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Research Article

# Enhancement of the performance of vertical-axis wind rotors with straight blades

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**Abstract**: In this study, it has been aimed to improve the performance of vertical axis wind rotors with straight blades. For this purpose, an additional performance-enhancing setup has been used, placed in front of the vertical-axis wind rotor with straight blades, in order to increase the performance. The effects on the rotor performance increase have been investigated numerically by keeping the dimensions of this performance-enhancing additional setup constant, by changing the number of blades of the straight bladed rotor, and by changing the blade angles if the straight blades have been angled. Numerical analyzes performed in this study have been validated by experimental literature data. After creating the solid models required for the rotor performance analysis, the computational fluid dynamics program ANSYS/Fluent has been used. Here, studies have been conducted with two, three, and four bladed rotors as the number of blades. As the blade angle, the effects of the angles between 180° and 120° have been examined. As a result of the study with the additional performance setup (APS), it has been found that the optimum performance has been determined with the vertical axis rotor with three blades and 150° blade angle. As a final result, it has been determined that the power-coefficient obtained from the optimum vertical axis rotor with additional performance setup increased approximately 2.6 times compared to the optimum rotor without setup.

**Keywords**: Wind energy; Renewable energy; Vertical axis rotor; Blade design; Straight blade

## 1. Introduction

In recent years, studies on wind energy have increased rapidly due to the rapid increase in countries' interest in clean, and renewable energy sources in dealing with energy shortage and climate change. While horizontal-axis wind turbines are mostly used in large scale power generation with wind energy, vertical-axis wind turbines come to the fore in small scale power generation. Vertical-axis wind rotors, such as Savonius wind rotors, are popularly used to meet small-scale energy needs such as home and garden lighting, especially in rural areas where the electrical grid cannot reach. Especially in order to improve the low performance of this type of rotors, many studies have been carried out in the literature both on the changes made in the rotor structure, and on performance enhancing additions placed around the rotor [1-4]. Considering the studies in the literature; It has been determined that the changes made in the rotor structure are generally classified as blade type, number of blades, and blade design dimension ratios [5-8]. In another method to increase rotor performance, rotor performances have been investigated by adding an additional performance setup in front of the rotor without making any changes in the rotor structure [9-11]. In this second method, it is ensured that especially the flow is directed on the positive-torque producing blade, and thus the negative-torque on the rotor is reduced. Li et al. [12] conducted a study to increase the performance coefficients of the straight bladed vertical-axis wind rotor with a wind gathering setup. This wind gathering setup was mounted around the rotor to allow for greater wind flow. Brusca et al. [13] obtained the coefficients of performance by examining the aspect ratio of a straight bladed vertical-axis H rotor. In their study, Kim and Gharib [14] experimentally investigated turbine performance by placing a flat deflector in front of a vertical-axis turbine with flat blades with opposite rotation directions. Yao et al. [15] increased the efficiency of vertical axis wind turbine with a tower cowling. Dragomirescu [16] studied numerically to estimate the crossflow wind rotor's performance. Park et al. [17] proposed a new wind rotor for use on building exteriors. This proposed system was investigated by several important designs of guide vanes. Pope et al. [18] conducted numerical and experimental investigations to determine the operating efficiency of vertical-axis rotor. Müller et al. [19] analyzed the Sistan type windmill, the oldest form of wind rotor used in buildings. Krishnan and Paraschivoiu [20] carried out a comprehensive study to improve the performance of wind rotor with diffuser on building roofs.

In this study, straight-bladed vertical-axis wind rotors

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operating under the effect of drag force, such as Savonius rotors, have been investigated. Here, in order to improve the performance of these straight bladed rotors, additional performance setups designed around the rotor, which are also used in Savonius rotors, have been considered. Accordingly, the wind collector setup addition, which has been considered to increase the rotor performance, has been placed in front of the vertical-axis wind rotor with straight blades, and the effect of this addition on the rotor performance has been examined. Also, the effects of rotor blade numbers and blade angle on rotor performance have been investigated numerically by keeping the dimensions of the addition placed in front of the rotor constant. Numerical analyzes have been performed using the ANSYS Fluent program, and verified with experimental data.

