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Modification of the Vertical Axis with Variations in the Number of Blades of the Savonius Wind Turbine

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Abstract-- The potential wind speed in Indonesia is generally low at 3 m/s to 7 m/s, so this type of vertical axis turbine is considered very suitable for use in wind conditions in Indonesia. There are several types of vertical-axis wind turbines. One type of vertical axis wind turbine is the Savonius wind turbine. This type of wind turbine has many advantages, such as receiving wind from all directions, being easy and cheap to manufacture, and rotating at a relatively low angular speed. This test was carried out to determine the performance of conventional and modified Savonius turbines with 2 and 3 blades variables in each turbine blade shape. The modification is made by changing the shape of the blade twisting by 45o. The turbine is carried out on a laboratory scale with a wind source using a fan directly opposite the turbine. The results showed that the highest turbine power occurred in a modified 2-blade turbine, namely 1.88 Watt with a torque value of 0.04 Nm and a shaft rotation of 450 rpm. 2 modified blades also obtain the highest rotation value at a wind speed of 6 m/s producing 896 rpm. However, the highest torque value is obtained by a conventional 2-blade turbine with a value of 0.136 Nm. A modified two-blade turbine receives the highest efficiency in each turbine, with an efficiency value of 36.92%. In comparison, the highest turbine efficiency for a modified 3-blade turbine reaches 11.69%, considered less efficient than other turbines.

***Keywords*—Savonius, Wind Turbine, Blades, Modification, Vertical Axis**

I. Introduction

Various levels of society need electrical energy. A power generation system can generate this electrical energy. However, most of the fuel to generate electricity still uses fossil fuels which are non-renewable fuels. Besides the long-term impact of using fossil energy is global warming, alternative energy sources are needed [1, 2].

With the depletion of fossil energy reserves, we need to think about alternative energy sources. By considering renewable energy as an energy source [3]. Given the geographical conditions of Indonesia, which has natural resources with good potential for developing new renewable energy sources, one of which is wind [4-6].

Wind energy can be used as an energy source by using wind turbines. A wind turbine is a device used to convert kinetic energy into mechanical energy (torque and rotation), which will convert mechanical energy into electrical energy using a generator.

There are two types of wind turbines: vertical-axis wind turbines and horizontal-axis wind turbines. The potential for wind speed in Indonesia is generally low at 3 m/s to 7 m/s, so the vertical axis turbine type is considered very suitable for use in wind conditions in Indonesia [7]. There are several types of vertical-axis wind turbines. The Savonius wind turbine is a vertical-axis wind turbine [8].

Many advantages this type of wind turbine has, such as being able to receive wind from all directions, being accessible and cheap to manufacture, and can rotate at a relatively low angular speed. However, the standard design of the Savonius type still has low efficiency compared to other kinds of vertical-axis wind turbines [9, 10].

Several researchers have conducted experimental studies by modifying the standard design. The improvements started from changing the shape of the blades to adding several components, and several modifications were made to increase the angular speed and maximum torque that the Savonius turbine could produce. In this work [11], an experiment was carried out to determine the most effective operating parameters, and two blade rotors were more efficient. Research [12] discusses improving the performance of the Savonius turbine by optimizing the effect of different geometric parameters and by developing new designs, resulting in an increase in the performance coefficient of 27.3% compared to conventional rotors. This study discusses further studies to determine the effect of variations in the number of blades on the performance of the Savonius rotor wind turbine.

II. Fundamental Theory

A. *Wind Power*

The wind is the air that moves due to differences in pressure on the earth's surface. Wind moves from an area of high pressure to a place of lower pressure. The wind that blows on the earth's surface occurs due to differences in solar radiation receivers, resulting in differences in air temperature. The difference in temperature causes a pressure difference, eventually causing air movement [13].

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Wind energy can be converted by wind turbines depending on the turbine's cross-sectional area of the wind turbine. Wind power can be calculated using Equation 1 [14].

$$P_A = \frac{1}{2}\rho A v^3 \quad (1)$$

P_A is wind power (watt), ρ is air density (1,2 kg/m^3), A is turbine cross-sectional area(m^2), and v is airspeed (m/s).

