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DOUBLE-STAGE SAVONIUS AND DARRIEUS WIND TURBINES FOR URBAN AREAS USING FIBERGLASS MATERIALS

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Key words: *wind turbine, vertical axis wind turbine (VAWT), savonius-darrieus, fiberglass*
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DOUBLE-STAGE SAVONIUS AND DARRIEUS WIND TURBINES FOR URBAN AREAS USING FIBERGLASS MATERIALS

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Wind generation is an alternative to energy generation that is renewable, widely distributed, and environmentally friendly. However, the use of wind energy in certain areas with limited land has constraints for installing large-scale generators; therefore, the concept of micro wind energy generation is an attractive solution to be developed at this time. In this case, the Vertical Axis Wind Turbine (VAWT) is preferred because it is reliable and economically feasible to operate at low wind speeds in all wind directions. In the case of turbine selection, the Savonius turbine is preferred because it has self-starting. Still, in terms of performance, the Darrieus turbine type has better power efficiency than the Savonius type. Besides that, because of their high solidity and heavier weight, drag-based turbines are less preferred. In this study, the combination of the two types of turbines between Savonius and Darrieus was carried out to overcome each type of turbine's shortcomings. In this case, the fiberglass material was chosen because it has reliable properties that increase the turbine's efficiency. The research design used an experimental method by configuring a double-stage Savonius-Darrieus turbine in the wind tunnel. The data was collected by measuring and recording the electric voltage, electric current, and the generator shaft rotation for each variation of the pitch angle at the 0°,5°,10°,15°,20°,25° and 30° blades and with wind speeds at 1.5 m/s up to 5 m/s with 0.1 m/s intervals. The results showed that adding variations in the pitch angle of the Savonius-Darrieus double-stage turbine blade was ineffective because it reduced the electric power generated and the turbine's performance. In this study, the resulting cut-in speed is 3.8 m/s. However, with the addition of variations in the pitch angle, there was a decrease in the value of electric power, power coefficient, and Tip Speed Ratio (TSR), where the maximum values were 3.14 W, 0.24, and 0.75, respectively.

Key words: wind turbine, vertical axis wind turbine (VAWT), savonius-darrieus, fiberglass

INTRODUCTION

Wind energy is one of the renewable energies that has continued to develop in the last few years [1]. Wind generation technology is also growing rapidly nowadays [2]. Wind generation is considered one of the best alternatives to fossil fuels because it is renewable, widely distributed, and without greenhouse gas emissions generated during operation. The utilization of wind energy in certain areas with limited land has constraints to install large-scale generators. Therefore, the concept of micro wind energy generation is quite interesting because it can produce in such limited locations [3]. Compared to high-speed wind resources, the areas with low wind speeds have several advantages, such as being closer to the urban electrical grid and easier to install [4]. Asia has dominated the turbines at low wind speeds in recent decades due to the low quality of wind resources [5]. During its development, wind energy utilizes several potential areas, one of which is the urban area. Some of these areas are the roofs of tall buildings, railroads, roads, and spaces between buildings [6]. The utilization of wind energy in urban areas has significant challenges, such as turbulent airflow due to buildings' layout in the urban area [7]. A study conducted by Longo et al. [8], who examined the influence of the urban environment on the Savonius wind turbine's performance, revealed that the building's location greatly affects local wind speed conditions. This environmental effect is challenging to characterize because it impacts various wind qualities. So it is necessary to have preliminary research on the characteristics of local winds before installing the turbine to obtain good energy efficiency [8]. Although low wind speed turbine technology helps reduce costs in meeting energy requirements, it also creates significant challenges for designing wind turbine blades to obtain the optimal configuration [9]. The most important thing in designing a wind turbine is the blades. In general, the main objective in designing wind turbine blades is to maximize the power coefficient. In a micro wind turbine, cut-in speed and economic viability are essential in optimizing the micro wind turbine blades [10, 11]. Apart from the continuous development of the Horizontal Axis Wind Turbine (HAWT), the Vertical Axis Wind Turbine (VAWT) has attracted a lot of attention in recent years due to the superiority of its mechanical structure, which is superior to application and easier to use directly [12, 13]. The