## 2. Materials and Methods

In this study, studies have been conducted to improve the performance of vertical axis wind rotors with straight blades. These studies have been carried out within the framework of a study methodology as shown in Figure 1. In this direction, as shown in the Figure, first of all, studies have been carried out to verify the computational fluid dynamics (CFD) method planned to be used in this study with the literature experimental data. In the main part, which is described as the subsequent design and performance studies, first the necessary design changes have been made for performance improvement. Especially when the literature studies are examined in terms of design changes; it has been determined that these investigated designs are collected in two main regions: vertical axis wind rotors in their own structure or outside their own structure by adding external additions such as setup [7,9]. In this study, the internal design changes of the straight bladed vertical-axis rotor have been considered by keeping the dimensions of the external additional performance setup used in vertical axis wind rotors constant. Performance analyzes of the rotors designed with new geometric parameters have been carried out. From this performance analyzes carried out, the rotor design with the best performance, that is, the optimum performance, has been determined.

The geometric parameters of vertical axis wind rotors with straight blades are shown in Figure 2. In this study, the dimensions of the additional performance setup (APS) shown in the figure have been kept constant since the effects of the internal design geometric parameters of the straight bladed vertical-axis wind rotors on the rotor performance have been examined. The dimensions of the additional performance setup used throughout the study have been taken as constant according to the rotor diameter. In addition, all interior design geometric parameters, including the height of the vertical-axis wind rotor with straight-blades, have been taken according to the rotor diameter. The diameter of the vertical-axis wind rotor with straight-blades has been taken as D=50 cm. Rotor performance effects in the case of angled (θ) straight blades of these vertical axis wind rotors have been investigated. In this direction, the angle range of the angled straight blades has been changed between 180° and 120°. In this study, the performance values of the θ=180° straight-blade rotor and θ=165°-150°-135°-120° the angled blade rotor have been determined, and evaluated. In the CFD analysis, the initial position of the vertical-axis wind rotor with straight blades has been taken as the position of the rotor blade perpendicular to the wind flow direction. From this position, the rotor performance values corresponding to a full rotor revolution have been determined.

For the optimum performance of the straight two-bladed vertical-axis wind rotor, the determined blade angle has been kept constant, and the effects of the number of blades on the rotor performance have been examined at

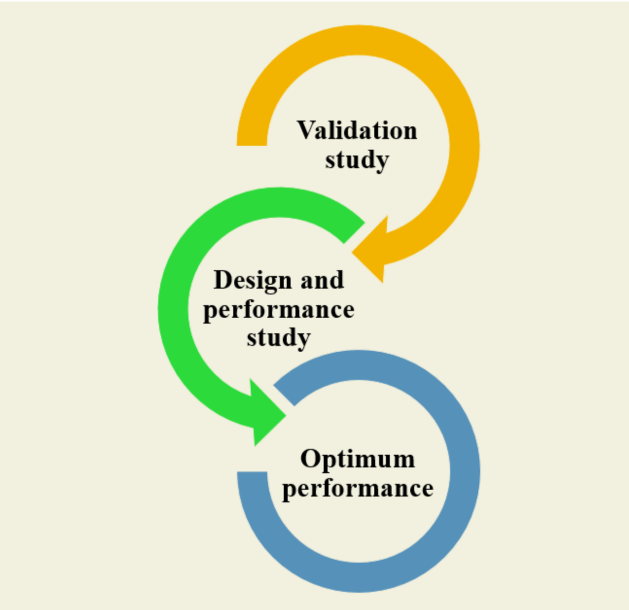


Figure 1. Methodology of study

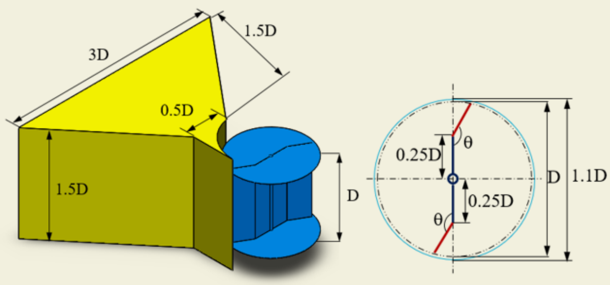


Figure 2. Geometric parameters

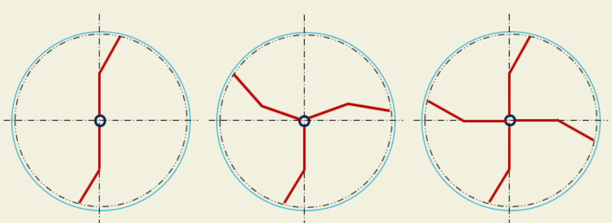

Figure 3. Number of blades

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different blade numbers, as shown in Figure 3. The performances of the two, three, and four bladed rotors have been determined, and compared with each other.

