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# Small-Scale Wind Power Generator with Inverse Taper and Taper Type Blades at Low Wind Speed

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**ABSTRACT**
The utilization of wind energy as one of the renewable energy sources in Indonesia is still limited. This is due to Indonesia's large wind potential, but it is at low speeds. One modification of wind turbines to overcome this problem is by using inverse taper and taper blades. Inverse taper blades have a chord distribution that increases from root to tip while taper blades have a chord distribution that decreases from root to tip. This research conducts the design and construction of inverse taper and taper blades on small-scale wind turbines using NACA 6412 airfoil type, then tested in the field and obtained the performance of each blade. The design was carried out using blade element momentum theory to obtain the blade geometry shape and perform performance analysis of each type of blade. Based on the simulation results obtained from QBlade, it shows that the inverse taper blade performance has a maximum Cp of 0.52 while the taper blade has a maximum Cp of 0.41. The power graph from field testing results shows that inverse taper blades provide good power generation at low wind speeds compared to taper blades. The inverse taper blade has a cut-in speed of 1.2 m/s and the best power production occurs at speeds of 1-4 m/s.

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## 1. Introduction

The consumption of fossil fuel-based electric power generation energy (petroleum, coal, and gas) remains dominant in Indonesia and worldwide, where these energy sources are non-renewable. Data from 2013 shows a power capacity of 43,523 MW. Of the total primary energy for power generation, coal consumption stands at 63% or 27,419.49 MW, followed by gas at 15% or 6,528.45 MW, and finally petroleum at 8% or 3,481.84 MW (Pristiandaru, 2016). This proves that there is still another 14% of energy that can be utilized for electric power generation. Therefore, energy conversion and research on new and renewable energy are needed to find solutions to fossil energy dependence. In its development aspect, energy must consider the 3 "E"s: energy, economy, and ecology. This certainly becomes a particular challenge for current technology development (Culp, 1996).

New and renewable energy that can be utilized includes solar energy, water, wind, and geothermal energy. Among these, wind energy has tremendous potential at present because wind is always available, clean, and its production process does not pollute the environment or cause greenhouse effects since wind has no exhaust gases. In Indonesia, the development of wind energy utilization is relatively low due to the average wind speed in Indonesian regions being classified as low wind speed, namely 3 m/s - 6 m/s, making it very difficult to generate large-scale electrical energy. Such low speeds cannot rotate large-diameter wind turbines because large-scale wind turbines have a cut-in speed

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(initial rotor movement) of 5 m/s - 7 m/s (Burton *et al*., 2011). Wind energy can be utilized to generate electrical energy using wind turbines. The type of blade widely used in Indonesia today is the taper blade or blade with a tip design that is smaller compared to its root section. Although this blade has advantages such as producing smaller thrust and drag, taper blades also generate small torque, impacting higher start-up speed values or making it more difficult to start rotating. This condition makes taper-type blades less suitable for use in fluctuating wind conditions, such as in Indonesia. Inverse taper blades are one type of blade capable of providing high efficiency at low wind speeds (Saoke, 2015). Inverse taper blades have a chord distribution that increases from the blade root to the blade tip, so the largest blade weight distribution will be at the blade tip. Higher solidity causes inverse taper blades to produce greater starting torque and makes the blades easier to rotate (Nishizawa, 2011).

### 1.1 Wind Energy

Wind is air that moves from high-pressure areas to low-pressure areas, or from low-temperature areas to high-temperature areas (Burton *et al*., 2011). Wind energy is a renewable energy source that has been utilized for more than a century (Ginting, 2007). Wind energy is kinetic energy and is defined as the amount of energy produced from wind movement. Wind energy is the result of half times the air density (ρ) with the cross-sectional area coverage of the wind turbine and the cube of the wind speed ($V^3$). Therefore, even a slight difference in wind speed can result in multiple times greater energy difference (Zahra, 2008).

$$E_k = \frac{1}{2} m v^2 \tag{1}$$

Where $E_k$ Kinetic energy (Joule), $m$: mass (kg), $v$: Wind speed (m/second), $\rho = m/V$, then equation (1) can be written as follows:

$$E_k = \frac{1}{2} P^V v^2 \tag{2}$$

Where, $\rho$: Density (g/cm³), $V$: Wind volume (m³).

The flowing wind volume is the multiplication between the area A passed during a certain distance and time unit, or can be written:

$$V = \frac{Av}{t} \tag{3}$$

Where $A$: Surface area (m²), $t$: Time (s).

Therefore, the power or wind energy per unit time obtained can be derived with the following equation:

$$P = \frac{1}{2} p A v^3 \tag{4}$$

$P$: Wind power (Watt)

Equation (4) shows that wind power is influenced by the wind speed passing through the turbine blades and the swept area of the blades, specifically the blade radius length.

### 1.2 Wind Turbine

A wind turbine is a device for converting wind energy into mechanical energy. Wind energy that rotates the blades will be transmitted to rotate the shaft on the generator so that electricity will be produced. For wind turbines, there are several performance parameters, namely performance on the generator that utilizes the design form of stator, rotor, and windings on the generator coils. Performance on wind turbine blades lies in its Cp value. Based on the stator position, wind turbines are divided into 2 types: horizontal axis and vertical axis. The most widely used wind turbine today is the horizontal axis wind turbine (HAWT) with 2 or 3 blade types, while vertical-axis wind turbines (VAWT) are Savonius and Darrieus types. Horizontal axis wind turbines have better Cp compared to vertical axis, which is 45%-50%, while vertical axis is generally below 40% (Eriksson *et al.*, 2008).

