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Simulation of Small-Scale Wind Turbine Performance with Taperless Blade

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ABSTRACT

Utilizing wind turbines typically involves a large-scale project with extremely huge wind turbine sizes. Because of this, the use of wind turbines in Indonesia is not yet very common and widespread among the community. Basically, a wind turbine has blades; the number of blades on a wind turbine can affect the overall performance of the turbine. Large-scale wind turbine projects usually implement tapered blades, while small-scale projects use taperless blades. Therefore, in this research, a horizontal-axis wind turbine with taperless blades will be used as the object of study to find out the optimal number of taperless blades that can achieve the best performance of a small-scale wind turbine category. The method used in this research is to design a horizontal axis wind turbine equipped with taperless blades with varying numbers of blades, namely three blades, four blades, and five blades, and then simulate the turbine's performance with wind speeds of 3 m/s to 6 m/s. The present research found that the greater the number of turbine blades tends to produce greater power. This is proven by research results, where the highest power in a small-scale horizontal axis wind turbine produces a power of 20,30 Watts in a 5-blade turbine variation for the wind speed of 6 m/s.

1. Introduction

1.1 Background

The use of electrical energy in Indonesia is currently very high. However, the energy used is still dominated by fossil energy, even though the potential for alternative energy in Indonesia is very large and cannot yet be utilized optimally, one of which is wind energy [1]. Society currently relies heavily on a single national electricity company (Perusahaan Listrik Negara or PLN) that produces electricity from fossil fuels such as coal, gas, and oil. Electricity is mainly used for household needs and other economic and social activities [2].

In several regions of Indonesia, wind energy has been used as an electricity generator. The amount of electricity produced depends on wind velocity. The wind velocity can be affected by obstacles such as tall buildings and trees. Therefore, coastal areas have higher wind potential, which

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can be converted into electrical energy with the help of wind turbines. There are two types of wind turbines, namely Vertical Axis Wind Turbine (VAWT) and Horizontal Axis Wind Turbine (HAWT) [3]. The Horizontal Axis Wind Turbine (HAWT) will be used as the research object in this research.

Basically, a wind turbine has blades that capture the wind's kinetic energy and convert it into usable mechanical energy. The number of blades on a wind turbine can affect the overall performance of the turbine. In large-scale projects, taperless blades are commonly used. However, this is not the case for the small-scale wind turbine project. Therefore, this research aims to analyze the effect of the number of taperless blades on the performance of a small-scale Horizontal Axis Wind Turbine (HAWT).

To determine variations in the influence of the number of blades on the performance of small-scale horizontal axis wind turbines, this research uses a simulation method using Solidworks software. This research focuses on calculating the performance of small-scale wind turbines with variations of turbine taperless blades that are three, four, and five blades without taking into account other factors that can affect wind turbine performance, such as the type of blade material.

1.2 Literature Reference

The wind is the air that moves due to differences in pressure on the earth's surface. Wind will move from an area with high pressure to an area with lower pressure. This wind that occurs on the earth's surface occurs due to differences in the reception of solar radiation, resulting in differences in air temperature. The difference in temperature causes a difference in pressure, ultimately causing air movement. The change in heat between day and night is the main driving force of the daily wind system due to the strong heat difference between the air over land and sea or between the air over high ground (mountains) and low ground (valleys) [4].

Wind energy can significantly contribute to reducing emissions because it does not produce CO2 emissions during the production of electrical energy by wind turbines [5]. Wind energy is an electrical energy source that can be used for free. The advantage of wind energy as a source of electrical energy is that it is widely available and unlimited in quantity. Several areas that have abundant wind potential include mountainous areas and beaches. Wind energy can be converted into electrical energy using a wind turbine. Energy from the wind is converted into kinetic energy or electrical energy. Therefore, wind turbines are often called Wind Energy Conversion Systems [6]. The Wind Energy Conversion System is a system that aims to convert kinetic energy into mechanical energy of the turbine shaft and then convert it again by the generator into electrical energy [7].