For rotor performance studies, performance coefficients have been calculated with the data obtained by CFD analysis, and compared with each other. Torque-coefficient ($C_t$), which is the ratio of the torque obtained by the rotor to the torque obtained by the wind force, has been calculated as in Equation 1. The power-coefficient ($C_p$), which is the ratio of the power produced by the rotor to the wind power, has been calculated as in Equation 2. Here (ρ) is the air density, (A) is the rotor swept area, and (V) is the wind speed. Since the height and diameter of the rotor have been taken as the same, the rotor swept area is $A=D^2$. As the rotor performance, the power- and torque-coefficients have been calculated using the mean torque values obtained by the rotor. In addition, performance studies have been determined at various tip speed ratios. The tip speed ratio (λ), which is the ratio of the blade tip speed to the wind speed, has been calculated as in Equation 3. Here (ω) is the angular velocity of the rotor.

$$C_t = \frac{T}{1/_4 \rho A V^2 D} \tag{1}$$

$$C_p = \frac{T\omega}{1/_2 \rho A V^3} \tag{2}$$

$$\lambda = \frac{\omega D}{2V} \tag{3}$$

Studies have been conducted to verify the numerical solution method used in this study with the literature experimental data. In the literature review, since no direct similar study could be found on the straight-bladed vertical-axis wind rotor, the Savonius wind rotors, which are one of the other vertical axis wind rotors, have been taken into consideration. When Savonius wind rotors have been examined in terms of their performance, it has been determined as the rotor that gives the closest performance values in the straight-bladed vertical-axis rotors. In this direction, for the validation of the numerical method, the rotor geometry of the study, which has experimental data published in the literature, has been redesigned, and the performance data have been determined and compared numerically. Therefore, the validation of the numerical analysis has been conducted by comparing it with the experimental data given by Altan et al. [9]. In the analysis validation study, Savonius wind rotor, flow domains and other conditions have been considered to this literature. In this direction, first of all, the mesh independence study has been conducted. The first mesh element number has been considered, where the mean torque-coefficient remains almost the same. In addition, the performance data of the rotor have been found numerically by taking the mean of the values obtained as a result of one full rotation of the rotor. The data obtained for the sensitivity and stability of the numerical analysis have been determined from the revolution time intervals where they are almost the same. The experimental and numerical change of the power-coefficient at different tip speed ratios for the rotor is shown in Figure 4. The obtained numerical data have been determined according to the average torque-coefficients of the rotor. As can be seen from the figure, it has been determined that the numerical data obtained for the Savonius rotor are generally compatible with the data obtained from the experimental study. Therefore, the validation of the numerical analysis has been confirmed. For the vertical-axis rotor with straight blades, the numerical analysis method whose validation has been determined throughout this study has been used.

In this research, the performance-analysis of the vertical axis wind rotor with straight blades has been carried out using the ANSYS/Fluent program with the validated numerical analysis method. Only the physical conditions of the validated numerical solution method have been changed according to the vertical axis wind rotor with straight-blades examined. In the rotor performance analysis studies, the wind speed has been chosen as 8 m/s. The dimensions of the flow domains used in CFD analyzes have been obtained according to the rotor diameter. The general dimensions of the determined flow do-