B. Turbine Cross-sectional Area

The cross-sectional area of the turbine is the effective area of the wind turbine blade capable of receiving kinetic energy from the wind and converting it into mechanical energy [15]. For the Savonius type, the cross-sectional area of this turbine is expressed in Equation 2.

$$A = H \; x \; D \quad (2)$$

H is the height of the wind turbine, and *D* is the diameter of the wind turbine.

C. *Tip Speed Ratio*

Tip Speed Ratio (TSR) is the ratio of the tip speed of the rotor to the wind speed. The *TSR* value can be calculated by equation 3 [16].

$$TSR = \lambda = \frac{\omega r}{v} \quad (3)$$

v is the airspeed (m/s), *ω* is the angular velocity (rad/sec), and *r* is the turbine radius (m).

D. The Angular Velocity

The angular speed is the blade tip speed concerning one shaft rotation per second, shown in Equation 4.

$$\omega = \frac{2\pi n}{60} \quad (4)$$

ω is the angular speed (rad/s) and n is the rotor speed (rpm).

E. Turbine Power

Turbine power is the power generated by the turbine due to the wind hitting the blade so that the tip of the blade starts to move in a circle, as shown in Equation 5.

$$P_T = T\omega \quad (5)$$

P_T is the power generated by the turbine (watts), *T* is the torque (Nm), and *ω* is the angular velocity (rad/second).

F. Torque

The torque coefficient can be calculated using equation 6.

$$T = F \; x \; r = m \; x \; g \; x \; r \quad (6)$$

T is torque (Nm), *F* is force (N), *r* is the pulley radius (m), *m* is the loading mass (kg), and *g* is gravity (m/s^2).

G. Turbine Efficiency

Turbine efficiency can be calculated using equation 7.

$$\eta = \frac{P_T}{P_A} \text{ X } 100\% \quad (7)$$

η is efficiency (%), P_A is wind power (Watt), and P_T is turbine power (Watt).

H. Daya Generator

Generator power can be calculated by equation 8.

$$Pg = V \,.\, I \quad (8)$$

V is Voltage (Volt) and *I* is Current (Ampere)

I. Savonius Turbine

Wind turbines were first discovered in Finland by a Finnish scholar named Sigurd J. Savonius in 1922 and are S-shaped when viewed from above. This type of turbine generally moves slower than the horizontal axis wind turbine type but produces large torque. The turbine construction is straightforward, consisting of two half-cylinder blades. [17].

During its development, the Savonius turbine underwent many changes in the shape of the blades. One of the parameters that significantly affect the Savonius-type wind turbine's total performance is the blades' shape or design. In general, the forms that have been researched and used to date are:

Semi-circular (Semi-circular)

Figure 1. Semi-circular shape [18]

This is the most common and frequently used form. The construction is straightforward, only using a cylinder split in half and arranged according to the shape of the letter 'S [19].

Helical

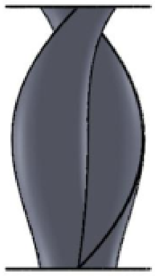

Figure 2. Helical bucket shape [18]

The spiral shape performs similarly to adding multiple stages to the rotor. The moment oscillation when operating using a helical rotor is significantly reduced. Based on research, the winding performance is not much different from the semi-circular profile performance [20].

Twisted

Figure 3. Twisted bucket shape

The rotor with bucket twist produces a more significant moment than the semi-circular profile bucket. [21], obtained a Cp value of 0.31 for a rotor with a bucket twist and 0.29 for a semi-circular. Below, plotting twist angle vs torque, we can note that the angle value that produces the highest torque is 45˚[22].

III. Research Methods

A. *Design Stage*

The design stage is a process for designing and designing the tools to be made. Making a design pattern for the devices is the first step to making it easier to develop tools according to the desired position and location. The test scheme can be seen as follows.

