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Study The Performance of Horizontal Axis Wind Turbine using Dual Rotor System

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Abstract

The aim of this study is to improve the power output of HAWT by using the dual rotor wind turbine. DRWT is consisting of a primary upwind rotor called front rotor, which has a diameter 0.9 m and using NREL S826 airfoil. An auxiliary downwind rotor called rear rotor using the same airfoil. The study is conducted by using computational fluid dynamics (CFD). The major goal of the research is to optimize the DRWT performance by adjusting two parameters: the diameter ratio of two rotors and the axial distance between them. In terms of the diameter ratio, there are three approaches. In the first one (DR=1.5), the rear rotor diameter is smaller than the front rotor. In the second one (DR=1), the two rotors have the same diameters. In the third one (DR=0.75), the rear rotor diameter is bigger than the front rotor diameter. The front rotor diameter is kept constant while the rear rotor diameter is changed. For the axial distance, used are as follow (0.25D1, 0.5D1, 0.75D1 and 1D1). The numerical model is performed by using k-ω SST Turbulence model. The results show that the axial distance parameter makes a little change in Power output. Using the model of DR=0.75 increases the CP by 13.3% at λ=5 with respect to the baseline model. Testing the model of DR=1.5 doesn't show sensible improvement while using the model of DR=1 increases the CP by 7.8% at λ=5.

Keywords: Counter-rotating dual rotor, tandem rotor, rear rotor configuration, computational fluid dynamics simulation.

Nomenclature:

Roman Symbols	**Description**	**Subscripts**	**Description**
A	Swept area of wind turbine rotor (m2)	HAWT	Horizontal Axis Wind Turbine
D1	Front Rotor Diameter (m)	SRWT	Single Rotor Wind Turbine
D2	Rear Rotor Diameter (m)	DRWT	Dual Rotor Wind Turbine
Cp	Power Coefficient	DR	Diameter Ratio (D1/D2)
N	Rotor Rotational Speed (rpm)	SST	Shear Stress Transport
Psh	Shaft Power (watt)	CR-DRWT	Counter Rotating Dual Rotor Wind Turbine
Tnet	Net Torque (N.m)	CO-DRWT	Co-Rotating Dual Rotor Wind Turbine
X	Axial Distance between Rotors (m)	FR	Front Rotor
Re	Reynolds Number	RR	Rear Rotor
Greek Symbols		CFD	Computational Fluid Dynamics
ω	Rotor angular velocity (rad/s)	RANS	Reynolds-averaged - Navier-Stokes
λ	Tip-Speed ratio (TSR)	NREL	National Renewable Energy Laboratory
ρ	Fluid density (kg/m3)		
μ	Fluid Viscosity (Pa.s)		

1. Introduction

The evolution of three-bladed horizontal axis wind turbine (HAWT) is very evident today. Rapid improvement leads to an increase in the performance of the turbine and a reduction in costs per kWh. Investigations into the turbine rotor blade models and geometry with modern airfoil profiles are very intense to optimize the power produced by wind turbines. The rotor of the wind turbine is the key in converting wind energy into mechanical energy.

According to Betz's limit, a wind turbine can theoretically capture approximately 59.6% from the airstream's energy. In real conditions, the power coefficient is lower than the theoretical value due to aerodynamic losses in the region near to hub (root region) also wake losses in wind frame due to the interaction between turbines.

The research focus has switched to design more efficient wind turbines and wind farm layouts, aiming to harvest more wind energy from the same incoming flow conditions. As a result, dual-rotor wind turbine (DRWT) configuration was proposed to achieve a higher efficiency in harnessing more wind energy from incoming airflows. Where the ideal power coefficient can be increased from 59% to 64% due to using the secondary rotor if positioned downstream to front rotor. It was conducted by Newman [1].

Dual rotor wind turbine (DRWT) has two rotors. The two rotors may rotate in the same direction where it is known as (CO-DRWT), or rotate in opposite directions where it is known as (CR-DRWT). DRWT has two rotors of the same or different diameters. Several researchers conducted numerical and experimental aerodynamic studies that showed greater performance of using dual-rotor wind turbines than using single rotor.