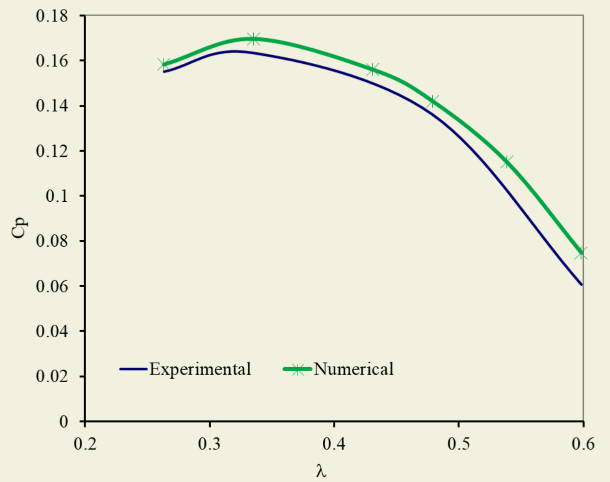


**Figure 4.** Validation of numerical analysis

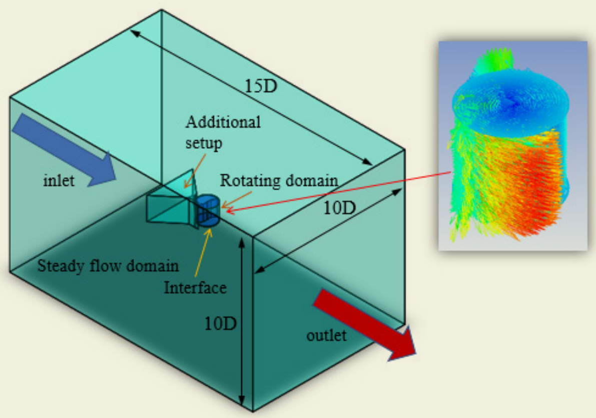


**Figure 5.** Domains and limits of numerical analysis

main and an example of rotor CFD performance analysis are shown in Figure 5. As can be seen in the figure, the flow-domain consists of two types of domains, a rotating flow domain and a steady flow-domain. An interface has been created between the rotating flow domain and the constant flow-domain. The cross-sectional dimensions of the flow-domain have been taken as 10Dx10D in order to avoid the blockage effect. The total flow-domain length has been taken as 15D. The same turbulence model has been used as the standard k-ε flow turbulence model of the numerical solution validated by experimental data. In the performance analysis, the standard k-ε, which is the turbulence model of the numerical solution validated, has been used. The mesh method used in the performance studies has been taken as the same as the mesh method of the validated numerical analysis. Rotor performance values obtained with different geometric parameters under the same numerical analysis conditions have been compared with each other and then optimum design conditions and rotor performances have been obtained.

## 3. Results and Discussion

In this research, the performance of vertical-axis wind rotors with straight blades has been investigated. In particular, the changes in the torque-coefficients obtained in the angled and different numbers of the rotor blades have been determined. Optimum torque coefficient has been determined among the obtained data. In order to compare the effects of geometric changes of rotor straight blades on rotor performance, the dimensions of the additional performance setup have been kept constant. Variations of optimum power coefficients have been obtained under the same geometric conditions of the rotor where the optimum torque coefficient has been obtained. Therefore, the geometric parameters of the rotor design, in which optimum performance values have been obtained, have been determined. Therefore, the geometric parameters of the rotor design, in which optimum performance values have been obtained, have been determined.

Variations and average values of torque coefficients obtained from straight two-bladed vertical axis wind rotors with different blade angles are shown in Figure 6. The variations of the torque-coefficients obtained have been determined from a stable full rotation of the rotor. In order to compare the rotor coefficient values, the rotor tip speed ratio has been taken as 0.33. As shown in the figure, the designations b180-b165-b150-b135-b120 show the cases where the blade angles are θ=180°-165°-150°-135°-120°, respectively. At the same time, Av.b180- Av.b165- Av.b150- Av.b135- Av.b120 designations represent the mean torque-coefficient values of the rotor in cases where the blade angles are θ=180°-165°-150°-135°-120°, respectively. When the variations in the torque-coefficients are investigated from the figure, it has been found that the maximum torque coefficients are obtained with b180-b165-b150-b135-b120 angled straight bladed rotors, respectively. When the variations in the torque-coefficients are investigated from the figure, it has been determined that the maximum torque coefficients are obtained with b180-b165-b150-b135-b120 angled straight bladed rotors, respectively. In addition, when the minimum torque variations in negative values are investigated, it has been found that the negative values are obtained in the maximum angle range in the case of the b180 angle, that is, the straight blade. Therefore, when the average torque coefficients are examined from the figure, it is seen that the average torque coefficient obtained with Av.b180 is the lowest compared to the others. When the other minimum torque changes are investigated, it has been found that the negative values are obtained in almost the same angle range in the case of b150-b135-b120 angled blade rotors. Therefore, when the variations in the average torque-coefficients are investigated, the maximum