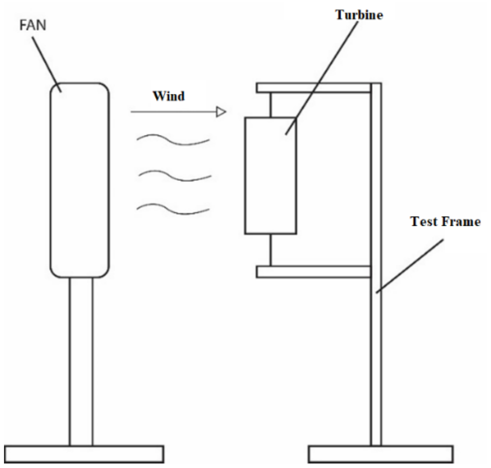

Figure 4. Test scheme

Judging from the test scheme above, it can be described in the Savonius turbine test as follows.

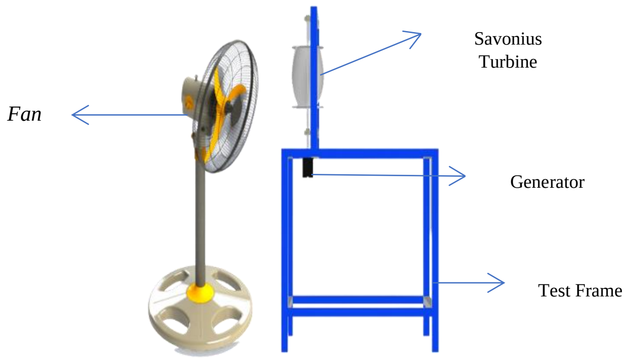

Figure 5. Testing image of savonius turbine with fan

B. *Test*

The testing steps, namely:

1. Prepare the necessary equipment
2. Ensure that the tools used are properly connected to each other
3. Ensure the turbine rotates properly
4. Ensure that the generator coupler is properly installed
5. Turn on the fan
6. Carry out the testing process
7. Vary the wind speed
8. Varying lamp load
9. Recording output data and other data
10. Repeat Steps 5-9 varying the turbine and lamp load
11. Testing completed

IV. Results and Discussion

In this study, tests were carried out to obtain the performance of the Savonius turbine with variations of the turbine blades of 2 conventional blades, two modified blades, three conventional blades, and three modified blades and modified savonius turbine with a torsion angle of 45°. Figure 6 is the process of testing the tool.

Figure 6. Tool testing

The wind speed used comes from a 50cm diameter fan by varying the wind speed of the turbine to be tested with wind speed 1, which is 4.2 m/s, wind speed 2 is 5.5 m/s, and wind speed 3 is 6 m/s. Fan placement can be seen in the test scheme with a position perpendicular to the turbine to be tested. Each turbine's electrical load testing variable uses 6 pcs 3-watt lamps, with a total lamp load of around 18 watts. In trying the Savonius wind turbine with turbine variations, several data collections were carried out to measure the performance of each turbine. The test results are obtained as follows.

Table 1. Test data

Turbine	Loading (G)	Shift Speed (Rpm)
2 Conventional Blades	0	833
	150	417
	235	241
	545	0
2 Modified Blades	0	896
	160	450
	295	211
	500	0
3 Conventional Blades	0	784
	160	212
	220	140
	405	0
3 Modified Blades	0	814
	150	152
	240	80
	375	0

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Table 2. Turbine test data with no-load generator

Turbine	Wind Velocity	Shift Speed (Rpm)	V (V)
2 Conventional Blades	1	364	27.1
	2	525	35.2
	3	604	40.8
2 Modified Blades	1	371	27.7
	2	532	36.6
	3	620	43.4
3 Conventional Blades	1	277	18.4
	2	369	27.6
	3	529	33.2
3 Modified Blades	1	242	16.2
	2	423	28.4
	3	519	36.3

Table 3. Test data for a conventional 2 blade turbine with a generator with a load of

