Journal of Mechanical Engineering *Vol 19(2), 79-96, 2022*

Design, Manufacturing and Testing of Inversed Taper NACA 4412 Airfoil with Blade Made of Hybrid Empty Fruit Bunch Bio-composites

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ABSTRACT

The continuous increase in electrical energy requirements as well as the decreasing amount of fossil fuels has led to the rapid development of studies in the field of renewable energy, one of which is wind energy. Wind energy with wind turbine was chosen due to its commercial acceptability such as low cost, ease of operation, and maintenance along relatively much less time from concept to operation. One of the important components in a turbine is the blade, the function of the blade is to trap the wind which is then forwarded to the generator. Therefore, this study aims to design, manufacture, and test blades for inversed taper NACA 4412, using a composite Empty Fruit Bunch (EFB) fiber combined with fiberglass. The wind turbine was placed above building at a height of ±15m and the data taken were in the form of wind speed, air temperature, voltage, and shaft rotation speed. Data collection was carried out using Arduino Uno, which was recorded on the data logger for 4 days and at the maximum speed, the power obtained was 48.2 Watt. Furthermore, the highest coefficient performance value obtained was 0.17 with a tip speed ratio value of 0.89 at a wind speed of 3.27 m/s.

Keywords: *Wind Turbine; Inversed Taper; Empty Fruit Bunch; Fiberglass*

Introduction

Presently, there has been a continuous increase in energy consumption. This is due to the rise in population impact on the electricity demand per capita [1]. According to the national energy council in 2025, electricity demand per capita

ISSN 1823-5514, eISSN 2550-164X

Received for review: 2021-05-31
Accepted for publication: 2022-01-31
Published: 2022-04-15

remained below the per capita electricity targets contained in the national energy policy [1].

One of the most widely used energy sources is fossil fuels [2]. Global interest in energy has raised concerns to the point of the greenhouse effect, triggered by the use of fossil fuels and excessive consumption of fuels [3]. Increased awareness of the adverse effects of changing global climate conditions, on regional and local scales has led individuals from all walks of life to utilize clean and renewable sources, in order to combat the increase in environmental pollution [4]. Renewable energy sources that are currently being developed include wind, solar photovoltaic, solar thermal, geothermal, biomass, municipal waste, hydrogen, large and small hydro-power plants, and others [4, 5].

Wind energy was chosen due to its commercial acceptability such as low cost, ease of operation, and maintenance along relatively much less time from concept to operation [4]. As a renewable energy source, it has great potential to address energy needs. Furthermore, it is the cleanest and most important source of renewable energy [6, 7]. Therefore, at the end of 2016, the total installed capacity of wind power plants reached 487 GW (around 4% of global electricity) [8].

The wind turbine is divided into two based on the direction of the axis, namely Horizontal (HAWT) and Vertical Axis Wind Turbine (VAWT) and each type of wind turbine has a different size and efficiency. HAWT has a higher efficiency compared to VAWT when energy is being extracted from wind forces. This is due to its design which allows for energy extraction through the full rotation of the blade when placed under consistent wind flow [9]. One of the important components in a wind turbine is a blade, the function of the blade is to trap the wind which is then forwarded to the generator [10].

The blade should be made of a material that allows it to easily achieve a 3D bending shape, lightweight, and high mechanical strength for aerodynamic loads and the mass generated during wind turbine operation [11]. Therefore, scientists and engineers have tested and used a variety of materials for the manufacturing of wind turbine blades such as wood, steel, aluminum, carbon, fiberglass, and composites [12]. These materials have advantages and disadvantages, which include the wood not having a pitch mechanism for optimization of the blade angle. Meanwhile, carbon fiber has high strength, fatigue, and stiffness and reduces the weight of the blade, which gives it an edge over fiberglass but is relatively more expensive [13]. Natural fiber composites were chosen because they have advantages, which include low density, non-abrasive, biodegradability, abundant availability of raw materials, and low price [14]. Empty Fruit Bunch (EFB) is one of the plantation and oil palm waste products that have not been optimally utilized in Riau Province [15]. Usually, this waste is processed into compost, organic charcoal, activated carbon, and fuel for boilers in palm oil mills [16]. Currently, the study of EFB has led to the discussion about natural composites (natural fibers) [17]. EFB waste contains 43-65%, 13-25% and 17-34% of cellulose, lignin and hemicellulose, respectively [18]. The potential of its fiber, namely its mechanical strength, to have high toughness, makes it ideal for several applications in the engineering scope [19]. Therefore, a composite empty fruit bunch fiber combined with fiberglass as the base material for the blade was chosen.

