Experimental Investigations on the Performance Characteristics of a Modified Four Bladed Savonius Hydro-Kinetic Turbine

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Abstract:- Torque variation along the angular positions of the rotor blade and lower efficiency are the main drawbacks of Savonius turbine. To overcome these problems several attempts have been made by the researchers in the recent past. In this work, an attempt has been made to increase the torque along the angular positions where the torque is low, by placing a set of additional blades called secondary blades in front of the concave side of main rotor blades. These secondary blades are interacting with the flowing fluid when the main blades are not in action. The performance of the modified Savonius turbine is compared with the conventional single blade 0 overlap and 0.2 overlap Savonius turbines, by carrying out the experiments in the open irrigation canal of size 42 cm x 45 cm. Results shows that, the efficiency is improved from 16 % to 19% and the torque values increased along the angular positions of 90°, 120°, 270°, 300°, 330°. From the observations, it has also been noted that, the modified four bladed Savonius turbine rotates smoothly in comparison with the conventional Savonius. The negative torque a common problem in conventional Savonius is also effectively eliminated in the modified design.

Keywords Savonius Rotor; Hydro-kinetic Turbine; Coefficient of Torque; Coefficient of Power; Overlap Ratio; Blade Aspect Ratio; Tip Speed Ratio.

1. Introduction

Energy from wind, solar, hydro ocean currents, ocean waves and tidal are considered as renewable energy sources, whereas the energy from coal, oil, gas and nuclear are considered as non renewable energy which are essentially stored as stocks in the earth. The use of renewable energy reduces the emission of green house gases also helps in meeting out the energy demands of the future. Hydrokinetic turbines are the low head hydro turbines converts kinetic energy of the flowing water into mechanical energy. The wind turbines and hydrokinetic turbines are working on the same principle of operation except the varied range of speed. Wind turbines operate in the range of 11-13 m/s, whereas hydro-kinetic turbines operate in the range of 1.75-2.25 m/s water velocity [1].

Islam et al.,[2] have studied the potentiality of small-scale hydro power plants at Gumati and Surma rivers of Bangladesh and observed that the hydrokinetic turbines have greater potential in the power generation and the kinetic energy possessed by the flowing water might be of greater source of energy for rural areas.

Turbines which convert energy from the flowing water are termed in various names such as water current turbine, ultra low head hydro turbine, free flow stream turbine and zero head hydro turbine. The stream hydro turbine, basically a river current energy conversion system is also commonly called as Savonius turbine in the name of the inventor. Savonius is simpler in design, has less moving parts and hence low noise and cost [3]. Generally the Savonius turbines lacked with poor efficiency and torque variation along angular position of the rotation. So for several attempts have been made by researchers to improve the coefficient of performance and torque variation of the turbine.

In general, the Savonius turbines are made by assembling two cut halves of hollow cylindrical metallic parts with end plates. This simplest turbine with two blades and no overlaps between them produces less efficiency than the other types of turbines. Several turbines have been fabricated and tested with the modified design to improve its performance characteristics. In the past few decades, researchers have designed their turbines by varying parameters like blade number, blade profile, blade shape factor, blade arc angle, end blades, deflectors and curtain arrangement. To verify the improvements in the performance characteristics, turbines are made with and without shafts.

From the literatures, it can be seen that more number of blades in a turbine resulted less efficiency and vice versa. Mutual interference between the blades is the reason for the poor efficiency in the turbines with more blades. Each blade in the three and four blade Savonius reflect the water on the concave side of the other balde.This water reflection cause the negative torque which reduces the efficiency of the rotor. Alexander et.al.[4] have reported that 3 bladed Savonius rotor is 30 % less efficient than 2 bladed rotor and four blade Savonius 50% less efficient than 2 bladed rotor. Saha et al. [5] have found that coefficient of power decreases with the increase in number of blades. Zhao et al [6] have conducted numerical investigation by changing number of blades in Savonius rotor, and found that 0.165 and 0.12 as coefficients of power with two blades and three blades Savonius respectively.

