International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Blade Design of TSD-500 Wind Turbine for Smart Grid Pilot Project of Udayana University

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ABSTRACT

The blade design of The Sky Dancer-500 (TSD-500) wind turbine for smart grid in microgrid pilot project is carried out by determining the parameters and the geometry of the blade. Design of the TSD-500 wind turbine blade is performed by using the taper blade type with NACA 4412 aerofoil. QBlade v.09 and Autodesk Inventor 2018 software is used in the design process. From the simulation, the maximum power generated by the blades at a maximum wind speed of 12 m/s is 506.7 Watts with an angular speed of 312 rpm.

Keywords:wind turbine, TSD-500 blade, smart grid

1. Introduction

Pilot Project Smart Grid in Microgrid is the result of collaboration and MoU number 1714/UN414.1.31/KS/2015 between R&D Department of Ministry of Energy and Mineral Resources and Udayana University to jointly develop technology in the field of energy and mineral resources, especially in the development of new and renewable energy [1]. According to the Annex of Presidential Regulation No. 22 of 2017, Bali has great wind potential. Wind Power Plant (WPP) in the pilot of Project Smart Grid in Microgrid of Udayana University has a power capacity of 5 kWp using 10 wind turbines consisting of two GH-500W and eight TSD-500s wind turbines [2]. In the current condition of the field, there is one wind turbine type The Sky Dancer (TSD) that does not work because there is a broken blade. This results in the WPP 10 x 0.5 kWp not working optimally. One solution to maximize the performance of WPP 10 x 0.5 kWp in the Smart Grid in Microgrid Pilot Project is to make a design from damaged blades, then make new blades to drive damaged wind turbines. The blade design is customized with type, shape, type of aerofoil, and blade size in 10 x 0.5 kWp wind turbine. The design of the blades is adjusted to the type, shape, type of aerofoil, and size of the blades on the WPP 10 x 0.5 kWp. Based on these problems, the idea arose to design a horizontal axis wind turbine type blade of The Sky Dancer taper type using NACA 4412 aerofoil and a maximum power limit of 500 kWp. The results of this design then simulated so that the performance of the blade to be created can be observed.

2. Distributed Generation

Distributed Generation (DG) is a small and medium-scale plant with a power range of between 1 kW to 10 MW, which is connected to a distribution system and is usually placed on a bus that directly supplies the load center and or at the distribution substation. Based on its function, DG is distinguished by two types, namely as a unit that is functioned to anticipate if there is a disconnection from the grid power supply or stand by unit and functions as a unit installed during peak load hours or peaking units [3].The following is a list of DG type classifications based on the range of power that can be produced.

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Table 1. DG type based on power range

DG Type	Power Range
Micro DG	1 Watt < 5 kW
Small DG	5 kW < 5 MW
Medium DG	5 MW < 50 MW
Large DG	<300 MW

3. Wind Turbine

A wind turbine is a power plant that uses wind as an energy source to produce electrical energy. Wind power plants convert wind power into electrical energy by using wind turbines. The rotation of the turbine caused by the wind is passed to the rotor generator where this generator has a copper winding that functions as a stator so that an electromotive force (GGL) occurs. The basic working principle of a wind turbine is to convert the energy of wind motion into rotary energy in the turbine, then the rotation of the turbine is used to rotate the generator, which will eventually generate electricity. In principle, the main components of the wind turbine consist of a rotor, a drive train, a yaw system, a main frame and a tower. Where the rotor part serves to convert kinetic energy from wind into mechanical energy connected to the main shaft, the rotor part consists of blades, hubs, aerodynamic control. The Drive train section functions as a component that connects mechanical energy from the rotor to the generator, the drive train consists of a gearbox, generator, mechanical brake, shaft and couplings connecting. Then the yaw system serves to rotate the turbine in the direction of the wind, the yaw system part consists of a yaw bearing turbine, yaw drive, yaw brake and yaw damper. The main frame or nacelle serves as the home of the components of the drive train and yaw system, and the tower consists of a foundation that functions as a part that supports all wind turbine components [4].

