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Wind turbine optimization through optimal blade shape design for low wind speeds

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ABSTRACT

Current electricity needs continue to rely on depleting fossil fuels such as fossil fuel and coal. The current government effort is to find non-fossil fuel alternative energy sources. Wind energy is one of the efforts to use ecologically friendly renewable alternative energy. Studies on the development and use of new and renewable energy are now undertaken. One of them is a series of research on the utilization of wind in numerous places of Indonesia through the construction of wind turbines. The blade that explicitly makes contact with the wind is one of the most critical sections of a wind turbine. The shape of the airfoil determines whether or not the blade is used. The focus of this research was to determine the optimal type of airfoil by comparing the coefficient of power (Cp), maximum power, and lowest power produced by various NACA (National Advisory Committee for Aeronautics) airfoils. NACA 4410, 4412, and 4415 airfoils were employed in this study.

1. INTRODUCTION

Thousands of islands in eastern Indonesia have significant wind energy potential, which is inversely related to the availability of electricity in these regions, which is still relatively low, particularly in rural places (Muhajir, 2021). Wind potential is suitable for power generation with output power ranging from 100 to 500 Watts. Although categorized as a small scale, this electric power is quite suitable to be used on a household scale. This very low output electricity can be acquired from alternate energy sources, particularly in places not served by PLN (Maulana et al, 2021).

Various studies have been conducted to obtain the best wind turbines in order to provide clean energy from wind power. The number of blades in a wind turbine has a significant impact upon the efficiency. Three blades are the most effective at a power coefficient of 50%. Furthermore, the material of the blade affects the turbine's performance (Multazam and Mulkan, 2019). However, in terms of rotation, a number of blades as many as 5 produces the highest average rpm value compared to a number of blades as few as 3 (Sifa et al, 2018; Effendi et al, 2019). Similarly, the greater the number of blades, the greater the power for the same wind speed conditions. As the number of blades increases, so does the total mass of the blades. The larger the mass of the blade, the greater the TSR (tip speed ratio) (Effendi et al, 2019). Meanwhile, pine wood is an excellent blade material for low speeds with a low power coefficient.

Research has been conducted and developed a prototype of a 3-blade HAWT wind turbine with fiberglass blades. The test was carried out at a reservoir area, utilizing a 1:1,2 gearbox. According to the results, the turbine can generate a voltage of 95 Volts and an electric current of 4.5 mA at a wind speed of 5.6 m/s (Sudrajat et al, 2020).

In addition, taperless blades for HAWT (horizontal axis wind turbine) turbines have been tested using simulation and analysis (Alfaridzi and Setiawan, 2020). The investigation, however, was limited to one type of airfoil blade, the NACA 4412. Understanding the characteristics of other types of taperless blades is necessary to provide a complete picture of each blade's effectiveness, allowing its use to be targeted at varied wind speed situations.

These diverse studies were conducted due to the benefits of wind turbines, which have abundant and renewable resources and do not generate environmental pollution in the form of exhaust emissions. However, the wind turbine currently on the market are not appropriate for wind speeds in Indonesia, particularly in the southern area of Java, which is categorized as low speed (between 3-6 m/s) (Buana et al, 2020). Furthermore, information on the potential of turbines using airfoils in line with NACA regulations at low wind speeds is currently few. Considering this, this research was conducted with the goal of designing a taperless wind turbine using various NACA airfoils based on wind speed in Indonesia and power generation.

2. METHOD

The research begins with an examination of the characteristics of the airfoil. At this stage, the Q-Blade software is used to analyze the characteristics of the airfoil. A graph of the ratio of lift force and drag force to angle of attack (Cl/Cd – α) as well as a graph of lift force to angle of attack (Cl – α) are the analyzed features. The objective at this stage is to observe the airfoil's inclination to its lift and drag forces.

The following step is to perform the design calculations. This stage is completed prior to designing the blade and determines the characteristics that will be utilized as the basis for developing the blade geometry. These parameters are as follows:

1.	Required wind power (W$_a$). The following equation can be used to calculate the required wind power (Golnary and Moradi, 2019):

$$w_a = \frac{W_e}{K} \tag{1}$$

$$W_e = \frac{1}{2}\rho A v^2 \tag{2}$$

w_a is wind power required (W), W_e is electrical power to be generated (W), K is system efficiency (%), ρ is density of air (kg/m^3), A is cross sectional area of the blade (m^2), and v is wind speed (m/s).

2.	Wind turbine system efficiency (K)
3.	Tip speed ratio / TSR (λ)

The following step is to calculate the geometry parameters of the blades based on the parameters listed above. The blade is separated into 11 parts in this section (1 base element and 10 equal length elements). The calculated geometry is as follows:

a.	Blade radius (R)
b.	TSR Partial
	Partial TSR is the ratio of the linear speed of the blade elements to the wind speed of different elements.
c.	Lift coefficient of each element (Cl)
d.	Angle of attack (α)
	The angle of attack is calculated by examining the Cl-graph produced by the airfoil analysis with Q-Blade software.
e.	Flow angle (ϕ)
f.	Twist (β)

After obtaining the above geometry, the blade model is designed using the Q-Blade v0.963 software by providing the dimensions of each element. The acquired results are then simulated using the rotor with the BEM (blade element momentum) method and the Q-Blade v0.963 software to get a graph showing the effect of the performance coefficient on the tip speed ratio (Cp–TSR) and the resulting power to wind speed (P– v). The blades are intended to provide P = 500 W of electricity at TSR 7 and a wind speed of 5 m/s.