Wang et al. [2] performed an experimental study in an Atmospheric Boundary Layer wind tunnel with scaled turbine models to investigate the aerodynamic performances and wake characteristics of DRWTs in either co-rotating or counter-rotating configuration, in comparison to those of a conventional single-rotor wind turbine (SRWT). The results of the measured power illustrate that 7.2% and 1.8% enhancements were found in the CR-DRWT and CO-DRWT models respectively, when operated in an isolated condition, in comparison to that in the SRWT model.

Ushiyama et al [3] tested the double wind turbines with counter rotating and co-axial theory by the variation of number of blades and using (DR=0.5). The turbine Power Coefficient increases with a low starting torque on the counter rotating turbine. This study demonstrates that the counter-rotating wind turbine is more powerful than co-axial wind turbine.

Yuan, Ozbay, et al. [4] conducted an experiment on a DRWT with co-rotating and counter-rotating configurations operating in isolated conditions. They discovered that the counter-rotating design could harvest more energy from the same incoming wind than the co-rotating configuration, which also confirms the findings reported in Yuan, Tian, et al. [5].

Kumar et al. [6] compared a single 3 bladed wind turbine to the CR-DRWT system consisting of two rotors with 3 blades each. An optimal axial distance was defined by the parametric analysis. The results show that the optimum distance between the two rotors is 0.65D1, also show that the power output of DRWT is higher than SRWT by 9.67%. A strong correlation has been found between the CFD results and the measurements. The results of the CFD simulations were significantly smaller than the test values in Jung, No, and Ryu [7].

Hwang et al. and Jung, No, Ryu, et al. [8] [9] compared the power output of a traditional single-rotor wind turbine (SRWT) relative to an identically sized dual-rotor wind turbine with CR-DRWT configuration. The measured results showed that the power coefficient of the CR-DRWT was 30% higher than that of an SRWT with only half solidity, but 5% lower than that of an SRWT with the same solidity.

Based on the previous studies, there isn't a clear conclusion for the increase in CP due to using the DRWT system. Therefore, the objective of the present study is to show the optimum case of DRWT due to the variation of the following parameters:

- The two rotors diameter ratio is as follow: (0.75, 1 and 1.5). In all cases the front rotor has constant rotor diameter.
- Axial distance between the two rotors is as follow: (0.25D, 0.5D, 0.75D and 1D). The analysis is conducted with varation of tip speed ratio from λ=2 to λ=8.

2. Physical Model

A three-bladed wind turbine model with NREL S826 airfoil is used in this study where the rotor diameter is 0.9m as shown in figure 1. The studied model is of the same design used by Akay et al. [10].

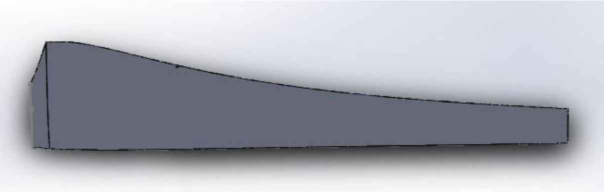

Figure 1: The Blade Shape

The rotor is modeled by solid works CAD software and imported ANSYS design modular. The numerical model uses a main domain extends from 4.5D upstream the rotor and 7.8D downstream the rotor. The main domain bunds a rotating domain of diameter 2m as shown in figure 2.

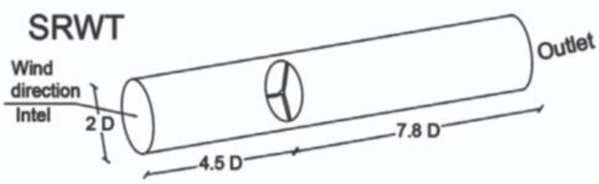

Figure 2: SRWT Design System

DRWT model consists of front and rear rotors. S826 airfoil is used in of the three-bladed rotors. The front and rear rotors are studied in order to obtain the optimum DR and axial distance between them. The same previous numerical model is used for the DRWT as shown in figure 3. Table 1 shows the used values of DR and X.

