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Taperless Type Blade Design with Naca 5513 Airfoil for Wind Turbine 500 TSD

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Abstract. The utilisation of wind energy in Indonesia is still low because the average wind speed in Indonesia is low. The design of the HAWT using a NACA airfoil which has a high C / C_d value and produces 500 W of power at wind speeds of 1 m/s up to 11 m/s. The research was conducted in 3 stages. First, the calculation stage to determine the radius, chord and twist of the blade. Second, the initial design stage of the blades is simulated to determine the NACA airfoil that is used and to know the coefficient of performance and power produced. Third, the stage of designing the 3D blade design. The design results show that the HAWT blades with NACA 5513 airfoil taperless type with the radius of 0.9 m on the airfoil simulation produced a higher C_l / C_d value with 152.73 when α = 4 °. In the C_p simulation for TSR, the C_p value reaches 20% in TSR 2 up to 10. Meanwhile, in the power wind speed (P - v) simulation, the power generated reaches 500 W at wind speeds of 11 m/s and angular velocity 263 up to 1000 rpm.

1. Introduction

Energy is the most considerable constituent of socio-economic development and economic growth. One of the most widely used energy sources is fossil fuels. The effect of using fossil fuels causes an increase in the temperature of the earth. To avoid a crisis and scarcity of fossil energy, the use of renewable natural resources is something that must and continues to be developed [1].

Wind turbines are divided into two based on the direction of the axis which is horizontal wind turbines (HAWT) and vertical wind turbines (VAWT). Each type of wind turbine has a different size and efficiency. Horizontal axis wind turbines are considered more efficient than vertical axis wind turbines [2]. The types of blades are divided into three based on the design which is taper (shrink to the end), taperless (base and tip have the same width), and inverse-taper (enlarged to the tip). The Sky Dancer-500 (TSD-500) is a horizontal wind turbine with three propeller blades with a diameter of 1.6 or 2 meters and has an efficiency of 40%. This turbine starts spinning at wind speeds of 2.5 m/s and starts producing electricity at wind speeds of 3 m/s. The maximum power that can be produced by a turbine is 500 Watt peak (Wp) at wind speed ≥ 12 m/s [3]. QBlade is open source software used for wind turbine simulation and design. QBlade simulation results in the form of graphs that show essential parameters that affect the performance of the blades, including power, torque, wind speed, rotation speed and efficiency of the blades [4].

Indonesia has sufficient wind energy potential for the development of renewable energy based on windmills because the average wind speed ranges from 3 m/s and up to 12 m/s [5]. So it needs to be designed blades that can operate at low wind speeds. The purpose of this study is to design a HAWT

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(Horizontal Axis Wind Turbine) blade using a NACA airfoil that has a high C_l / C_d value and produces 500 W of power at wind speeds of 1m/s and up to 11 m/s.

2. Material And Methodology

2.1. Research flow chart

The research flow chart looks like in figure 1.