Following the extraction of the expected blade coordinates from the design calculation data, the next step is to develop a 3D design in Solidworks 2016 software and generate a blade engineering drawing.

3. RESULTS AND DISCUSSION

The blade is designed by identifying the initial parameter of the blade, which is the overall system efficiency. After determining the system's efficiency, determine the necessary electrical power capacity (W$_e$), which is 900 W with a maximum wind speed of 5 m/s under field conditions. The required wind power (W$_a$) is

calculated using equation 1, and the results are 4115.2 W if the blade efficiency is 30% and 3086,4 W if the blade efficiency is 40%. However, a blade cannot be extremely efficient. The Betz coefficient explains why a turbine blade cannot convert 100% of the energy in the wind into kinetic energy. This is due to losses in turbine components such as the main shaft, gearbox, and generator (Lololau et al, 2021).

Table 1. Defining the blade initial parameters

| W_e (W) | Efficiency | | | | | w_a (W) | A (m^2) | R (m) |
	Blade	Generator	Transmission	Controller	System			
900	0.3	0.9	0.9	0.9	0.22	4115.2	3.89	1.11
	0.4				0.29	3086.4	2.92	0.96

Before calculating the geometry of the blade, one must first know the angle of attack (α) and the Lift Coefficient (Cl). The angle of attack is the angle at which the wind collides with the airfoil, while the lift coefficient (Cl) is the coefficient of lift; the lift must be greater than the drag coefficient for the blade to rotate. The angle of attack and lift coefficient data are determined using simulations using the Q-Blade v0.963 software. Figure 1 depicts the modeling results of the NACA 4410, 4412, and 4415 airfoils.
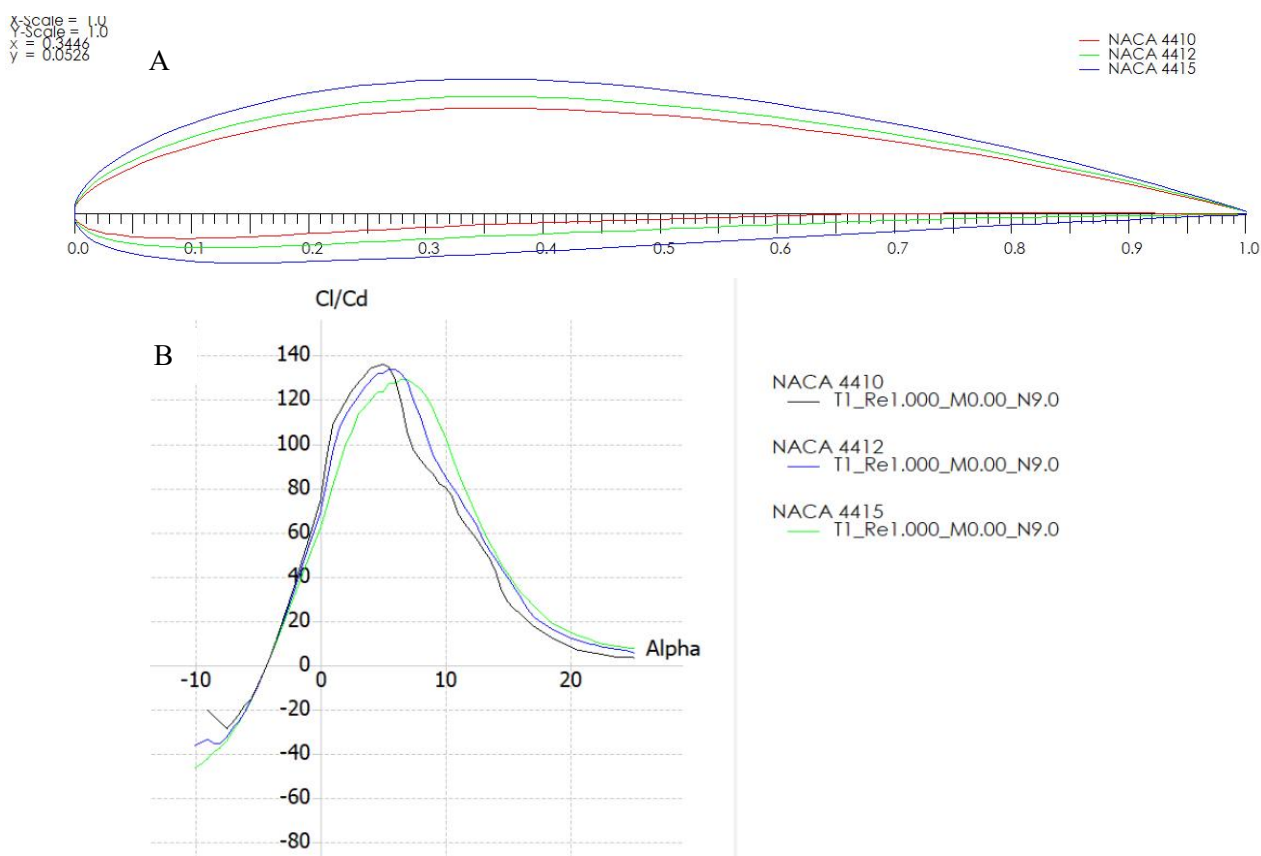