Lamp Load (W)	Wind Velocity	Shift Speed (Rpm)	V (V)	I (mA)
3	1	186	7.9	8.3
	2	220	8.2	12.6
	3	248	8.4	17.5
6	1	186	7.7	9.3
	2	217	7.8	12.7
	3	240	7.9	17.1
9	1	184	7.7	8.4
	2	216	7.8	12.4
	3	244	7.9	16.7
12	1	186	7.7	7.8
	2	211	7.8	12.2
	3	238	7.8	16.4
15	1	181	7.7	7.5
	2	207	7.8	11.7
	3	237	7.8	16.2
18	1	179	7.6	7.4
	2	206	7.7	11.4
	3	233	7.8	15.7

Table 4. Test data for a modified 2 blade turbine with a generator with a load

Lamp Load (W)	Wind Velocity	Shift Speed (Rpm)	V (V)	I (mA)
3	1	182	8	7.1
	2	218	8.3	12.2
	3	246	8.5	16.2
6	1	176	7.8	6.5
	2	209	7.9	11.6
	3	243	8	16.7
9	1	174	7.7	5.4
	2	203	7.8	10.5
	3	236	7.9	15.4
12	1	171	7.7	5.1
	2	202	7.8	10.1
	3	236	7.9	14.6
15	1	167	7.6	4.9
	2	199	7.7	9.7
	3	233	7.8	13.7
18	1	165	7.6	4.5
	2	198	7.7	8.8
	3	227	7.8	13.2

Table 5. Test data for a conventional 3-blade turbine with a generator with a load

Lamp Load (W)	Wind Velocity	Shift Speed (Rpm)	V (V)	I (mA)
3	1	162	7.9	3.5
	2	189	8	6.7
	3	208	8.1	9.2
6	1	158	7.7	3.2
	2	182	7.8	6.5
	3	201	7.9	8.7
9	1	157	7.6	2.6
	2	176	7.7	6.6
	3	198	7.8	8.3
12	1	153	7.6	2.2
	2	176	7.7	6.4
	3	197	7.8	7.8
15	1	142	7.6	1.9
	2	171	7.6	6.2
	3	196	7.7	7.5
18	1	142	7.5	1.6
	2	168	7.6	5.9
	3	196	7.7	7.1

Table 6. Test data for a modified 3-blade turbine with a generator with a load

Lamp Load (W)	Wind Velocity	Shift Speed (Rpm)	V (V)	I (mA)
3	1	137	7.7	1.9
	2	164	7.9	5.4

	3	196	8.1	8.9
	1	133	7.5	1.8
6	2	164	7.7	5.3
	3	193	7.8	8.7
	1	131	7.5	1.7
9	2	162	7.6	5.1
	3	185	7.7	8.4
	1	130	7.5	1.7
12	2	158	7.6	4.7
	3	180	7.7	8.3
	1	127	7.4	1.6
15	2	158	7.6	4.6
	3	180	7.6	7.9
	1	127	7.4	1.5
18	2	155	7.5	4.6
	3	177	7.6	7.9

The wind power generated by the fan at the wind speed variation of the turbine under test is:

1. Wind speed 1
   $\rho = 1{,}2\ kg/m^3$
   $A = 0{,}0375\ m^2$
   $v = 4{,}2$ m/s
   $P_A = \frac{1}{2}\rho A v^3$
   $P_A = \frac{1}{2} 1{,}2\ x\ 0{,}0375\ x\ 4{,}2^3 = 1{,}743$ watt
2. Wind speed 2
   $\rho = 1{,}2\ kg/m^3$
   $A = 0{,}0375\ m^2$
   $v = 5{,}5$ m/s
   $P_A = \frac{1}{2}\rho A v^3$
   $P_A = \frac{1}{2} 1{,}2\ x\ 0{,}0375\ x\ 5{,}5^3 = 3.915$ watt
3. Wind speed 3
   $\rho = 1{,}2\ kg/m^3$
   $A = 0{,}0375\ m^2$
   $v = 6$ m/s
   $P_A = \frac{1}{2}\rho A v^3$
   $P_A = \frac{1}{2} 1{,}2\ x\ 0{,}0375\ x\ 6^3 = 5.083$ watt