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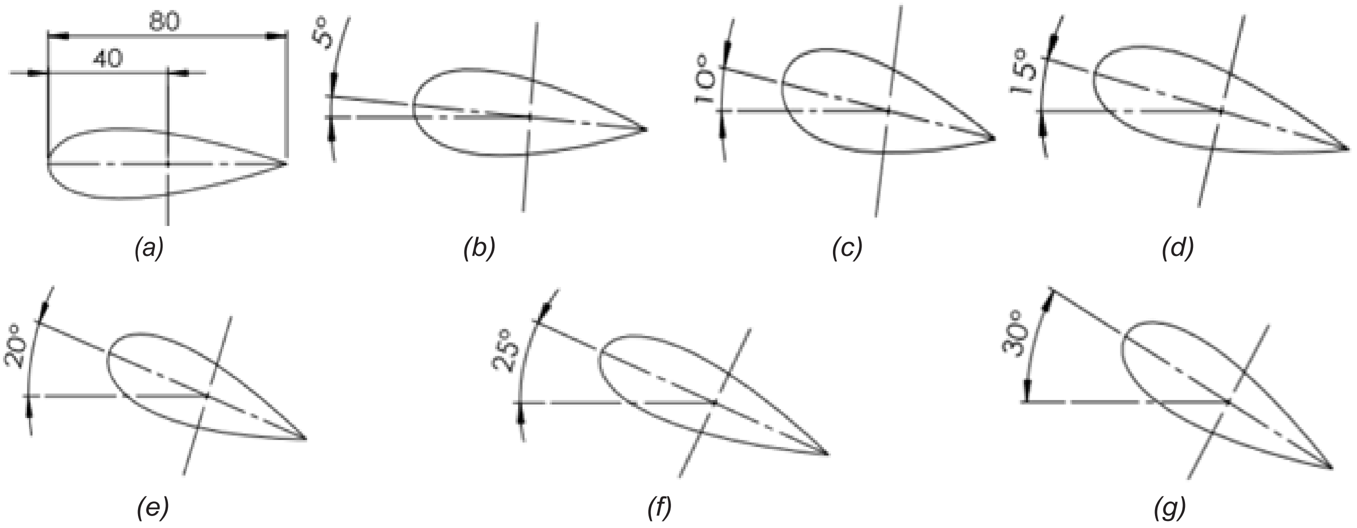
Vertical Axis Wind Turbine (VAWT) is usually chosen for urban areas with low average wind speed [14]. The VAWT is preferred in compactness and economic feasibility to operate at low wind speeds in all wind directions [14]. Besides, VAWT at small and medium sizes can also be used effectively as a low-speed wind energy generation (less than 10 m/s) if the efficiency can be further improved [15, 16]. The challenge of developing such a VAWT installation is increasing the built environment's efficiency, which depends on the blade profile design. Several types of wind turbines are used to extract wind energy in urban areas, including the Savonius wind turbine. Turbine Savonius was chosen because it has better self-starting compared to other turbine types. Several parameters that affect the Savonius wind turbine's performance include blade shape, number of blades, and wind speed [17, 18, 19]. Another type of turbine used is the Darrieus turbine. This turbine is different from the Savonius type, which uses a drag force. The Darrieus turbine utilizes lift force to rotate its axis. This type of turbine has better power efficiency compared to the Savonius type [20]. Several parameters that affect turbine efficiency include pitch angle, blade shape, and the number of blades [15, 21, 22]. Due to their high solidity, heavier weight, and relatively low-efficiency drag-based turbines are less desirable, such as the Savonius turbine, which has a power coefficient of not more than 25% [23]. However, drag-based turbines have the advantage of the self-starting capability. Several parameters have been tested to maximize turbine efficiency, such as the blade profile on the Savonius blade, where the elliptical profile has the highest Cp of 0.34 at TSR=0.8 [24]. Another parameter that can be changed is the addition of Storage on the Savonius. This gives the effect of torque distribution and increases Cp [25,26]. Therefore, these are commonly found as small turbines in urban and remote areas with relatively low wind speeds. The advantage of lift-based straight type VAWT is that the blades are simple and extruded, so the manufacturing costs are lower [19]. The multi-stage VAWT has aerodynamic and structural parameters that are considered as design variables. Numerical results obtained by the mechanics simulations determine a solidity rotary engine ($\sigma = 0.3$), providing the simplest mechanics performance. A two-blade stage is suggested to reduce the rotor weight, lowering the cut-in speed [27]. The turbine radius influences Cp, where the increasing radius decreases Cp. An interesting thing happens when the radius increases, the power generated increases [27]. The optimization process also considers airfoil design to improve aerodynamic and structural performance with the integrated airfoil theory method [4]. In addition to obtaining better power efficiency, various structural variations are carried out to combine the advantages and reduce the disadvantages of the type of turbine used. Based on previous research analysis, rotor innovations such as the Darrieus-Masgrowe two-stage rotor, the Combined Savonius, the Darrieus rotor, and the two-leaf semi-rotating rotor have high starting torque and power efficiency [19]. Combining two types of turbines between Savonius and Darrieus is usually done to overcome each type of turbine's shortcomings. This hybrid system can work in the broader range of operating conditions compared to each component alone, namely for a Tip Speed Ratio (TSR) between 0.5 and 4, compared to a range of 0.5 to 1 for the Savonius and 1.7 types up to 4 for the Darrieus type [24]. In addition, the influence of the material in making this turbine will also affect the performance of the turbine [25]. VAWTs are also preferred more than HAWTs because they are less sensitive to turbulent and fluctuating winds, cost-effective, and environmentally friendly [6]. Based on these problems, turbine material choice is one important thing that needs to be considered in designing a turbine. In this study, fiberglass material is used in developing wind turbines because it has a significant strength-to-weight ratio and is easily formed to contribute to high turbine efficiency [26]. This study highlights fiberglass's use in its application in the double-stage Savonius-Darrieus wind turbine for urban areas.

