Journal of
Renewable Energy Research and Applications (RERA)

Vol. 4, No. 1, 2023, 13-19 *DOI: 10.22044/rera.2022.11282.1084*

Investigation of Arc Angle Rotor Blade Variations Effect of Savonius Vertical Axis Wind Turbine on Power and Torque Coefficients Using a 3D Modeling

M. Akhlaghi [1*] and F. Ghafoorian [2]

1. Assistant Professor, Manager, Turbomachinery Research Laboratory, Department of Energy Conversion, School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran.
2. MSc Student, Turbomachinery Research Laboratory, Department of Energy Conversion, School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran.

Received Date 09 October 2021; Revised Date 09 February 2022; Accepted Date 26 June 2022
**Corresponding author: mohammad.akhlaghi@iust.ac.ir (M. Akhlaghi)*

Abstract
An unacceptable air pollution leads to a remarkable increase in the consumption of renewable energy. Wind energy is known as one of the conventional renewable sources, and therefore, installation of wind turbines has increased over the past three decades. Savonius wind turbine is one of the types of vertical axis wind turbines. This type has many advantages, namely low noise, self-start capability, and closer spacing. Some studies have been carried out to increase the efficiency of wind turbines by optimizing the geometry. In the present work, the arc angle of Savonius turbine blades and its effects as one of the geometric parameters affecting the efficiency of the turbine have been investigated within a CFD method. The amount of arc angle, also called camber angle, is very effective in the optimal efficiency of Savonius wind turbine. In order to investigate this issue, three different arc angles in the different tip speed ratios are evaluated. The values of power and torque coefficients that play a vital role in the efficiency of the above turbine are considered with respect to the changes in the amount of three different arc angles. The results of 3D numerical solution show that the highest power and torque coefficients are obtained with values (0.0261) and (0.501) at a 180 degree arc angle, respectively. Adopting values other than the above value will cause a significant drop in the efficiency.

Keywords: *Vertical axis wind turbine, Savonius wind turbine, Arc angle, Power coefficient, Torque coefficient, Tip speed ratio.*

