The effect of axial distance on dual rotor wind turbine’s performance

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Abstract. Dual-rotor wind turbine (DRWT) is the development of wind turbine design with the addition of rotors placed on the same shaft. The addition of rotors causes the turbine to improve its performance. Experimental research was conducted to determine the performance that can be achieved by the DRWT type using the wind tunnel module. The test was carried out on three variations of the axial distance ratio of 0.08; 0.12; and 0.16. Comparing with a single-rotor wind turbine (SRWT), the DRWT type gives better performance. The DRWT type can rotate at a lower tip speed ratio than SRWT type. The power generated by the DRWT type is increasing up to 100% at tip speed ratio of 0.08 in all axial distance ratio while SRWT type can not rotate at tip speed ratio of 0.8. The DRWT type with a ratio of 0.12 is able to reach the highest coefficient of power which is 0.35 at tip speed ratio of 1.2. There was an increment of 53.7% in mechanical power from the SRWT type under the same conditions. Furthermore, the numerical method was used to know the flow phenomenon in the two rotors. The wake flow behind the first rotor causes backflow that give a loss to DRWT’s performance but still has enough energy that can be extracted by the second rotor and converted to mechanical power. Greater energy conversion will reduce wasted wind energy.

1. Introduction

Increased awareness of the environmental impact of the development and utilization of fossil fuels has led to a significant increase in the use of renewable energy sources for power plants. Wind energy is one of the new renewable energy sources that play an important role in the production of electrical energy in recent years through the use of wind turbines [1]. Wind turbine technology is relatively easy with short construction times but has good durability. The use of wind energy will reduce the production of greenhouse gas emissions which is one of the main focuses on environmental problems.

Today, horizontal axis wind turbine (HAWT) is a widely applied wind turbine design and the majority is a single-rotor wind turbine (SRWT). This type has high energy conversion capability with assumptions without viscosity and losses. However, in the field, SRWT's energy conversion capability generally decreases due to several factors, one of that is the configuration of the blades on the SRWT type. Blades have a function to receive kinetic energy from the wind then convert it into rotational energy on the drive shaft. Some improvements are made to the blade design to maximize conversion [2,3]. However, the best aerodynamically designed modern SRWT type can extract maximally up to 50% of the energy available in the wind. Thus, almost 50% of the energy in the wind escaped without being harnessed. Even though the energy in the wake behind an SRWT is not very small. At the same
time, the maximum energy that can be extracted by two rotors of the same diameters is increased to 64% [4]. Therefore, the concept of dual-rotor wind turbine (DRWT) was developed to increase the utilization of environmental wind energy [5].

The DRWT is a HAWT type that has two rotors installed in one shaft and placed axially one behind another. The second rotor is able to exploit kinetic energy that is not utilized from the wake flow that has passed through the first rotor to increase energy utilization in the system. Numerical studies and experiments have been carried out successfully by several researchers and prove that the efficiency of the DRWT type is better than SRWT type. In the study conducted by Jung et.al. using a 30 kW DRWT prototype showing a power increase of 21% from SRWT at a speed of 10.6 m/s [6]. Research by Habash et.al. using a small scale DRWT tested in a wind tunnel also shows that DRWT is capable of producing up to 60% more energy than the SRWT type in the same condition [7].

In the DRWT type, the axial distance of the two rotors affects the amount of residual energy from the wake flow utilized by the second rotor. Several studies with different geometry have been done on the relative axial distance in DRWT type which is determined based on the ratio between the axial distance and the first rotor diameter (X/D) showed in figure 1. This parameter is used to obtain more general results. Kumar and Abraham conducted computational analysis at an axial distance ratio of 0.25; 0.50; 0.65; and 0.75 using NACA 4415 for front rotor and NACA 0012 for a rear rotor. The results showed that the largest maximum power increase occurred at a distance of 0.65 by 9.67% [8]. In the recent study, Bramantya and Huda explored a DRWT using the NACA 0012 airfoil with front and rear rotor diameters of 0.23 m and 0.40 m. The axial distance ratio used is 0.44; 0.61; and 0.70 tested at speeds of 2.0 m/s, 3.0 m/s, and 4.2 m/s. The best configuration is obtained at a ratio of 0.61 at speeds of 4.2 m/s with a 24% increase from SRWT type [9]. But, Howard R. Harrison has patented the best axial distance value at ratio of 0.10 [10]. The design was later adapted by Akhmadan used different airfoils. The result showed a good performance in ratio 0.10 up to 100% at wind speed below 5 m/s [11].