3.1. Theory of wind turbine

A wind turbine extracts electricity from the wind by slowing down the flow of the wind. When the wind speed is less strong to rotate the rotor, the rotor obviously does not produce power and at very high rotational speeds exceeding the rotor's rotational capacity then no power is generated. The power generated (Pkin) by a wind turbine is the overall kinetic energy of a wind turbine (from the initial air speed V1 to a turbine with an airspeed of V2) given as an equation (1).

$$P_{kin}=\frac{1}{2}m(V1^2-V2^2) \qquad (1)$$

The wind mass flow rate (m) is given by the community equation as the product of density (ρ), the area that sweeps the rotor from the turbine (A) and the speed of approach of air (Va), given by the equation

$$m=\rho A\,V_a \qquad (2)$$

therefore, the power becomes

$$P_{kin}=\frac{1}{2}\,\rho AVa(V1^2-V2^2) \qquad (3)$$

because the rotor speed is the average speed (Va) between the inlet and the outlet, so

$$Va=\frac{1}{2}(V1+V2) \qquad (4)$$

therefore,

$$P_{kin}=\frac{1}{2}\rho A\frac{1}{2}(V1+V2)(V1^2-V2^2)$$

$$P_{kin}=\frac{1}{4}\rho A(V1^3-\,V2^3-V1\,V2^2+V1^2V2)$$

$$P_{kin}=\frac{1}{4}\rho A[1-\left(\frac{V2}{V1}\right)^3-\left(\frac{V2}{V1}\right)^2+V2/V1] \qquad (5)$$

to find the maximum power extracted by the rotor, lower the equation against V2 and equate it to zero

$$dP_{kin}/dV2\ =\frac{1}{4}\rho A(-3V2^2-2V1V2\ +\ V1^2)=0 \qquad (6)$$

since the area of the rotor area (A) and the density of air (ρ) cannot be zero, the expression in the bracket of equation (6) must be zero therefore, the equation becomes

$$(3V2-V1)(V2+V1\,)=0 \qquad (7)$$

V2 = - V1 is unrealistic in this situation, there is only one solution, i.e. equation (7) gives

$$V2=1/3V1 \qquad (8)$$

input equation (8) to equation (5) so that it is obtained

$$P = (0.5925)\ \tfrac{1}{2}\ \rho A (V1)^3 \qquad (9)$$

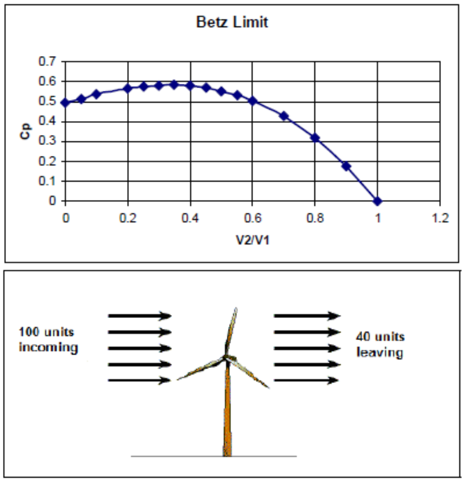

Fig. 1 Betz limit and wind energy efficiency

The theoretical maximum fraction of power coming from the wind that an ideal wind turbine could take, therefore the fraction of 0.5925 is called the Betz Coefficient (Cp) [5]. Due to aerodynamic imperfections in any engine there will practically be a loss of power, the extracted power is reduced. The wind turbine effect designs implications the power generated and harnessed from incoming wind. Wind efficiency depends on the production of the optimal speed ratio providing maximum power or close to maximum power.

3.2. Types of wind turbine

Horizontal Axis Wind Turbine

Horizontal type wind turbines have a propeller-like concept, where the Horizontal Axis Wind Turbine (HAWT) rotor rotates against the horizontal axis and is almost parallel to the wind flow. Horizontal turbines are currently very dominant in use in wind turbine technology. The advantages of this type of turbine are that it has a relatively high power coefficient value, the rotor speed and output power can be controlled by controlling the pitch on the rotor blades, the shape of the blades can be aerodynamically optimized and can achieve the highest efficiency when aerodynamic lifts are exploited to the maximum [6]. Horizontal wind turbines are categorized into one blade (single bladed), two blades (two bladed), three blades (three bladed), and many blades (multi bladed). The number of blades on the horizontal turbine each has characteristics, the more the number of blades, the easier it is to start the rotor because the more wind energy is captured by the blades but the aerodynamic losses the higher while the number of blades one and two has balance problems. Most commercial turbines use the three-blade type because they are more balanced and the aerodynamic load is more uniform [7].