1. Introduction

The rising concerns about rising global warming and pollution of the environment and energy resources have boosted interest in renewable energy. Sources of clean fuels such as wind, solar, hydropower, geothermal, and biomass are alternatives to fossil fuels. The wind energy can be most appropriate. Wind energy is essentially free of NOx, SO_2 and other pollutants. Waste from traditional coal-fired power plants and nuclear fuel waste is very dangerous and polluted, which is not a problem in wind energy, and is significantly reduced. With the development of wind energy, they are also reducing their dependence on the fossil fuels, which are volatile in price and supply. Unprecedented growth in wind energy in 2009 became a world record, rising from 37 GWh to 158 GWh. Extracting mechanical force from the wind is an ancient practice that is at least 3,000 years old, and was first used in the shipping industry and gave technical insight to the humans. It was then used in windmills and the grain industry. Modern wind turbines can be classified into horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWTs) when considering the rotation axis of rotor blades [1]. Wind turbines have been widely used to generate electricity for urban consumption, and their economic viability has been investigated [2]. Today, most commercial wind turbines belong to the horizontal axis type, in which the axis of rotation of the blades is parallel to the wind flow. The advantages of this type of wind turbines include high turbine efficiency, high power density, speed drop in wind speed, and low cost for each power output unit [3]. In contrast to the vertical axis turbines, the blades of the vertical axis wind turbines rotate according to their vertical axes that are perpendicular to the ground. An important advantage of a vertical axis wind turbine is that the turbine can accept wind from any direction, and therefore, does not need a yaw control system [4]. Since the wind generator, gearbox, and other major turbine components can be mounted on the ground, it greatly simplifies the design and construction of the wind turbine, thus reducing the cost of the turbine. However, VAWTs must use an external energy source to rotate the blades in the initial stage [5]. Since the wind turbine shaft is only supported at one end at the ground level, its maximum practical height is limited. Due to their lower efficiency, VAWTs now make up only a small percentage of wind turbines. However, they have a lot of potential for growth [6]. It should be noted that modern wind turbines are evaluated in addition to the type of axis from other perspectives, which can be coastal or offshore types, upstream or downstream, and on-grid or off-grid. Turbines are also evaluated in terms of type of installation and foundation, which can be referred to single-pile, weight, and floating foundations, all of which can be used for vertical and horizontal axis turbines, depending on the situation [7]. Important types of vertical axis turbines include Darrieus and Savonius turbines. The Darrieus wind turbine, known as the egg stirrer due to its egg appearance, was invented in 1931 by George Darrieus. This VAWT is a high-speed and low-torque machine that is suitable for generating AC power [8]. In order to increase the efficiency of this type of turbine and reduce the initial torque, the geometry of the turbine is changed and optimized; one of the optimization methods include adding a winglet to the blades [9]. Darrieus turbines typically require some starting torque to start up. Although this torque is low, it is one of the disadvantages of this type of wind turbine; it should be mentioned that this turbine works with lift force [10]. Savonius turbine is a vertical axis turbine that Sigord Savonius invented this wind rotor in 1925. It is based on the drag force [11]. This turbine generally consists of two parts, concave and convex. The operation of the turbine is such that the wind exerts a force in its direction on the turbine blades. The reason for the rotation of the rotor is that the wind drag force is greater in the concave part than in the convex part. Due to high torque, it is suitable for applications such as pumping water from wells [3]. Another advantage of this type of rotor is that they do not need the initial torque; as mentioned, the basis of the work of this turbine was drag force. Unlike Darrieus turbines, they do not require initial torque, as a result they can be combined with Darrieus or helical turbines to increase efficiency and provide self-starting force [12]. Other vertical axis wind turbines that have recently been studied include the Gorlov helical vertical axis turbine, which was originally a cross-flow water turbine that operated with tidal currents, but today as a wind turbine has been put into operation [13]. Various parameters affect the performance of Savonius turbines. The number of blades has an important effect on the performance of the rotor, and this basic parameter has been investigated in the laboratory with wind tunnel, and the efficiency of the turbine in the presence of three or two blades has been evaluated [14]. Another study showed that the aerodynamic performance of the Savonius rotor was highly dependent on the dimensions and diameter of the blades, and by changing their size, the performance of the turbine and its efficiency has changed [15]. The effect of blade diameter on the Savonius turbine efficiency has also been studied experimentally [16]. Also a two-stage Savonius turbine was tested experimentally in a wind tunnel, and the presence and absence of upper and lower ending plates was evaluated on the turbine efficiency [17]. Another effective parameter in the efficiency of Savonius turbine can be the overlap ratio of the blades, which changes the efficiency and the amount of power and torque [18]. It is a known fact that the accessories such as end plates, shields, and guide vanes (smooth, curved) usually improve the performance of the Savonius rotor; however, all of these shapes have been found to increase the complexity of the rotor geometry [19]. Other experimental and numerical studies have shown that other methods and changes in geometry such as twisting spoons or designing multi-stage Savonius turbines, increase efficiency, which also increases the construction costs [20]. Another effective parameter in the operation and efficiency of the Savonius turbine is called the arc angle. This method is cheaper than the mentioned methods to increase the efficiency, and has acceptable economic benefits [21]. In an experimental and numerical study, all of the above optimization methods and their effects on the efficiency and power and torque coefficients, as well as a comparison of their advantages and disadvantages in a Savonius turbine, in general, are presented to provide an optimal geometry [16]. Two methods are used to analyze the aerodynamic performance of VAWTs. The first method is the multi-stream tube (MST) method that is a potential solution, and such 2D solutions are not able to satisfy the weak flow and turbulence behind the turbine [22]. This method is used by the Qblade software, which can be used to analyze the horizontal and vertical axis turbines

that work with lift force [23]. Also the enhanced method has been performed on huge Darrieus vertical axis turbine called Sandia, which is 17 m long, and the values of power and torque coefficients have been widened [24]. The second method, which is a very accurate method that simulates all the flows behind the turbine, is based on the Reynolds average Navier-Stokes equation (RANs) method or the Large eddy Simulation (LES) method, which is used by an analytical software such as Fluent or CFX [25]. Another numerical method includes the hot-wire test method, for example, the effect of increasing wind speed, and turbulence on the efficiency of a wind turbine has been investigated due this method [26].
In the present work, the effect of arc angle on the performance of a Savonius wind turbine is evaluated. For this purpose, numerical simulation based on computational fluid dynamics (CFD) method using CFX finite volume software is used, and two important parameters of power and torque coefficients are considered to evaluate the efficiency of the turbine.