Table 1: Data of Rotors dia. and axial distance between rotors

D1	D2	X	DR	X/D1
0.9	1.2	0.225	0.75	0.25
0.9	0.9	0.45	1	0.5
0.9	0.6	0.675	1.5	0.75
-	-	0.9	-	1

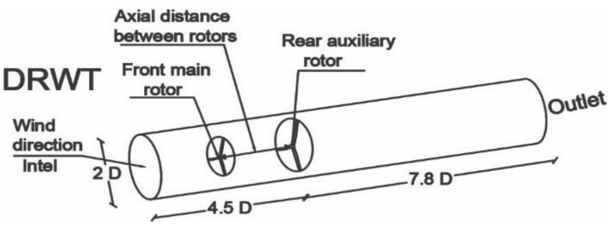

Figure 3: DRWT Design Model

3. Meshing of SRWT and DRWT models:

The mesh setup is performed using ANSYS mesher. The meshing quality is determined by mesh skewness from 0 to 1 and aspect ratio. For SRWT, 3.3 million cells are used to mesh the model with average mesh skewness 0.225 and average aspect ratio 1.838. For DRWT, the number of cells is between 7 M to 12 M cell based on the size of rear rotor with average mesh skewness 0.25 and average aspect ratio 1.9. The Mesh grade independence is considered in the present as shown if figure 4, which shows that there is no change in torque when the number of elements equals or above 3.2 million elements.

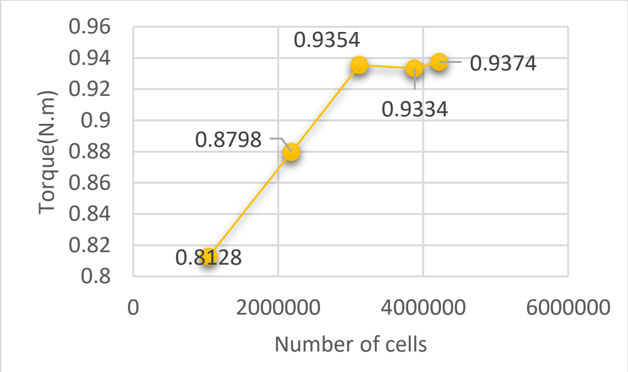

Figure 4: Mesh Independence curve

4. Turbulence model:

DRWT and SRWT are studied using both of k–ε turbulence model and the k–ω (SST) turbulence models.

The K-ω shear stress transport (SST) Turbulence model is used to valid the present results with those of Akay et al.[10] and also to model the DRWT. The Navier-Stokes non-linear equations (RANS) are translated into a series of algebraic equations with a pressure-based solver by the ANSYS Fluent R19.1 numerical solving method. Due to the large number of cells, it gives better numerical results but naturally with longer solving time. Mesh geometry is the key of the accuracy level and the time of the computation process, The K-ω (SST) turbulence equations model obtained from the general equation of fluid flow are the Reynolds-averaged Navier- Stokes (RANS) equations in Menter [11].

In solution methods for pressure-velocity coupling in ANSYS the coupled scheme is chosen. The pressure and momentum equations are solved using a Second -order upwind.

The inlet freestream velocity is kept constant at 10 m/sec. The tip speed ratio (λ) variation is obtained by the variation of rotating domain angular velocity. The performance is studied by CP calculation at each value of λ. The goal of the study is to get the optimum value of CP for DRWT with respect to SRWT based on the variation of the used parameters.

5. Validation

The SRWT results validation is performed by comparing the values CP to those of Akay et al. [10].

Equation 1 provides the meaning of CP. Power Coefficient (Cp) is a measure of wind turbine efficiency often used by the wind power industry. Cp is the ratio of actual power produced by a wind turbine divided by the total wind power flowing into the turbine blades at specific wind speed.

$$Power\ Coefficient\ (C_p) = \frac{Tnet.\omega}{0.5\rho A v_0^3} \qquad (1)$$

where v_0 *is the freestream Velocity.*

CFD results of SRWT show the CP with λ as in Figure 5. The CP results of the present numerical study are in good agreement with the experimental results of Akay et al. [10]. The optimum CP value is 0.45 at λ=6.