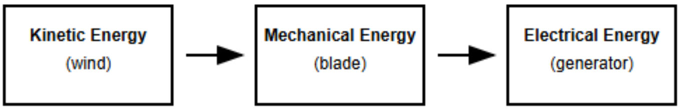



Figure 1. Energy conversion scheme in wind turbines

The energy conversion mechanism performed by wind turbines as shown in Figure 1. Kinetic energy originating from wind will hit the blades. This shape causes aerodynamic forces in the form of lift force and produces positive torque on the blades. Torque causes the blades to rotate and generates mechanical power to rotate the generator rotor. The rotor rotation in the generator is connected to the blades using a shaft. Based on electromagnetic principles, this rotation will generate electricity. Small-scale wind turbine systems generally consist of several components: blades, turbine tail (fin), tower, generator, controller, data logger, and battery as shown in Figure 2.

### 1.3 Wind Turbine Blades

Blades are the rotor part of wind turbines that function to convert wind energy into mechanical energy to rotate the generator shaft. The rotation from the blades is then converted into torque used to rotate the generator shaft (Haris, 2019). The power generated from a rotating blade is shown in Equation 5.

$$P_{mechanical} = Tw = P_{wind}\ x\ C_p \quad (5)$$

| | |
|---|---|
| $P_{mechanical}$ | : Mechanical power due to blade rotation (Watt) |
| T | : Blade torque (Nm) |
| ω | : Blade rotational speed (rad/second) |
| $P_{wind}$ | : Wind power (Watt) |
| $C_p$ | : Power coefficient. |

Based on their design, horizontal wind turbine blades are divided into 3 types:

1) Inverse Taper
   A type of blade that has chord width increasing from root to tip.
2) Taper
   A type of blade that has chord width decreasing from root to tip.
3) Taperless
   A type of blade that has the same chord width from root to tip.

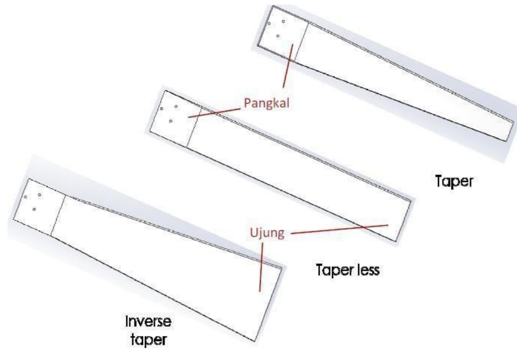



Figure 2. Types of HAWT wind turbine blades

### 1.4 Blade Element Momentum Theory

Blade element momentum theory is a combination of blade element theory and momentum theory. This theory can be used to design turbines designed to achieve predetermined performance parameters. Blade element theory is a simplification of force calculations acting on blades, by dividing the blade into N elements (between 10 to 20 elements). Blade element theory works based on 2 assumptions: each blade element does not affect other elements or there is no aerodynamic interaction between each element, and the force on blade elements is determined by Cl and Cd values. Each blade element will experience different wind flow due to differences in rotational speed (ω), chord length (c), and blade twist. Forces acting on blades are analyzed using airfoil angle of attack characteristics and wind speed hitting each element, then integrated to obtain the total force acting on the blade (Gomez-leon, 2016). The overall force acting on one element is represented at one center point in that element. Element division on blades is shown in Figure 3 (Haris, 2019).

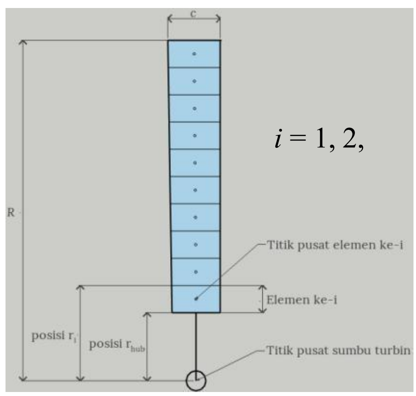



Figure 3. Element division and position r on blades

Momentum theory is force analysis on a specific control volume based on linear momentum and angular momentum. Forces acting on blades are only caused by changes in air momentum passing through the blades. Momentum theory assumes blades as a simple disk/actuator disk passed by ideal fluid resembling a streamtube so there are pressure and velocity differences on the blade surface. Momentum theory assumes that wind speed passing through the disk is the same, developed into angular momentum theory. In angular momentum theory, wind hitting the blades experiences rotational velocity so tangential velocity at each radial position is not the same (Burton *et al*., 2011; Gomez-leon, 2016).

### 1.5 Airfoil

Wind turbine blades have an aerodynamic cross-sectional design shape called an airfoil. An airfoil is a specific geometric shape used to generate mechanical force due to the relative motion of the airfoil against the fluid around the airfoil (Manwell *et al*., 2010). The airfoil shape used in blade design becomes one of the factors influencing the determination of blade radius and width (chord). To rotate properly, blade planning is based on high Cl/Cd ratio (lift coefficient/drag coefficient) and insensitivity to roughness or angle changes (Ragheb, 2017; Timmer & Van Rooij, 2003).

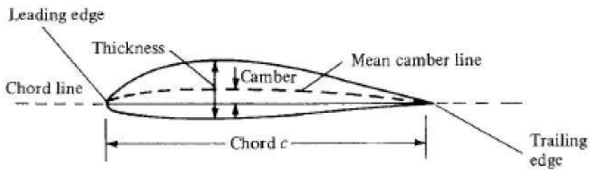



Figure 4. Parts of an airfoil.

1) Camber line is the center line between the upper and lower surfaces of the airfoil.
2) Leading edge is the frontmost point of the airfoil that encounters wind.
3) Trailing edge is the rearmost point of the airfoil that encounters wind.
4) Chord line is the connecting line between leading edge and trailing edge.
5) Chord is the distance between leading edge and trailing edge perpendicular to the chord line.
6) Camber is the distance between mean camber line perpendicular to the chord line.
7) Thickness is the distance between upper and lower surfaces perpendicular to the chord line.
8) Angle of attack is the angle between relative wind and chord line.