To get the cross-sectional area of the turbine can be done as follows:

$A = H\ x\ D$
$= 0{,}25$ x $0{,}15$
$= 0{,}0375$ m

The angular velocity of the turbine is:

$\omega = \frac{2\pi n}{60}$
$\omega = \frac{2\ x\ \pi\ x\ 241}{60}$
$= 25{,}2$ rad/s

The TSR values are:

$\lambda = \frac{\omega R}{v}$
$\lambda = \frac{25{,}2\ x\ 0{,}075}{6}$
$= 0{,}315$

Torque value as follows:

$T = m.g.r$
$= 0{,}235$ x $9{,}8$ x $0{,}0254$
$= 0{,}0584$ Nm

The turbine power rating is as follows:

$P_{turbine} = T\omega$
$= 0{,}0584$ x $25{,}2$
$= 1{,}471$ watt

The turbine efficiency values are as follows:

$\eta = \frac{P_T}{P_A}\ x\ 100\%$
$= \frac{1{,}471}{5{,}083}\ x100\%$
$= 29\ \%$

The rated power of the generator is as follows:

$P_g = V\ x\ I$
$= 8{,}4$ x $17{,}5$
$= 147$ mw

After getting the results of data analysis, the table of the results of data analysis in table 7-10 is obtained as follows:

Table 7. Results of no-load data analysis without generator

Turbine	Load (g)	n (RPM)	T (Nm)	P_{wind} (watt)	$P_{turbine}$ (watt)	η (%)
2 Conventional Blades	0	833	0	5.083	0	0
	150	417	0.037	5.083	1.63	32.08
	235	241	0.058	5.083	1.48	29.04
	545	0	0.136	5.083	0	0
2 Modified Blades	0	896	0	5.083	0	0
	160	450	0.040	5.083	1.88	36.92
	295	211	0.073	5.083	1.62	31.92
	500	0	0.124	5.083	0	0
3 Conventional Blades	0	784	0	5.083	0	0
	160	212	0.040	5.083	0.88	17.39
	220	140	0.055	5.083	0.80	15.79
	405	0	0.101	5.083	0	0
3 Modified Blades	0	814	0	5.083	0	0
	150	152	0.037	5.083	0.59	11.69
	240	80	0.060	5.083	0.50	9.85
	375	0	0.093	5.083	0	0

Table 8. Results of data analysis of a conventional 2 blade turbine with a generator with a load

Load (W)	n_{wind} (m/s)	n_{shaft} (RPM)	V (V)	I (A)	P (Watt)
	1	186	7.9	8.3	65.57
3	2	220	8.2	12.6	103.32
	3	248	8.4	17.5	147
6	1	186	7.7	9.3	71.61

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	2	217	7.8	12.7	99.06
	3	240	7.9	17.1	135.09
9	1	184	7.7	8.4	64.68
	2	216	7.8	12.4	96.72
	3	244	7.9	16.7	131.93
12	1	186	7.7	7.8	60.06
	2	211	7.8	12.2	95.16
	3	238	7.8	16.4	127.92
15	1	181	7.7	7.5	57.75
	2	207	7.8	11.7	91.26
	3	237	7.8	16.2	126.36
18	1	179	7.6	7.4	56.24
	2	206	7.7	11.4	87.78
	3	233	7.8	15.7	122.46

Table 9. Results of data analysis of a modified 2 blade turbine with a generator with a load

Load (W)	n_{wind} (m/s)	n_{shaft} (RPM)	V (V)	I (A)	P (Watt)
3	1	182	8	7.1	56.8
	2	218	8.3	12.2	101.26
	3	246	8.5	16.2	137.7
6	1	176	7.8	6.5	50.7
	2	209	7.9	11.6	91.64
	3	243	8	16.7	133.6
9	1	174	7.7	5.4	41.58
	2	203	7.8	10.5	81.9
	3	236	7.9	15.4	121.66
12	1	171	7.7	5.1	39.27
	2	202	7.8	10.1	78.78
	3	236	7.9	14.6	115.34
15	1	167	7.6	4.9	37.24
	2	199	7.7	9.7	74.69
	3	233	7.8	13.7	106.86
18	1	165	7.6	4.5	34.2
	2	198	7.7	8.8	67.76
	3	227	7.8	13.2	102.96