Vertical Axis Wind Turbine

A vertical axis wind turbine is a wind turbine with a perpendicular mounted shaft or rotor axis, this vertical main rotor axis will allow for the turbine to be able to receive and capture wind from any direction of the wind. The advantages of this type of turbine will be useful in areas that have wind conditions that often change or vary So that it is more efficient in utilizing wind energy and is very suitable for the construction of power plants in coastal areas. In this type of turbine, tower construction is not needed because the generator can be placed closer to the ground level and makes it easier in terms of maintenance.

3.3. Forces of wind turbine

Lift

The lift force (L) appears in the direction, which is perpendicular to the flow of air caused by the Bernoulli effect which decreases the above pressure, causing a higher flow velocity at the bottom so that it experiences a lower pressure. The lift force is described by the coefficient of lift force (C_L) such as the congregation.

$$C_L = \frac{L/A}{1/2\rho V^2} \qquad (10)$$

Drag

The inhibition force (D) is the force that is contrary to the lift (L) for the air flow caused by the Bernoulli effect which decreases the pressure below which causes a higher flow velocity than the top so that it experiences lower pressure. The inhibition force is described by the coefficient of the inhibition force (C_D) as an equation.

$$C_D = \frac{D/A}{1/2\rho V^2} \qquad (11)$$

Thrust

The resultant of the lift and tensile force is an effective push force (T) that effectively rotates the rotor angle [8]. The resultant ratio of the elevator for Drag L/D is the function of the Angle of Attack, for some aerofoil the maximum value of the L/D Ratio Profile in accordance with the optimal angle of the attack to achieve the maximum efficiency of the Wind Turbine Rotor.

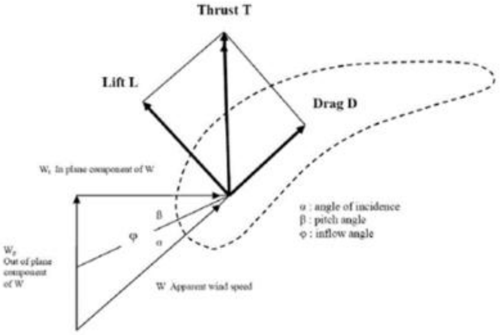

Fig. 2 Geometry of the force on aerofoil

4. The Blade

The blade on the mill is an important element. The blade works to turn the wind into a mechanical motion. As the development of Wind Turbine technology, the blade has undergone a variety of developments with the increasing variation of materials, measurements, aerofoil types, and the number of blades. On the horizontal wind turbine axis, the most important thing to note are the fingers of the blade, the amount of the blade, the pitch angle, the length of the chord, the aerofoil type, and the blade material. The turbine rotor dimension affects the ability of turbines to capture winds that pass-through turbines. The greater the diameter of the rotor, the greater the wind sweeping area that can be utilized. But this will affect the speed of the turbine rotor, the greater the rotor, the greater the power coefficient and the turbine rotation speed will be lower. HAWT is very sensitive to changes in the profile and design profiles. The main parameters that affect the performance of the HAWT blades are as follows:

4.1. Tip speed ratio

Tip speed ratio is defined as the relationship between rotor blades and relative wind speeds, TSR is the most important design parameter where all other optimum rotor dimensions are calculated.

$$\lambda = \frac{\Omega r}{V} \qquad (12)$$

With λ is the speed ratio tip, Ω is the rotation speed of the blades (rad/s), r is the radius (m), and v is the wind speed (m/s). Wind Turbine Horizontal axis which has 3 blades has the highest power coefficient value and tip ratio tip when compared to other types.