A wind turbine is a windmill that drives an electric generator and produces electrical energy. The working principle of wind turbines is based on energy conversion and uses renewable natural resources, namely wind. To capture wind energy, wind turbines are equipped with two or three blades designed to resemble airplane wings. The blades play an important role like airplane wings. Wind turbines consist of two types, namely Vertical Axis Wind Turbines and Horizontal Axis Wind Turbines [8]. These two types of turbines have their respective advantages. However, compared to their ability to extract wind power, the horizontal axis type has the best efficiency [9].

Complex analysis of wind turbines using Computer-Aided Engineering (CAE) software to model and analyze intricate geometries and loading conditions. The three-dimensional model of the RM1 NACA-4415 wind turbine reveals that maximum deformation occurs at the blade tips, while maximum stresses are observed near the blade centers [10]. Numerical simulations provide a cost-effective method for designing large-scale turbines, with potential improvements including the use of composite materials and various wind conditions. The study also identifies the optimal design for HAWT OPT, where TSR 6 shows the best performance. However, beyond the turbine's operational limit, increased wind speed no longer affects performance [11]. Factors such as twist angle and chord length significantly impact blade performance by ensuring proper pressure and velocity distributions. Further research is needed to evaluate performance changes with different twist angles. Additionally, the study finds that blade deformation and stress increase with wind speed and Yaw angle, with discrepancies compared to previous studies attributed to variations in blade size, geometry, materials, boundary conditions, and loading conditions [12].

The diffuser dimensions are the main parameters to increase velocity inside the shroud throat, where a long diffuser with a low converging angle drags more air inside the shroud, reaching in some cases more than double the upwind velocity [13]. Research shows that even small-scale wind turbines using the NACA 0012 airfoil can achieve a high power coefficient of about 43% at low wind speeds, such as 3 m/s. However, to meet the minimum requirement of 600 W for household electricity, a wind speed of at least 5 m/s is necessary, which can be achieved in low wind speed regions with the use of diffusers [14]. In some studies that extended this parameter to include long diffusers as Elsayed [15].

Wind turbines in use can be identified based on the amount of electricity produced and the turbine's height. According to the International Electrotechnical Commission (IEC) 61400-2 standard, it is divided into two classes, namely large wind turbines (LWT) and small wind turbines (SWT). Also, according to the UK (United Kingdom) small and medium wind market report in 2013, commercially produced SWT is separated into three categories: micro wind turbines, small wind turbines, and small-medium wind turbines [16].

2. Methodology

2.1 Modeling and Simulation Software

In this research, the tool used for creating a three-dimensional model is Solidworks 2018 software, while the model's performance analysis was performed using ANSYS CFX2020.

2.2 Data Collection

Data collection was carried out to support the research process. The collection of research-supporting data was carried out using existing references. The necessary data were mainly turbine and blade specifications and dimensions that are commonly used in small-scale wind turbine systems.

2.2.1 Horizontal axis wind turbine specifications

In this research, a horizontal wind turbine will be used with detailed specifications as in Table 1 [17].

Table 1
Horizontal wind turbine specifications

Specifications	Value
Turbine height	1500 mm
PMSG Type Generator	100 Watt
Rotor diameter	850 mm
Blade length	400 mm
Number of blades	3, 4 and 5
Blade material	Polylactic Acid

2.2.2 Airfoil profile selection

An airfoil is a shape of the cross-section of the blade, which is produced by cutting the blade perpendicular to the rotor [18,19]. The wind turbine blade airfoil profile used is the SG6043 airfoil as shown in Figure 1, based on research data taken from a website that provides airfoil profile specification data. The following are the specifications for the SG6043 airfoil profile. The maximum thickness value is 10% at 32,1% chord, and the camber thickness is 5,1% at 53,3% chord. The maximum Cl/Cd ratio value of SG6053 is 39,7 at α (Angle of Attack) = 8,75˚ with Cl = 1,3560 and Cd = 0,11226 [20].