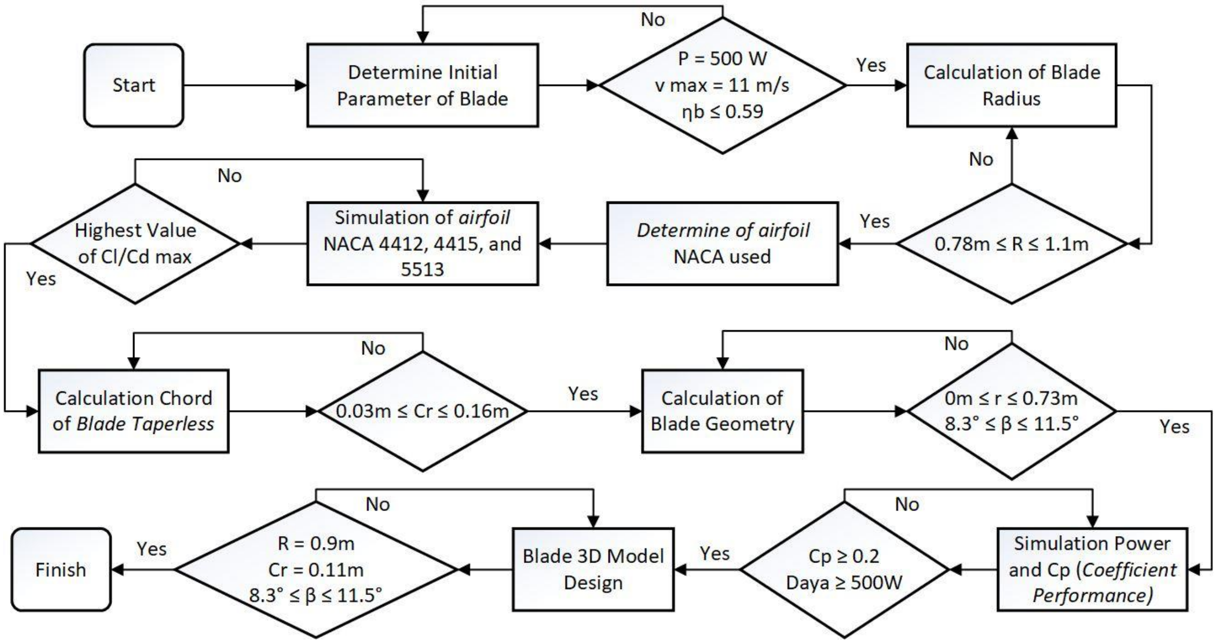

Figure 1. Research flow chart

2.2. Research methodology

The procedure in this study was divided into three which is the calculation of the design, the design of the blades in a simulation using QBlade software, and the design of the 3D model of blades using the software Solidworks. Each procedure is described as follows:

2.2.1. Blade calculation and design. The windmill blades that will be used are designed in advance by determining the parameters that will be used as the basis for designing the blades. The equation used to determine the initial parameters of the blade is in the following table 1 [6].

Table 1. The initial parameter equation of blade

a.	The wind power needed for each system efficiency	$P_a = \frac{P_l}{K}$ $P_a = \frac{1}{2}\rho A v^3$
b.	The efficiency of the wind turbine system	$K = \eta_b \times \eta_t \times \eta_g \times \eta_k$
c.	Generated electricity	$P_l = \omega T$
d.	Coefficient performance (C_p)	$C_p = \frac{Pl}{Pa}$

e.	Blade radius	$A = \frac{2P_a}{\rho v_{max}^3}$ $R = \sqrt{\frac{A}{3.14}}$
f.	TSR is the ratio of the blade tip linear velocity to the wind speed	$\lambda = \frac{\omega \times R}{v}$
g.	Partial radius	$r = r_0 + \left[\left(\frac{R - r_0}{n}\right) \times (element)\right]$
h.	Flow angle of each element	$\phi = \frac{2}{3} tan^{-1} \frac{1}{\lambda_p}$
i.	Partial TSR is the ratio of the blade element linear velocity to the wind speed of the different elements	$\lambda_p = \frac{r}{R} \lambda$
j.	Blade width (chord)	$C_r = \frac{16\pi \times R \times \frac{R}{r}}{9\lambda^2 \times B \times C_l}$
k.	The lift coefficient (C_l)	$C_l = \frac{16\pi \times R \times \frac{R}{r}}{9\lambda^2 \times B \times C_r}$
l.	Twist angle	$\beta = \phi - \alpha$

The nomenclature of table 1 is in the following table 2.

Table 2. Nomenclature

A	Cross-sectional area (m^2)	**K**	System efficiency
B	Number of blades	**n**	Number of elements
Cl	Lift coefficient	P_l	Electrical power (Watt)
Cp	Coefficient performance	P_a	Wind power (Watt)
Cr	Blade width / Chord (m)	**v**	Wind velocity (m/s)
v_{max}	Maximum wind velocity (m/s)	η_g	Generator efficiency
R	Blade radius (m)	η_k	Controller efficiency
r	Partial radius (m)	η_t	Transmission efficiency
r_0	Partial element radius 0	λ	Tip speed ratio
T	Torque (Nm)	λ_p	Partial TSR
z	Chord after twisting (m)	ρ	Density (Kg/m^3)
α	The angle of Attack (°)	ϕ	Flow angle (°)
β	Twist (°)	ω	Angular velocity (rad/s)
η_b	Blade efficiency		

2.2.2. Simulation using QBlade software. The simulation is carried out using QBlade software to determine the NACA airfoil used and find out the C_p and Power generated. The results of the airfoil simulation are C_l/C_d graph of α. By comparing the maximum C_l/C_d values will be obtained a NACA airfoil which will be used in the blade design. Blade simulation is carried out to see the C_p value at TSR 1 - 10 and the power generated at wind speed 1 - 11 m/s and angular velocity of 200 - 1000 rpm.

