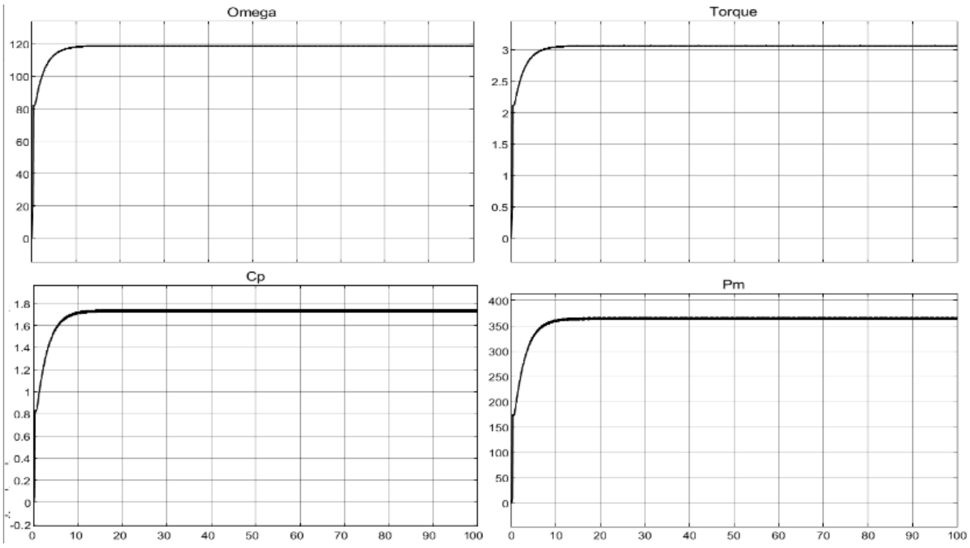

Fig. 4. Wind Turbine Output with Pitch Control at Fixed Wind Speed

From Fig. 5, the V_{L-L} produced by PMSG reaches 41.0130 volts with an I_{Line} of 0.9472 A. From the line-line voltage and line, the RMS value is 38.9710 V and 0.9 A. The electrical power obtained by the turbine wind at a speed of 7 m/s obtained 57.1153 watts.

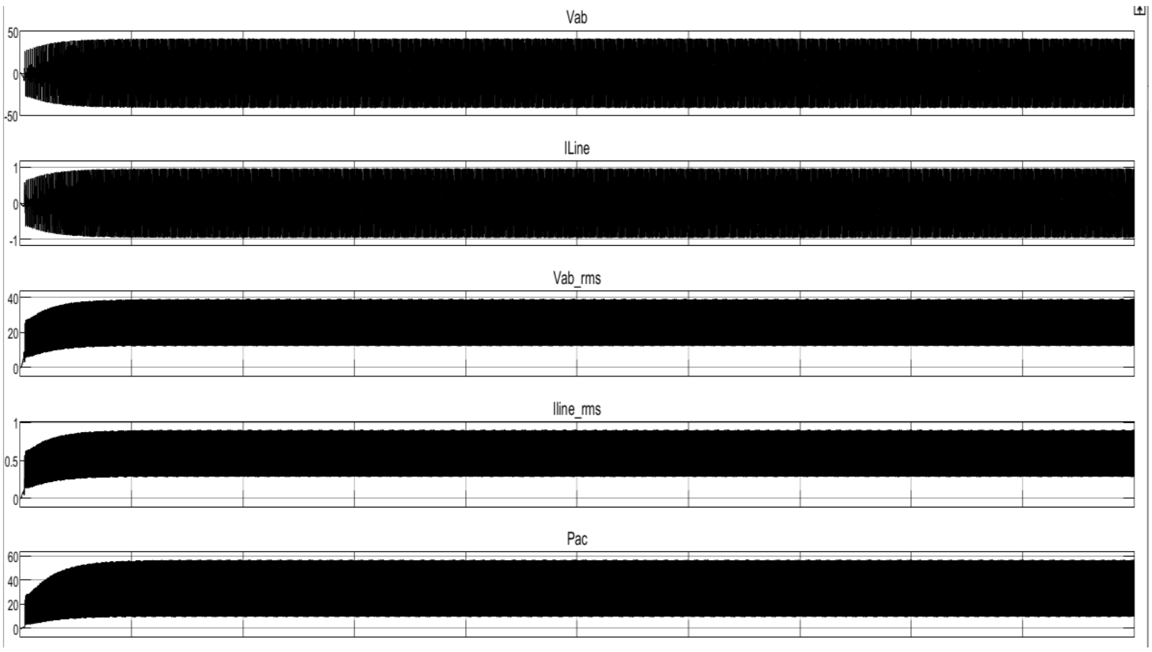

Fig. 5. PMSG Output with Pitch Controller at Fixed Wind Speed

3.2. Testing with a Variable Wind Speed

The variable wind speed applied in this test is shown in Fig. 6. This wind speed variation is generated through the signal generator block. This signal will later be used as input for the resulting wind speed. The results of a wind turbine simulation with a pitch controller are shown in Fig. 7.