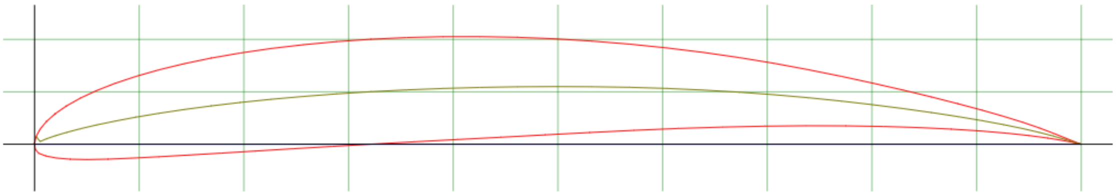

Fig. 1. Airfoil SG6043

2.2.3 Variations in the number of blades and wind speed

The variations in the number of taperless blades in this study were variations of three, four, and five blades. Meanwhile, the variations in wind speed used are 3 m/s to 6 m/s with intervals of 1 m/s.

2.3 Blades Modeling

At this stage, small-scale horizontal wind turbine modeling uses Solidworks 2018 software. The size and shape of this wind turbine are in accordance with the specifications shown in Table 1. After modeling, fluid flow analysis will be carried out in the model using Solidworks Flow Simulation 2018 to obtain the analysis results.

The taperless blade cross-section is shown in Figure 2. The turbine modeling is based on the variations that will be simulated, namely variations in the number of blades, which are 3, 4, and 5 blades, as shown in Figure 3.

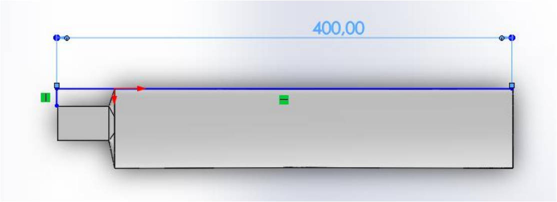

Fig. 2. Blade cross-section

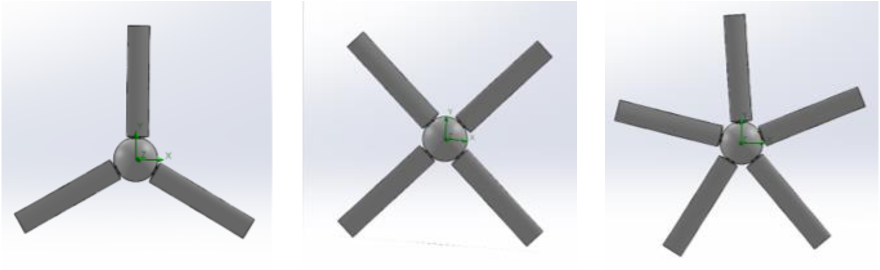

Fig. 3. Variations in HAWT taperless blades

3. Results and Discussion

After modeling, performance analysis is carried out by carrying out simulations. Before performing computational fluid dynamics analysis to determine the power of a wind turbine, the parameters required to calculate the turbine's power are angular velocity and torque. The angular velocity can be calculated using the following equation.

$$n = \frac{60 \cdot \lambda \cdot V_0}{2\pi \cdot r} \tag{1}$$

$$n = \frac{60 \cdot 3{,}5 \cdot 3}{2\pi \cdot 0{,}55} = 182.40 \text{ RPM}$$

where the tip speed ratio (λ) of 3.5 was used, with an initial wind speed of 3 m/s, 4 m/s, 5 m/s, and 6 m/s, and a rotor radius of 0.55 m. Table 2 shows the angular velocity values, which were calculated using the following equation. These angular velocity values were used as input data for the CFD simulation.

$$\omega = \frac{n \cdot 2\pi}{60} \tag{2}$$

$$\omega = \frac{182{,}40 \cdot 2\pi}{60} = 19.09 \text{ rad/s}$$

Table 2
Turbine rotational speed and angular velocity

Blade number variation	Initial wind velocity (m/s)	Turbine rotational speed (RPM)	Angular velocity (rad/s)
3	3	182.40	19.09
	4	243.20	25.45
	5	304.00	31.82
	6	364.79	38.18
4	3	182.40	19.09
	4	243.20	25.45
	5	304.00	31.82
	6	364.79	38.18
5	3	182.40	19.09
	4	243.20	25.45
	5	304.00	31.82
	6	364.79	38.18

3.1 Simulation with Computational Fluid Dynamics (CFD)

The simulation in this study was conducted using ANSYS CFX 2020. This simulation aimed to obtain the turbine torque values and fluid flow velocity after passing through the turbine for each variation of the number of turbine blades. Several stages in CFD simulation using ANSYS 2020 R2 software include geometry, meshing, setup, solution, and result.