### 1.6 Wind Turbine Blade Design Parameters

Several parameters in designing a blade are as follows:

1) Blade radius, affects how much wind energy can be obtained based on the blade swept area.
2) Twist or twist angle, is the angle between chord line and rotor rotation plane. Optimum blade twist depends on tip speed ratio (TSR) value and desired airfoil angle of attack (α) value. Providing twist is useful for increasing blade efficiency (Handoko, 2019) and twist angle linearization is commonly done to facilitate the manufacturing process (Schubel & Crossley, 2012).
3) Coefficient of performance, is the blade's ability to absorb wind energy it receives. The larger the Cp value, the greater the ability of a turbine to convert the wind energy it obtains. The maximum coefficient of performance value is 59.3% (Betz, 2013).
4) Tip speed ratio (TSR), is the ratio of blade tip speed to wind speed passing through it.
5) Torque coefficient, is used to calculate the amount of torque produced by the blade.

### 1.7 QBlade Software

QBlade is an open-source software with GPL license used for wind turbine calculations (Marten, 2015). This software is used for aerodynamic design and simulation of wind turbine blades (Marten, 2015). In its calculations, QBlade works using the Blade Element Momentum method both in designing and evaluating the created design. This software is integrated with XFOIL, which is a tool for airfoil design and analysis. XFOIL is used to perform airfoil analysis, then the analysis results are extrapolated into 360° polar to be used in blade element momentum theory analysis (Marten, 2015). The wind turbine analysis process using QBlade is shown in Figure 5.

## 2. Methodology

An experimental method is used in this study for the analysis and comparison of performance of inverse taper and taper blade designs of small wind turbines working at low and variable winds. The methodology includes several steps including geometric design analysis, blade manufacturing, performance testing and data analysis. A series of steps are taken in each phase to enable combat stability and validity. The research methodology is characterized by a structured combinatory study containing theoretical analysis by simulation software and practical implementation by means of blade manufacturing and field testing. This integrated approach supports the full assessment of the performance of blades in realistic operating conditions while ensuring scientific quality in measurement and processing of data.

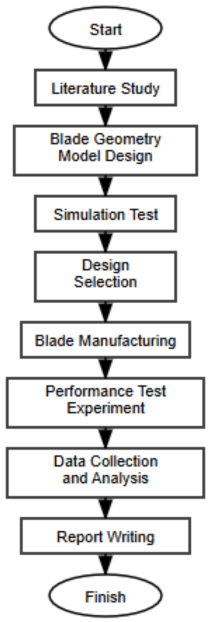



Figure 5. Research methodology flowchart

### 2.1 Determining Blade Geometry

Geometric shape analysis is conducted to determine the effective blade geometry for use in low and fluctuating wind speeds. Analysis is performed on chord widening ratio and airfoil type. Simulation is conducted using QBlade software to obtain blade performance data such as coefficient of performance curves. The designs to be analyzed are blades with root-to-tip chord width ratios of 1:1, 1:1.2, and 1:0.2. Analysis is performed to determine the blade design with the best chord widening ratio according to requirements. Comparison of chord widening ratios will be conducted with the same airfoil specifications, namely NACA 6412, with a blade radius length of 0.8 meters and using the twist angle linearization method referring to optimization linearization research conducted by Liu (2016).

### 2.2 Blade Geometry Design

The blade design work steps are as follows:

1) Determining input and calculated parameters. Input parameters include the planned electrical power capacity according to needs, maximum wind speed where the turbine will operate (e.g., 12 m/s) (Abdillah *et al*., 2015). Then input transmission, generator, controller, and blade efficiency values by assuming transmission, generator, and

controller efficiency values of 0.9 (Abdillah *et al*., 2015). For blade efficiency, input an efficiency value of 0.3 (Abdillah *et al*., 2015).

2) Determining blade type. The blade type is determined by adjusting to design requirements, such as the wind turbine installation location and wind speed potential at the location.
3) Determining airfoil. Each airfoil has data in the form of graphs including CL/CD versus α graphs. Find an airfoil that has the highest peak CL/CD value, meaning the lift force effect is greater than the drag force so the blade can rotate.
4) Determining tip speed ratio (TSR). TSR will be estimated at this stage. However, at the end of the simulation, TSR may change. For 3-blade wind turbines, the TSR used ranges from 6-8 (Strong, 2008).
5) Determining blade chord width.
6) Dividing the wind turbine blade into 10 elements to facilitate blade geometry calculations. The partial radius (r) at element 0 or the blade root section is adjusted to the TSD-500 generator, which is 0.17 meters.
7) Calculating partial TSR for each blade element.
8) Determining flow angle and twist angle values.
9) Running simulation of the designed blade using QBlade software to determine good blade performance that can produce good electrical power. Then continue with creating blade technical drawings using SolidWorks software.

### 2.3 Performance Simulation Using QBlade Software

QBlade software performs performance test calculations on the created blade design (Marten, 2015). The performance calculation process in QBlade can be divided into two main parts: airfoil analysis using the XFOIL module within QBlade and blade analysis using blade element momentum theory available.

### 2.4 Blade Manufacturing

1) Blade Material Selection

   Blade manufacturing is performed using wood material. Wood is one of the most frequently used materials in wind turbine blade manufacturing besides resin composites. Wood is used because it is lightweight, strong, and easy to shape. Compared to resin materials, wood base material is chosen for blade manufacturing because it is cheaper, easily available, and easier to shape as it does not require a base mold in its manufacturing. The type of wood used in this research is mahogany wood. Furthermore, before the manufacturing process, the wood needs to undergo a drying process to reduce water content until reaching water content balanced with working environment conditions, without reducing the quality of the wood (Piggott, 1997).