4.2. Design shape and sum of blade

Design of the shape and number of blades refers to the Betz method which gives the basic shape of the modern wind turbine blades. In practice, more advanced methods with optimization are often used. Following are equations that can be used in design form and number of blades [9].

$$C = \frac{2\pi r}{n} \frac{8}{9Cl} \frac{Uwd}{\lambda\, \mathrm{Vr}} \qquad (13)$$

V_r value = $\sqrt{V^2 - U^2}$, for r is the radius of the blade (m), C_l is the coefficient of the elevator, λ is the tip speed ratio, V_r is the total wind speed (m/s), U is the wind speed (m/s), U_{wd} is the speed of wind design (m/s) and C_{ops} is the optimum chord length.

4.3. Aerofoil

The ideal form of propeller is the aerofoil form because the shape can absorb the kinetic energy of the wind into the maximum rotating energy. Aerofoil consists of the following parts:

- Mean Chamber Line is the midline between the upper and lower surface of the aerofoil.
- Leading Edge is the front point on the Mean Chamber Line.
- Trailing edge is the back point on the mean chamber line.
- Chord Line is a straight line that connects leading edge with trailing edge.
- Chord (C) is the distance between leading edge and trailing edge along the chord line.
- Chamber (a bumpy surface) is the distance between the mean chamber line, perpendicular to the chord line.
- Thickness is the distance between the upper and lower surfaces, also perpendicular to the chord.

- Angle of Attack is the angle between the relative wind and the chord line.

4.4. Blade design

Maximum energy extract of the bar is 59% or also called the Betz coefficient but from the results of the bladder literature ranges from 20% (Holland type) to 40% (propeller type). By accepting the initial efficiency of the blades, where the efficiency of the power component is also known, the efficiency of the wind turbine can be known by the formula:

$$K = \eta bladesx\eta \text{transmission x } \eta \text{generator x } \eta \text{controller} \qquad (14)$$

With K is the system efficiency, ηblade is the efficiency of the blades, ηtransmission is the efficiency of the transmission, ηgenerator is the efficiency of the generator, and the ηcontroller is the controller efficiency [10]. After getting a wind turbine efficiency system and has previously determined the electrical energy produced, then it can be estimated that the wind energy needed using the formula.

$$Pa = \frac{Pe}{K} \qquad (15)$$

$$Pa = \frac{1}{2}\rho \mathrm{A}\, Vmax^3 \qquad (16)$$

With P_a is the wind power capacity, P_e is an electric power capacity, ρ is air density, A is the area of sweeping, V_{max} is the maximum wind speed. Then to find the radiusof the blade, then the equation becomes:

$$R = \sqrt{\frac{A}{3{,}14}} \qquad (17)$$

Further determination of the geometric parameters of the blades is carried out. To find the value of the parsial radius can use the formula:

$$r = ro + \left[\frac{R - ro}{n}\right] x\ elemen \qquad (18)$$

Where r is the partial radius, r_o is the partial radius of the initial blade determination, R is the radius of the blade, n is the number of elements. In designing aerofoil blades, it is necessary to determine the twist (β) by determining the flow angle (φ) of each and the angle of attack (α) [11]. The flow angle of each element can be determined by the formula:

$$\phi = \frac{2}{3}\tan^{-1}\frac{1}{\lambda \mathrm{r}} \qquad (19)$$

With λr is the partial speed ratio tip value at each element. To determine λr can use the formula (20) and twist (β) using the formula (21):

$$\lambda r = \frac{r}{R}\lambda \qquad (20)$$

$$\beta = - \alpha \qquad (21)$$

After determined the twist, another important geometry is the width of the blades (chords). This chord must be specified on each element when, with the formula:

$$C_r = \frac{16\pi R\left(\frac{R}{r}\right)}{9\lambda^2 B C_l} \qquad (22)$$

with C_l is the value of the lift coefficient and λ is the value of the tip speed ratio.

5. Wind Turbine of Smart Grid in Microgrid Pilot Project

Another source of power used in the Smart Microgrid system of Udayana University is from Wind Power Plant(WPP). The total power source capacity of WPP on Smart Microgrid Udayana is 5 kWp. WPP Smart Microgrid Udayana University is located above the DH building of the Electrical Engineering Study Program of Udayana University. The number of wind turbines installed is as many as 10 turbines with rated power of 500 Wp. Of the 10 wind turbines installed, there are 8 wind turbines with the TSD-500 model made in Indonesia and 2 wind turbines with the GH-500W model made in China. The single line diagram of WPP in the Smart Grid in Microgrid Pilot Project is shown in Fig. 3, and the WPP TSD-500 specification is shown in Table 2.