The pre-processing stage aims to create the geometry model and computational domain that represent a physical problem. The pre-processing stages in CFD simulation using ANSYS CFX R2 2020 software include geometry modeling, meshing, and setup. Modeling is performed using Solidworks

2018 software. After the model is completed, it will be imported into ANSYS Design Modeler, as shown in Figure 4.

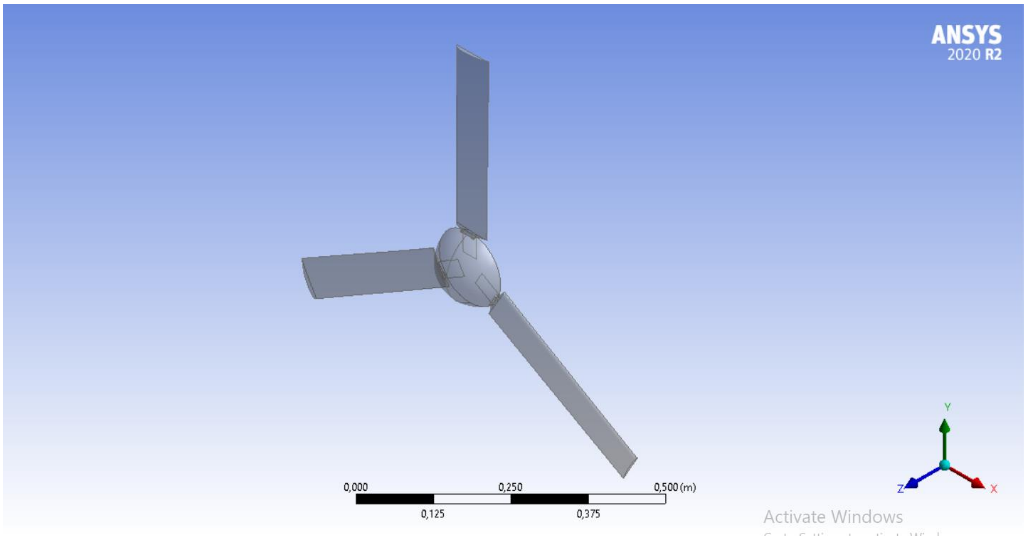

Fig. 4. Result of import geometry model of three-bladed horizontal axis wind turbine

One of the most influential factors in this simulation is the meshing or grid generation stage. This stage significantly affects the accuracy, convergence, and simulation speed. The meshing information for the 3-blade of the turbine is shown in Table 3.

Table 3
Mesh information of three-bladed turbine

Parameter	Dimension
number of nodes	179375
number of elements	955566
element shape	tetrahedron

The meshing results for the 3-blade turbine are shown in Figure 5.