2. Solution strategies and Vvalidation

As mentioned earlier, the arc angle is one of the most important parameters in the design of Savonius turbines. This angle is shown in figure 1 with the symbol φ.

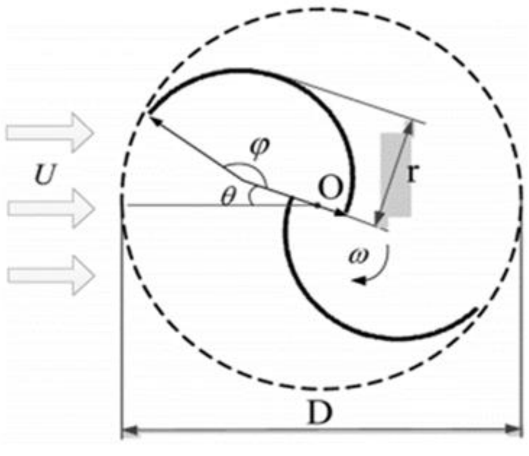


Figure 1. Arc angle in Savonius wind turbine.

In VAWTs, the two quantitative values of the power coefficient and the torque coefficient are indicative of the turbine efficiency, which are given in Equations 1 and 2, respectively.

$$C_p = \frac{P}{0.5 \times \rho \times A \times V_w^3} \qquad (1)$$

$$C_m = \frac{M}{0.25 \times \rho \times A \times V_w^2} \qquad (2)$$

where V is the wind speed entering the turbine blades, ρ is the air density (1,225 kg/m^3), P is the amount of power extracted from the turbine, A is the swept area by the turbine rotor, and M is the turbine torque. It is noteworthy that the two parameters of power and torque are calculated by the software and with the help of the above equations; the values of power and torque coefficients are obtained. The swept area and power values are obtained from equations 3 and 4, respectively.

$$A = D \times H \qquad (3)$$

$$P = T \times \omega \qquad (4)$$

where D is the diameter of the turbine rotor (m), H is the height of the turbine (m), T is the torque (N.m), and ω is the angle velocity (rad/s). To study the values of power and torque coefficients, first a specific geometry with exact dimensions was selected. The selected geometry was based on the turbine studied by Wenehenubun *et al*. [27], which was experimentally evaluated by a wind tunnel. The schematic image of the turbine is shown in figure 2, and the dimensions and size specified in figure 2 are shown in table 1.

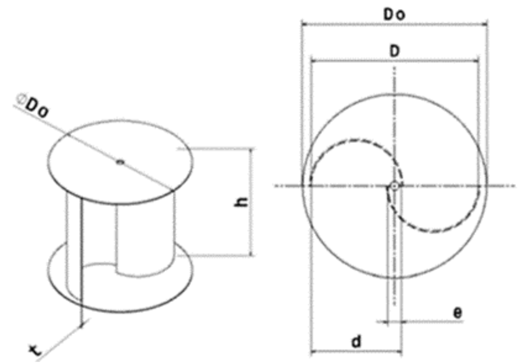


Figure 2. Schematic representation of studied turbine.

Table 1. Dimensions of turbine.

	Quantity	Value
1	Diameter of plate (Do)	407 (mm)
2	Diameter of rotor (D)	370 (mm)
3	Diameter of blade (d)	200 (mm)
4	Gap (e)	30 (mm)
5	Height of rotor (h)	370 (mm)

According to the exact dimensions of the studied turbine, the geometry was drawn and meshed for the numerical analysis. Based on the experimental study and to validate the numerical solution, the conditions defined in the wind tunnel test including boundary and initial conditions are determined in the CFX software. The inlet wind speed is equal to 7 m/s, and all boundaries of the computational domain except the inlet section is considered as the boundary condition of the open boundary with a pressure of 1 atm [27]. The turbulence model is considered the k-omega standard. It should also be noted that the transient solution is considered for this numerical simulation. The steps performed for numerical simulation including the number of rotations (rpm) and the angular velocity (rad/s) in the specified TSRs are given in table 2.