Table 10. Results of data analysis of a conventional 3-blade turbine with a generator with a load of

Load (W)	n_{wind} (m/s)	n_{shaft} (RPM)	V (V)	I (A)	P (Watt)
3	1	162	7.9	3.5	27.65
	2	189	8	6.7	53.6
	3	208	8.1	9.2	74.52
6	1	158	7.7	3.2	24.64
	2	182	7.8	6.5	50.7
	3	201	7.9	8.7	68.73
9	1	157	7.6	2.6	19.76
	2	176	7.7	6.6	50.82
	3	198	7.8	8.3	64.74
12	1	153	7.6	2.2	16.72
	2	176	7.7	6.4	49.28
	3	197	7.8	7.8	60.84
15	1	142	7.6	1.9	14.44
	2	171	7.6	6.2	47.12
	3	196	7.7	7.5	57.75
18	1	142	7.5	1.6	12
	2	168	7.6	5.9	44.84
	3	196	7.7	7.1	54.67

Table 11. Results of data analysis of a modified 3-blade turbine with a generator with a load

Load (W)	n_{wind} (m/s)	n_{shaft} (RPM)	V (V)	I (A)	P (Watt)
3	1	137	7.7	1.9	14.63
	2	164	7.9	5.4	42.66
	3	196	8.1	8.9	72.09
6	1	133	7.5	1.8	13.5
	2	164	7.7	5.3	40.81
	3	193	7.8	8.7	67.86
9	1	131	7.5	1.7	12.75
	2	162	7.6	5.1	38.76
	3	185	7.7	8.4	64.68
12	1	130	7.5	1.7	12.75
	2	158	7.6	4.7	35.72
	3	180	7.7	8.3	63.91
15	1	127	7.4	1.6	11.84
	2	158	7.6	4.6	34.96
	3	180	7.6	7.9	60.04
18	1	127	7.4	1.5	11.1
	2	155	7.5	4.6	34.5
	3	177	7.6	7.9	60.04

Figure 7 is a graph of the relationship between shaft rotation and torque with variations in turbine blades. Based on the chart above, it can be seen that the modified two-blade turbine has the highest shaft speed of 450 rpm while the modified three-blade turbine has the lowest shaft speed among other turbines with the highest speed obtained, namely 152 rpm with the same wind speed value.

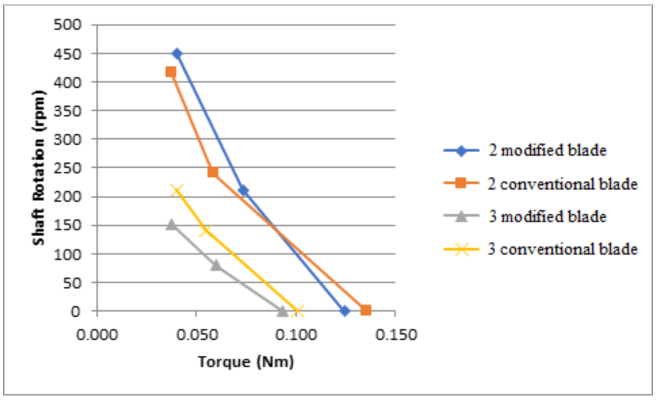

Figure 7. Graph of the relationship between shaft rotation and torque with turbine blade variations

This is due to the addition of the number of blades which significantly reduces the value of the angular position for the advancing bucket, where the rotor moment is lower, because of the possibility of the bucket (blades) being in an excellent position to extract the momentum of the airflow to increase. The conventional 2-blade turbine has the highest torque value of 0.136 Nm, while the modified 3-blade turbine has the lowest torque value of 0.093 Nm with the same wind speed value. The increase in the angle of twisting causes this. The energy captured by the bottom of the turbine increases drastically compared to the top, and the impact is a reduction in the torque value.