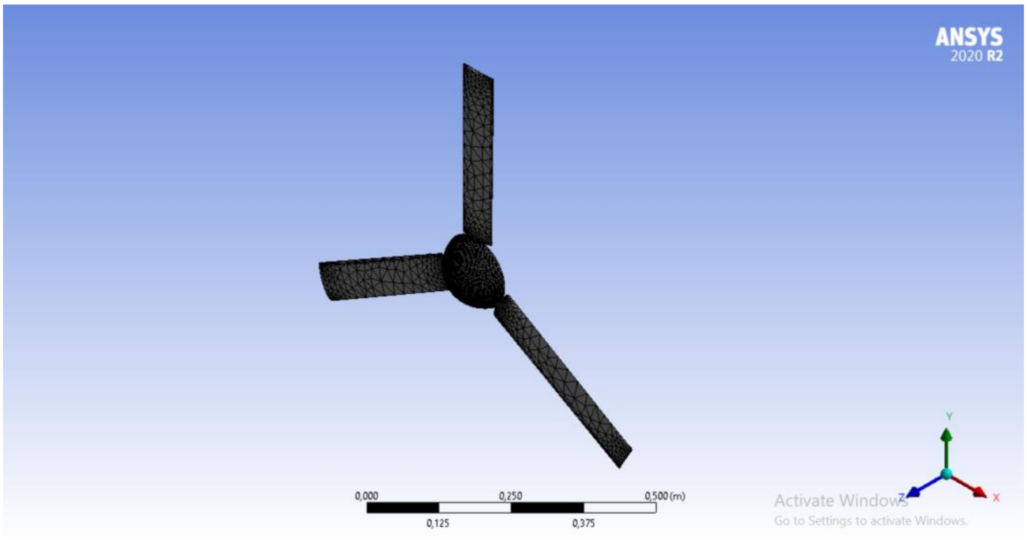

Fig. 5. Result of meshing model of three-bladed turbine

In the setup stage, variables supporting the simulation results to be analyzed are determined. In this step, the type of fluid used in the simulation is determined, and several boundary conditions are set. In this simulation, the fluid used is air at a temperature of 25°C and a pressure of 1 atm, conditioned in a steady state.

In solver, the numerical calculation process (running) is carried out using the basic fluid dynamics equations in Computational Fluid Dynamics (CFD) according to the set iteration limit. Figure 6 shows the iteration graph of the simulation result when the fluid flow condition passes through the three-bladed horizontal axis wind turbine at 3 m/s. It can be observed that the iteration process reaches a value of 500 iterations. This occurs because the set analysis type is a steady-state analysis, where there are no significant changes in fluid flow variables from one iteration to the next.

```
+--------------------------------------------------------------------+
|           CPU Requirements of Numerical Solution - Total           |
+--------------------------------------------------------------------+

Subsystem Name                  Discretization      Linear Solution
                               (secs.   %total)     (secs.   %total)
----------------------------------------------------------------------
Mesh Displacement              1.92E+03   9.0 %     1.23E+03   5.7 %
Wall Scale                     6.98E+02   3.3 %     3.66E+02   1.7 %
Momentum and Mass              7.31E+03  34.2 %     1.33E+03   6.2 %
TurbKE and TurbFreq            1.68E+03   7.9 %     9.90E+02   4.6 %
                               -------- -------     --------  ------
Subsystem Summary              1.16E+04  54.3 %     3.92E+03  18.3 %

File Reading                   8.56E-01    0.0 %
Search Calculations            5.03E-02    0.0 %
Variable Updates               1.74E+03    8.1 %
File Writing                   4.63E+00    0.0 %
Miscellaneous                  4.12E+03   19.3 %
                               --------
Total                          2.14E+04

+--------------------------------------------------------------------+
|                    Job Information at End of Run                   |
+--------------------------------------------------------------------+

Job finished:   Sat Aug 10 21:31:57 2024

Total wall clock time: 5.347E+03 seconds
            or: (          0:          1:         29:      6.715 )
                (       Days:      Hours:    Minutes:    Seconds )



--> Final synchronization point reached by all partitions.
End of solution stage.

+--------------------------------------------------------------------+
| The results from this run of the ANSYS CFX Solver have been        |
| written to E:/PUNYA AUDRYE                                         |
| COMEL/TAPERBLADE/Taperblade_pending/dp0_CFX_6_Solution_6/Fluid     |
| Flow CFX_002.res                                                   |
+--------------------------------------------------------------------+


+--------------------------------------------------------------------+
| For CFX runs launched from Workbench, the final locations of       |
| directories and files generated may differ from those shown.       |
+--------------------------------------------------------------------+

This run of the ANSYS CFX Solver has finished.
```

Fig. 6. Result of meshing model of three-bladed horizontal axis wind turbine

The post-processor is the result file of the simulation conducted, which includes visual images of the model flow and numerical data. In this study, the desired result parameters are torque values and velocity after passing through the wind turbine. The simulation results can be seen in Table 4.