METHOD

Material

The turbine's design and manufacture with the dimensions, components, and materials have been prepared in the turbine preparation stage as specified in Table 1. Darrieus turbine in this study uses the NACA 0030, with variations in the pitch angle as shown in Figure 1, wherein each test of the pitch angle remains the same throughout the turbine rotation. This Darrieus turbine blade was chosen because it has the best performance based on its shape with no basin to increase the thrust [27]. Besides, based on Subramanian et al. [28], who examined the Darrieus turbine using CFD simulations, obtained that the best value of Cp and TSR was NACA 0030. In this case, a Savonius turbine with two semi-circular blades of the cross-section is used. The double-stage configuration of Savonius and Darrieus turbines is arranged parallel to the main axis, as shown in Figure 2. It aims to maximize experimental results by combining the advantages of each turbine while working. The use of fiberglass material in the manufacture of turbines is considered because it has the characteristics shown in Table 2. In this study, the type of fiberglass used is EGR-glass, which has an average value for properties that is better than other types. This type of fiberglass material is used to make the Savonius and Darrieus turbine blades. In making the Darrieus blade using fiberglass, the aerosol mixture ratio is 2:1, with the hand lay-up method [29].



(a) (b) (c) (d) (e) (f) (g)

Figure 1: Darrieus turbine blade pitch angle configuration (a) 0°, (b) 5°, (c) 10°, (d) 15°, (e) 20°, (f) 25°, and (g) 30°

Table 1: Specifications for the double-stage Savonius turbine

Specification	Information
Seat height	500 mm
Generator	100 watts
Main shaft diameter	120 mm
Rotor diameter	404 mm
Savonius blade diameter	300 mm
Darrieus blade diameter	404 mm
Savonius blade height	350 mm
Darrieus blade height	400 mm
Savonius blade number	2 pieces
Darrieus blade number	3 pieces
Blade material	Fiberglass
Mass of Savonius blade	150 grams/piece
Mass of Darrieus blade	250 grams/piece
Profile of NACA Darrieus	NACA 0030

