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Study of Vertical Axis Wind Turbine for Energy Harvester in A Fishing Boat

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Abstract. The wind speed in the southern beach of West Java Indonesia is quite promising for wind energy harvesting. A field survey reported that the wind speed reached 10 m/s, while the average recorded in a year is about 4.7 m/s. In this study, two vertical axis wind turbines (VAWT) were compared to be used in that area through calculation as well as experiments. The experiments measured that the turbines can produce about 7.82W and 2.33W of electricity respectively. These experiments are compared with theoretical calculation to obtain the performance of both turbines used. The coefficient of performance (cp) experimentally is 0.09 for Turbine 1 (hybrid Savonius-Darrieus rotor) and 0.14 for Turbine 2 (Savonius rotor). While, rotor's mechanical performance Cpr, obtained theoritically through calculation, is 0.36 for Turbine 1 and 0.12 for Turbine 2. These results are analysed from mechanical and electrical view.

1. Introduction

Rancabuaya village, Garut, West Java, is a village located in the coastal area. Based on the survey that we had conducted, the majority of people there work as fishermen. During the sail, fishermen need electricity to support their activities. For example, for lighting and storing the fishes in refrigerator. Nowadays, fishermen using diesel fuel, which is a contributor to air pollution. Hence, the supply of electrical energy using renewable resources is a solution that can be offered. Solar panels and wind turbines will be used to harvest energy. Rancabuaya beach itself has a high potential of solar and wind energy. The daily average wind velocity is 4.27 m/s and the sun irradiation is 672 W/m^2 [1]. This paper focused on the study of wind turbine performance on the boat, which will be reviewed in September, as the fishing season is in September. The wind turbines used are Vertical Axis Wind Turbine. Turbine 1 uses hybrid Savonius-Darrieus rotor, while Turbine 2 uses Savonius rotor. Both will be compared aerodynamically and electronically, based on the electricity produced on application and on theory.

2. Experimental

2.1. Wind turbine testing

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Wind turbines brand Mars Rock with models VAWT-VA300W1224-A type hybrid Savonius-Darrieus would later be called as **Turbine 1** and model VAWT-VA300W1224-S type helix Savonius would later be called as **Turbine 2**. Both turbines used has a maximum power of 300 W and can start to rotate at a wind speed of 1.3 m/s. Maximum power is obtained at an average wind speed of 10 m/s.

2.1.1. Mechanical power
Mechanical power carried by the wind at a certain speed is expressed by the following equation [2].

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

At a height of 50 m, data that was collected by NASA satellite [1] shows the average wind speed in September on the Rancabuaya beach is 5.91 m/s. By using the speed comparative law by altitude [3]:

$$\frac{U(z)}{U(z_r)} = \left(\frac{z}{z_r}\right)^{\alpha} \tag{2}$$

$U(z)$: wind speed (m/s)
$U(z_r)$: reference wind speed (m/s)
z : height (m)
z_r : reference height (m)
α : surface roughness
Where:

$$\alpha = \frac{1}{ln\frac{z}{z_0}} \tag{3}$$

z_0 : surface roughness parameter
Z_0 value depends on the roughness of the surface where wind turbines are installed. For water surface, z_0 value is 0.0001.

Hence, the wind speed at a height of 2 m (target altitude of wind turbine installation on the boat) can be calculated. By comparing the speeds at a height of 50 m, average wind speed obtained at a height of 2 m is 4.27 m/s. On experiment using wind tunnel, the value that approaches the speed of 4.27 m/s is 4.6 m/s. Values of air density ρ depends on the air temperature at the time. The average air temperature at Rancabuaya beach at a height of 2 m is 24.3°C. By interpolation of the air density data at a temperature of 20°C and 25°C, obtained ρ = 1.22 kg/m^3. Using equation (1), the comparison of mechanical power between Turbines 1 and 2 is shown in **Table 1**.

Table 1. Mechanical Power by Wind for Both Turbines.

	Turbine 1 (W)	Turbine 2 (W)
Area = A (m^2) (Approached as triangle, a = 1 m, and t = 0.75 m)	A_1 = 0.375	A_2 = (0.75)(0.4) = 0.3
Mechanical Power = P (W)	22.27	17.81

2.1.2. Electrical power measured
Voltage and current measurement results are obtained from the sensors that are connected to the Arduino microcontroller. In this calculation, the measured power is calculated by the equation $P = VI$, in units of Watts, as shown in the **Table 2**.