The types of blades are divided into three based on the design which are taper (shrink to the end), taperless (base and tip have the same width), and inversed taper (enlarged to the tip) [2]. Each type of blade functions at a different wind speed. The daily wind speed at BKMG Pekanbaru, Indonesia, is shown in Figure 1.

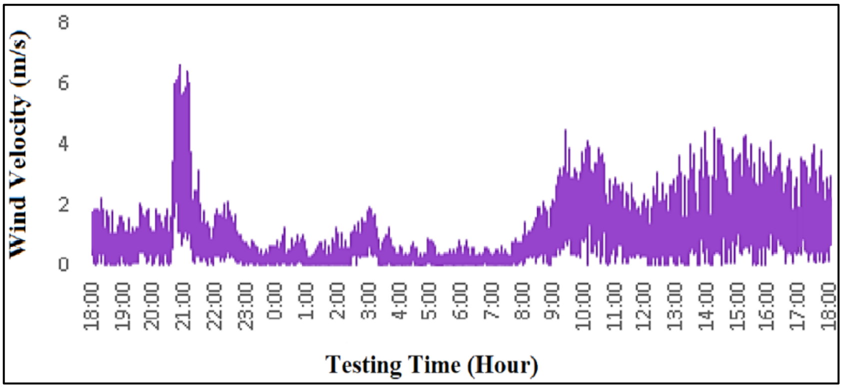

Figure 1: Daily wind speed data in Pekanbaru [20]

The wind speed data released by BMKG data showed an average wind speed in July 2019, which amounted to 1.9 m/s [20]. Therefore, the blade which corresponds to the wind speed in Pekanbaru is an inversed taper. Nishizawa (2013) also carried out a study on various types of inversed taper blades [21].

Meanwhile, a study on airfoil shape optimization for low wind speeds was carried out and, it was concluded that the inversed taper adaptation is capable of increasing the aerodynamic efficiency of the blades. In this study, the tapered and inversed taper blades were compared. The inversed taper blade shape showed excellent aerodynamics at Tip Speed Ratio (TSR) ≤ 3 [22]. A study on airfoil shape optimization for low wind speeds was carried out, using inversed taper blades with a length of blade radius of 0.3 m. After testing, the maximum power was obtained, namely 48.87 Watt, which occurred at a wind speed of 10 m/s with a Power Coefficient (Cp) of 0.29 [23]. However, there is a continuous development of wind turbines at low wind speeds.

Therefore, this study aims to design and manufacture a horizontal axis wind turbine, as well as determine its performance according to the wind speed in Pekanbaru, with the inversed taper blade NACA 4412, using a composite EFB fiber combined with fiberglass.

Methodology

Design

In blade design, the Cp and TSR values were required and a study that varied the number of inversed taper blades at wind speeds between 4-12 m/s was carried out [21]. A total of 5 inversed taper blades were chosen because they had the highest Power Coefficient (Cp), which was 0.44 at TSR 2.5 [21]. Furthermore, wind speed data were needed. The wind speed data retrieval in Pekanbaru was carried out above Building C Faculty of Engineering, University of Riau. Data collection was carried out for 3 days and a maximum speed of 6.5 m/s was obtained. The wind speed design chosen was the maximum wind speed.[24]. This was to avoid damage to the blades when receiving high wind speeds. Furthermore, it is necessary to know the design power of the wind turbine. The design power in this study was 300 Watt. In addition, the wind turbine efficiency should not exceed 59.3%. This parameter is commonly known as the power coefficient and where the max Cp = 0.593, it is referred to as the Betz limit [25]. In order to effectively model the performance of the wind turbine, the geometry of the blades produced is determined by the chord, twist, and airfoil [26]. Input parameters should be identified for the design, such as several variables that are calculated and determined in the initial steps of designing the wind turbine blades, as shown in Table 1.