Table 4
Simulation results of turbine performance in ANSYS 2020 R2

Blade number variation	Initial wind velocity (m/s)	Final wind velocity (m/s)	Torque (N.m)
3	3	1.79	0.04
	4	2.38	0.08
	5	2.99	0.12
	6	3.59	0.17
4	3	1.81	0.11
	4	2.41	0.19
	5	3.02	0.30
	6	3.62	0.43
5	3	1.82	0.13
	4	2.43	0.24
	5	3.04	0.37
	6	3.65	0.53

3.2 Numerical Simulation Results

This horizontal axis wind turbine simulation was carried out using ANSYS 2020 R2 software at varying velocities. In this research, the turbine is simulated at rest, and the fluid is in motion. Figure 7 and Figure 8 show the contour of the turbine with 3-blade variations. Figure 7 shows the wind speed distribution, showing that the speed becomes smaller after the wind hits the turbine blade. Meanwhile, Figure 8 shows the distribution of wind flow pressure, showing that after the wind hits the turbine blade, the pressure becomes smaller.

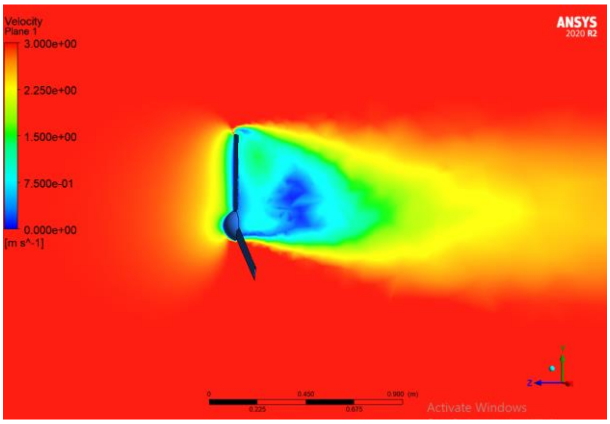

Fig. 7. Wind speed distribution

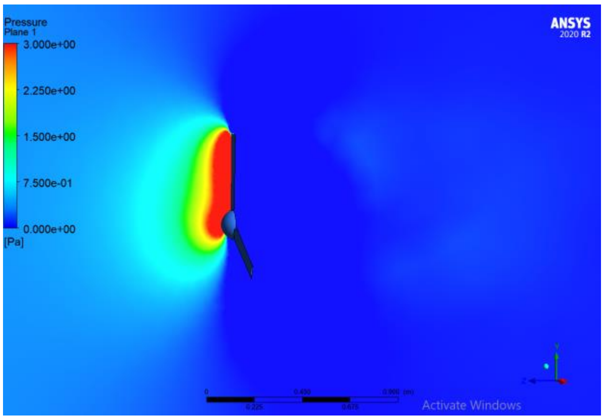

Fig. 8. Pressure distribution

Figure 9 shows the flow trajectories that occur in the turbine with a variation of three blades and a wind velocity of 3 m/s. The bright color of the contour represents wind energy that the turbine can absorb. The highest wind velocity simulation result was 1.79 m/s.