2.2.3. Design of 3D blade simulation result. The stages of designing 3D blade using Solidworks software are as follows [6]:

a. Blade coordinates data preparation

NACA 5513 airfoil data coordinates can be downloaded in the Qblade program (coordinates have no units).

b. The processing of NACA 5513 airfoil coordinate data using Microsoft office excel software

The coordinates derived from Qblade are the x and y coordinates. The x and y coordinates are multiplied by 100 units to simplify the calculation and add the z coordinates. Write 0 for the coordinates of the z-axis. A value of 0 indicates that this element is in the position of 0 mm, then subtract z coordinates with the distance between the elements, the reduction is made as much as the number of design elements that are ten elements except element 0 because element 0 is the base of the blade. Processing of coordinate blade data is in the following table 3.

Table 3. Processing of coordinate blade data

NACA 5513		0			1		
		x	y	z	x	y	z
1.00000	0.00136	100.000	0.136	0.000	100.000	0.136	-73
0.99280	0.00388	99.280	0.388	0.000	99.280	0.388	-73
0.97989	0.00833	97.989	0.833	0.000	97.989	0.833	-73
0.96352	0.01382	96.352	1.382	0.000	96.352	1.382	-73

c. Saving blade coordinates

Each x, y and z coordinate data are exported to notepad program in the .txt format, and the data will be input into the SolidWorks software. The blade coordinate data is shown in figure 2.

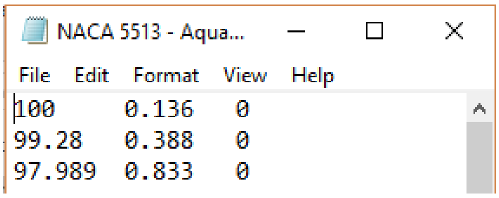

Figure 2. Blade coordinate data

d. Preparation of making 3-Dimensional blade models

The coordinate data of each element is input with the Curve toolbar (Curve Through XYZ Points) found in the Solidwork software and will produce an airfoil shape. The results of the coordinate data input are shown in figure 3.

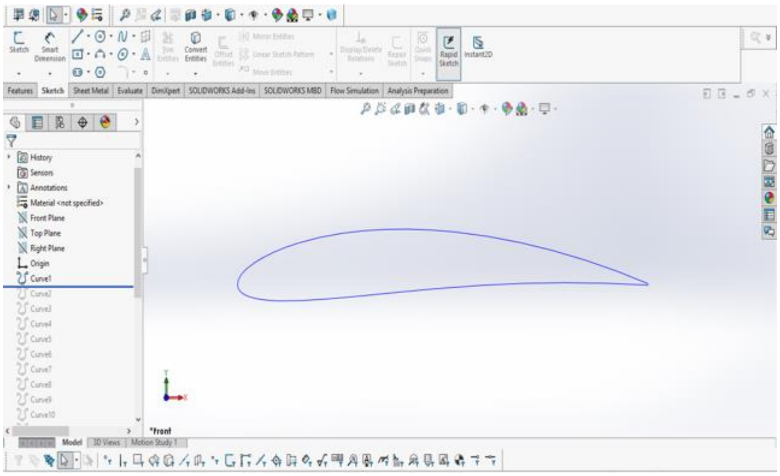

Figure 3. The results of coordinates data input on the Solidworks software

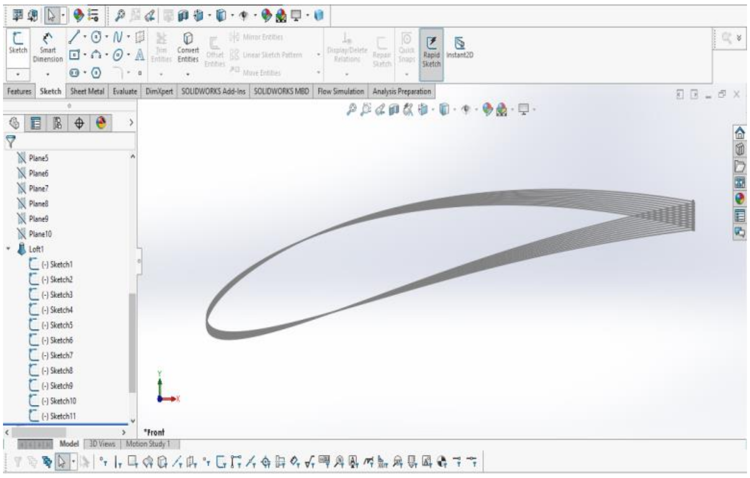

Figure 4. The results of the enlargement chord and twisting angle of the airfoil data input on the Solidworks software

e. Blade element size calculation

Adjustment of design size is the width of the chord and the angle of twist of each element using the equation:

$$z = \frac{C_r}{cos\beta} \qquad (1)$$

The difference in the twist angle (β) of each element makes the value of *z* different. Divide the z value obtained by 100 to calculate the zoom. Value of 100 is the coordinates of the airfoil chord in the QBlade software.