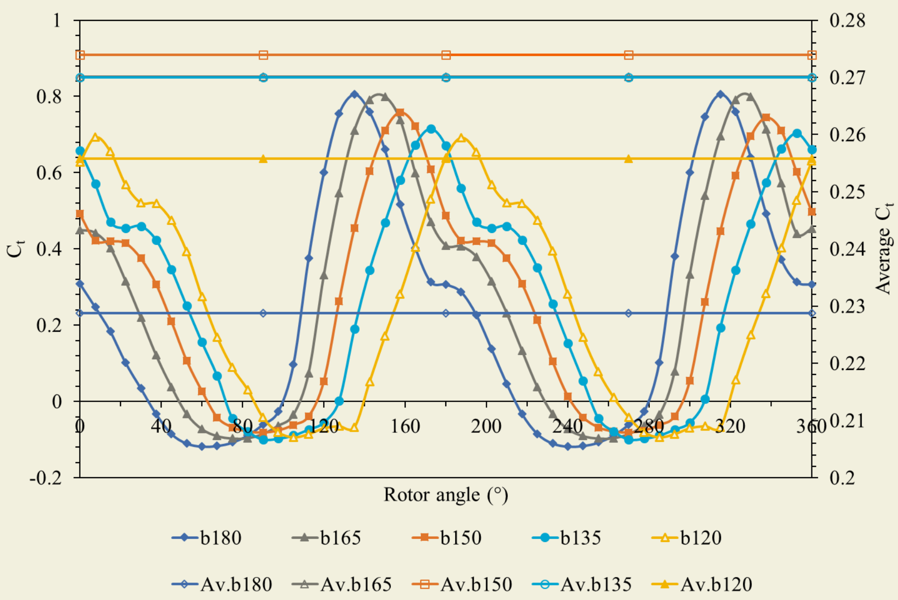


**Figure 6.** The effect of the blade angle on the torque-coefficient

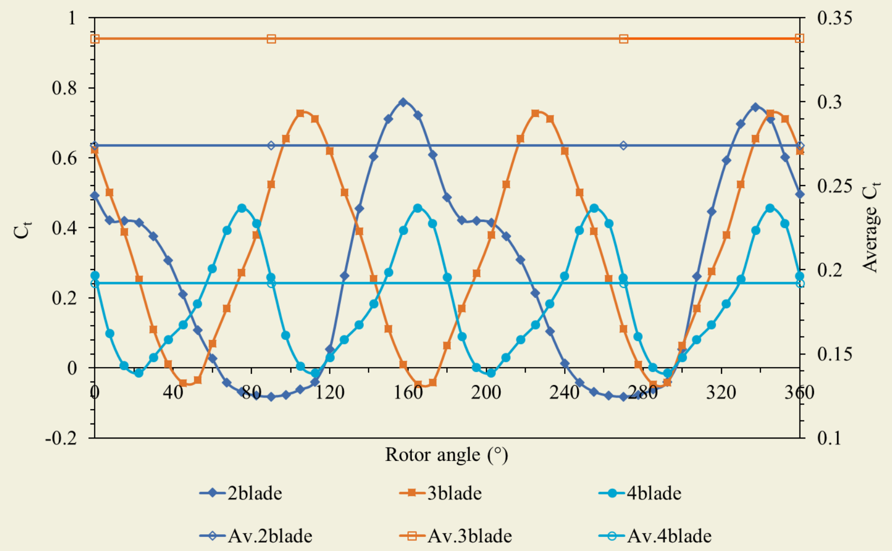


**Figure 7.** The effect of the number of blades on the torque-coefficient

average torque coefficient value has been obtained with Av.b150. According to the comparisons made, the blade angle at which the average torque coefficient value is optimal has been determined as θ=150°.