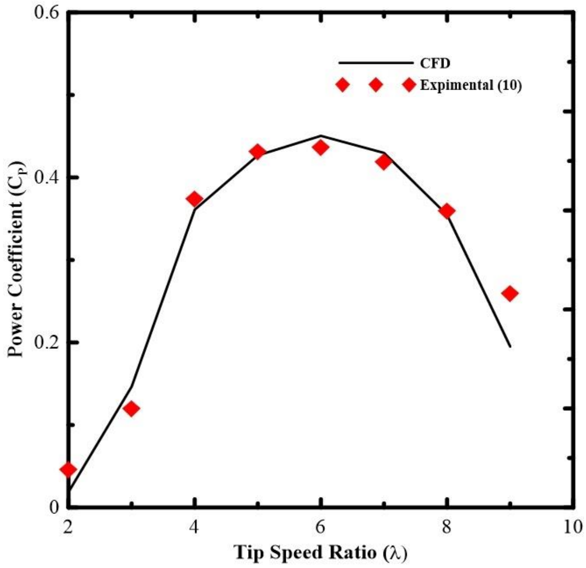

Figure 5: Power Coefficient for present numerical against experimental data

6. Results and Discussion

A large portion of the wind energy harvested by upstream wind turbines causes power losses in the wake region. So, the target of the dual-rotor designs is to enhance the mixing in the wake flows, which aims to achieve a faster velocity recovery than that in the single-rotor case, which leads to making power output of DRWT greater than SRWT.

In this study, the power coefficient is calculated using equation 1. The influence of the axial distance between the rotors and the rotor diameter ratio on the performance of the DRWT will be discussed in this section.

6.1 Effect of rotors diameter ratios on DRWT performance

Figures 6, 7 and 8 show the power coefficient for 3 different of diameter ratios for dual rotor system, DR=0.75, 1 and 1.5 respectively.

Figure 6 shows that the power coefficient of the front rotor decreases by 23.7% at λ=5 relative to the single rotor. The decrease is due to the flow obstruction by the rear rotor. On the other hand, the rear rotor shares with 30% of the overall power coefficient of the dual rotor system. because it accelerates the velocity recovery more than the single rotor. The combined power coefficient of the dual rotor system is the sum of the power coefficients of the front and rear rotors. Dual rotor system increases the power coefficient from 0.427 to 0.51 relative to SRWT at λ=5 or increases by 19.4%.

Figure 7 shows how the effect of the rear rotor decreases with increasing diameter ratio at DR=1. The reduction of the rear rotor diameter reduces its shared part in the overall power coefficient. The power coefficient of the rear rotor presents 25.8% of the total Cp. The combined power coefficient increases from 0.427 to 0.485 at λ=5 relative to SRWT, or increases by 13.6%.

Further increase in DR decreases the functionality of the dual rotor system. Figure 8 shows that at DR= 1.5, the combined power coefficient decreases from 0.427 to 0.4 at λ=5. The more decrease in the rear rotor diameter the more decrease in the total area capturing the wind energy. Therefore, the combined power coefficient decreases on increasing DR.

Figure 9 shows that DRWT at DR=0.75 gives the largest maximum power coefficient Cp=0.51 at λ=5 relative to that of SRWT which is 0.45 at λ=6. Increase represents about 13.3%