f. Making the structure geometry of the blades

The chord enlargement data and the torsional angle (β) are input to the airfoil form found in the SolidWorks software. The results of the input data of the chord magnification and the twisting angle on the airfoil are shown in figure 4. The airfoil on element 0 is connected to the base of the blade. The length of the base of the blade until the airfoil in element 0 corresponds to the size of the partial radius of element 0.

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3. Result and Discussion

3.1. Initial determination of blade parameters

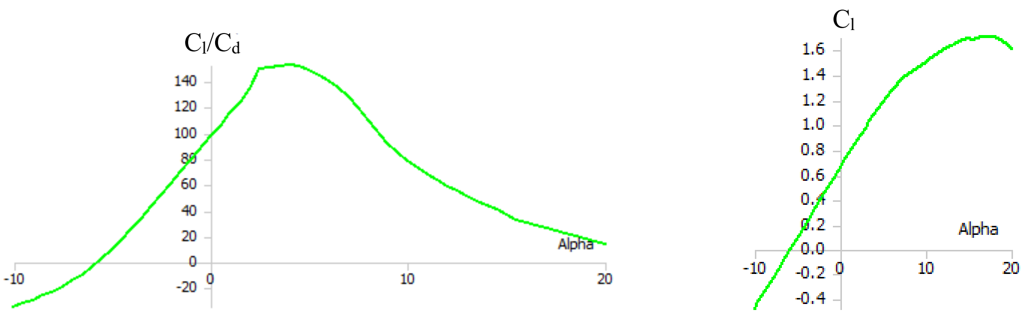
The design of the blades is done by determining the initial parameters of the blades. Overall system efficiency there are four that the efficiency of blades, transmission, generator and controller. The maximum energy that can be extracted from the wind by the blades is 59% or also called the Betz coefficient (C_p) [7]. Transmission Efficiency is 100% because the rotation of the blades is directly connected to the generator without using transmission. In this study, the value of the efficiency of the generator and controller is the maximum value of the system on the LAN (LenteraAngin Nusantara) wind turbine that is equal to 90% for each system. The maximum electrical power output of the TSD-500 wind turbine is 500 W. Estimated maximum wind speed to obtain 500 W of power is 11 m/s. The wind power is obtained using the equation in point of table 1. The radius of the blade is obtained from the equation in point e of table 1, giving a result of 0.9 m. Data for determining the initial parameters of the blade is presented in table 4.

Table 4. Determining the initial parameter of the blade

P_l	η_b	η_g	η_t	η_k	K	P_a	v	ρ	A	R	R used
500	0.2	0.9	1	0.9	0.162	3086.42	11	1.23	3.79	1.10	0.9
	0.4				0.324	1543.21			1.89	0.78	

3.2. Determination of the blade geometry

Before determining the geometry, the blade must determine the airfoil used. The airfoil used is determined by comparing the highest maximum C_l/C_d value from the results of NACA 4412, 4415 and 5513 airfoil simulations. The highest maximum C_l/C_d value is NACA 5513 which is 152.73 when α = 4 ° as shown in Figure 5a. From the value of α = 4 °, the value of C_l = 1.1 is obtained as shown in Figure 5b. This C_l value will be used to determine the width of the blade (Chord) using the equation in point j table 1. Because the chords on the taperless bar are the same from the base to the end, it is necessary to choose a chord size to be used. In this design, the chord used is 0.11 m because it is to simplify the process of making slats. The results of the NACA 5513 airfoil simulation are presented in figure 5.



(a) (b)

Figure 5. Results of NACA 5513 airfoil simulation (a) C_l/C_d - α graph, (b) C_l - α graph

Based on the results of the NACA 5513 airfoil simulation, the coefficient of lift increases with increasing angle of attack until it reaches a certain point where the airflow behind the cross-section separates and forms turbulence. As a result, the top of the airfoil is not passed through the fluid and causes the lift force to drop rapidly. This phenomenon is called stalling. At this time, the lift force on the bar is very small, and the thrust is large.