Table 1: Blade design parameters

No.	Variable	Value
1	Design Power (P_e)	300 Watt
2	Design Wind Velocity (v_D)	6.5 m/s
3	Tip Speed Ratio (λ)	2.5
4	Number of Blades (B)	5
5	Blade Efficiency (C_P)	0.44
6	Blade Type	Inversed Taper
7	Ambient Temperature	30 °C
8	Air Density (ρ_{air}) @ 30 °C	1.16 kg/m^3

The radius of the blade depends on the power expected from the turbine and the wind speed at which the turbine operates. The various disadvantages involved in the energy conversion process should also be considered [24].

$$P_{e} = \frac{1}{2} C_{pd}\,\eta_{T}\,\eta_{g}\,\rho_{a}\,A_{T}\,V_{D}^{3} \tag{1}$$

The rotor radius is estimable, using Equation 2.

$$r = [\frac{2\,P_{e}}{C_{pd}\,\eta_{T}\,\eta_{g}\,\rho_{a}\,\pi\,V_{D}^{3}}]^{\frac{1}{2}} \tag{2}$$

Furthermore, to obtain the chord length, The twist angle and partial tip speed ratio of each element should be known. The blade geometry modeling that was created is shown in Figure 2.

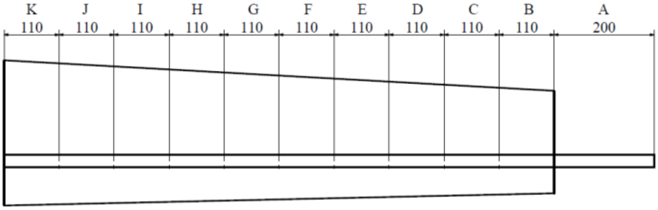

Figure 2: Blade geometry

The partial tip speed ratio is the ratio between the speed of the blade element at a certain position and the speed of the wind that hits the blade. The partial tip speed ratio was determined using Equation (3) [24].

$$\lambda_{r} = \frac{r}{R} \times \lambda \tag{3}$$

To calculate the torsional angle for each blade element, the flow angle of each blade element was first calculated. This was carried out using Equation (4) [24].

$$\emptyset = \frac{2}{3} tan^{-1} \frac{1}{\lambda_{r}} \tag{4}$$

After the flow angle was calculated, the torsion angle of each element was calculated using Equation (5) [24].

$$\beta = \emptyset - \alpha \tag{5}$$

After the torsional angle was calculated, the chord length of each element was further calculated using Equation (6) [24].

$$C_r = \frac{8\pi r}{BC_L} \times (1 - \cos\phi) \tag{6}$$

Furthermore, linearization and optimization of the blade were carried out to produce efficient blades and facilitate the production process, and based on the results of this study and previous literature studies, 75% linearization and optimization were applied in the desired design [27]. The results of linearization and optimization are shown in Table 2.

Table 2: Linearization geometry of the blade

Local Radius (m)	Torsion Angle (°)	Chord (m)
0.20	23.9	0.17
0.31	22.2	0.19
0.42	20.6	0.21
0.53	18.9	0.22
0.64	17.3	0.24
0.75	15.6	0.26
0.86	14.0	0.27
0.97	12.3	0.29
1.08	10.6	0.30
1.19	9.0	0.32
1.30	7.3	0.34

Airfoil is the geometric part of the blade that determines the efficiency of the blade once the radius and chord data are known. Its selection requirements for blade profile design were chosen from large C_L/C_D values based on the angle of attack (α) [22]. The force of the component perpendicular to the direction of flow is called the lift force (F_L), while the force of the component in the direction of flow is called the drag force (F_D) [28]. Therefore, the selected airfoil was NACA 4412 [29]. Furthermore, to obtain the highest C_L and C_D values on airfoil NACA 4412, Q-blade simulation was used, where the angle of attack greatly influenced C_L compared to C_D [30]. The simulation results of blade design using Q-Blade software are shown in Table 3.

From the design and manufacture of blades, the blade radius, and hub, were 1.3 m and 0.2 m, respectively with a chord length of 0.17 m and 0.34 m at the base and end, respectively with a torsional angle at the base of 23.9° and torsion angle of 7.3° at the end and airfoil with type NACA 4412.

Based on the Q-blade simulation results, the maximum stress that occurred on the blade is 43.46 MPa. To make the right wind turbine blades, material selection should meet the criteria of easy access to material, strength to weight ratio, low cost, uncomplicated manufacturing process, and ability to withstand the load [27].

Table 3: Airfoil data for NACA 4412

Data NACA 4412	
Ratio of the lift and drag coefficient (C_L/ C_D)	111.36
Angle of attack (α)	6.5°
Lift coefficient to angle of attack (C_L)	1.163
Drag coefficient to angle of attack (C_D)	0.010
Reynold number (Re)	525,500
Ncrit	9

The composite used in this study was tested for its tensile strength using the ASTM D638 test standard and a value of 63.44 MPa was obtained. Therefore, a composite EFB fiber combined with fiberglass was chosen, given that it has good strength, low cost, low density, and biodegradability [15].