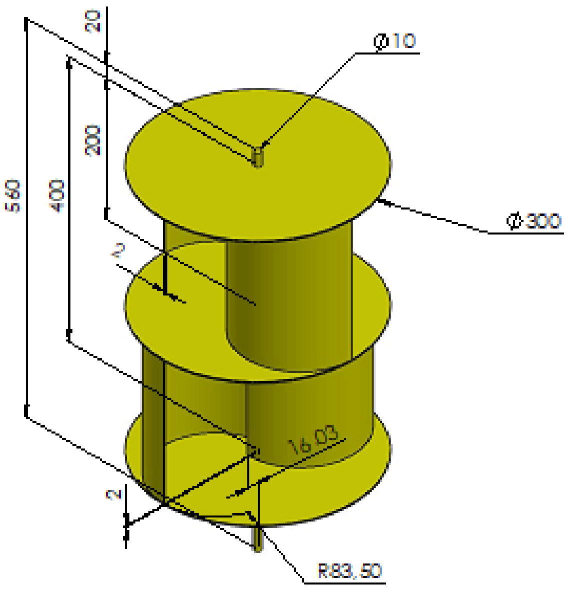


Figure 2: Double-stage Savonius turbine dimensions and configuration

Table 2: Physical and mechanical properties of fiberglass [30]

Fiber	Density (g/cm^3)	Tensile Strength (GPa)	Young's Modulus (GPa)	Elongation (%)	Coefficient of Thermal Expansion (10^{-7}/°C)	Poison's Ratio	Refractive Index
E-Glass	2.58	4.445	72.3	4.8	54	0.2	1.558
C-Glass	2.52	3.310	68.9	4.8	63	-	1.533
S2-Glass	2.46	4.890	86.9	5.7	16	0.22	1.521
A-Glass	2.44	3.310	68.9	4.8	73	-	1.538
D-Glass	2.11-2.14	2.415	51.7	4.6	25	-	1.465
R-Glass	2.54	4.135	85.5	4.8	33	-	1.546
EGR-Glass	2.72	3.445	80.3	4.8	59	-	1.579
AR-Glass	2.70	3.241	73.1	4.4	65	-	1.562

Equation Design

In this case, wind power is directly proportional to air density and wind speed cubic. The amount of wind power that passes through the turbine rotor is:

$$P_0 = \frac{1}{2}\rho A v^2 \tag{1}$$

The ratio between the mechanical power of the rotor and the mechanical power of the wind passing through the rotor, described as follows (27,35):

Experimental Set-Up

The research design used an experimental method by configuring a double-stage Savonius-Darrieus turbine. The activities carried out in this study include turbine preparation, testing equipment set-up, data collection, and data analysis. The turbine is placed at 2 meters in front of the blower because the uniform wind has been achieved in this position. The measurement of the uniformity of wind speed used a digital anemometer Krisbow SKU10176567 with an airflow velocity error of 3.5%. Measurements were made at nine surface points

$$Cp = \frac{P}{P_0} = \frac{T\omega}{\frac{1}{2}\rho A v^3} \times \frac{R\omega}{v} = C_m . \lambda \tag{2}$$

In addition, TSR is also needed to find out the specifications of the turbine. TSR is the ratio of rotor speed to wind speed. Wind speed will affect the rotational speed of the turbine rotor so that the power produced is highly dependent on the TSR, with the equation (27,35):

$$\lambda = \frac{R\omega}{v} = \frac{\pi D n}{v} \tag{3}$$

which were divided equally. The electrical voltage and current were measured using a multimeter with 0.7-2.8% error. Then the speed rotation was measured using a tachometer with a 0.05% error. Furthermore, the measurement equipment used in this study is shown in Table 3. This experimental set-up the turbine with 0°,5°,10°,15°,20°,25° and 30° blades and wind speeds at 1.5 m/s up to 5 m/s with 0.1 m/s intervals. The wind speed in this range was chosen because, at higher wind speeds, the turbine will experience a decrease in power, as in a study conducted by Pamungkas et al. [31]. Overall, the test steps in this study can be seen in Figure 3.

Table 3: Experimental tools

Device	Measurement Range	Error
Krisbow Digital Anemometer SKU10176567	0.4 - 20 m/s	3.5%
Krisbow Digital Tachometer SKUKW0600563	2 - 20,000 rpm	0.05%
Sanwa Digital Multimeter CD800a	DCV 400m/4/40/400/600V ACV 4/40/400/600V DCA 40m/400mA ACA 40m/400mA	0.7% 1.6% 2.2% 2.8%