![Figure 1. Axial distance ratio](image)

This study discusses the effect of the ratio of axial distance to the performance of DRWT type with different variations based on the previous study by Akhmadan using Clark-Y airfoil. It uses to obtain a wider range of data so that it can display more representative wind turbine characteristics. The purpose of this study was to obtain the best configuration of DRWT based on energy capabilities that can be converted to predetermined geometry.

2. Research Method
The applied method in this study is the experimental method and the numerical method. The experimental method is done by using a wind tunnel in laboratory scales to determine the performance of wind turbines. The numerical method is done by using ANSYS Fluent 14.5 to determine the
aerodynamics of wind turbines. The test object is in the form of a scalable DRWT in the co-rotating condition (two rotors are rotating in the same direction). The test is carried out at three axial distance ratios of 0.08; 0.12; and 0.16 at different wind speeds. From the study, the performance of DRWT was obtained experimentally and from computational testing obtained the flow characteristics in DRWT.

2.1. DRWT design
The design of the wind turbine was carried out with Computer Added Design (CAD) SolidWorks 2014x64 Edition SP01 software and printed using a 3D printing process as in figure 2. The geometry of DRWT that was used in this paper is two rotors with three blades in each rotor. The first and second rotor have the same geometry design. The airfoil used is Clark-Y because it has a high comparison of the lift coefficient ($C_L$) and drag coefficient ($C_D$) so that it is easier to rotate [2,11]. The ratio of the first rotor and second rotor diameters ($D_1/D_2$) used is 1 because it shows a better coefficient of power [5,10,11]. To maximize the performance of DRWT, a pitch angle is added so that the blade is able to adjust to the conditions of non-constant wind and the addition of angular displacement to increase the amount of wind energy that can be captured by the second rotor [10,11,12]. The SRWT and DRWT configurations used are shown in table 1.

![Figure 2. (a) Design of DRWT used software CAD SolidWorks 2014x64 Edition SP01, (b) 3D printing result](image)

### Table 1. Specification of SRWT and DRWT type

| Specification     | First rotor | Second rotor |
|-------------------|-------------|--------------|
| Blade number      | 3           | 3            |
| Rotor diameter    | 0.26 m      | 0.26 m       |
| Chord             | 0.026 m     | 0.026 m      |
| Twist             | 12.94°      | 12.94°       |
| Pitch angle       | 2°          | 2°           |
| Angular displacement | 0°       | 10°          |

2.2. Wind tunnel module
The wind tunnel is used to create wind speed as needed showed in figure 3. The air is flowed by being sucked by the fan to get a laminar flow. Wind speed cannot be adjusted directly but converted from fan frequency values by an inverter using a pressure analyzer to obtain wind speed data. DRWT is placed on a test section that has been connected to a torque sensor and RPM sensor. Torque and RPM data will automatically be recorded and displayed using a PC with the help of wind turbine test section (WTTS) software.
The obtained data will be processed to get a graphic of coefficient of power \((C_p)\) to tip speed ratio (TSR) to represent the performance of the wind turbine. \(C_p\) is defined as the ability of a wind turbine to convert energy based on a comparison between the mechanical power capable of being generated by wind turbines with wind power that hit wind turbines. TSR is a comparison of velocity in blade tip with wind speed in the environment. The value of \(C_p\) and TSR is found by using equations (1) and (2).

\[
C_p = \frac{P_m}{P_a} = \frac{T\omega}{\frac{1}{2} \rho AV^3}
\]  

(1)

Where \(P_m\) is mechanical power obtained from multiplying torque (T) and angular velocity (\(\omega\)) from a wind turbine. Then, \(P_a\) is wind power obtained from multiplying air density (\(\rho\)), swept area of wind turbine (A), and wind velocity (v) that hit the wind turbine.

\[
TSR = \frac{\omega R}{v}
\]  

(2)

Where \(R\) is a radius of the wind turbines.