2) Tools and Materials

   The tools and materials required during the manufacturing process include:

   a) Mahogany wood with dimensions 123 cm × 15.5 cm × 5 cm
   b) Printout of technical drawings of cross-sections for each element and root and tip with 1:1 ratio
   c) Planing machine
   d) Grinding sander
   e) Iron sander
   f) Drill machine
   g) Sandpaper with grits 80, 150, 240, 320, 1000
   h) Measuring tape
   i) Scale
   j) Plywood for making blade molds (airfoil)
   k) Plywood saw
   l) Fox glue

3) Work Steps

The manufacturing work steps include:

a) Prepare wood that has been dried under sunlight and ensure the wood has been cut evenly and squarely according to the designed blade radius
b) Create element lines on the wood to facilitate making twist angle lines, chord, and ease the wood carving process
c) To create inverse taper blade type, draw lines from root to tip expanding according to the designed chord distribution for each element from the trailing edge and leading edge airfoil
d) Prepare printouts of technical drawings of cross-sections for each blade element from root to tip to facilitate airfoil formation on wood and ease twist angle formation
e) Create positive and negative molds using thin plywood according to the airfoil of each blade element on the printout with 1:1 ratio
f) Measure and determine airfoil endpoint positions at the blade tip section. Then attach the mold according to the endpoint position using glue for stronger attachment
g) Measure and determine airfoil endpoint positions at the blade root section. Then draw straight lines from tip to root as guide lines for creating twist angles
h) Create guide lines marking the parts to be removed and extend lines from tip to root considering the twist angle
i) Cut those parts using a planing machine according to the slope of the parts to be removed until forming like the upper part of the airfoil. Then do the same for the lower part of the airfoil
j) Shape and smooth the upper and lower parts of the blade using grinding sanders. Perform periodic checks using negative molds on each blade element and re-smooth the upper and lower airfoil surfaces using iron sanders
k) Shape the root using molds by attaching printouts to the root section and providing holes in the blade according to the generator hub to be installed.

### 2.5 Blade Balancing

Before blade testing, blades need to be balanced because turbine blades as rotating masses will have centrifugal forces on bearings due to uneven mass distribution on the blades (Schubel & Crossley, 2012). This centrifugal force will cause shaft vibration, which can reduce bearing life, reduce blade rotation speed, and create noise. The blade balancing process requires carving and filling parts of the blade as needed. Carving and filling are done while maintaining blade weight and dimensions. All three blades must have equal weight without changing the blade dimensions that have been made. Turbine blade balancing is performed by conducting static balancing and dynamic balancing tests (Schubel & Crossley, 2012). Static stability testing is done by installing blades one by one to the generator and clamping using flanges then locking with appropriate bolts and keys. Then blade balance testing is performed by positioning the blade perpendicular to the wind turbine pole. Static stability is achieved when the blade does not rotate when positioned at the test position or at any angular position relative to the bearing. Dynamic stability is tested by rotating the blade until it stops by itself. Dynamic stability is achieved when the blade stops without reversing direction from its rotation position when rotated and there is no vibration when the blade rotates. Dynamic stability can only be achieved when static stability is achieved.

### 2.6 Blade Installation

Blade installation to the generator on the pole for testing begins by catching the turbine tail and directing it in another direction so the wind turbine faces against the wind direction and will stop rotating. Then the balanced blade is installed to the generator on the pole.

### 2.7 Blade Testing

Blades are tested on the wind power plant system located at PT Lentera Bumi Nusantara field site with a TSD-500 generator installed on a tower at 12 meters height along with wind speed testing equipment (anemometer), controller with maximum power capacity of 500 Watts, deep cycle gel battery with minimum voltage of 24V and maximum voltage of 48V connected to the load. The controller used has a cut-in speed value that will start operating and produce power at wind speed of 3 m/s and has a cut-out speed value that will shut down and stop producing power at wind speed of 12 m/s. The blade testing location on the wind turbine is shown in Figure 6.

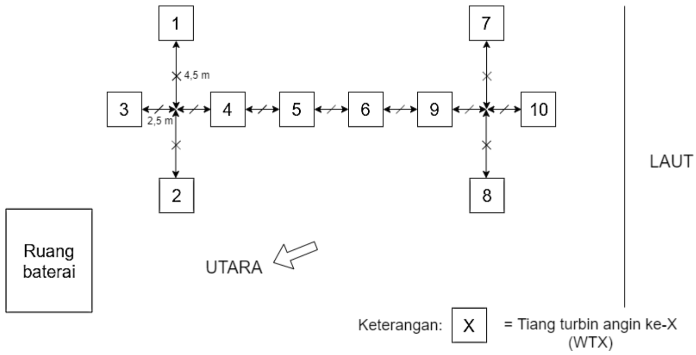



Figure 6. Layout of blade testing location at PT Lentera Bumi Nusantara

From Figure 6 above, research is conducted with wind turbine number WT 2 for inverse taper blades and WT 4 for taper blades.

Figure 7. Blades installed on wind turbine

From Figure 7 above, the designed blades for both inverse taper and taper models have been completely installed on wind turbines 12 meters above ground level and are ready for testing.

### 2.8 Data Collection Method

Data collection is performed for 7 days obtained using a data logger developed by PT. Lentera Bumi Nusantara. The data collected includes electrical voltage data, electrical current data, wind speed data, and wind direction data. The data recorded by the data logger is raw voltage and current data generated from voltage and current sensors on the controller and wind speed data from anemometers installed on the tower at 10 meters height. The data logger used collects data per second, resulting in 86,400 voltage, current, and wind speed data points per day. The data logger will read the controller power output.

### 2.9 Data Processing Method

The 86,400 voltage, current, and wind speed data points per day will be processed into per-minute data first to facilitate the data processing. This is done by calculating the average of per-second data per-minute data, resulting in 1,440 data points per day. System efficiency during blade testing can be determined by calculating the ratio between theoretical power or P_wind and generated power or P_out. Since the controller used has a cut-in speed value of 3 m/s, P_wind will only sum power from wind with speeds above 3 m/s, while P_out sums all power generated by the system. Additionally, data is also processed to obtain the relationship between power generated by blades and wind speed passing through them. Data is grouped based on wind speed data, then the collection of power data at that wind speed will be averaged to obtain a power versus wind speed graph or P-v graph. The distribution of wind speed received by each blade will certainly differ, so it is necessary to determine the minimum amount of wind speed data for data processing to be performed.