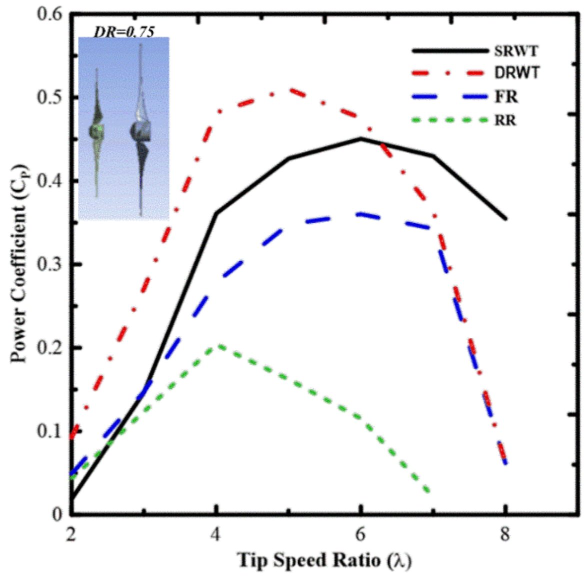

Figure 6: Power Coefficient of Front rotor, Rear rotor, DRWT against SRWT with Variation of TSR for DR=0.75

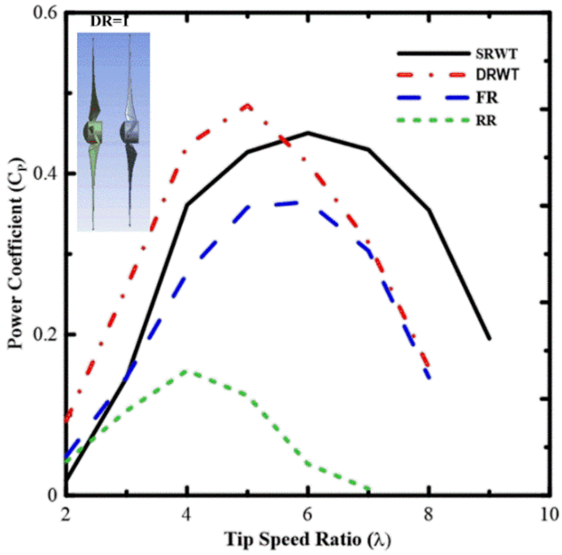

Figure 7: Power Coefficient of Front rotor, Rear rotor, DRWT against SRWT with Variation of TSR for DR=1

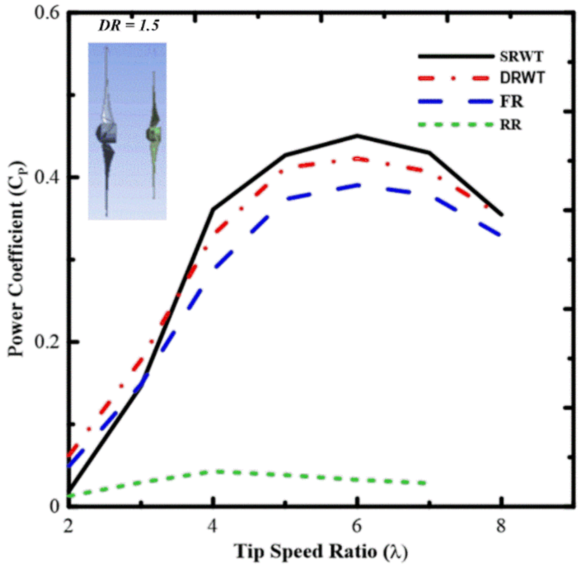

Figure 8: Power Coefficient of Front rotor, Rear rotor, DRWT against SRWT with Variation of TSR for DR=1.5