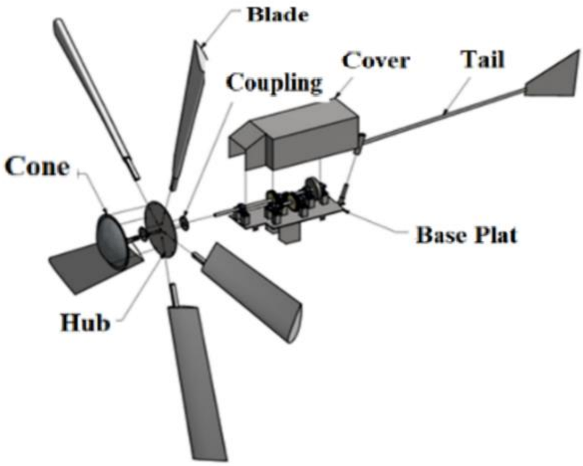

Figure 3: Wind turbine components

Materials

The composite material on the blade is a combination of fiberglass as the base material with EFB fiber as reinforcement and resin as the matrix. The EFB was obtained in Riau Province and has been treated with an alkaline treatment of 5%.[15]. Furthermore, its fiber size had a length of 30 mm. The fiberglass used is a type of Woven Roving Mat (WRM) 200, this type of fiberglass is produced with a neat webbing from two directions, namely horizontal and vertical with a heavy 200 g/m² [31]. An epoxy resin 555 A matrix was used with epoxy hardener EPH 555 B in a ratio of 2:1. According to the Q-blade simulation, the value of the tensile strength required by the blade material was 43.46 MPa. Table 4 shows the tensile test values on EFB fiber and fiberglass.

Therefore, to ascertain the strength of the blade material that is resistant to the tensile strength of 43.46 MPa, it is necessary to carry out a tensile test on the specimen of the EFB + WR 200 2 layers blade using a universal testing machine. The standard used was ASTM D638 [32].

Table 4: Tensile strength of materials

Material	**Length of Fiber (mm)**	**Testing Standards**	**Tensile Strength (MPa)**	**Reference**
EFB	30	JIS K6781	20.1	Fatra, 2016
WR 200 (2 layers)		ASTM D638	55.98	Shomad, 2021
EFB + WR 200 (2 layers)	30	ASTM D638	63.44	Current results

Manufacturing process

Prior to the manufacture of blades, two molds were made by using a combination of epoxy resin with fiberglass.

Figure 4: Inversed taper blades mold

The empty fruit bunch was cleaned and the fiber was taken. Furthermore, an alkaline treatment was administered, after which it was dried for 2-3 days [15]. The fiberglass was cut based on the geometry blade surface.

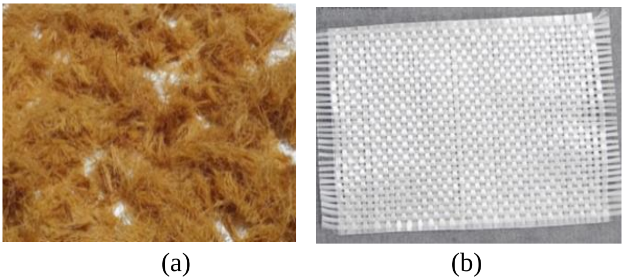
(a) (b)

Figure 5: (a) Empty fruit bunch (b) Fiberglass

A mixture consisting of resin and hardener was made. Subsequently, the blade was made with a repeated process from the hand lay-up method using the sequence of fiberglass, empty fruit bunch fiber, and fiberglass into the blade mold. As shown in Figure 6, hand lay-up was placed at ambient temperature after which the vacuum bag was applied and sealed for the vacuum bagging process.