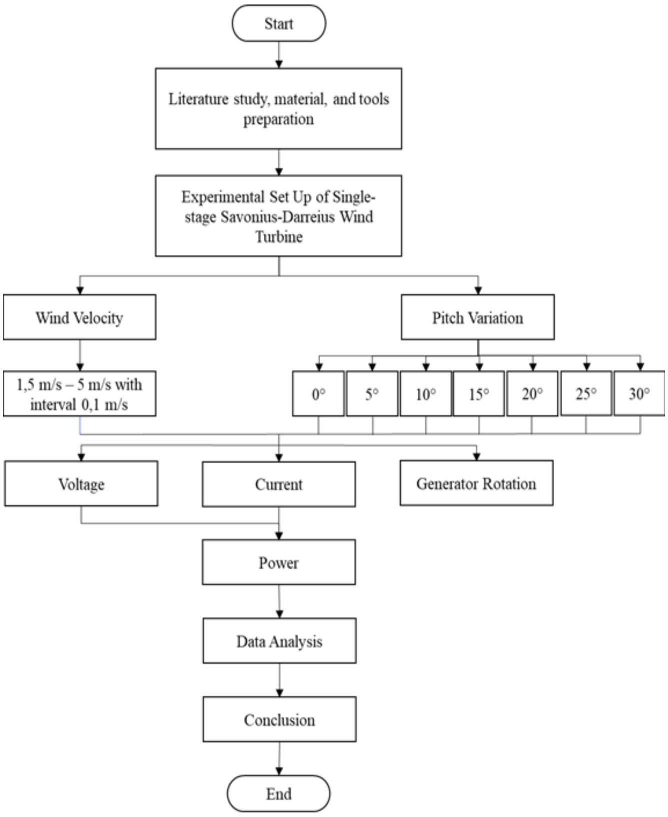
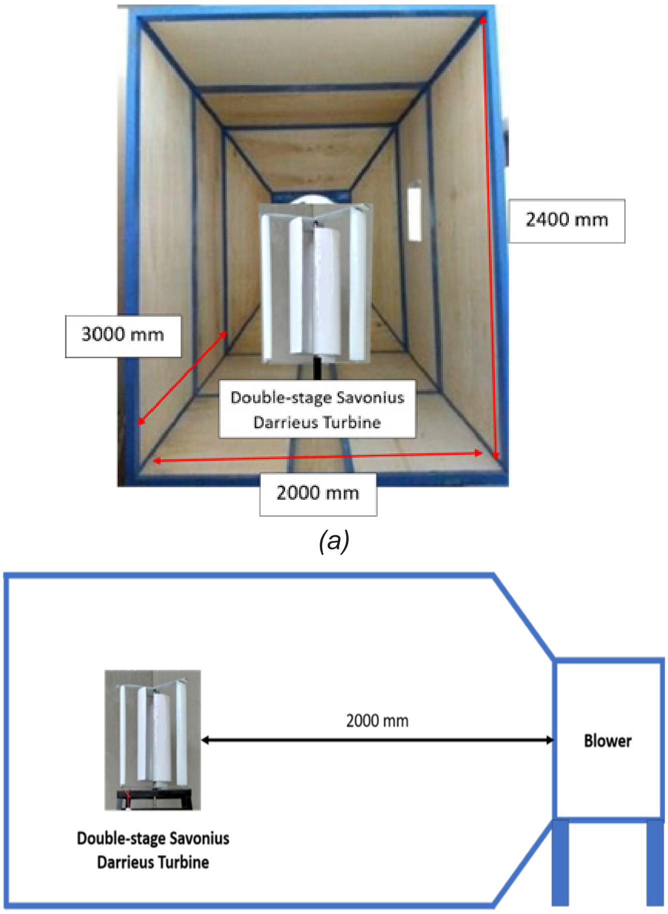


Figure 3: Research flow scheme

This experiment uses a wind tunnel to simulate wind speed conditions specified in the research design. The experimental specifications and set-ups in the wind tunnel are shown in Figure 4, using a blower with wind speeds from 0.1 m/s to 10 m/s.



(a)

(b)

Figure 4: (a) Specification and (b) Experimental set up of wind tunnel

RESULT AND DISCUSSION

Generator Rotation Speed

In all variations of the pitch angle in the double-stage Savonius-Darrieus turbine test, the generator has not been able to rotate at wind speeds of less than 2 m/s. The new turbine can produce rotations at wind speeds above 2 m/s at a pitch angle of 0°, which results in a generator speed of 32.86 rpm. At pitch angles of 5°, 10°, and 15°, the generator speed is 30.53 rpm, 33.76 rpm, and 30.26 rpm. While the variation of the 20° pitch angle just rotates at a wind speed of 2.5 m/s, which is 32.93 rpm, and variations in the pitch angle of 25° and 30° just produce a rotation at a wind speed of 3 m/s each of 33.81rpm and 34.16 rpm. Based on the data shown in Figure 5, it can be seen that an increase in wind speed affects the rotational speed of the generator produced.