Figure 1. NACA 4410, 4412, and 4415 airfoil simulation results. (a) airfoil profile, (b) Cl/Cd vs Alpha

Furthermore, the complete determination of the blade geometry is shown in table 2.

Table 2. Determination of blade design geometry

TSR	Airfoil	Cl/Cd	Cr	Blade number
7	NACA 4410	135.8	0.1	3

Figure 2 depicts the simulation results of the performance coefficient compared to TSR (Cp-TSR). According to the simulation, the blade has 49 percent Cp at TSR 7. The obtained Cp is fairly satisfactory. This demonstrates that the turbine blades can effectively convert wind energy (Nursidik et al, 2021). The highest TSR is reached at a value of 5, and as TSR increases, Cp decreases. The drop in Cp caused by increased TSR is due to

torque's considerable influence on blade tip speed (Suresh and Rajakumar, 2020). If somehow the speed of the blade's tip exceeds the intended limit, structural damage will occur, further reducing the blade's effectiveness.
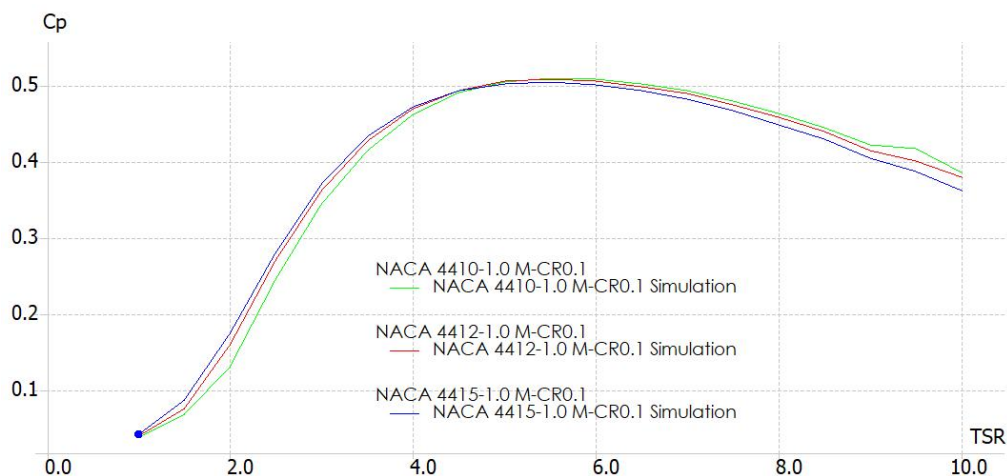

Figure 2. Performance coefficient relationship to TSR (Cp-TSR)

After defining the geometrical parameters of the blades, Solidworks 2016 software is used to design 3D blades. It is vital to find the coordinates of the shape of the airfoil in each element to assist the blade design process. Each element's airfoil coordinate data is analyzed in Microsoft Excel before being imported into the Solidworks 2016 software. Figure 3 depicts the results.
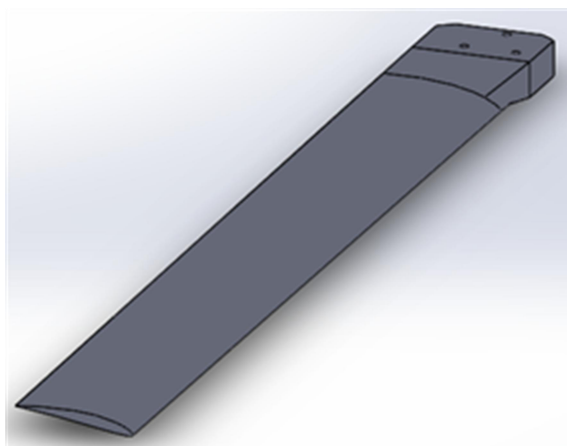

Figure 3. NACA 4410 taperless blade model

4. CONCLUSION

The following conclusions can be obtained from the work that has been done in designing wind turbines specifically for the needs in Indonesia which have low wind speed specifications.
1. The NACA taperless blade design yielded a radius of 1.0 m and a chord width of 0.1 m.
2. The blade design provides a maximum Cp of 49 %, a maximum power of 1700 W, and a minimum power of 590 W at a wind speed of 5 m/s for NACA 4410. While NACA 4412 has a maximum Cp of 48 %, a maximum power of 1700 W, and a minimum power of 550 W. The highest Cp for NACA 4415 is 47 %, the maximum power is 1680 W, and the minimum power is 480 W. This demonstrates that NACA 4410 is well suited for use on wind turbines in low wind speed scenarios.

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