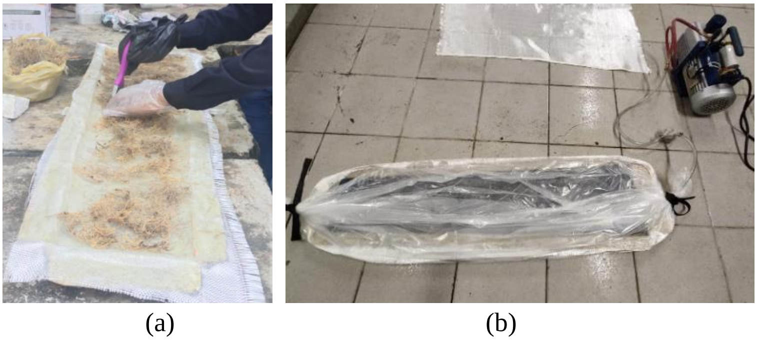
(a) (b)

Figure 6: (a) Hand lay-up (b) Vacuum bagging

The two sides of the blade were joined together, after which fixed rectangular steel was attached to the ribs, and the edges of the blade were glued.

(a) (b)

Figure 7: (a) Wind turbine (b) Inversed taper blade

Experiment procedure

This study was carried out to determine the effect of wind speed on the electric power generated. The wind turbine tested was a horizontal axis wind turbine with 5 inversed taper blade types at a design wind speed of 300 Watt, which is 6.5 m/s. Figure 8 shows the scheme of the measuring instrument circuit.

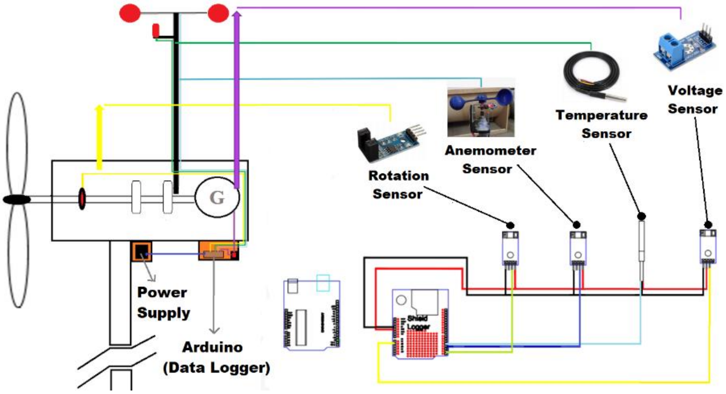

Figure 8: Installation suite of sensors

Data collection was carried out directly, based on the results of testing a wind turbine that had a 4.2 m high pole and was placed above a building at a height of ± 15 m. Furthermore, data recording was carried out using a data logger and an open-source Arduino as a microcontroller. The test data obtained include wind speed, shaft rotation speed, ambient temperature, and generator voltage. In addition, data processing was carried out to obtain parameters such as wind power potential, power coefficient, tip speed ratio, and actual power.

The wind turbine testing procedure was prepared to test equipment. Subsequently, the sensors installed on the wind turbine and Arduino connected to the data logger. After the test device was connected to the wind turbine, the USB cable was connected to the power supply, in order for the indicator on the Arduino to lit up. Furthermore, the SD card was installed in the data logger. It was ensured that all connectors were properly installed in order for the sensor light to be yellow. The SD card in the data logger was lowered once a day for data retrieval, after which it was removed from the memory card module and connected to the computer using a memory card adapter.

Wind turbine testing was carried out on the first, second, and third days in a row starting on August 15, 2020, from 18.00 Western Indonesian Time (WIB) until August 18, 2020, at 18.00 WIB.

Results and Discussion

The tensile strength of the wind turbine blades is higher than the tensile strength allowed in the design, thus the turbine blades can withstand a load with wind speeds above the design wind speed of 6.8 m/s. The testing data was processed with calculation parameters and are shown in Table 5 and Figure 9.

Table 5 and Figure 9 show the comparison of the wind speed data obtained for 3 days, to that for 1 full day in Pekanbaru. It is seen that at 22.00 - 07.00 WIB, there was a minimal fluctuation in the wind speed of the Pekanbaru area. Where the wind conditions do not generate electricity at the generator, then at 11.00-13.00 WIB the wind speed increases which could move the blades, until the generator managed to get power.

The actual power generated by the generator is shown in Table 5. It is seen that generator is capable of generating electricity at speeds above 2 m/s. Table 5 shows that the greater the wind speed, the higher the amount of power generated by the wind turbine. This implies that the wind speed is directly proportional to the power produced. The third day of testing which was carried out on 17 and 18 August, obtained the highest wind speed at 19:00 WIB, namely 6.8 m/s with a power generation of 48.2 Watt.