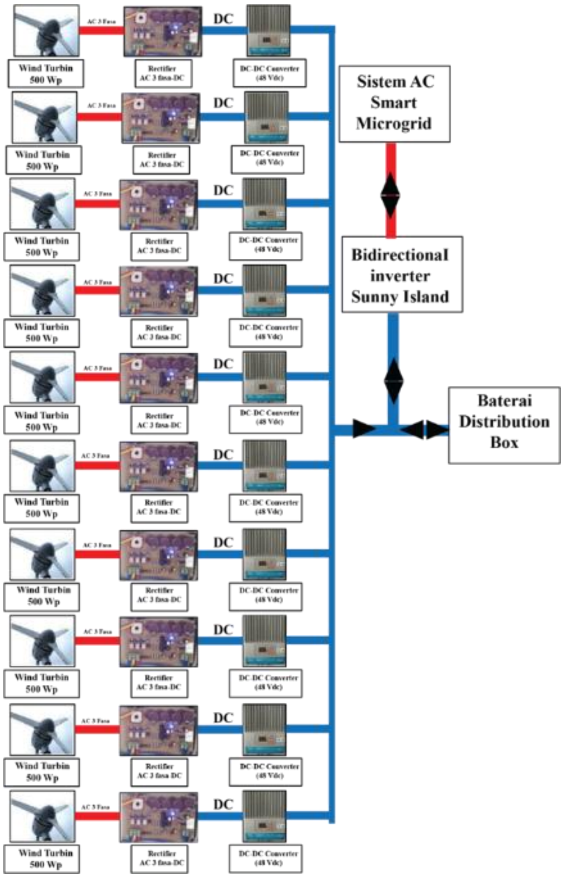

Fig. 3 WPP single line diagram

The WPP installation configuration uses a DC coupling system, where the WPP is connected to the DC busbar and used entirely to charge the battery. Because the output voltage from WPP is a 3-phase AC voltage system, in order to be connected to the DC busbar, it must be converted into DC voltage using a rectifier. The output VL-L voltage range of each wind turbine output is 20 – 110 V.

Table 2. WPP TSD-500 specification

System Name	TSD-500
Turbine Type	HAWT
Maximum Power Output	500 Wp at 12 m/s above
Start Up Wind Speed	2.5 m/s
Cut in Wind Speed	3 m/s
Survival Wind Speed	33 m/s
Generator Type	3-phase permanent magnet
Number of Blades	3 blades
Blade Material	Pine wood
Maximum RPM	1000 RPM
Storage System	24 V
Weight of Turbine System (except pole)	25 kg

(Source: LBN, 2017)

Each wind turbine output is connected to a full rectifier. The output voltage of the rectifier depends on the input voltage of the rectifier. But on the other hand, the nominal voltage of the battery is 48 Vdc. After the voltage is converted into DC, to carry out the charging process to the battery, a charge controller in the form of MPPT EPSOLAR IT3415ND is used to change the rectifier output voltage to 48 Vdc according to the battery voltage system. The MPPT EPSOLAR specification is shown by Table 3.

Table 3.MPPT EPSOLAR IT34515ND specification

Operation	Input Voltage (V)
High Volt Disconnect	64
Charging Limit Voltage	60
Boost Voltage	56.8
Float Voltage	55.2
Under Voltage Warning	48
Low Voltage Disconnect	44.4

Based on the specification data from MPPT EPSOLAR IT34515ND in table 3, it can be analyzed that MPPT will carry out the charging process (float charging) at an input voltage of 55.2 Vdc. At an input voltage of 56.8 Vdc, MPPT will be in the boost voltage operating mode. The maximum input voltage that can be received by MPPT to carry out the charging process is 60 Vdc. The minimum input voltage acceptable by MPPT is 44.4 Vdc. Thus, when the output voltage from the rectifier is above the maximum voltage of 53 or below the minimum voltage of charging MPPT, then MPPT will not carry out the charging process to the battery.