The changes and average values of the torque-coefficients found from vertical axis wind rotors with straight blades with θ=150° blade angles with different blade numbers are shown in Figure 7. In numerical studies, the rotor tip speed ratio has been taken as 0.33. As shown in the figure, 2blade-3blade-4blade designations show the cases where the number of blades is 2, 3, and 4, respectively. Average torque coefficients are shown as Av.2blade-Av.3blade-Av.4blade respectively. First of all, when the variations in the torque-coefficients in the figure are examined, it has been determined that the peaks where the maximum values are obtained vary depending on the number of blades. When the torque-coefficient variations are investigated, the maximum torque coefficient values have been found when the number of rotor blades is 2 and 3. However, it has been found that the rotor angle range, in which the minimum torque-coefficients are obtained, is wider than the others in the case of 2 blades. It has been determined that the maximum values of the torque-coefficient found from the rotor are quite low compared to the others when the number of rotor blades is 4. When the variations in the average torque coefficients are investigated, the maximum average torque coefficient value has been obtained with Av.3blade. According to the evaluations made, the number of blades for which the average torque coefficient value is optimal has been determined as 3. It has been determined that the mean torque-coefficient value with the 3-bladed optimum wind rotor is increased approximately 1.2 times according to the 2-bladed condition and approximately 1.8 times according to the 4-bladed condition.

The velocity contours of the rotors with different blade numbers are shown in Figure 8. In order to examine the effects of the rotor blade numbers on the rotor performance, the dimensions of the additional performance setup have been taken as constant. According to the CFD analyzes performed, it has been observed that the flow coming on the blade rotating against the wind is more in the two-bladed rotor than in the others. On the other hand, this situation negatively affects the rotor performance, which is supported by the numerical values of the analysis. With the number of blades being 4, it has been observed that fewer flow exits from the rotor region than other rotors because it causes a situation such as flow compression in the flow coming to the rotor. According to all these examinations, it has been determined that the best flow direction is on the 3-bladed rotor.

In Figure 9, the change of the power-coefficient found from the optimum vertical axis wind rotors with 3 blades and straight-blades with a blade angle of θ=150° according to the tip speed ratio is shown. The optimum vertical axis wind rotor has been examined both with and without additional performance setup (APS) in order to make the rotor performance comparison. With the optimum vertical axis wind rotor without additional performance setup, the tip speed ratio is approximately 0.33, while the maximum power-coefficient has been obtained around

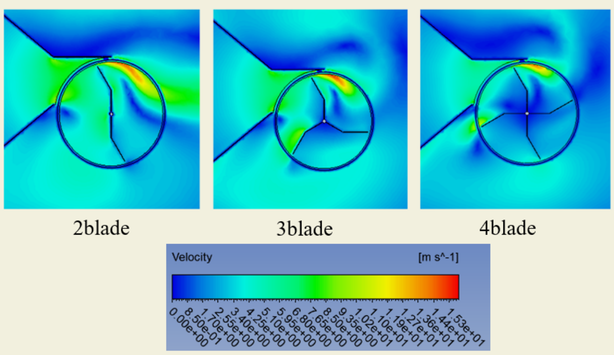


**Figure 8.** Velocity contours with different rotor blade numbers

0.043. With the optimum vertical axis wind rotor with additional performance setup, the tip speed ratio is approximately 0.40, while the maximum power-coefficient has been obtained around 0.114. Therefore, it has been determined that the power-coefficient obtained with the optimum vertical-axis wind rotor with additional performance setup has been increased approximately 2.6 times compared to the power-coefficient obtained without the additional performance setup.

The change of the torque-coefficients at the maximum power coefficients of the optimum vertical-axis wind rotors with and without additional performance setup is shown in Figure 10. It has been found that the best positive torque-coefficient values are obtained with the use of the straight blade rotor with the additional performance setup compared to the use without the additional performance setup. Thus, the torque-coefficient values of vertical axis wind rotors with straight blades have been improved.