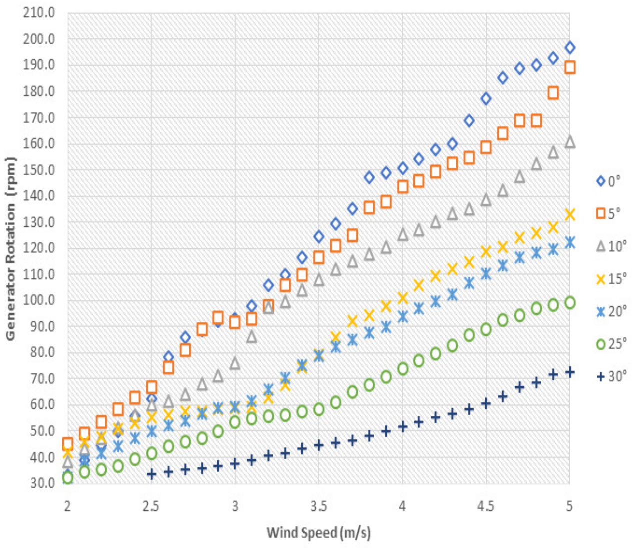


Figure 5: Relation of wind speed and double-stage Savonius-Darrieus turbine generator rotation

From Figure 5, it can be seen that the highest generator rotation speed is obtained at a wind speed of 5 m/s, where for the variation of the 0° pitch angle it is got 186.55 rpm, the 5° pitch angle is 178.77 rpm, the 10° pitch angle is equal to 160.1 rpm, 15° pitch angle of 123.9 rpm, 20° pitch angle of 96.36rpm, 25° pitch angle of 83.6 rpm, and 30° pitch angle of 69.8 rpm. In this case, the 0° pitch variation produces the highest generator rotation, 186.55 rpm. In addition, it can also be seen that with the increasing variety of the pitch angle, the resulting generator rotation has decreased.

Effect of Pitch Angle Variation on Electrical Power

Figure 6 shows that with each increasing variation in the pitch angle, the wind speed required for the generator to produce electric power also increases.

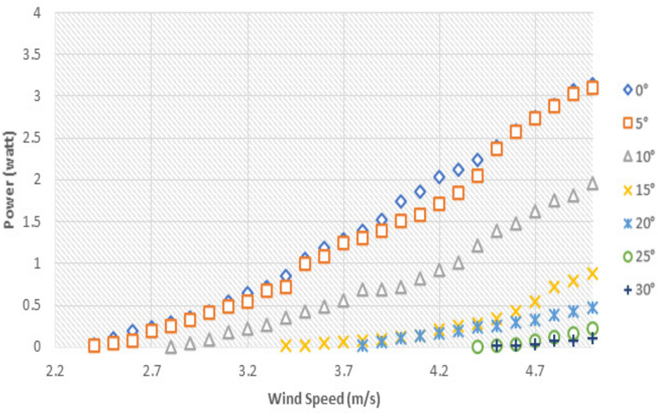


Figure 6: Relation of wind speed and double-stage Savonius-Darrieus turbine electric power

Based on figure 6, it can be seen that the highest electric power is generated by a variation of the pitch angle of 0° at a wind speed of 5 m/s, which is 3.14 watts. These data show that the addition of variations in the pitch angle of the Savonius-Darrieus double-stage turbine blades reduces the electrical power generated by the generator. It is also proportional to the large rotational speed produced by the generator experiencing the same phenomenon. The double-stage Savonius-Darrieus turbine works by exploiting the positive lift and drag forces of the wind. The data obtained show that the greater the pitch angle, the more lift and drag are acting on the turbine blades. The addition of the pitch angle on the Darrieus turbine blade aims to increase the area of the Darrieus turbine which is exposed to the wind, but what happens is the opposite where the addition of the pitch angle on the Darrieus turbine causes the braking force on the Savonius turbine because the wind received by the Savonius turbine blades is hampered. This resulted in the Savonius-Darrieus double-stage turbine blades using variations in the pitch angle to produce less electric power than without using variations in the pitch angle. The area of the Darrieus blade increases the drag force that occurs. The greater the drag force acting on the Darrieus blade causes increased pressure along the blade area. This makes the Savonius turbine blades even less to obtain maximum thrust. Therefore, the greater the pitch angle added to the Darrieus blade, the smaller the Savonius turbine blade gets the thrust which causes the resulting electrical power to be smaller. The variation without adding the pitch angle on the Darrieus turbine blade can produce the greatest positive drag force compared to the variation with the pitch angle's addition. It shows that the variation of pitch addition is less effective for double-stage Savonius-Darrieus turbine blades.