## 3. Results

### 3.1 Creating Geometric Model and Blade Design

1) Analysis of airfoil used

The selection of airfoil used on the blade is determined based on the high Cl/Cd ratio of the airfoil and insensitivity to changes in angle of attack (α). Airfoil analysis was conducted using QBlade software on NACA 4412 and NACA 6412 type airfoils as shown in the figure below.

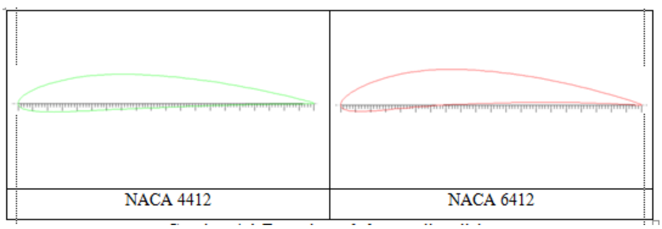



Figure 8. Shape of airfoils analyzed

The analysis results shown from both airfoils are that NACA 6412 has a Cl/Cd ratio to angle of attack of 147.1 and a lift coefficient value of 1.34, while NACA 4412 has a Cl/Cd ratio to angle of attack of 133.6 with a lift coefficient value of 1.125. In the Cl/Cd curve against α, there is a difference shown between the two airfoils, and the NACA 6412 airfoil has a better Cl/Cd ratio value as well as the Cl curve shown. In the Cl/Cd curve shown, the NACA 6412 airfoil experiences a significant increase from the NACA 4412 airfoil. Based on the analysis results between the two airfoils, this research will create blades with NACA 6412 airfoil.

2) Design of inverse taper and taper type blades

The blade geometry design was carried out using the blade element momentum method by dividing the blade into 10 elements. Based on measurements on the TSD-500 generator, the distance from the turbine axis to the first part of the blade that has an airfoil (rhub) is 0.17 m. The manual calculation results of blade geometry are shown in Table 1.

Table 1. Geometric Data Of Designed Inverse Taper And Taper Blades

| Element | Radius (r) (cm) | Partial TSR (m/s) | *Linear Chord Inverse Taper (cm)* | *Chord Linear Taper (cm)* |
|---|---|---|---|---|
| 0 | 0,17 | 1,4875 | 0,107 | 0.107 |
| 1 | 0,23 | 2,03875 | 0,109 | 0.078 |
| 2 | 0,30 | 2,59 | 0,111 | 0.061 |
| 3 | 0,36 | 3,14125 | 0,113 | 0.051 |
| 4 | 0,42 | 3,6925 | 0,115 | 0.043 |
| 5 | 0,49 | 4,24375 | 0,117 | 0.037 |
| 6 | 0,55 | 4,795 | 0,120 | 0.033 |
| 7 | 0,61 | 5,34625 | 0,122 | 0.030 |
| 8 | 0,67 | 5,8975 | 0,124 | 0.027 |
| 9 | 0,74 | 6,44875 | 0,126 | 0.025 |
| 10 | 0,80 | 7 | 0,128 | 0.023 |

After optimization, the blade design was obtained for the manufacturing process in the next stage. The blade design results are shown in Figure 9.

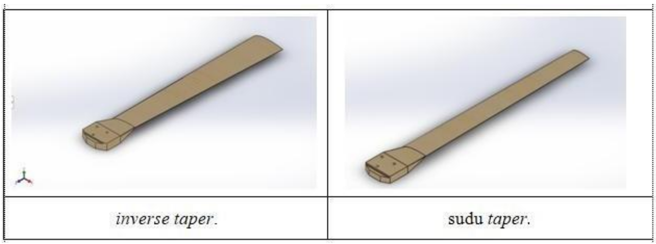



Figure 9. Design of inverse taper and taper NACA 6412 blades in SOLIDWORKS

### 3.2 Wind Turbine Blade Manufacturing

The blade material used to form the blade is mahogany wood with dimensions of 123 x 15.5 x 5 cm that has been dried for 3 days to reduce the water content in the wood. The initial step is to attach the design template on plywood for the cutting process as shown in Figure 10.

Figure 10. Process of cutting the template that has been printed out on plywood

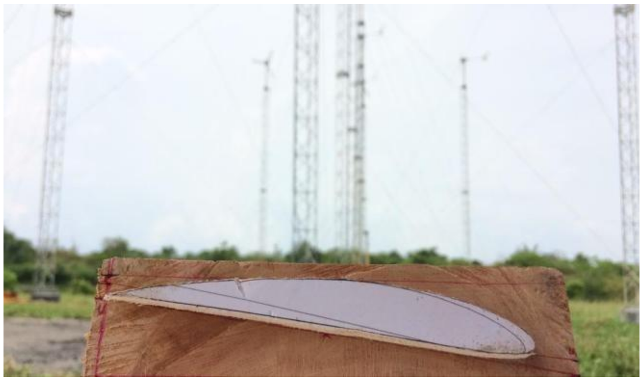
Then positive and negative templates were formed using plywood to facilitate the process of forming airfoil and twist on the blade at each blade element as shown in Figure 11.

Figure 11. Positive and negative blade templates

Then measurement and determination of the position of the base and tip points of the airfoil on the wood were carried out and continued by making straight lines from each base point to the tip that had been determined as guide lines in forming the blade twist. Next, cutting of the upper and lower parts of the wood was carried out using a planing machine to form the upper and lower parts of the airfoil while paying attention to the twist inclination that had been determined as shown in Figure 12.