Table 2. Electrical Power Measured from both Turbines.

	Turbine 1 (W)	Turbine 2 (W)
Wind Speed (m/s)	4.6	4.6
Voltage (V)	4.34	7.00
Current (A)	0.48	0.40
Power (W)	2.06	2.83

Figure 1. Wind Turbine Testing Using Wind Tunnel.

3. Results and Discussion

The tests aim to determine the performance of each wind turbine for each wind speed. This performance is shown by two coefficients: Cp (coefficient of performance) and Cpr (coefficient of rotor performance).

$$c_p = P_{measured}/P_{max} \quad (4)$$

$$c_{pR} = P_{rotor}/P_{max} \quad (5)$$

The graphs in Figure 2-7 are the test results that demonstrate the performance of each wind turbine, compared to TSR. TSR stands for Tip Speed Ratio, and is a comparison of angular velocity of rotor to wind velocity. TSR value will determine whether a wind turbine has reached a self-start condition or not. Self-start is a condition where the rotor has accelerated to a steady condition, where it produces significant amount of power [4]. Self-start happens when TSR > 1.

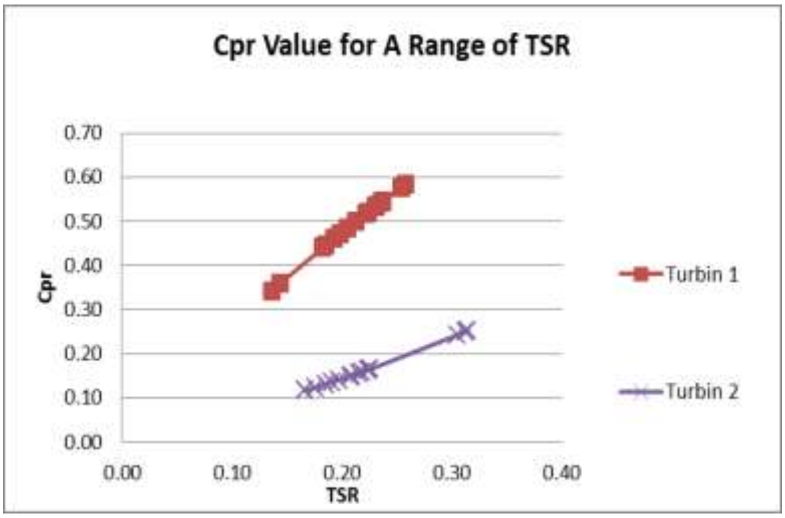

Figure 2. Relation of Cpr over TSR for Both Turbine.

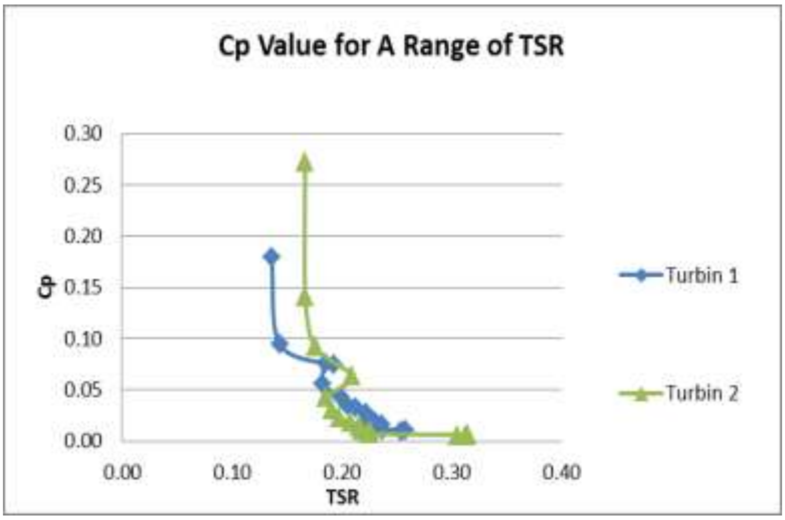

Figure 3. Relation of Cp over TSR for Both Turbine.