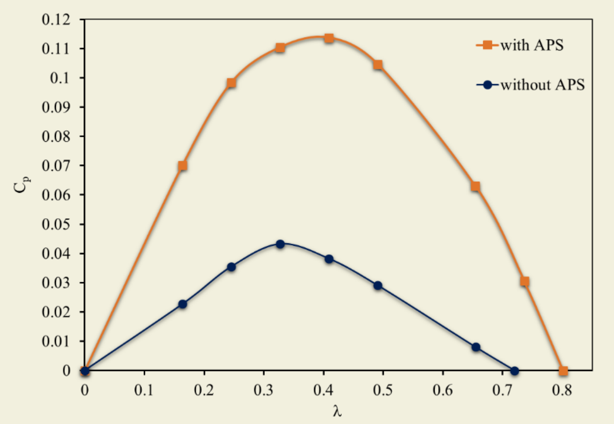


**Figure 9.** Variation of the power coefficients of the optimum straight blade vertical-axis wind rotor

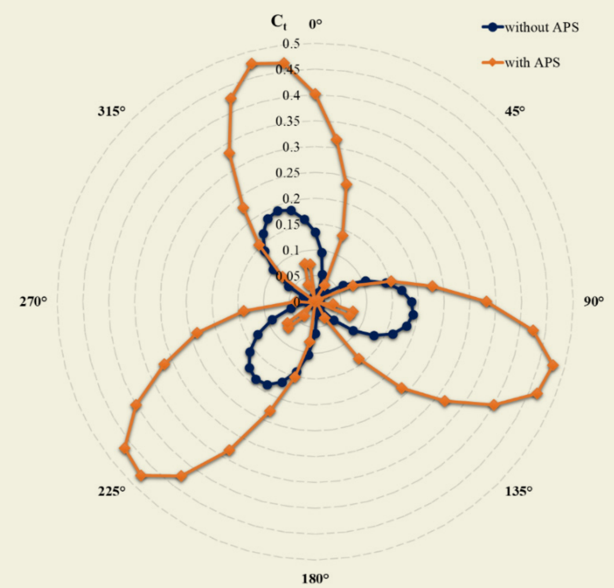


**Figure 10.** Variation of torque coefficients at the maximum power coefficients

## 4. Conclusions

In this research study, the performance of vertical axis wind rotors with straight blades with additional performance setup has been investigated. In this context, the effects of rotor design geometric parameters on rotor performance have been examined and the results obtained have been evaluated by comparing them with each other. Torque and power performance increase values have been determined for the best design parameters.

In this study;

- Optimum design geometric parameters have been found by examining the changes in torque-coefficients obtained from vertical axis straight bladed wind rotors with additional performance setup.
- The blade angle of the optimum vertical axis wind rotor has been determined as θ=150° and the number of blades as 3.
- It has been determined that the average torque-coefficient value obtained with straight 2-bladed rotors with θ=150° angle is approximately 1.2 times higher than the values obtained with θ=180° angled, straight 2-blade rotors.
- It has been determined that the average torque-coefficient value with the 3-blade optimum wind rotor is increased approximately 1.2 times compared to the 2-blade condition and 1.8 times compared to the 4-blade condition.
- It has been found that the power-coefficient of 0.114 obtained with the optimum vertical axis wind rotor with additional performance setup has been increased by approximately 2.6 times compared to the power-coefficient obtained from the additional performance setup.
- It has been found that the average positive performance values are increased by reducing the negative effect of the straight blade rotating against the wind, especially by using the vertical-axis wind rotor with straight-blades and additional performance setup.

With this study, it has been determined that the power-coefficient obtained with the optimum vertical-axis wind rotor with additional performance setup has been improved approximately 2.6 times compared to the power-coefficient obtained from the vertical axis wind rotor without additional performance setup. Thus, straight-bladed vertical axis rotors, which are unusable due to their very low efficiency, especially when used without an additional performance setup, will be transformed into highly efficient with additional performance setup, allowing them to be used in small-scale energy needs and to be widespread.

## 5. Nomenclature

| | |
|---|---|
| A | Rotor swept area |
| APS | Additional performance setup |
| CFD | Computational Fluid Dynamics |
| $C_p$ | Coefficient of power |
| $C_t$ | Coefficient of torque |
| D | Diameter of rotor |
| T | Torque produced by the rotor |
| V | Wind speed |
| $\lambda$ | Tip-speed ratio |
| $\rho$ | Air-density |
| $\theta$ | Angle of the straight blade |
| $\omega$ | Angular speed |

## 6. Declaration

There is no conflict of interest.

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