Figure 12. Making guide lines in twist formation

The next step taken is to shape and smooth the upper and lower parts of the blade using grinding sandpaper. Then periodic checking was carried out using positive and negative templates to obtain the desired airfoil shape and twist according to the design and smooth again the upper and lower surfaces of the airfoil using iron sandpaper. Scraping using grinding sandpaper is done starting from sandpaper with small numbers or coarser sandpaper, and moving to sandpaper with increasingly larger numbers or increasingly smooth. In this process, sandpaper with numbers 80, 150, 240, 320 is used for grinding sandpaper and for finishing, sandpaper with number 1000 is used using iron sandpaper as shown in Figure 13.

(a) (b)

Figure 13 Blade formation (a) and blade airfoil checking using template (b)

Then the blade base was formed using a template by attaching the print out designed in SOLIDWORKS to the base part and continued with making holes in the blade according to the TSD-500 generator hub using a drill machine as shown in Figure 14 below.


(a) (b)

Figure 14. Blade base manufacturing (a) and completed blade (b)

### 3.3 Balancing and Blade Installation

The balancing process is carried out with the aim that when the blade is installed on a pole with a height of 10 meters above ground level, the pole does not vibrate. Vibration on this pole can reduce the power performance produced and cause the pole foundation to collapse. Initial blade balancing is done by equalizing the weight of the three blades that have been made. If the weight of the three blades is not the same, then scraping and filling need to be done on the blade parts as needed while still paying attention to the blade dimensions. Then continued with static stability testing which is done by installing the blades one by one to the generator and clamped using flanges then locked with bolts. This test is carried out by positioning the blade perpendicular to the wind turbine pole. Next, static stability testing is carried out by rotating the blade until it stops by itself without reversing direction from its rotation position as shown in Figure 15. After the manufactured blade successfully passed the balance test, then the blade was installed on the wind power plant system located at the PT Lentera Bumi Nusantara field site with a TSD-500 generator installed on a tower with a height of 10 m for testing as shown in Figure 16.

Figure 15. Balance testing process on the blade

Figure 16. Process of installing blades on the pole

### 3.4 Test Results

Field test data was recorded every second so it has a large amount of data of 86,400 data points. This data was then averaged per minute so the amount of data became 1,440 data points. The data obtained includes voltage and current data, charging power data, and wind speed data. Wind turbine blade data collection was carried out for 3 days from September 17, 2019 to September 19, 2019. Summary of per-minute data collection is shown in Table 2.

Table 2. Daily Wind Turbine Data Summary

| Parameter | Unit | 17 September 2019 | | 18 September 2019 | | 19 September 2019 | Taper |
|---|---|---|---|---|---|---|---|
| | | Inverse Taper | Taper | Inverse Taper | Taper | Inverse Taper | |
| Charging Data | | | | | | | |
| Maximum Voltage | (V) | 27.68 | 27.68 | 27.64 | 27.64 | 27.48 | 27.48 |
| Minimum Voltage | (V) | 22.54 | 22.54 | 24.22 | 24.22 | 24.41 | 24.41 |
| Maximum Current | (A) | 7.45 | 7.43 | 10.51 | 10.33 | 13.14 | 12.20 |
| Power Data | | | | | | | |
| Average Power | (W) | 28.04 | 26.41 | 49.86 | 45.42 | 70.72 | 54.94 |
| Maximum Power | (W) | 204.24 | 202.42 | 286.63 | 281.53 | 359.44 | 333.81 |
| Total Energy | (Wh) | 673.06 | 633.94 | 1196.6 | 1090 | 1697.3 | 1318.6 |
| Wind Data | | | | | | | |
| Maximum Speed | (m/s) | 16.01 | | 8.87 | | 11.80 | |
| Minimum Speed | (m/s) | 0.12 | | 0.92 | | 0.63 | |
| Average Speed | (m/s) | 4.62 | | 3.87 | | 3.87 | |
| Total Wind Power | (Wh) | 6894.99 | | 3175.07 | | 3898.97 | |

Based on Table 2, the highest wind turbine charging power was obtained on September 19, 2019, which was on the third day of blade testing with total power obtained of 1,697.6 Wh for inverse taper model blades and 1,318.6 Wh for taper model blades, average power of inverse taper model blades was 70.72 W and 54.94 W for taper model, and maximum power obtained by inverse taper model blades was 359.44 W and 333.81 W for taper model. However, in wind data, the best wind speed was obtained on September 17, 2019 with an average speed of 4.62 m/s, maximum speed of 16.01 m/s, and minimum speed of 0.12 m/s. On the second day, an average speed of 3.87 m/s was obtained, maximum speed of 8.87 m/s, and minimum speed of 0.92 m/s. On the third day, an average speed of 3.87 m/s was obtained, maximum speed of 11.8 m/s, and minimum speed of 0.63 m/s. Data collection for 3 days showed the same pattern, namely wind turbines produce the best power in the time range from 08:00 to 16:00. The measured voltage is battery voltage, so high battery voltage at 08:00-16:00 indicates the battery condition is in full charge state. While at night, the recorded voltage has a low value indicating that the battery is in charging state.

### 3.5 Design Application for Low Wind Speed Wind Turbines

This research was conducted to obtain which blade type design is most suitable for low wind speeds, namely around 1 - 4 m/s as shown in Figure 17.