6. Design Flowchart

Based on blade design of The Sky Dancer Wind Turbine 10 x 0,5 kWp Smart Grid in Microgrid Pilot Project, a flowchart is required as reference in wind turbine manufacturing process. The flowchart is shown in Fig. 4.

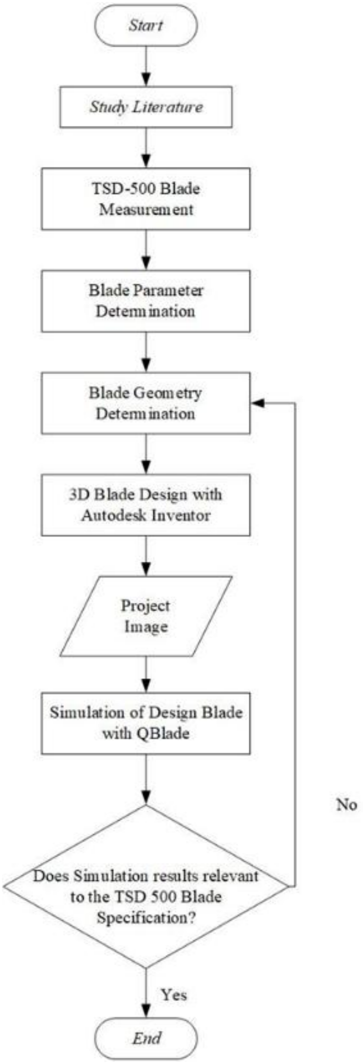

Fig. 4 Design flowchart

7. Determination of Blade Parameters

Blade design is done by determining the initial parameters of the blade, namely the overall system efficiency. There are four overall system efficiency named blade efficiency, transmitter efficiency, generator efficiency, and controller efficiency. According to the formula blade only could extract energy maximum about 59% or it is called Betz Coefficient (Cp). In this blade design, lowest blade efficiency is 30% and highest blade efficiency is 40%, at the same time transmitter efficiency, generator efficiency, and controller efficiency are maximum values of LBN (LenteraBumi Nusantara) wind turbine system with 100% transmitter efficiency, 90% generator efficiency, and 90% controller efficiency. After obtain system efficiency from wind turbine's electric power is 500 Watt with maximum wind speed (Vmax) is 12 m/s and based on international atmospheric standard, density above the sea level is 1,225 kg/m3. Wind power (Pa) is determined by formula (16).

Table 4. Determination of blade parameters

***Pe* (Watt)**	**Efficiency**					***Pa* (Watt)**	**V_{max} (m/s)**	**A (m^2)**	***R* (m)**
	Blade	Transmission	Generator	Controller	System				
500	0.3	1	0.9	0.9	0.243	2057.613	12	1.944	0.8
	0.4				0.324	1543.209		1.458	

8. Determination of Blade Geometry

Blade geometry is determined by blade's shape, number of blades, aerofoil's profile, and tip speed ratio. In this design, the blade geometry is customized to have the same property as the original blade of The Sky Dancer 500 wind turbine. The geometry is shown in Table 5, and the aerofoil is shown in Fig.5

Table 5. Determination of blade geometry

Blade's shape	**Aerofoil**	**C_l/C_d**	**α**	**C_l**	**TSR**	**Number of blades**
Taper	NACA 4412	133.6	6	1.14	7	3

Other parameter is required to design a blade such tip speed ratio (TSR), TSR is the ratio between the wind speed and the tangential speed of the tips of wind turbine blades.

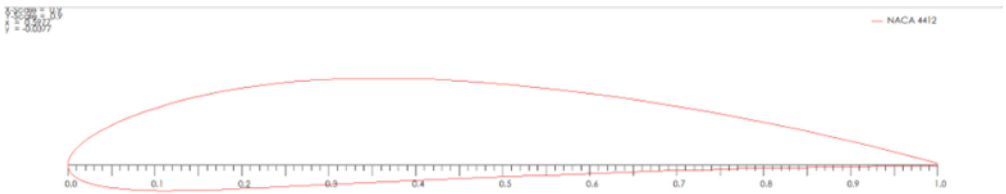

Fig. 5 NACA 4412 aerofoil

Blade design of TSD-500 in Microgrid used three blades and TSR value of three blades is about 6 to 8. In this design, 7 is used as TSR value.Blade geometry determination using angle of attack parameter, lift coefficient, and TSR value for each of aerofoil and shape of blade is modelled with QBlade software.NACA 4412 aerofoil QBlade design is shown in Fig. 6.