The Effect of Pitch Angle Variation on the Performance of Double-stage Savonius-Darrieus Turbine

The Savonius-Darrieus double-stage wind turbine's performance is indicated by the power coefficient (Cp) and the TSR (λ) value. The power coefficient states the turbine efficiency, which is the ratio of the actual power value generated with the turbine's ideal power. At the same time, TSR shows the ratio of the turbine rotor's rotational speed with wind speed. Based on equations 2 and 3, the Cp and TSR values can be seen in Figures 8 and 9. Figure 8 shows that the highest power coefficient value is obtained for the turbine without variations in the pitch angle at a wind speed of 5 m/s, 0.24. Along with the addition of variations in the pitch angle, the resulting power coefficient decreases. Figure 9 shows that the highest TSR value obtained for the turbine without variations in the pitch angle at the wind speed of 5 m/s is 0.75. From these data, it is known that the addition of variations in the pitch angle affects the TSR value, which is decreasing. In Table 5, the coefficient of power generated reduced as the pitch angle increases.

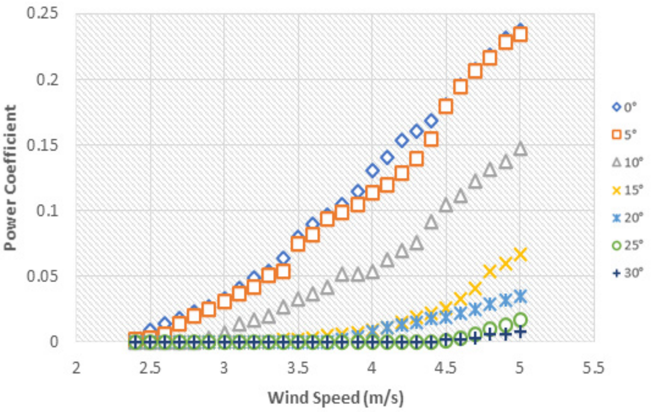


Figure 7: The relation of wind speed and power coefficient (Cp)

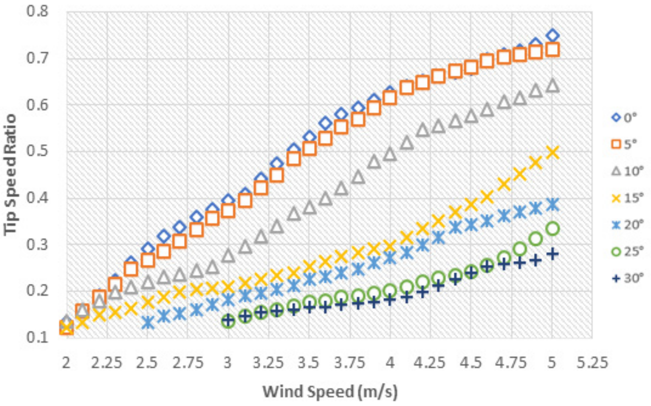


Figure 8: Relation of wind speed to Tip Speed Ratio (TSR)

Table 5: Pitch Angle effect on power coefficient

Pitch Angle					
5°	10°	15°	20°	25°	30°
-1.26 %	-40.92 %	-74.6 %	-87.34 %	-95.7 %	-97.7 %

The pitch angle also affects TSR, and Table 6 shows that TSR reduces as the pitch angle increases.