Table 2. Dimensions of turbine.

Quantity (Unit)	ω (rad/s)	N (rpm)	TSR
1	3.72	36	0.108
2	13.76	132	0.400
3	17.82	170	0.518

By knowing TSR, considering the rotor radius and with the help of the following mathematical equation, the relation between the angular velocity (rad/s) and the number of turbine rotations (rpm) have been determined as:

$$N = \frac{30 \times \omega}{\pi} \quad (5)$$

where N is the number of turbine rotations (rpm) and ω (rad/s) is the angular velocity that must be considered in the initial condition settings. In order to analyze the power and torque coefficients, the need to calculate these coefficients in each TSR has been determined. This dimensionless parameter is calculated with the following equation:

$$TSR = \frac{R \times \omega}{V_w} \quad (6)$$

where V_w is the assumed the input wind speed.
After placing the values of table 2 as the initial operating conditions of the turbine and problem analysis based on the CFD solution for the three TSRs, the results were compared with the experimental results of Wenehenubun et al. to validate the numerical analysis [27]. The diagram is shown in figure 3.

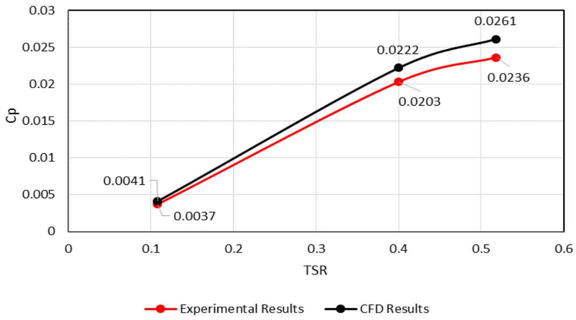


Figure 3. Comparison of numerical and experimental results of C_p on TSR for validation.

As it can be seen in figure 3, the results of the numerical solution are reasonably close to the results of the experimental study, and have been validated with an error of less than 8%. This has shown that the numerical solutions and simulations are reliable. The next important step after validation has been done to solve the problem of meshing accuracy. Meshing is one of the most important simulation tools to achieve a high accuracy and prevent the lack of convergence. A grid independence study should be conducted. It should be noted that to improve the accuracy of the solution the boundary layer mesh around the blades is used to prevent the sudden growth of the mesh layers and increase the accuracy of the solution. Figure 4 shows the mesh for the base position, i.e. the arc angle of 180.

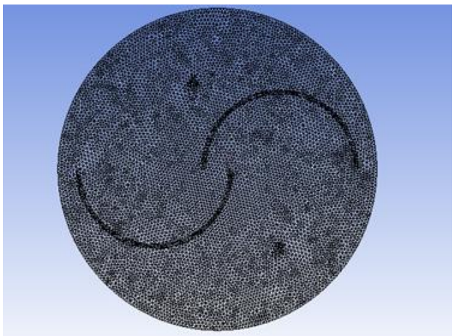


Figure 4. 2D turbine with mesh.

The number of grids was reduced to achieve about five million nodes. The values obtained for the power coefficient in the number of different meshes are not significantly different, thus it could be claimed that the solution has a suitable accuracy, and proper meshing has been done. The graph of C_p variations for TSR of 0.4 in the number of different grids is shown in figure 5.

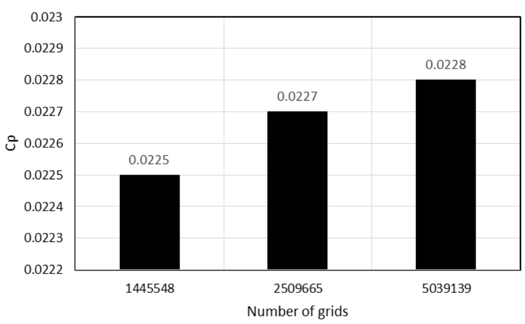


Figure 5. Grid independent solution diagram.

Figure 6 also shows a 3D image of a Savonius turbine in computing domain in the CFX software. In this shape, the inlet boundary condition is shown in blue and the output (opening) boundary condition is displayed in black.