The most important aspect of this study on wind turbines is the ability of wind turbine blades to convert wind energy into mechanical energy. This ability is also seen through the Power Coefficient (Cp). However, the blade Cp obtained was relatively small as shown in Table 5. The main factor that affects the small Cp obtained is that the wind turbine always tries to face the direction of the wind, but before the wind turbine faces the wind direction, the wind direction changes. Unlike the case with the wind speed sensor used, the cup anemometer was able to receive wind from all directions. This results in low generator output power, while the wind speed reading remains high, consequently, the available wind potential becomes high. Cp is inversely proportional to wind potential, therefore Cp obtained is relatively small.

In theory, it is known that the turbine tip speed ratio helps to maximize the power output and efficiency of wind turbines, where if the rotor rotates too slow, it will make more wind pass through the gaps between the blades instead of delivering energy to the turbine [23]. Also if the blades spin too fast, they can create too much turbulent air or act as a solid wall against the wind. So, the tip speed ratio is helpful in maximizing turbine efficiency.

Table 5: Test results

Time (WIB)	**Wind Velocity (m/s)**			**Actual Power**		
	Day			**Day**		
	1st	**2nd**	**3rd**	**1st**	**2nd**	**3rd**
18:00	2.42	2.38	4.26	2.79	3.14	28.64
19:00	1.38	1.94	6.8	1.24	0.00	48.2
20:00	2.73	0.92	5.32	4.89	0.00	37.37
21:00	0.95	0.41	3.56	0.85	0.00	21.3
22:00	0.32	0.32	0.54	0.29	0.00	0.00
23:00	0.88	0.54	0.22	0.79	0.00	0.00
00:00	0.44	0.28	1.06	0.39	0.00	0.00
01:00	0.27	0.62	0.33	0.24	0.00	0.00
02:00	0.53	0.38	0.94	0.48	0.00	0.00
03:00	0.29	2.72	0.28	0.26	4.54	0.00
04:00	0.39	1.14	0.72	0.35	0.00	0.00
05:00	0.42	1.27	0.52	0.38	0.00	0.00
06:00	0.27	3.14	0.24	0.24	12.57	0.00
07:00	0.62	2.24	0.82	0.56	2.44	0.00
08:00	2.64	0.64	0.38	4.19	0.00	0.00
09:00	4.2	0.73	1.28	26.54	0.00	0.00
10:00	4.78	2.24	2.24	30.38	3.84	2.79
11:00	3.27	4.12	3.87	17.81	24.1	22
12:00	5.12	3.31	4.02	32.83	17.81	24.1
13:00	2.74	3.08	3.61	4.54	7.33	20.95
14:00	2.95	1.15	1.32	5.94	0.00	0.00
15:00	1.46	1.24	2.45	1.31	0.00	3.14
16:00	3.28	0.41	1.16	13.27	0.00	0.00
17:00	2.34	0.38	0.43	2.1	0.00	0.00

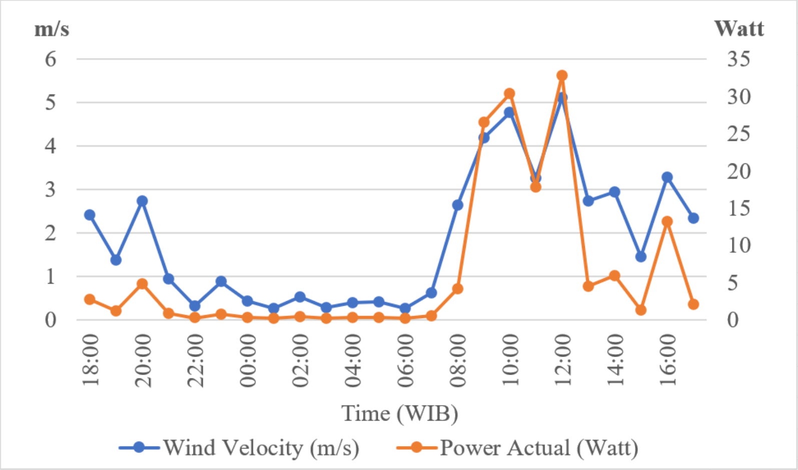

Figure 9: Wind speed data against power generated at first day

In Figure 10, The highest Cp was produced in the research conducted by Nishizawa [21] and then Saoke [23], however, it can be seen in Figure 9 that the graph of this study has similarities with other studies. It is seen that the relationship between power coefficient and tip speed ratio plays an important role in assessing the capacity of a turbine to capture wind energy. From theory, it is known that the turbine tip speed ratio assists in maximizing the power output and efficiency of the wind turbine when the blades also rotate slowly. Therefore, more wind will pass through the gaps between the blades rather than energizing the turbine. The inverse taper blade has a low TSR value, it is due to the low torque produced [33]. Therefore, a gearbox transmission is needed to increase rotation and thus increase the power capacity generated.