It can be seen from the figure that when the wind speed is 7 m/s, the available wind power is 221.4 watts. The wind turbine produces torque from the wind speed of 2.265 N.m and a rotational speed of 86.57 rad/s. From the torque and rotational speed, the mechanical power of the wind turbine is 196.1 watts. The coefficient of power achieved by the wind turbine when the wind speed is 7 m/s is 0.8856. Then for 25 seconds, the wind speed increased to 10 m/s, and the available wind power increased to 612.4 watts. At the same time, the wind turbine also experienced an increase in torque of 5.947 N.m and rotational speed of 166.2 rad/s. The mechanical power produced by the wind turbine at that time increased to 988.4 watts. The coefficient of power achieved by the wind turbine when the wind speed is 10 m/s increases to 1.614.

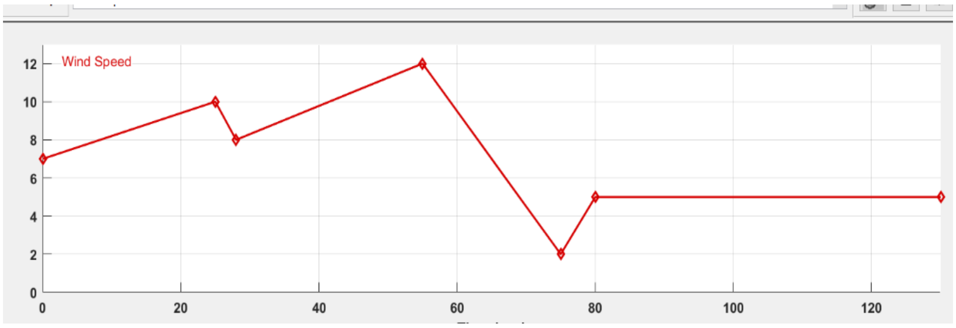

Fig. 6. Simulink Block Wind Speed Changes

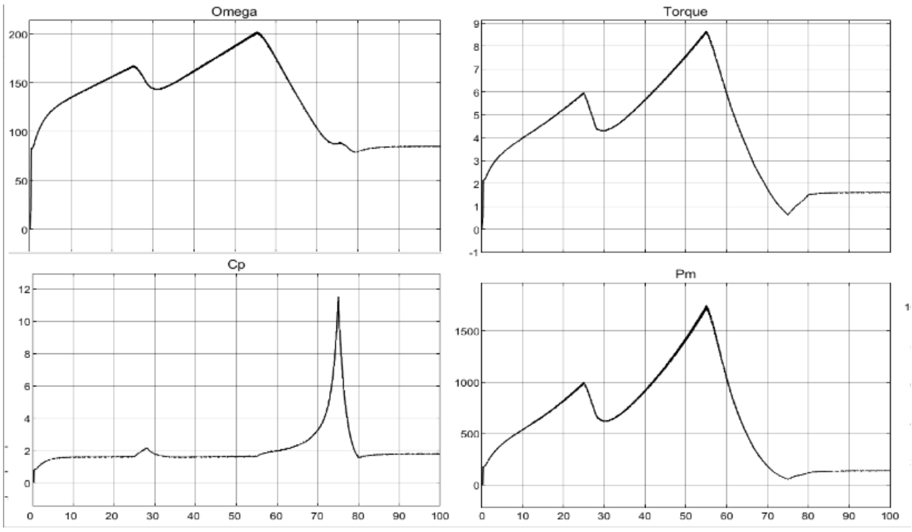

Fig. 7. Wind Turbine Output with Pitch Control at Variable Wind Speed

Furthermore, the wind speed decreased in a short time to 8 m/s, which caused the torque produced to decrease slightly to 4.424 N.m. This also causes the wind turbine to slow down to 152.8 rad/s and causes the mechanical power obtained to drop to 675.7 watts. Because the available power in the wind is also reduced to 313.6 watts, the power coefficient continues to increase to 2,155. After 27 seconds, the wind speed rose to 12 m/s. This causes the wind turbine to spin faster to 200 rad/s and the torque generated to climb high to 8,613 N.m. The mechanical power of the wind turbine is 1723 watts. Due to the wind power available at that time being 1058 watts, the wind turbine power coefficient decreased to 1.628.