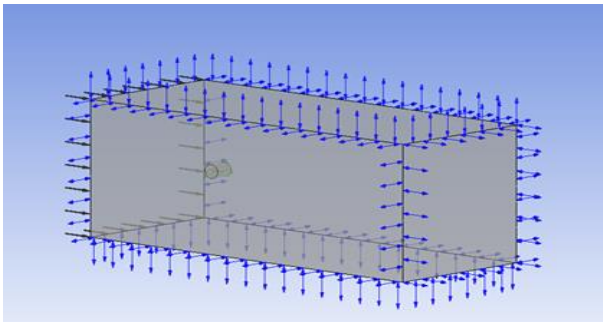
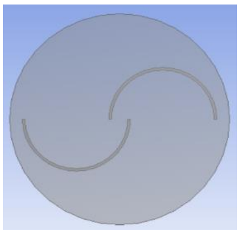


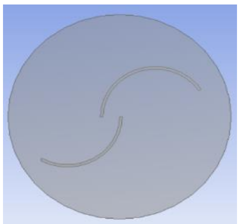
Figure 6. Schematic of the rotor and computational domain (stator).

3. Effect of arc angle

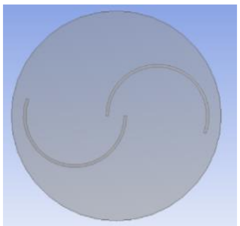
As mentioned earlier, various parameters are effective in the operation of Savonius turbines, one of which is the arc angle of the blades. In this work, the diameter of the rotor and the blade is assumed to be constant, and only the value of the arc angle for the three values of 180°, 150°, and 200° is examined. The diagrams of power and torque coefficients were evaluated in terms of different TSRs for all the three angles. In order to determine in which case and at which arc angle the maximum values of power and torque coefficients are obtained and better efficiency is achieved, the top view of the turbine with the various arc angles shown in figure 7.



A



B



C

Figure 7. 2D view of turbine with different arc angles. A) φ = 180°, B) φ = 150°, and C) φ = 200°.

As mentioned above, the values of diameter length, overlap angle, and blades diameter are all constant; only the arc angle in each shape is changed. It should be noted that for the calculation, the number of rotations (rpm) and the angular velocity (rad/s) in different TSRs are considered exactly as the contents of Table 2. This helps to accurately evaluate the C_p and C_m values in similar TSRs. In Figures 8 and 9, for all three arc angles, the power factor and torque coefficients are plotted in terms of TSR, respectively.

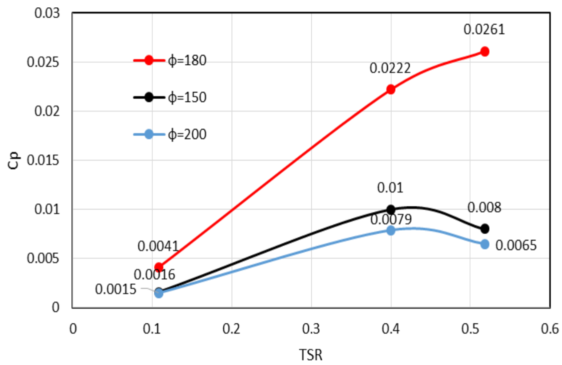


Figure 8. C_p in terms of TSRs for different arc angles.

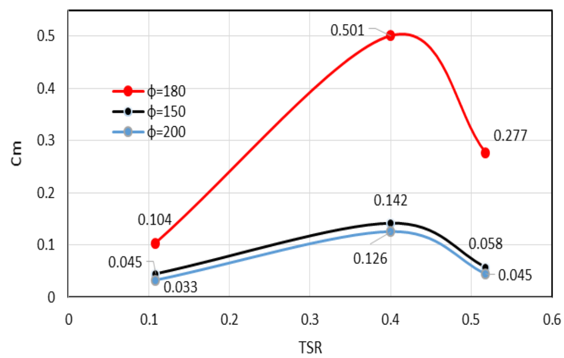


Figure 9. C_m in terms of TSRs for different arc angles.