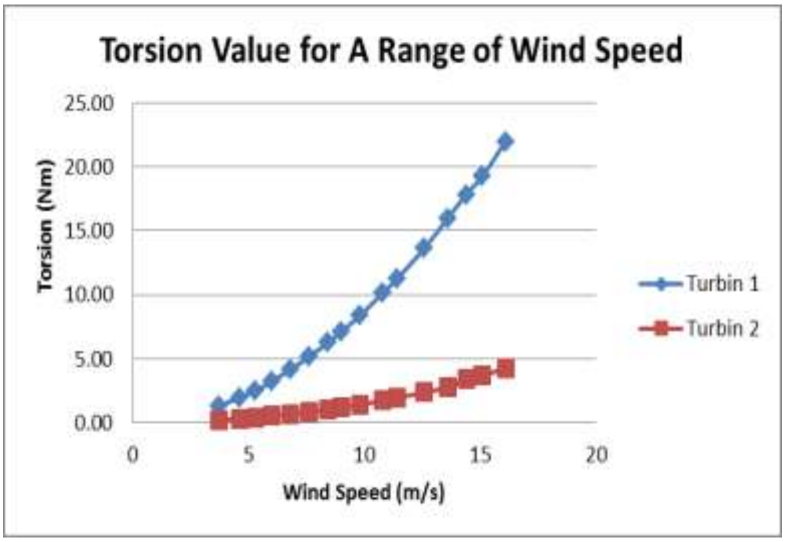

Figure 4. Relation of Torque over Angular Velocity for both Turbine.

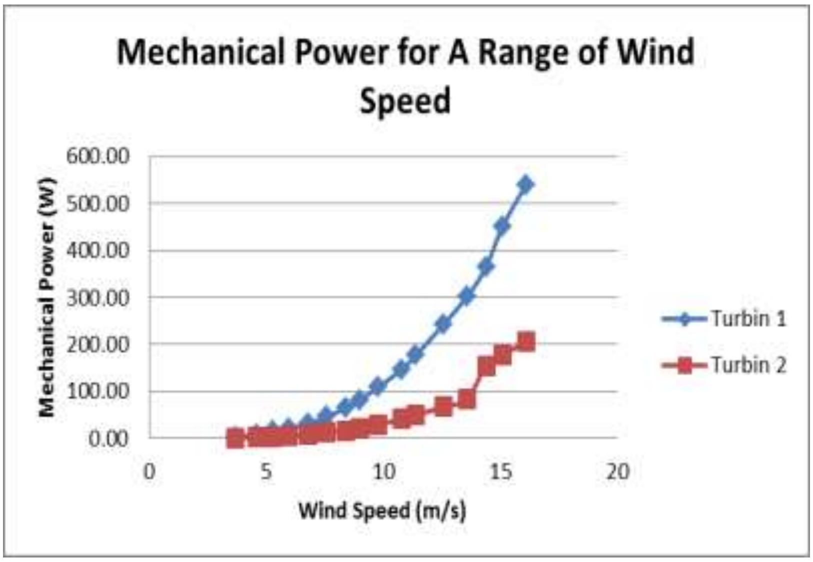

Figure 5. Relationship of Mechanical Power over Anguar Velocity for both Turbine.

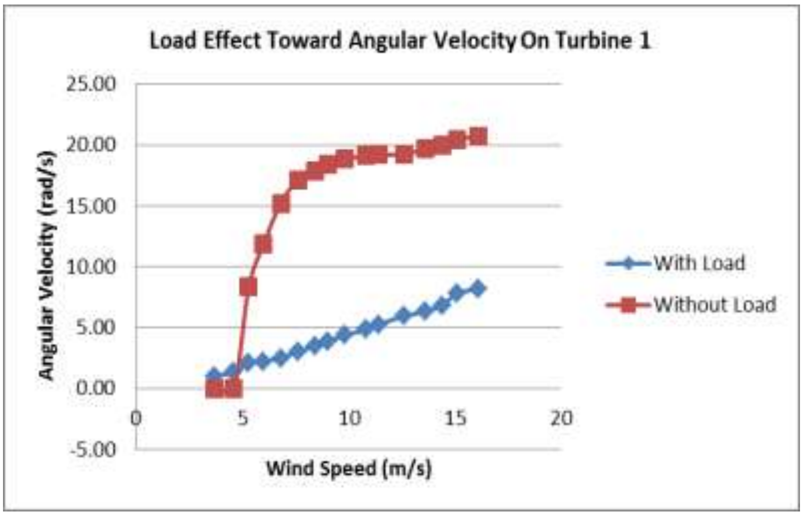

Figure 6. Effect of Loading to Angular Velocity for Turbine 1.