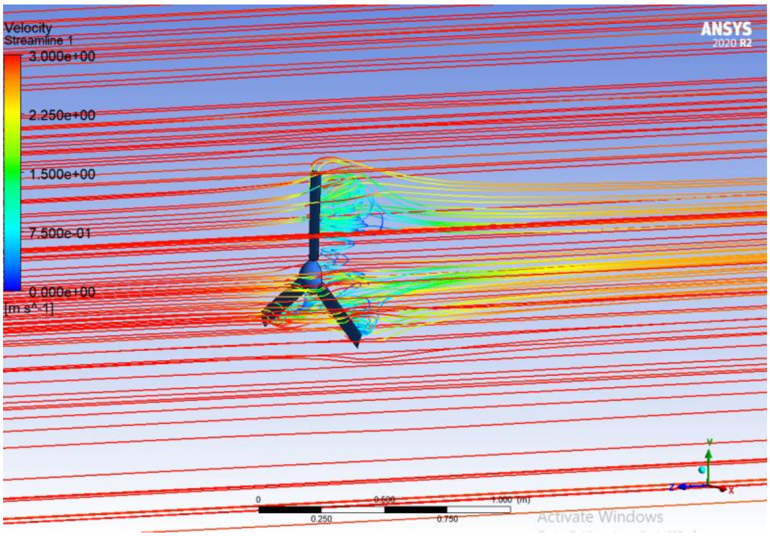

Fig. 9. Velocity contours of a three-blade wind turbine at 3 m/s

3.3 The Turbine Power

After obtaining the CFD simulation results in ANSYS 2022 R2, which include the turbine torque, the next step is to calculate the power generated by the horizontal axis wind turbine in this study. The power equation is as follows:

$$P_{turbine} = T \cdot \omega \tag{3}$$

where, $P_{turbine}$ is turbine power, ω is the optimum angular velocity (rad/s), and T is torque (Nm). Table 5 shows the results of turbine power calculations.

Table 5
Wind turbine power

Number of blades	Velocity (m/s)	Power (Watt)
3	3	0.82
	4	1.94
	5	3.79
	6	6.55
4	3	2.07
	4	4.90
	5	9.58
	6	16.55
5	3	2.53
	4	6.01
	5	11.75
	6	20.30

3.4 Results Analysis

Based on simulation data from each variation in the number of horizontal axis wind turbine blades and variations in wind speed in this research, the wind turbine can produce electrical power. Figure 10 shows that the number of blades on a horizontal axis wind turbine affects the power output. The highest power output in this simulation is for the five-blade horizontal axis wind turbine at a wind speed of 6 m/s, producing 20.30 Watts. Wind turbines with five blades can generate the highest power compared to those with fewer blades. Turbines with fewer blades have lower rotations than those with five blades due to the larger distance between the blades, which can lead to uneven wind distribution compared to other blades.

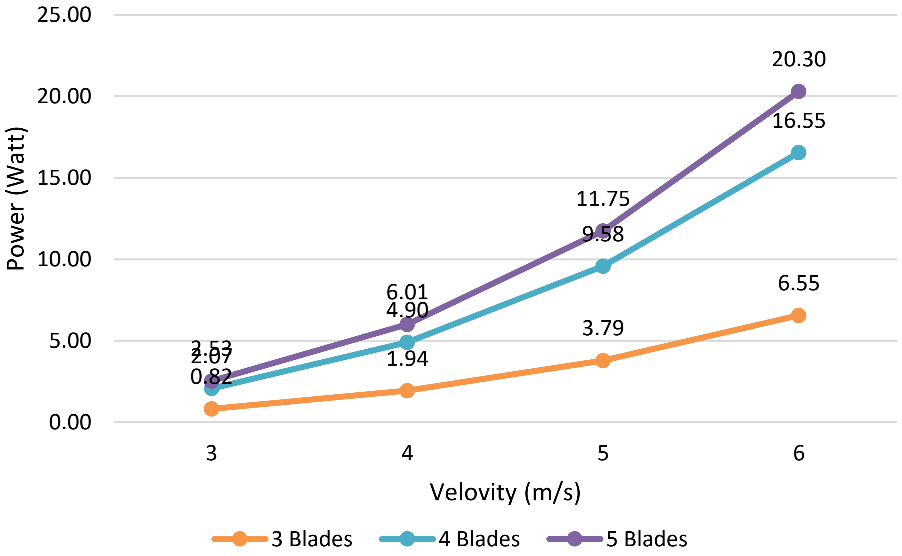

Fig. 10. Turbine produced power

4. Conclusions

Variation in the number of blades affects the power generated under various wind speed conditions in small-scale horizontal-axis wind turbines. The more taperless blades there are, the tendency is to produce greater power. In this study, the highest power was generated by a horizontal-axis wind turbine with 5 taperless blades at a speed of 6 m/s, producing 20.30 Watts. This is because turbines with fewer blades have lower rotations compared to those with 5 blades due to the greater distance between the blades, which can cause uneven wind distribution compared to other blades.

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