As shown in figures 8 and 9, the best arc angle for turbine rotor design is 180°. Under these conditions, the highest values for C_p and C_m were obtained, which indicates the highest efficiency in this case. It is also clear that the C_p and C_m values are not always increasing, and the efficiency start decreasing at a special TSR.

4. Discussion and conclusion

In the research work that was conducted, firstly, the wind turbines and the importance of this power generating device were briefly discussed, and then the VAWTs were introduced, and since the turbine studied was the Savonius rotor, this turbine was briefly introduced, and its performance and benefits were discussed. Then in order to orient the subject, the existing ways to increase the efficiency of Savonius turbines were examined and explained, and one of the approaches, which was a change in the amount of arc angle, was selected for analysis. Before entering the simulation, the existing methods for numerical analysis of wind turbines were discussed, and the advantages and disadvantages of each were considered. Since the RANs equation was more accurate than the other methods, it was selected for the present work. As the power and torque coefficients were important parameters for all researchers to compare the efficiency of all wind turbines, both horizontal and vertical axes, these critical parameters were studied in different TSRs for the three arc angles of 150, 180 and 200 degrees. The results were reported graphically. These results indicated that in similar TSRs, the maximum values of C_p and C_m were obtained in 180 degrees. It is noteworthy that by considering values greater or less than 180 degrees, the values of power and torque coefficients were significantly dropped.

5. References

[1] S. L. Dixon and C. A. Hall, Fluid mechanics and thermodynamics of turbomachinery, Seventh edition. Amsterdam ; Boston: Butterworth-Heinemann is an imprint of Elsevier, 201
4.

[2]R. Alayi, S. R. Seyednouri, M. Jahangiri, and A. Ma'arif, "Optimization, Sensitivity Analysis, and Techno-Economic Evaluation of a Multi-Source System for an Urban Community: a Case Study," p. 10.

[3]M. M. Aslam Bhutta, N. Hayat, A. U. Farooq, Z. Ali, Sh. R. Jamil, and Z. Hussain, "Vertical axis wind turbine – A review of various configurations and design techniques," Renewable and Sustainable Energy Reviews, Vol. 16, No. 4, pp. 1926–1939, May 2012, doi: 10.1016/j.rser.2011.12.004.

[4] A. Alaimo, A. Esposito, A. Messineo, C. Orlando, and D. Tumino, "3D CFD Analysis of a Vertical Axis Wind Turbine," Energies, Vol. 8, No. 4, pp. 3013–3033, Apr. 2015, doi: 10.3390/en8043013.

[5] S. Brusca, R. Lanzafame, and M. Messina, "Design of a vertical-axis wind turbine: how the aspect ratio affects the turbine's performance," Int J Energy Environ Eng, Vol. 5, No. 4, pp. 333–340, Dec. 2014, doi: 10.1007/s40095-014-0129-x.

[6] N. M. Ali, "The Effect of Darrieus and Savonius Wind Turbines Position on The Performance of The Hybrid Wind Turbine at Low Wind Speed," p. 17.

[7] J. Velarde, C. Kramhøft, and J. D. Sørensen, "Global sensitivity analysis of offshore wind turbine foundation fatigue loads," Renewable Energy, Vol. 140, pp. 177–189, Sep. 2019, doi: 10.1016/j.renene.2019.03.055.

[8] O. S. Mohamed, A. A. Ibrahim, A. K. Etman, A. A. Abdelfatah, and A. M. R. Elbaz, "Numerical investigation of Darrieus wind turbine with slotted airfoil blades," Energy Conversion and Management: X, Vol. 5, p. 100026, Jan. 2020, doi: 10.1016/j.ecmx.2019.100026.

[9] S. S. Dol, A. Khamis, M. T. Abdallftah, M. Fares, and S. S. Pervaiz, "CFD Analysis of Vertical Axis Wind Turbine with Winglets," Renewable Energy Research and Applications, 2021, doi: 10.22044/rera.2021.11122.1074.

[10] B. Hand, "A review on the historical development of the lift-type vertical axis wind turbine_ From onshore to offshore floating application," Sustainable Energy Technologies and Assessments, p. 11, 2020.