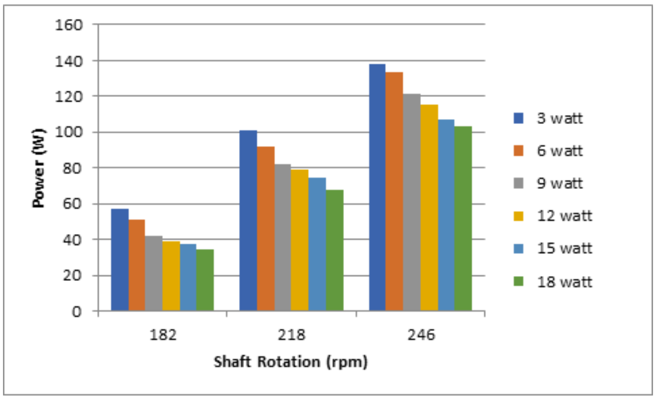

Figure 8. Graph of the relationship of electric power to shaft speed with variations in load on a modified 2-blade savonius wind turbine

Figure 8 shows the relationship between shaft rotation and electric power with load variations. Based on the chart above, it can be seen that the largest electric power generated is 137.7 mW with a shaft speed of 246 rpm at a wind speed of 6 m/s, while the lowest electric power generated is 34.2 mW with a shaft speed of 165 rpm at the lowest wind speed of 4.2 m/s. This is because the shaft speed decreases with the increasing load applied and increases with increasing wind speed.

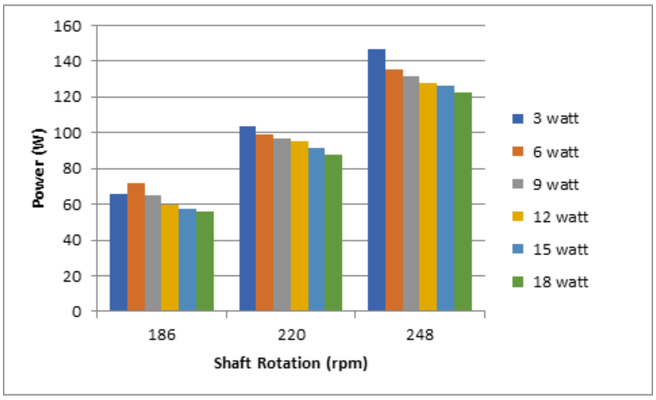

Figure 9. Graph of the relationship of electric power to shaft speed with variations in load on a conventional 2-blade savonius wind turbine

Figure 9 shows the relationship between shaft rotation and electric power with load variations. Based on the chart above, it can be seen that the largest electric power is generated at a load of 3 Watt, namely 147 mW, shaft speed is 248 rpm with a wind speed of 6 m/s while the lowest electric power is generated at 18 Watt load 56.24 mW, shaft speed is 179 rpm with a speed of 179 rpm. The most downwind is 4.2 m/s. This is because the shaft speed decreases with the increasing load applied and increases with increasing wind speed.

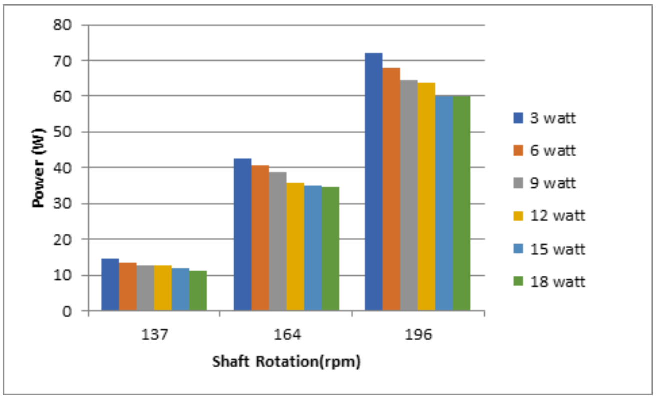

Figure 10. Graph of the relationship of electric power to shaft speed with variations in load on a modified 3 blade savonius wind turbine

Figure 10 shows the relationship between shaft rotation and electrical power with load variations. Based on the chart above, it can be seen that the largest electric power is generated at a load of 3 Watt, namely 72.09 mW, shaft speed is 196 rpm with a wind speed of 6 m/s while the lowest electric power is generated at a load of 18 Watt 11.1 mW, shaft speed 127 rpm. With the lowest wind speed of 4.2 m/s. This is because the shaft speed decreases with the increasing load applied and increases with increasing wind speed.