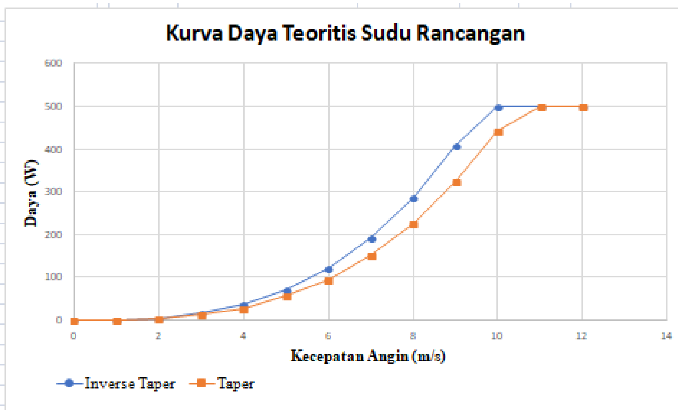
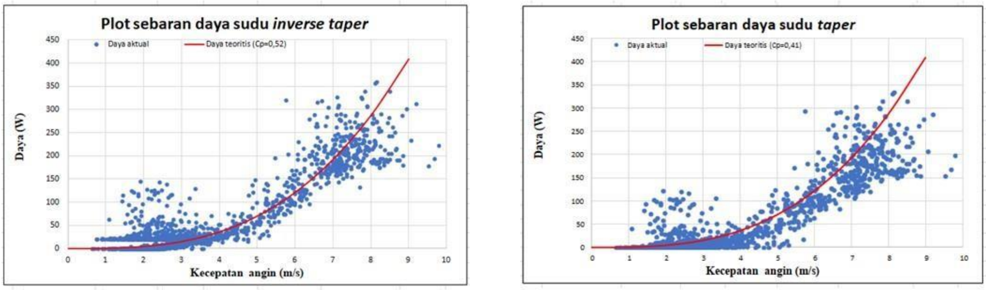



Figure 17. Theoretical power curve of designed blades

Figure 17 shows the theoretical calculation results of power produced by the designed inverse taper blade with a maximum Cp value of 0.52. For taper blades, a maximum Cp value of 0.41 was obtained. The curve shows a significant power increase along with the increase in wind speed that occurs. However, because wind turbines have output power limitations due to controller limitations of 500 W, theoretical output power above 500 W is reduced to 500 W. Then a comparison of theoretical power Cp = 0.52 for inverse taper model blades and Cp = 0.41 for taper model against actual power in the field was made as shown in Figure 18.




(a) (b)

Figure 18. Power output curve against wind speed in theoretical calculations and field testing

Figure 18 shows the output power in theoretical calculations according to the design of inverse taper (a) and taper (b) model blades and field testing against wind speed. Research analysis is focused on low wind speeds, namely below 4 m/s. Based on Figure 18, it shows that turbines are capable of producing power at low wind speeds. The power and speed plot shows that power extraction starts at wind speeds of 1.2 m/s and continues to experience increased power production up to wind speeds of 4 m/s. At wind speeds above 4 m/s, it shows that power production in wind turbines begins to experience a decrease. The power produced by wind turbines shows that the designed blades meet the design requirements, namely being able to produce good power in the range of low average annual wind speeds in Indonesia. From the curve above, it can be seen that the power produced at low wind speeds of 1 - 4 m/s in inverse taper model blades is greater than taper type blades.

## 4. Discussion

Based on the research findings, the selection of NACA 6412 airfoil demonstrates significant advantages over NACA 4412. Analysis using QBlade software reveals that NACA 6412 achieves a Cl/Cd ratio of 147.1 with a lift coefficient of 1.34, while NACA 4412 only reaches a Cl/Cd ratio of 133.6 with a lift coefficient of 1.125. This approximately 10% difference proves highly meaningful for wind turbine efficiency, particularly for low wind speed applications that characterize Indonesia's wind conditions. The larger camber profile of NACA 6412 (6%) compared to NACA 4412 (4%) provides superior aerodynamic characteristics at low angles of attack, which becomes especially relevant for Indonesia's typical wind conditions ranging from 1-4 m/s. This airfoil selection forms the foundation for developing wind turbines that can effectively harness the available wind resources in tropical regions. The geometric design implementation using the blade element momentum method with 10-element division produces distinctly different chord distributions between the two blade types. The inverse taper blade shows chord progression from hub (0.107 cm) to tip (0.128 cm), while the taper blade experiences chord reduction from hub (0.107 cm) to tip (0.023 cm). The inverse taper design provides larger surface area at the tip section, which theoretically enhances torque and efficiency at low wind speeds. Field testing results consistently validate this theoretical advantage, demonstrating that the inverse taper configuration effectively captures more energy from available wind resources. This geometric approach challenges conventional blade design principles and opens new possibilities for optimizing small-scale wind turbines.

The manufacturing process demonstrates an appropriate approach for small-scale applications. Selecting mahogany wood as the blade material, combined with a 3-day drying process, effectively reduces moisture content and minimizes deformation risks. The manual fabrication technique using positive-negative templates enables excellent quality control over airfoil profiles and twist distribution. The progressive sanding process from 80 to 1000 grit shows serious attention to surface quality, which becomes crucial for reducing drag and improving aerodynamic efficiency. The balancing procedure also proves essential for preventing system vibration, considering the installation on a 10-meter tower requires high structural stability. These manufacturing considerations demonstrate that high-quality wind turbine blades can be produced using locally available materials and techniques. Field testing results over three days provide strong empirical evidence of the inverse taper design's superiority. Data shows that on the third day (September 19, 2019), the inverse taper blade generated total energy of 1,697.3 Wh with average power of 70.72 W, while the taper blade only produced 1,318.6 Wh with average power of 54.94 W. This 28.7% performance improvement consistently occurs across all testing days, indicating that the inverse taper advantage represents an inherent design characteristic rather than a momentary anomaly. The maximum power achieved by inverse taper (359.44 W) also exceeds taper performance (333.81 W) by 7.7%, demonstrating superior capability in utilizing optimal wind conditions. These results provide compelling evidence for adopting inverse taper design in practical applications.

Interestingly, optimal performance does not always correlate directly with highest wind speeds. Although the highest average wind speed occurred on September 17 (4.62 m/s), the best energy output was achieved on September 19 with average wind speed of 3.87 m/s. This phenomenon indicates that wind speed consistency becomes more important than peak velocity for optimizing total energy production. The system demonstrates optimal efficiency in moderate speed ranges with minimal fluctuations, allowing turbines to operate in steady-state conditions for extended periods. This finding has significant implications for site selection and turbine placement strategies, suggesting that locations with consistent moderate winds may outperform sites with higher but more variable wind speeds.