2.3. Computational fluid dynamic
Numerical methods in DWRT modeling have been carried out in recent years. This method tends to be used to analyze flow characteristics that pass through DRWT so that further development can be done [13-16]. Computational fluid dynamic (CFD) is one of the numerical methods using the Reynolds Averaged Navier Stokes (RANS) equation as a solver from the modeling by accepting the average value of the equation solution.
CFD simulation is performed using ANSYS Fluent 14.5 software. DRWT modeling for CFD simulation is adjusted to the dimensions of the test model used in the experimental method. The Moving Reference Frame (MRF) method is used. MRF method the steady-state method for moving component modeling [8,17]. Figure 4 shows the modeling of DRWT and figure 5 shows the meshing of the DRWT modeling. Meshing is a process of counting to make a fluid path move. Meshing density affects the results of iterations. Viscous used is Realizable k-ε that suitable for the rotating model [17].

![Figure 5. (a) and (b) is a meshing on DWRT’s model](image)

3. Result and Analysis

Based on experimental results, the final data in the form of power output, Cp to TSR value, and flow characteristics between two rotors.

3.1. Power output

Experimental data are presented with different TSR of 0.8; 1.0; and 1.2 that showed in table 2 and table 3.

| Table 2. Experimental data on wind turbine performance |
|-------------------------------------------------------|
| **TSR** | **SRWT** | **X/D = 0.08** | **X/D = 0.12** | **X/D = 0.16** |
| RPM | Torque (Nm) | Power (W) | RPM | Torque (Nm) | Power (W) | RPM | Torque (Nm) | Power (W) |
| 0.8 | 0 | 0 | 0 | 259 | 0.011 | 0.287 | 208 | 0.009 | 0.196 | 245 | 0.004 | 0.113 |
| 1.0 | 343 | 0.008 | 0.301 | 263 | 0.011 | 0.312 | 390 | 0.014 | 0.581 | 330 | 0.016 | 0.560 |
| 1.2 | 518 | 0.012 | 0.674 | 444 | 0.015 | 0.703 | 399 | 0.025 | 1.036 | 431 | 0.023 | 1.048 |

| Table 3. Power increased of DRWT comparing with SRWT |
|-----------------------------------------------------|
| **TSR** | **DRWT** | **X/D = 0.08** | **X/D = 0.12** | **X/D = 0.16** |
| 0.8 | 100% | 100% | 100% |
| 1.0 | 3.7% | 93.0% | 86.0% |
| 1.2 | 4.3% | 53.7% | 55.5% |

Based on the data obtained, mechanical power generated by the DRWT type is greater than the SRWT type in all ratios. The addition of the second rotor will provide additional torque for the wind turbine to rotate to increase the energy generated. Mechanical power increases along with the increment of TSR. The biggest increase in power was achieved by all ratio axial distance variations of DRWT in TSR of 0.8 because the SRWT type has not been able to rotate on the same TSR. Then, the
increase in power of the DRWT type began to decrease along with the increase in TSR because the SRWT type had been able to produce power at TSR 1.0 and 1.2. The ratio of 0.08 has an increase in DRWT power of less than 5% because it produces a lower torque than other ratios and approaches the torque of SRWT type so that the power produced is low. At TSR 1.0, the ratio of 0.12 has the highest increase because it has the highest RPM value. While the ratio of 0.16, the increase in mechanical power is lower because the RPM produced is lower than ratio of 0.12 so the mechanical power produced is lower. At TSR 1.2, the ratio of 0.16 has the highest power increase because it is able to produce higher RPM with a high torque than ratio of 0.12. The torque and RPM that can be produced by wind turbines affect the amount of power that can be generated.

3.2. Relationship of Cp to TSR

The relationship of Cp to TSR is one of the parameters used in determining the performance level of wind turbines. Cp is only used to measure wind turbine capabilities in terms of designing a wind turbine rotor and does not cover overall wind turbine efficiency. However, the Cp value is very helpful in developing a blade design that is an important component of a wind turbine. A high Cp value will increase the efficiency of the wind turbine because the mechanical energy converted to electrical energy by the generator increases. The selection of TSR as a parameter makes it easy to determine the characteristic of wind turbines in general because wind turbine performance will tend to be the same when tested at the same TSR value on any scale. Wind turbine characteristics are shown in figure 6.