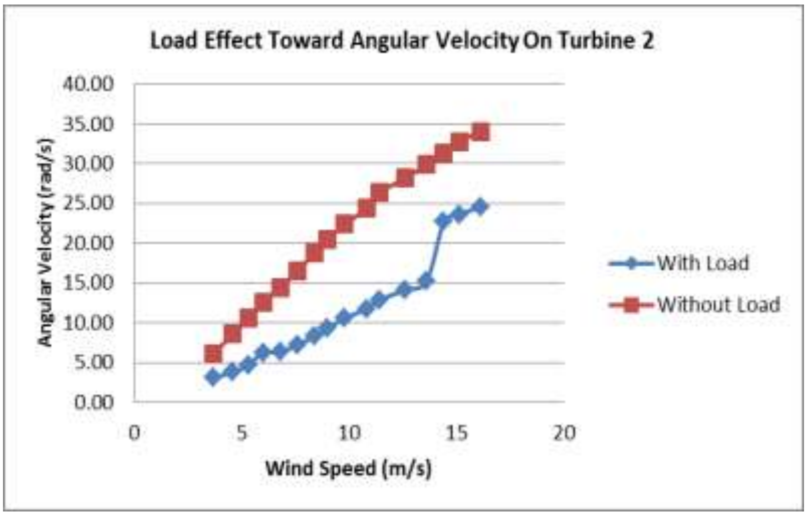

Figure 7. Effect of Loading to Angular Velocity for Turbine 2.

The output power obtained is only ± 2W at wind speeds of 4.6 m/s for each wind turbine. According to the calculations, the range of TSR on Turbine 1 is only on the range of values 0.14 – 0.25 and on the value of 0.17 – 0.31 for Turbine 2. We can conclude that both turbines fail to reach the self-start condition. This failure will be analyzed from the view of aerodynamics of rotor and effect of electrical loading.

3.1. Wind turbine aerodynamics performance
To understand the aerodynamic conditions of rotor as spinning objects, the force, direction, and speed that works on it need to be reviewed. Figure 8 depicts these parameters.

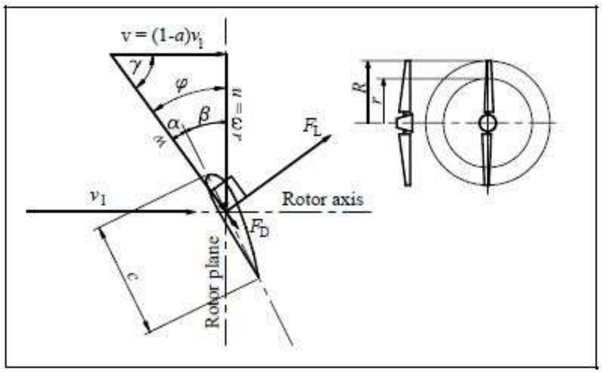

Figure 8. Vector of Direction, Speed, and Force Worked on One Blade [5].

Based on Figure 8, the force that drives the rotor to keep spinning is FL, the lift force. Lift Force themselves is perpendicular to the drag force FD. Both of these force contribute to the magnitude of the resultant torque, as described in **Figure 9**.

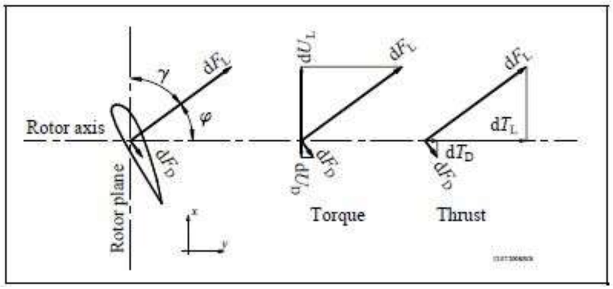

Figure 9. Vector of Force Worked on Blade Element [5].