At 75 seconds, the wind speed decreased drastically to 2 m/s, so the rotational speed and torque also decreased drastically to 88.26 rad/s and 0.6389 N.m. The mechanical power of the wind turbine at that time also decreased to 56.39 watts. When the wind power at that time was 4.899 watts, the power coefficient was 11.51. The power coefficient has decreased to 0.5539. the wind speed again decreased drastically to 2 m/s at 75 seconds which caused the power coefficient to soar to 26.3. After a while, at 80 seconds, the wind speed increases to 5 m/s so that the turbine rotation speed becomes 79.46 rad/s, and the resulting torque is 1.51 N.m. The mechanical power of the wind turbine at that time also experienced a slight increase to 120 watts. The coefficient of power produced by the wind turbine is 1.567. After knowing the output of the wind turbine, it is necessary to observe the output of the PMSG, which is shown in Fig. 8.

From Fig. 8, when the wind speed is 7 m/s, PMSG produces VL-L of 30 volts and ILine of 0.7 A. From the VL-L and ILine voltages, electrical power of 33.64 watts is obtained. Then for 25 seconds, the wind speed increased to 10 m/s, and PMSG also experienced an increase in VL-L of 77.5 volts and ILine of 1.8 A. The electrical power produced by PMSG at that time increased to 165 watts. Furthermore, the wind speed decreased in a short time to 8 m/s, which caused the resulting VL-L to slightly decrease to 57 volts. This also causes the ILine to decrease to 1.365 A and causes the electrical power obtained to drop to 106 watts.

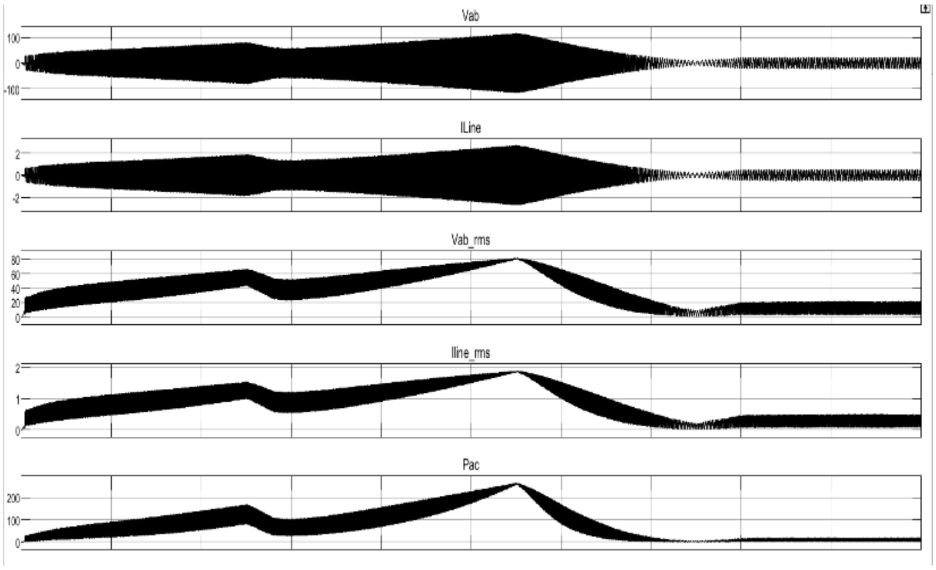

Fig. 8 PMSG Output with Pitch Control at Variable Wind Speed

After 27 seconds, the wind speed rose to 12 m/s. This causes the VL-L to be higher to 104 volts and the resulting ILine also to increase to 2.6 A. The electrical power produced is 260 watts. At 75 seconds, the wind speed decreased drastically to 2 m/s, so the VL-L and ILine also decreased drastically to 8.7 volts and 0.2 A. The electric power of the wind turbines at that time also decreased to 2.58 watts. After a while, at 80 seconds, the wind speed increased to 5 m/s so that the VL-L became 20 volts and the resulting ILine was 0.45 A. The electrical power of the wind turbine at that time also increased to 14.31 watts. The efficiency of this study was then compared with the results of previous researchers. A comparison of the results of using the method can be seen in Table 1.

Table 1. Comparison of Research Result

No	Researcher	Method	Efficiency (%)
1	Nagare	Combined Blade	0.009570681
2	Zhang	Collective Pitch Control	16
3	Antar	Blade Transitioning Capability	18
4	Ying-bin	Collective Pitch Control	17
5		PID Pitch Blade Control	20

4. CONCLUSION

The simulation results show that the pitch blade controller works well and can accelerate the system to produce a stable output. When the wind speed is constant, the wind turbine produces a power coefficient of 1.7261 and a mechanical power of 362.595 watts. Thus, the electrical power generated is 57.1153 watts. When the wind speed varies, the system output produces a small offset error and steady-state with the largest power coefficient of 26.3 and the largest mechanical power of 1723 watts. The greatest value of electrical power obtained by the wind turbine is 260 watts and based on these results, the control can be increased by adjusting the value of the controller.

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