This experiment was carried out in open spaces and it is resulting the blades must follow the direction of the wind from various directions, it is very different if the experiment is carried out in a wind tunnel because in the wind tunnel the direction of the wind only in one direction. When the blade reaches the maximum Tip Speed Ratio value from the design, the tip speed ratio power coefficient value will decrease. Meanwhile, when the blade rotates too fast it is able to create sufficient air turbulence or act as a solid wall against the wind. This implies that the tip speed ratio assists in maximizing turbine efficiency.

The highest power was obtained at a maximum wind speed of 6.8 m/s, namely 48.2 Watts, and at a TSR of 2.4. However, the resulting Cp was very small, namely 0.05. This is because the blade was designed for a maximum speed of 6,5 m/s, which causes blade instability that affects the rotation instability of the shaft. The torques of the turbines shown above are based on the generator as the load and gearbox as the load too. In addition to the points mentioned above, the temperature obtained in data collection affected the power generated by wind turbines, although it was relatively small. This was because the higher the temperature, the lower the power produced and vice versa.

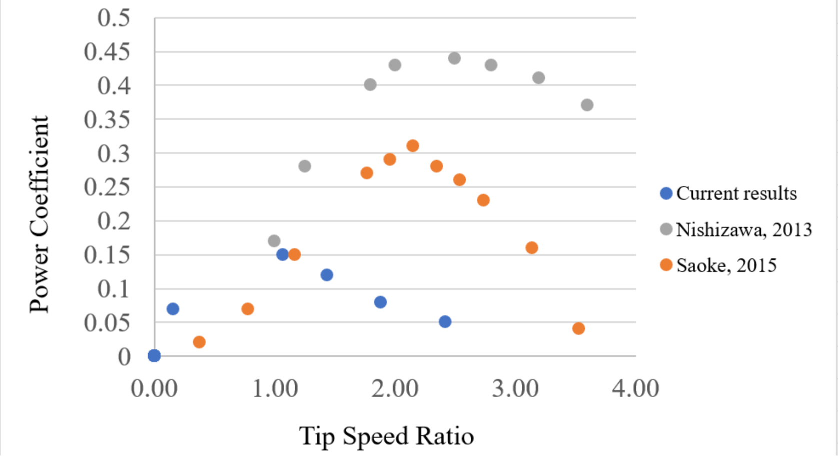

Figure 10: Power coefficient VS tip speed ratio

Conclusion

In this study, a horizontal axis wind turbine was designed and made with the inversed taper blade type 1 NACA 4412, using a composite Empty Fruit Bunch (EFB) fiber combined with fiberglass. The gear ratio used was 1:16 and a 300 Watt generator with a current of 12 Amperes and generator efficiency value of 80% or 0.8 of the resulting Watt. The test was carried out at an altitude of ±19 meters above ground level at the Faculty of Engineering, University of Riau. Based on the data obtained during the test, the wind speed recorded on the logger data ranged from 0 m/s to 6.8 m/s. The highest wind speed was obtained on the third day, namely 6.8 m/s, and at this maximum speed, the power obtained was 48.2 Watt. Furthermore, the Cp and TSR values obtained in the test were at 48.2 Watt with a TSR and Cp Value of 2.42 and 0.05, respectively. The highest Cp value obtained was 0.17 with a TSR value of 0.89 at a wind speed of 3.27 m/s.

Acknowledgement

The authors express gratitude to the Riau University ADB AKSI Project in 2020, for supporting the students in completing the Final Project course.

Nomenclature

A_T	Sweep area
n	Shaft rotation
P_e	Design power
r	Blade radius
d	Blade diameter
V	Wind velocity
λ	Tip speed ratio
Ω	The angular velocity
ρ_a	Air density
I	Electric current
E	Kinetic energy
Cp	Power coefficient
V	Voltage
ηt	Transmission efficiency
ηg	Generator efficiency
F_D	Drag force
F_L	Lift force
C_D	Drag coefficient
C_L	Lift coefficient
α	Angle of Attack
β	Twist Angle
$\emptyset$	Angle Flow

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