Table 6: Pitch Angle effect on TSR

Pitch Angle					
5°	10°	15°	20°	25°	30°
-4.04 %	-13.51 %	-33.78 %	-48.64 %	-55.40%	-62.16 %

The previous description shows that there is a relationship between the TSR value and the power coefficient of the Savonius-Darrieus double-stage wind turbine. The same with Palotta et al. [24], the hybrid configuration between the Savonius and Darrieus turbines can increase their performance by more than 20% for tip speed ratios below 1.5, which achieves an increase of up to 40% at λ = 0.7. As Fertahi et al. [32] explained, the hybrid turbine design has important power in the tip speed ratio being considered. Therefore, this device can be considered as a small-scale generating system.

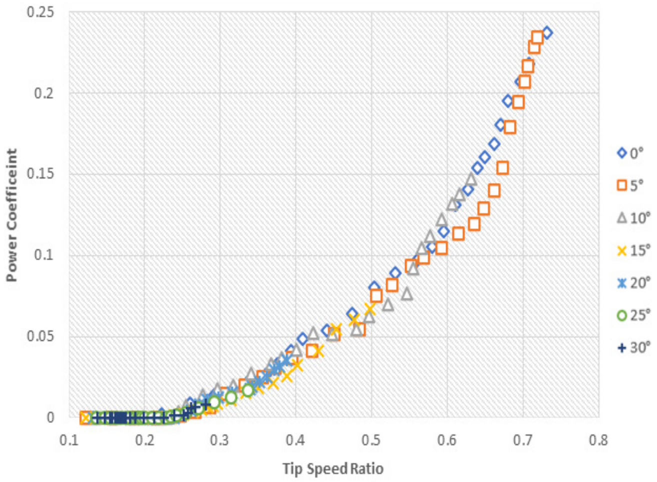


Figure 9: Relation of power coefficient (Cp) and Tip Speed Ratio (TSR)

Figure 10 above shows that the variation in the pitch angle of 5° at the wind speed of 5 m/s produces the highest Cp value of 0.24 or 24 % with a TSR value of 0.75. The power coefficient shows the wind energy amount converted from wind kinetic energy through the turbine rotor cross-section. Meanwhile, the TSR value shows the turbine rotor's ability to convert wind kinetic energy into mechanical energy for rotor rotation. The wind turbine's construction influences the power coefficient and TSR value, including the rotor design and dimensions. Besides, this is also influenced by wind speed, blade material, transmission system, and the type of generator used. The value of Cp and TSR generated from the Savonius-Darrieus double-stage wind turbine varies with each wind speed. This is influenced by wind kinetic energy, turbine blades' ability to convert wind kinetic energy into rotor mechanical power, generator speed, and rotor speed. This also correlates with the material used in the turbine blades. In this case, fiberglass is the material chosen because it has superior properties in its development.

CONCLUSION

Combining the two types of turbines between Savonius and Darrieus was carried out to overcome each type of turbine's shortcomings. In this case, fiberglass material is used to increase high turbine efficiency based on its properties. Based on the results of the research and discussion that has been previously described, the following conclusions can be drawn:

- Each increase in wind speed in the test range of 1.5-5 m/s can improve performance, such as the rated power, cut-in speed, power coefficient, and TSR of the Savonius-Darrieus double-stage turbine. The Savonius-Darrieus double-stage turbine without variation in pitch angle can produce the highest electric power, which is 3.14 Watt at a wind speed of 5 m/s.
- Adding this variation of the pitch angle can improve the cut-in speed's reliability on the Savonius-Darrieus double-stage wind turbine. The best cut-in speed value for the Savonius-Darrieus turbine was obtained at a 30° pitch variation of 3.8 m/s.
- Meanwhile, the optimal power coefficient value is produced by the Savonius-Darrieus double-stage turbine without variations in pitch angle. The highest power coefficient value of the Savonius-Darrieus double-stage turbine produced without variation in pitch angle is 0.24.
- In addition, the highest TSR value is also produced by the Savonius-Darrieus double-stage turbine without variation in pitch angle. The highest TSR value of the Savonius-Darrieus double-stage turbine produced without variation in pitch angle is 0.75.
- Based on the above, it can be seen that the addition of variations in the pitch angle of the Savonius-Darrieus double-stage turbine blades is ineffective because it reduces the electric power generated and the performance of the turbine. Although the resulting cut-in speed is better, a decrease in the value of electric power, power coefficient, and TSR is obtained for each additional variation of the applied pitch angle.

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