Overlap is the small passage between the blades which increase the positive torque by allowing small quantity of fluid from concave side of the advancing blade to concave side of the returning blade, so that the pressure difference between the blades reduced [6]. Alexander and Holownia [7] found that overlap ratio between 0.2-0.3 provide the maximum co-efficient of power in their work. Fujiswa et al. [8] and Blackwell et.al [9] have observed through their experiments that, the optimum overlap lies between 0.1 and 0.15 for better efficiency.

Blade profile plays a vital role in the enhancement of power coefficient. Authors [10] have observed better power coefficient, during the reduction of drag coefficient on convex side of the returning blade and gaining of drag coefficient on concave side of advancing blade. The authors have also observed that, higher power coefficient in bach type rotor in comparison with classical and elliptical types of rotors. Sansui [11] found that combined blade made up of conventional and elliptical Savonius rotor shown better stability, improved efficiency than the conventional and elliptical blade. According to Roy et al., [12] a modified wind turbine showed higher performance gain and self starting gain than the bach, bench, semi elliptical and conventional designs.

Increasing aspect ratio significantly increases the coefficient of power, since the higher aspect ratio blades permits to utilize more quantity of working fluid. Poor efficiency was observed with a low aspect ratio (1.2) turbine blades whereas blades with higher aspect ratio (4.2) shown a better efficiency (up to a value of 0.243) [7]. Mahmoud et al. [13] have tested various Savonius turbines with different aspect ratios (values ranging from 0.5 to 5) and observed increase in power coefficient value as the increase of aspect ratio.

Multiple stages of Savonius turbine can be used to reduce the torque variation along the angular position of the rotor. Single stage Savonius rotor shows more static and dynamic torque variations due to variable quantity of fluid strike the projected area of the rotor. Each blade in the various stages significantly reduces the torque variation by receiving fluid in the equal interval so that the variation is less compared to the single stage rotor. Double stage Savonius rotor shows better performance even in low velocity of water [14]. Hayashi et al. [15] and Rus et al. [16] have tested both single and multi stages rotors and found multi stage rotors show less fluctuation of dynamic torque coefficient than the single stage rotor.

An end plate can slightly improve the performance characteristics of the turbine by preventing the flow from the blades. Both top and bottom blades help to keep the fluid inside as well as increase the pressure to a satisfactory level. It has been observed that, rotor with end plate increases the efficiency compared to the rotor without end plate [14]. Jeon et al. [17] have noticed a 36% improvement in efficiency on a rotor with the end plates in comparison on a rotor without end plates.

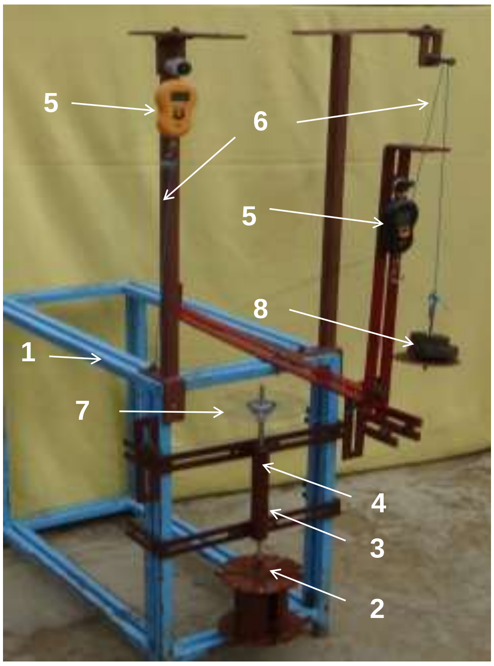
Kamoji et al.[18] have tested the turbine with and without shafts between endplates and found blades without shaft between endplates shown improved efficiency but lacks rigidity. Turbine characteristics can also be improved by using deflectors which reduces drag forge on the convex side of the returning blade. Deflectors not only prevent the flow it also orient and concentrates the flow on concave side of the advancing blade. Golecha et al. [19] reported that single stage Savonius rotor with deflector shows 50% improvement in coefficient of power than the rotor without deflector.