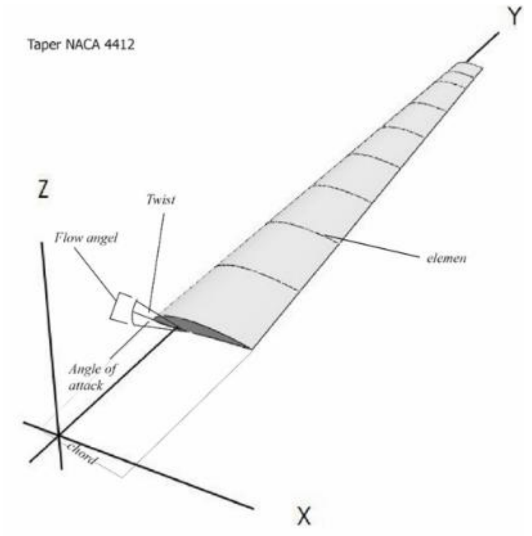

Fig. 6 NACA 4412 QBlade design

After finding the value of the partial radius, partial TSR, flow angle, twist, optimum twist, and chord at each element, results are obtained as shown in Table 6.

Table 6. Geometry of NACA 4412 taper blade

Element	Partial Radius (m)	Partial TSR (deg)	Flow Angle (deg)	Twist (deg)	Optimum Twist (deg)	LinearTwist (deg)	Chord (m)
0	0.170	1.48	22.72	16.72	11.6		0.125
1	0.233	2.04	17.4	11.42	10.8		0.092
2	0.296	2.59	14.1	8.08	10.0		0.072
3	0.359	3.14	11.8	5.78	9.2		0.059
4	0.422	3.69	10.2	4.10	8.4		0.051
5	0.485	4.24	8.8	2.84	7.6		0.044
6	0.548	4.80	7.9	1.85	6.9	6.9	0.039
7	0.611	5.35	7.1	1.06	6.1	6.1	0.035
8	0.674	5.90	6.4	0.42	5.3		0.032
9	0.737	6.45	5.9	-0.12	4.5		0.029
10	0.800	7.00	5.4	-0.58	3.7		0.027

Based on values in the Table 6, 3D shape of TSD-500 is designed using Autodesk Inventor software with taper shape and aerofoil NACA 4412. The design is shown in Fig. 7.

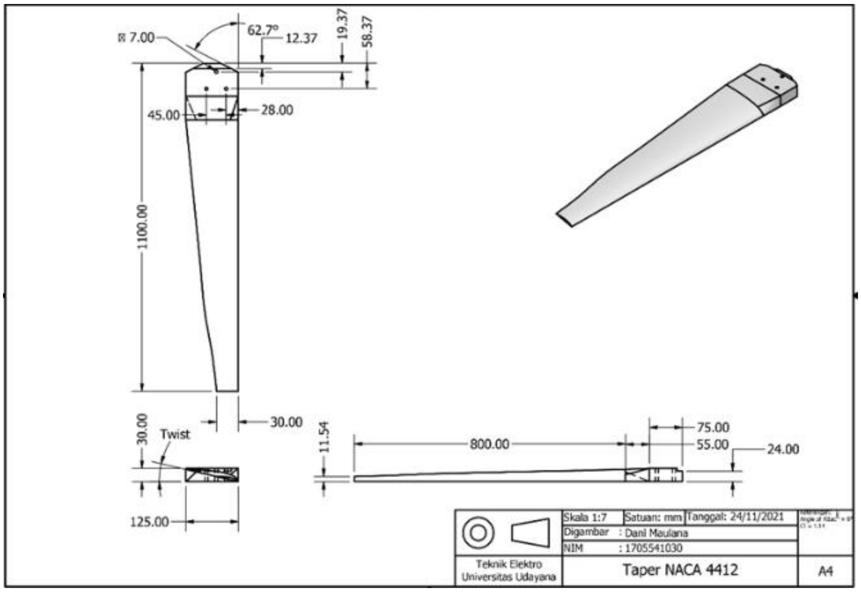

Fig. 7 Design image

9. Simulation

Coefficient power value (Cp) is influenced by shape of blade and aerofoil. As shownFig. 8, maximum coefficient power of tapered blade with NACA 4412 aerofoil equals to 0.48 or 48%. Next step is to run power simulation in the generator related to wind speed at the wind turbine, based on the specification of TSD-500, the power generated is 500 Watt with maximum wind speed 12 m/s.