The blade element momentum theory contains mathematical models for calculating the ideal power of a wind turbine, the force of the wind on the turbine and the effect of turbine operation on the surrounding wind conditions [8]. With blade momentum theory, the blade is divided into several elements. The partial radius of element 0 is the distance from the centre of the hub to the part of the blade that is not attached to the generator. Partial radius on elements other than 0 is obtained using the equation in point g of table 1. Another parameter needed in designing the blade is the TSR. In general, the TSR value is influenced by the number of blades used. TSR values on the blades, amounting to 3 pieces, are valued between 6-8 [9]. Partial TSR is obtained using the equation in point i table 1. By using C_r = 0.11m, a different C_l is obtained for each blade element. C_l values are obtained using the equation in points to table 1. The α value is obtained from the C_l-α graph in figure 5b using the C_l value in table 5. Flow angle and β values are obtained using the equations at points h and l of table 1. Data for determining the geometry parameters of the blades are presented in table 5. The geometry in the blade can be seen in figure 6 and figure 7. Numbers 0-10 in figure 6 are blade elements.

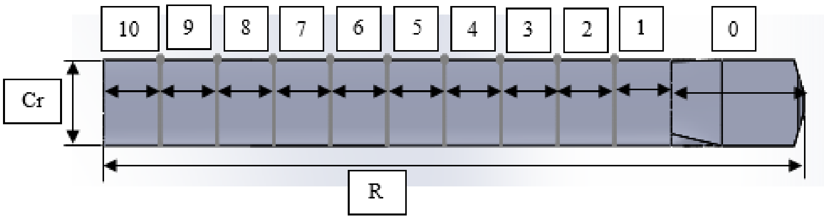


Figure 6. The blade geometry top view

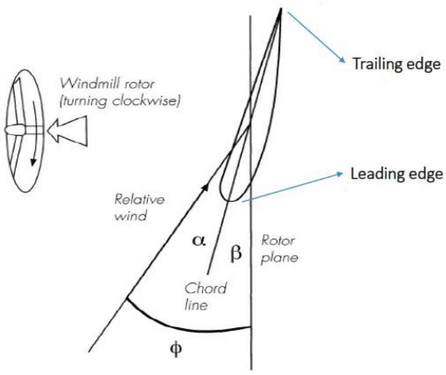


Figure 7. The blade geometry side view

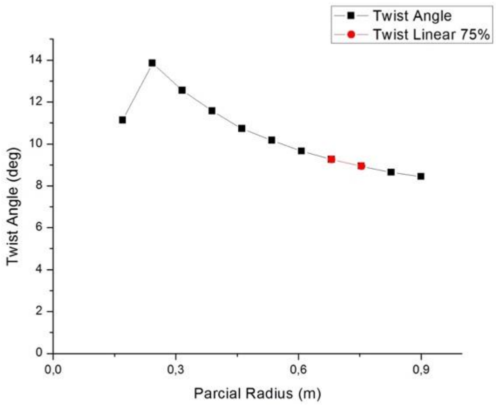


Figure 8. The twisted angle line graph

Data for determining the geometry parameters of the blades are in the following table 5.

Table 5. Determining the geometry parameters of blades

Element	r	λ_p	C_r	C_l	α	ϕ	β	Twist Linear 75%	Optimisation Twist
0	0.17	1.3	0.16	1.65	13.6	24.7	11.1		11.5
1	0.243	1.9	0.11	1.15	4.74	18.6	13.8		11.2
2	0.316	2.5	0.08	0.89	2.21	14.8	12.6		10.8
3	0.389	3.0	0.07	0.72	0.62	12.2	11.6		10.5
4	0.462	3.6	0.06	0.61	-0.36	10.4	10.7		10.2
5	0.535	4.2	0.05	0.52	-1.16	9.0	10.2		9.9
6	0.608	4.7	0.04	0.46	-1.69	8.0	9.7		9.6

Element	**r**	λ_p	**C_r**	**C_l**	**α**	**ϕ**	**β**	**Twist Linear 75%**	**Optimisation Twist**
7	0.681	5.3	0.04	0.41	-2.13	7.1	9.3	9.3	9.3
8	0.754	5.9	0.04	0.37	-2.49	6.5	8.9	8.9	8.9
9	0.827	6.4	0.03	0.34	-2.75	5.9	8.6		8.6
10	0.900	7.0	0.03	0.31	-3.02	5.4	8.4		8.3

Optimization of the torsional angle of the blade is carried out to facilitate the production process and produce an efficient blade. Two points as a reference to make a linear line equation are the 7th and 8th points because the position of 75% of the radius is the most optimal point for making a linear line equation. The optimization twist is obtained from the line equation after linearization. The graph of the twist angle can be seen in figure 8.