On the x-axis and y-axis, which is the rotor axis and rotor field, there are two vector forces work. From these two forces, the one contributes to generate torque is dU. Where [5]:

$$T = F\ x\ r \tag{6}$$

T : torsion (Nm)
F : tangential force (N)
r : force arm (m)
Because of the lift force and drag force, the force components dU are also divided into dUd and dUl. Then the resultant force becomes dU. Thus, the components of this force will become maximum when the lift force is maximum and drag force is minimum. Value of dU will be integrated, with each element gives the overall force U. Maximum force U will provide the maximum torque value to produce maximum mechanical rotor power. Mechanical rotor power itself is given by the equation

$$P_{rotor} = T\omega, \tag{7}$$

where ω is the angular speed of the rotor. If the rotor consist of B blades, the power equation becomes

$$P_{rotor} = BT\omega. \tag{8}$$

Thus, to maximize the rotor power, parameters that need to be reviewed is the torque and angular speed.

Based on the data shown in Figure 2 and 3, it is found that Cp value of Turbine 2 is greater than the Turbine 1. While, the Cpr value of Turbine 1 is greater than 2. This means, aerodynamically, (in theory) Turbine 1 shows a better performance than the turbine 2. This is supported by the fact that Turbine 1 has more blades and larger cross-sectional area, so the wind power harvested is higher. Meanwhile, Cp comparison shows that the performance of Turbine 2 is better than the Turbine 1. This is because both turbines failed to reach self-start.Tthe maximum power that can be obtained by Turbine 1 in theory is higher than Turbine 2 because of larger cross-sectional area; while in practice, both turbine produce the same amount of power. Hence, Cp of Turbine 1 is lower than Turbine 2.

Based on Figure 4 and 5, it can be seen that Turbine 1 produce torque and rotor power that are higher than Turbines 2 at the same wind speed. It means that Turbine 1 has resultant force U larger than Turbine 2. This is caused by the design and the number of blades of each turbine.

Turbine 1, Darrieus-type blades, generate lift force greater than Turbine 2, Savonius type. Darrieus-blades type are generally designed to have a certain angle which gives a bigger lift force so that the maximum torque is greater than the Savonius-blades type.

Turbine 2 generate lift force smaller (or smaller resultant force U), because the shape of the blade is like a spoon. When the concave side faces the direction of the wind, the blades provide a drag force that blocks the rotor rotation. At the same time, the convex side that is also facing the direction of the wind generate lift force that push the rotor to keep rotating. Because these two forces work together, the resultant force of the two forces is small, so that the torque and mechanical power generated is also small. It is also shown by the value of Cpr of Turbine 2 which is much smaller than the first turbine, especially at higher speeds.

3.2. Effect of electrical loading

As already mentioned, the low output power produced by both turbine is because of failure to reach the self-start. This failure can also be caused by the load experienced by the rotor's generator and the electrical load that was connected to the rotor. In this case, the load of the electricity used is 12 V 35 Ah battery, charge controller, and 180 W refrigerator. These loads give significant effect on inhibiting the rotor rotation, as shown in Figure 6 and Figure 7.

It is found that the angular velocity ratio of Turbine 1 and Turbine 2 are not in accordance with the theory of the rotor. Turbine 1 should give a higher speed than the Turbine 2, because theoretically it gives a higher lift force. This can be caused by several things. Turbine 1, which is a hybrid type failed to achieve self-start even with the help of Savonius type rotor. In fact, this Savonius rotor may also act as a load to the rotation of the Turbine 1's rotor, because two rotors are connected by the same hub to the generator. Because the self-start condition has not been reached, the lift force generated by Darrieus rotor can not balance the loads that it receives and cause the rotor angular velocity lower.

Other causes which give effect to the failure of the self-start is the generator that does not function as it should. In other words, it has low level of efficiency.

4. Conclusion

Hybrid type wind turbine, Darrieus-Savonius (Turbine 1) and Savonius type (turbine 2) used in this study showed a low performance. Indicated by the overall performance Cp which is 0.09 for Turbine 1 and 0.14 for Turbine 2. While, rotor's mechanical performance Cpr is 0.36 for Turbine 1 and 0.12 for Turbine 2. The value Cp and Cpr is at wind speeds of 4.6 m/s. For higher wind speeds, it is obtained that the both coefficient value had declined.

Based on these values, in theory, Turbine 1 produced mechanical power greater than turbine 2. Meanwhile, if it observed from its overall performance, Turbine 2 showed a better performance.

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