[11] R. D. Maldonado, "Design, Simulation and Construction of a Savonius Wind Rotor for Subsidized Houses in Mexico," Energy Procedia, p. 7, 2014.

[12] A. Pallotta, D. Pietrogiacomi, and G. P. Romano, "HYBRI – A combined Savonius-Darrieus wind turbine: Performances and flow fields," Energy, Vol. 191, p. 116433, Jan. 2020, doi: 10.1016/j.energy.2019.116433.

[13] V. Jayaram, "A brief review on the Gorlov helical turbine and its possible impact on power generation in India," Materials Today, p. 9.

[14] M. H. Ali, "Experimental Comparison Study for Savonius Wind Turbine of Two & Three Blades At Low Wind Speed," Vol. 3, No. 5, p. 9, 2013.

[15] M. Zemamou, M. Aggour, and A. Toumi, "Review of savonius wind turbine design and performance," Energy Procedia, vol. 141, pp. 383–388, Dec. 2017, doi: 10.1016/j.egypro.2017.11.047.

[16] I. B. Alit, "Effect of Overlapping Ratio, Blade Shape Factor, and Blade Arc Angle to modified Rotor Savonius performances," Vol. 13, No. 1, p. 6, 2018.

[17] N. Mishra, A. Jain, A. Nair, B. Khanna, and S. Mitra, "Experimental Investigation on a Ducted Savonius Vertical Axis Wind Turbine and its Performance Comparison with and without Endplates," Renewable Energy Research and Application, Vol. 1, No. 1, Nov. 2019, doi: 10.22044/rera.2019.8533.1005.

[18] M. Ebrahimpour, R. Shafaghat, R. Alamian, and M. Safdari Shadloo, "Numerical Investigation of the Savonius Vertical Axis Wind Turbine and Evaluation of the Effect of the Overlap Parameter in Both Horizontal and Vertical Directions on Its Performance," Symmetry, Vol. 11, No. 6, p. 821, Jun. 2019, doi: 10.3390/sym11060821.

[19] D. Borzuei, S. F. Moosavian, and M. Farajollahi, "On the Performance Enhancement of the Three-Blade Savonius Wind Turbine Implementing Opening

Valve," Journal of Energy Resources Technology, p. 11.

[20] U. K. Saha, S. Thotla, and D. Maity, "Optimum design configuration of Savonius rotor through wind tunnel experiments," Journal of Wind Engineering and Industrial Aerodynamics, Vol. 96, No. 8–9, pp. 1359–1375, Aug. 2008, doi: 10.1016/j.jweia.2008.03.005.

[21] Z. Mao and W. Tian, "Effect of the blade arc angle on the performance of a Savonius wind turbine," Advances in Mechanical Engineering, Vol. 7, No. 5, p. 168781401558424, May 2015, doi: 10.1177/1687814015584247.

[22] M. Moghimi and H. Motawej, "Developed DMST model for performance analysis and parametric evaluation of Gorlov vertical axis wind turbines," Sustainable Energy Technologies and Assessments, Vol. 37, p. 100616, Feb. 2020, doi: 10.1016/j.seta.2019.100616.

[23] J. V. Akwa, H. A. Vielmo, and A. P. Petry, "A review on the performance of Savonius wind turbines," Renewable and Sustainable Energy Reviews, Vol. 16, No. 5, pp. 3054–3064, Jun. 2012, doi: 10.1016/j.rser.2012.02.056.

[24] A. Hosseinkhani and S. Sanaye, "Performance Prediction of a SANDIA 17-m Vertical Axis Wind Turbine Using Improved Double Multiple Streamtube," Vol. 14, No. 12, p. 5, 2020.

[25] Q. Li, "Effect of number of blades on aerodynamic forces on a straight-bladed Vertical Axis Wind Turbine," p. 12, 2015.

[26] J. Taghinezhad, E. Mahmoodi, M. Masdari, and R. Alimardani, "Spectral Analyses of an Optimized Ducted Wind Turbine Using Hot-wire Anemometry," Renewable Energy Research and Application, doi: 10.22044/rera.2021.10938.1060.

[27] F. Wenehenubun, "An Experimental Study on the Performance of Savonius Wind Turbines Related With The Number Of Blades," Energy Procedia, p. 8, 2015.