The blade model in the QBlade software is obtained by entering the geometry of the blade, namely the partial radius, the chord, and the optimization twist angle of elements 1-10. Element 0 is the base of the blade to connect the blades to the generator which will be included in the 3D blade design. The blade design in the QBlade software can be seen in Figure 9, and the 3D design blade in Solidworks software can be seen in figure 10.

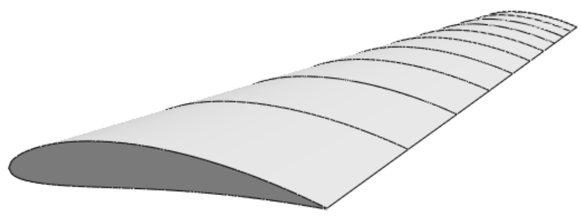


Figure 9. NACA 5513 blade model in QBlade software

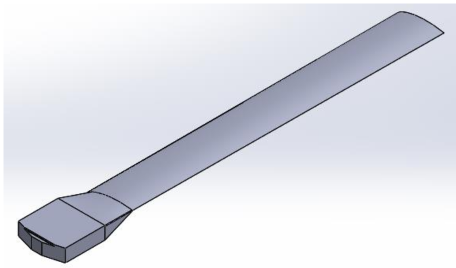
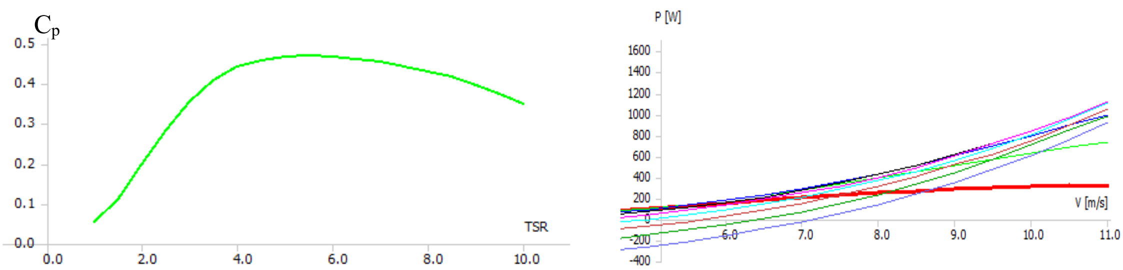


Figure 10. 3D design blade in Solidworks software

3.3. Blade simulation

Simulation of BEM (Blade Element Momentum) rotor produces a TSR graph against C_p. The C_p-TSR graph simulation results using QBlade software are presented in figure 11a. Based on the simulation, C_p increases with increasing TSR to the optimum point where the angular velocity and torque produce maximum power then decreases due to less effective torque when the angular velocity is too high. C_p values reached 0.2 on TSR 2-10.



(a) (b)

Figure 11. Graph of simulation results (a) C_p - TSR, (b) Power - Wind velocity

The more blades used in the wind turbine, the more blades that produce additional drag force due to the weight of the blades in the opposite direction of rotation so that the resulting torque is very small or even minus and this also affects the power coefficient produced [10]. The graph of power - wind speed (P - v) simulation results using QBlade software is shown in figure 11b. Based on the P - v graph, the power increases with increasing wind speed. At each wind speed, there is a certain angular speed and torque where the optimum power generated. At wind speeds of 11 m/s, the power increases with increasing angular velocity to an angular velocity of 600 rpm where the power produced is optimal then decreases due to reduced torque due to additional drag force as a reaction to its angular velocity. The blades reach a power of 500 W at 11 m/s wind speed when the angular velocity is 263 - 1000 rpm.

3.4. Blade design using solidworks software

Blade design using Solidworks software produces 3D slats design which will be used to assist the manufacturing process. The 3D design of the slats is shown in figure 10.

4. Conclusions

Based on the results of the design of the taperless blades with NACA 5513 airfoil, NACA 5513 airfoil simulations that have been carried out produce a maximum C_l/C_d value of 152.73 when $\alpha = 4°$. NACA 5513 blade simulation with 0.9 m radius, chord = 0.11 m, and twist angle = 8.3° - 11.5° in C_p - TSR simulation, C_p values reached 20 % at TSR 2-10. Meanwhile, the simulation of wind power-speed results in power reaching 500 W at 11 m/s wind speed when the angular velocity of the blade is 263 - 1000 rpm.

Acknowledgements

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