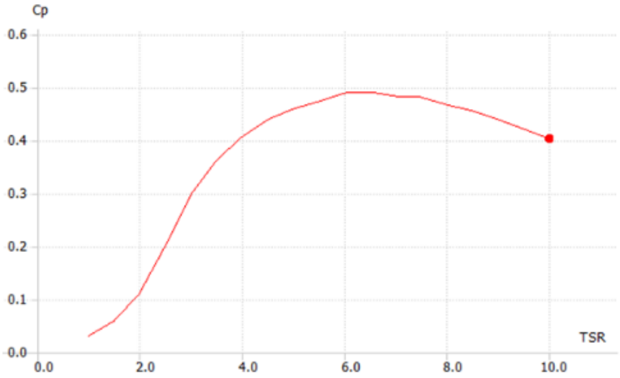

Fig. 8 Simulation graph of TSRandCp

On Turbine BEM simulation, cut value in TSD-500 wind turbine is 3 m/s and simulated with blade tangential speed at 312 rpm. At 3 m/s wind speed, the generated power value is 17,8 Watt, whereas at 12 m/s wind speed the generated power value is 506,7 Watt. Wind speed and power value is shown in Table 7.

Table 7. Power and wind speed value

V (m/s)	P (Watt)
3	17.18
4	48.33
5	94.12
6	153.4
7	224.89
8	303.08
9	381.86
10	448.21
11	481.01
12	506.7

From the QBlade software simulation, the graph of power and wind speed at the wind turbine is shown in Fig. 9.

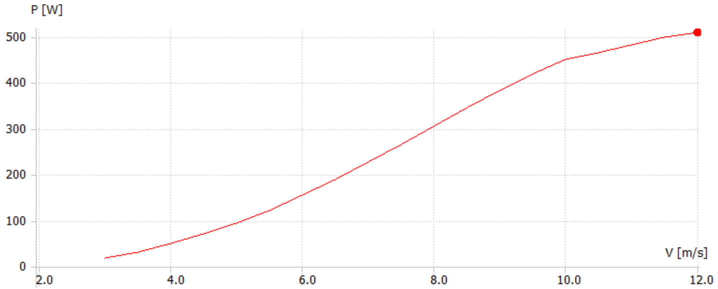

Fig. 9 Simulation graph of wind speed and power

The area of rotor sweep (A) of the TSD-500 is 0.797 m^2, air density(ρ) is 1.225 kg/m^3, and maximum wind speed is 12 m/s. From the (9) formula, the power value is calculated as follow:

$$P = (0.5925)\ \tfrac{1}{2}\ \rho A(V1)^3$$
$$P = (0.5925)\ \tfrac{1}{2}\ (1.225)(0.797)(12)^3$$
$$= 0.5925 \times 843.5448$$
$$P = 499.8 \text{ Watt}$$

10. Conclusions

According to the results of the research that have been carried out, the conclusions are:

- From the results of observation, have been known that the damage blade is TSD-500 type HWAT (horizontal axis wind turbine) blade which is work if the wind speed is 3 m/s minimum and has a maximum power of 500 Watt on the generator if the wind speed reach 12 m/s or more.
- At the blade design, the shape of blade used is taper with NACA 4412 aerofoil and the number of blades is3. On NACA 4412 specification, the angle of attack (α) is 6°, coefficient lift (Cl) is 1.14 and tip speed ratio (TSR) value is 7.
- At the bladesimulation experiment, maximum coefficient lift (Cp) value is 47%. At the blade angularspeed of 312 rpm and wind speed of 12 m/s, the generator can produce power at 506.7 Watt.

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