Based on figure 6, there is an increase in the value of Cp along with the increase in TSR. This type of wind turbine is still capable of rotating and does not cause stall at a low TSR. The DRWT type shows better performance than the SRWT type. DRWT type in each ratio is able to achieve a Cp value that is much higher than the SRWT type. This shows that the DRWT type is able to utilize greater wind energy to be converted into mechanical energy. In fact, the addition of the axial distance ratio is not always followed by the addition of the Cp value [8,9]. Each DRWT design has a certain distance which causes a decrease in Cp because the second rotor operates too far from the first rotor. The highest Cp is achieved by a ratio of 0.12 at TSR 1.2 which is 0.35. SRWT type can only reach Cp of 0.06 on the same TSR. The DRWT type is capable of rotating at a lower TSR with a higher Cp value than the SRWT type. SRWT type starts rotating when it reaches TSR 1.0 and can only produce Cp of 0.07. While the DRWT type is capable of rotating at TSR <0.1.

3.3. Flow characteristic on DRWT type

The numerical method is done on all DRWT ratios on TSR 1.2. From the results of computational simulation, it can be seen the flow phenomena that occur in the DRWT type. Figure 7 shows a
streamlined fluid flow that hit the two DRWT rotors. After the fluid passes through the blade on each rotor, flow separation occurs which causes a relatively low-pressure area that is large enough as seen in figure 8. This area is called the wake region. Wake region forms a turbulent flow that occurs in both rotors because of the high moment of inertia. The intensity of turbulence is lower when approaching the tip of the blade. The rest of the wind flow energy in this wake region is utilized by the second rotor to extract more energy from wind. At a certain distance from the DRWT, the wind flow returns laminar and approaches environmental wind speeds.

**Figure 7.** Velocity contour and streamline and of DRWT

**Figure 8.** Pressure contour of DRWT

**Figure 9.** Velocity contour and vector of DRWT from side view at (a) X/D = 0.08, (b) X/D = 0.12, (c) X/D = 0.16
In the wake region, a vortex flow is formed. It is rotating flow forms due to backflow in both rotors as in figure 9. Backflow is the air that moves back and hits another airflow. That causes a decrease in speed at the flow so that there is an increase in drag force. This gives a loss to the second rotor because the torque value decreases.

Figure 10 confirms that there is a deficit velocity in the wake region, caused by energy extraction from the wind turbine. The flow behind the first rotor has a lower speed decrement than the second rotor. But it is increasing again before crashing into the second rotor. The flow behind the second rotor was approaching blocked and flow was either stopped or received. At each variation in the axial distance ratio, the decrease in speed due to backflow is uncertain. But based on the speed contour between the two rotors, the decrease in speed tends to increase along with the reduction in axial distance in the two rotors. At a distance of 0.02 m after passing through the first rotor, the decrease in speed reaches 38% at a ratio of 0.08, 17% at a ratio of 0.12 and 12% at a ratio of 0.16. A negative value in the X-axis represents the wind velocity inlet of wind turbines. Negative values caused by coordinates of (0,0) are located in wind turbine model while inlet velocity is located far behind wind turbine model. Decreasing speed causes the residual energy from the first rotor to decrease. However, velocity of 6.6 m/s is attained in wake of the first rotor at ratio of 0.16 to hit the second rotor. This shows that the second rotor is able to optimally utilize the incoming flow to be converted into mechanical energy in the DRWT.

![Figure 10. Graphic of velocity between two rotors](image)

4. Conclusion
The axial distance ratio has a significant effect on the performance of DRWT. Increasing the ratio of axial distance is not always accompanied by an increase in the value of Cp. Based on this experiment, the highest Cp can be achieved by a ratio of 0.12 which is 0.35 on TSR 1.2. Whereas the biggest increase occurred in all variations in the ratio of the DRWT axial distance of 100% to the TSR 0.8 because the SRWT type has not been able to rotate on the same TSR. The extracted energy in the second rotor comes from the residual energy in the wake flow that occurs after passing the first rotor. Wake flow causes losses because it reduces the energy extracted by the second rotor due to the backflow effect. The decrease in speed tends to increase along with the reduction in axial distance. The biggest decrease occurred in the ratio of 0.08 which reached 38%.
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