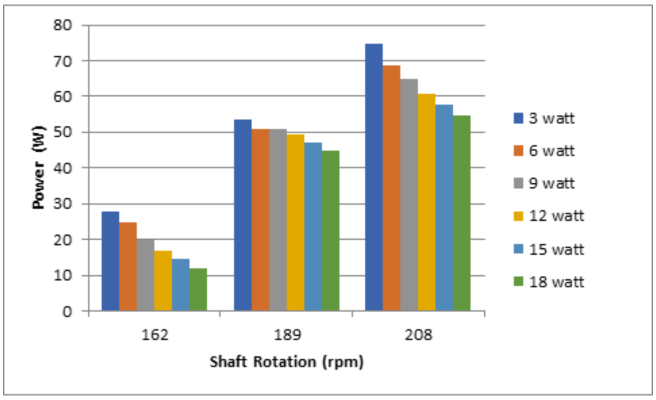

Figure 11. Graph of the relationship of electric power to shaft speed with variations in load on a conventional 3-blade Savonius wind turbine

The picture shows the relationship between shaft rotation and electrical power with load variations. Based on the chart above, it can be seen that the largest electric power is generated at a load of 3 Watt, namely 74.52 mW, the shaft speed is 208 rpm with a wind speed of 6 m/s. In comparison, the lowest electric power is generated at a load of 18 Watt 12 mW. The shaft speed is 142 rpm, with a rate of the most downwind is 4.2 m/s. This is because the shaft speed decreases with the increasing load applied and increases with increasing wind speed.

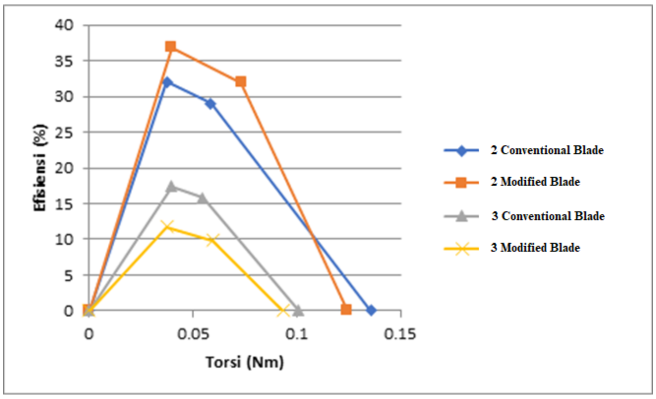

Figure 12. Graph of the relationship between efficiency and tordque with variations in wind turbine blades

The picture is a graph of the relationship between efficiency and torque. Based on the chart above, it can be seen that the initial torque value is the highest on the modified two-blade turbine, but in the end, the conventional two-blade turbine remains higher. The highest efficiency value is two modified blades with an efficiency value of 36.92%, and the lowest is three modified blades with an efficiency value of 9.85%.

V. Conclusion

Based on the results of the research on the design of the two-blade wind turbine rotor made, the turbine with the highest efficiency value, namely two modified blades, reached 36.92% with a torque value of 0.040 Nm and a shaft rotation of 450 rpm at a wind speed of 6 m/s and a loading of 160 g. The turbine power generated under these conditions is 1.88 mW. In comparison, the efficiency of the modified 3-blade turbine only reaches 11.69% with a torque value of 0.037 Nm and a shaft rotation of 152 rpm at the same wind speed with a loading of 150 g and turbine power generated is 0.59 mW.

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