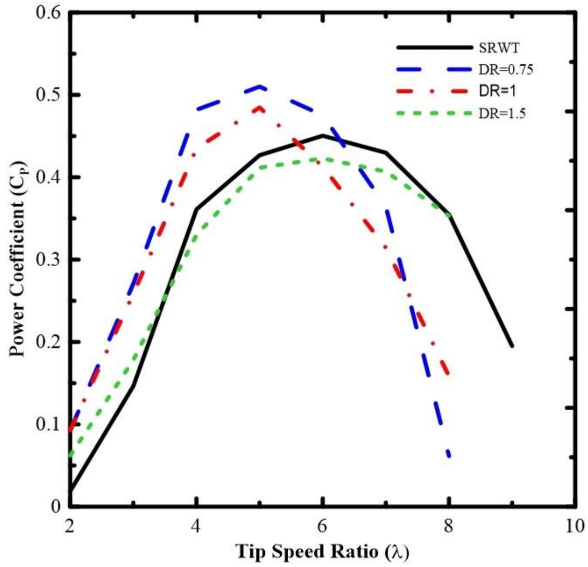

Figure 9: Power Coefficient of DRWT for 3 DRs against SRWT with variation of TSR

6.2 Effect of axial distance between rotors on DRWT Performance

Figures 10 and 11 illustrate the influence of the four axial distances (X/D=0.25, 0.5, 0.75, and 1) on the power coefficient of DRWT system. It is found the maximum power coefficient is obtained at X/D= 0.75 for DR=0.75 and X/D=1 for DR=1, which agrees with results in Lee et al [12]. Even though the front rotor's power coefficient grows with distance, the rear rotor's CP drops and vice versa, resulting in nearly constant total performance. Also the figures show that the four axial distances have very small effects on maximum power coefficient obtained.

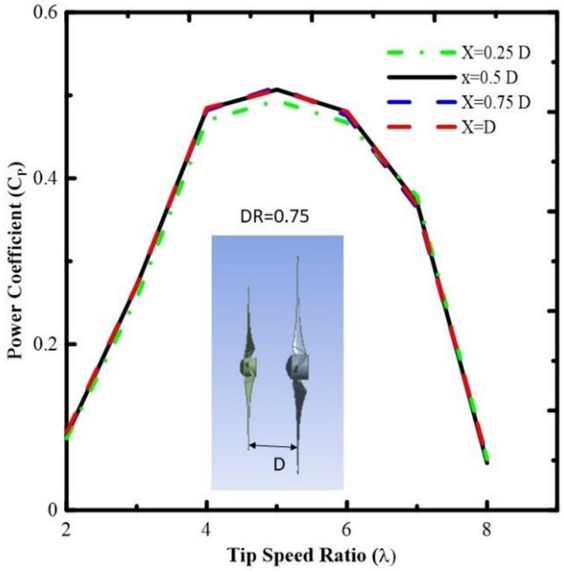

Figure 10: Variation of power Coefficient for DR=0.75 against TSR according to axial distance ratio.

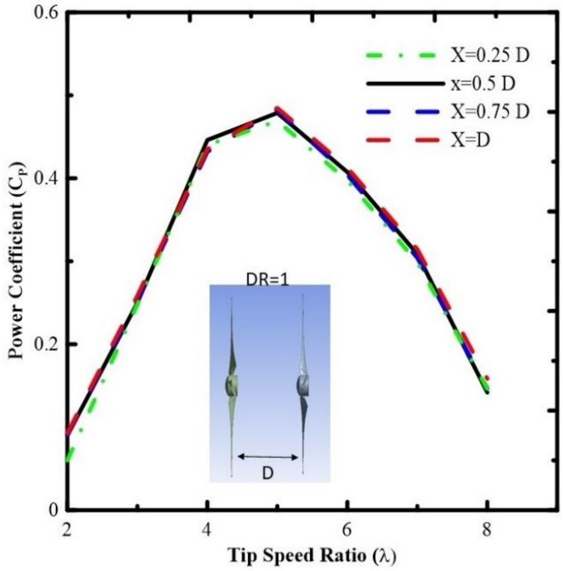

Figure 11: Variation of power Coefficient for DR=1 against TSR according to axial distance ratio.

7. Conclusions

The performance of a dual-rotor wind turbine system was computationally studied in this paper. The effect of the presence of the rear rotor with three different diameters on the system's performance was investigated. The results showed that as the diameter of the rear rotor increases, the power coefficient increases. Using DRWT at DR=0.75 increases the maximum power coefficient by 13.3% relative to SRWT. The optimum operating tip speed ratio reduces to 5 with respect to the optimum operating tip speed ratio of 6 in the case of a single-rotor system. In addition, the axial distances between the two rotors were also investigated, which were 0.25D, 0.5D, 0.75D, and 1D. It is concluded that there is no significant difference in the power coefficient for the studied distances.

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