The consistent daily operational pattern with optimal power production during 08:00-16:00 hours shows good correlation with local diurnal wind patterns. High voltage recorded during daytime periods indicates full battery conditions, while low nighttime voltage shows active charging processes. This pattern confirms that the system operates according to design specifications and successfully optimizes available wind energy utilization. The charging characteristics also demonstrate effective energy storage management, ensuring continuous power availability even during low wind periods. Understanding these operational patterns becomes crucial for integrating small wind turbines into distributed energy systems. Design validation for low wind speed applications shows satisfactory results. Theoretical calculations yielding Cp values of 0.52 for inverse taper and 0.41 for taper are confirmed through consistently superior field performance of the inverse taper design. The cut-in speed of 1.2 m/s aligns with design targets for Indonesian conditions, enabling turbines to begin power generation at relatively low wind speeds. Optimal efficiency in the 1-4 m/s range perfectly matches Indonesia's average wind characteristics, making this design highly applicable for local implementation. These validation results demonstrate successful translation of theoretical design principles into practical wind energy solutions.

The advantages of inverse taper design extend beyond technical aspects to include significant economic implications. The 28.7% improvement in daily energy efficiency translates to reduced payback periods and enhanced economic viability for small-scale wind turbine projects. Performance consistency across various wind conditions provides better predictability for energy planning, while torque optimization through increasing chord distribution toward the tip delivers superior leverage for low wind conditions. These economic benefits become particularly important for rural electrification projects where initial investment costs must be carefully managed. The improved performance characteristics make small wind turbines more competitive with other renewable energy technologies.

Manufacturing considerations reveal that high-quality wind turbine components can be produced using locally available materials and traditional woodworking techniques. This approach reduces dependency on imported components and creates opportunities for local manufacturing industries. The template-based fabrication method can be easily replicated and scaled for small-scale production, supporting distributed manufacturing strategies. Quality control procedures developed during this research provide guidelines for maintaining consistent product standards while utilizing manual production methods. These manufacturing insights contribute to developing sustainable wind energy industries in developing countries. This research provides important contributions to developing wind turbine technology suitable for Indonesia's geographical and climatological conditions. The inverse taper design with NACA 6412 airfoil proves to be an effective solution for addressing low wind speed energy harvesting challenges. These results open opportunities for further development of small-scale wind turbine technology that can be widely implemented throughout Indonesia, supporting energy diversification programs and reducing fossil fuel dependency. The research methodology and findings also provide valuable references for similar studies in other tropical regions with comparable wind characteristics. Future research directions should focus on optimizing blade materials, exploring advanced manufacturing techniques, and investigating hybrid renewable energy systems that incorporate these improved wind turbine designs.

## 5. Conclusions and Recommendations

Based on the comprehensive design and testing of blades for low wind speed wind turbines, several important conclusions emerge from this research. The optimal blade design developed through this study is the inverse taper blade configuration utilizing NACA 6412 airfoil with a 0.8-meter radius, where the chord widening distribution implements a 20% progression from the root to the blade tip. This design approach represents a significant departure from conventional taper blade configurations and demonstrates superior performance characteristics specifically tailored for low wind speed applications commonly found in tropical regions like Indonesia. The simulation results obtained using QBlade software provide compelling evidence for the superiority of the inverse taper design over traditional taper configurations. The inverse taper blade achieves a maximum coefficient of performance (Cp) of 0.52, substantially outperforming the taper blade which reaches only 0.41. This 26.8% improvement in theoretical efficiency translates directly to enhanced energy capabilities in real-world applications. The selection of NACA 6412 airfoil proves particularly advantageous due to its exceptional lift-to-drag ratio of 147.1 at optimal angles of attack, combined with a lift coefficient of 1.34. These aerodynamic characteristics make this airfoil especially suitable for low wind speed conditions where maximizing lift generation becomes crucial for turbine startup and sustained operation. Field testing validation confirms the practical effectiveness of the designed blade system, demonstrating reliable operation throughout the testing period under varying wind conditions. The empirical results strongly support the theoretical predictions, showing that inverse taper blades consistently outperform conventional taper designs in generating usable power at low wind speeds. This performance advantage becomes particularly significant for applications in regions with limited wind resources, where conventional wind turbines often fail to achieve economic viability. The successful field demonstration proves that the developed blade design can effectively harness wind energy in challenging low-speed environments, opening new possibilities for distributed wind energy systems in previously unsuitable locations.

The findings of this research establish a solid foundation for future developments in small-scale wind turbine technology, yet several areas warrant further investigation to maximize the potential of these innovations. Future research should focus on expanding the airfoil analysis by incorporating a broader range of airfoil types and configurations through comprehensive modeling studies. This expanded analysis could potentially identify even more efficient airfoil profiles specifically optimized for low wind speed applications, possibly leading to further performance improvements beyond what has been achieved with NACA 6412. Additionally, investigating hybrid airfoil designs or variable-geometry concepts could provide adaptive capabilities that optimize performance across wider wind speed ranges. Material selection represents another critical area for future development, particularly the exploration of advanced composite materials such as carbon fiber, fiberglass, or hybrid fiber composites. While the current research successfully demonstrates the viability of wooden blade construction, advanced materials could offer significant advantages in terms of weight reduction, durability, and manufacturing precision. Fiber-based materials would also enable more complex geometric designs and potentially allow for larger blade diameters without proportional weight increases. Furthermore, investigating manufacturing techniques suitable for these advanced materials, including molding processes and quality control methods, would be essential for transitioning from prototype development to commercial production. These material and manufacturing improvements could significantly enhance the economic viability and widespread adoption of small-scale wind turbine technology in developing markets.

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