Lee et al. [20] performed numerical and experimental investigation on helical Savonius with various twist angles of 0°, 45°, 90° and 135° and reported helical angle of 45° shown higher efficiency and between the angles 90°, 135° appeared to produce lower efficiency. The unique features of each turbine utilized when it is combined with the other turbine. High starting torque characteristics of the Savonius turbine used to start the Darrieus turbines [21].

In this work, an attempt has been made to develop a modified four bladed Savonius turbine to enhance the moment and power characteristics. This modified Savonius consists of two conventional blades and two modified blades. The secondary blades placed in front of the conventional blades for receiving the fluid on that negative torque region. These secondary blades added to receive the flow as well as deflect the flow on concave side of the advancing blade.

2. Experimental Details

The experimental setup is shown in Fig. 1. The experimental setup is designed and fabricated like a table using metallic channels. In order to accommodate all necessary components such as rotors, weighing pan, rotatable angular disk, rotor shaft, rotor holding attachment and other necessary components, number of slots are provided in the metallic channels, as shown in Fig. 1.



1.Base 2.Savonius rotor
3.Shaft holding device 4.Shaft
5.Weighing scale 6.Nylon rope
7.Rotating slotted angular disk
8.Weighing pan and weights

Fig.1 Fabricated Experimental setup

Two vertical rods assembled on the table to hold the digital weighing scale and weighing pan which are necessary to execute a dynamic analysis. To perform static analysis an inelastic fishing nylon string used. One end of the nylon string connected to digital weighing scale and another end is connected to rotors end plate. Few slots which are small in size are provided on the end plates to accommodate the nylon string for measuring tangential force of the rotor. The static torque is calculated from the measured tangential force. Slots are made at an interval of 30 degrees on the outer periphery of the rotor end plates. Proper fastening of rotor shaft is achieved by adjusting the fasteners with correct location and sufficient tightness. The slots, studs and fasteners in the table help to position the rotor shaft in the canal. Digital laser tachometer is used to measure the speed of the rotor. Digital weighing scale is shown in Fig.1 which is used to measure static torque of the rotor. Dynamic characteristics of the rotor are measured by varying the load acting on the rotor. The load is varied gradually on the weighing pan than the corresponding speed of the rotor measured with the help of digital laser tachometer. Water velocity is measured from the rising of water level in the U-tube monometer and stagnation tube and the measure water velocity is used for the further calculations.

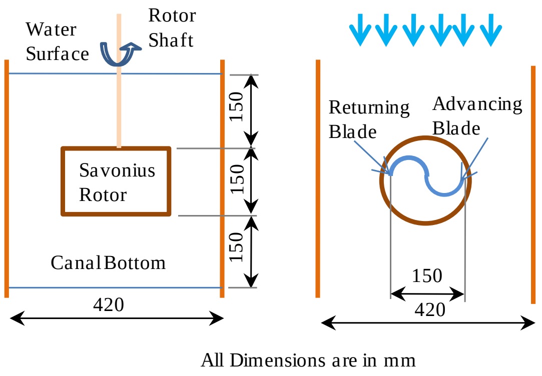
The fabricated modified Savonius turbine is placed centrally in the open irrigation water canal. The cross sectional area of the canal is 42 cm x 45 cm. This irrigation canal is one of outlets in the Krishnagiri Reservoir Project (KRP dam) which is situated in the Krishnagiri district of Tamil Nadu. South India. The photograph of the canal and the experimental setup in the canal is shown in Figs. 2(a) and 2(b).

(a) Irrigation canal

(b) Setup in canal

Fig.2. Photograph of the irrigation canal and the setup in the canal

For the sake of clarity a schematic of Savonius turbine facing the water front is shown in Fig. 3(a) and 3(b).



(a)Front view (b) top view

Fig. 3 Schematic view of the experimental setup

It can be noted that the rotor is positioned at 150 mm above the ground level and 150 mm below the level of water flow. This way of positioning the rotor, it is made sure that, the rotor is fully engaged with the flowing water. This can be seen in Fig. 2(b). The average water velocity in water channel is found to be 0.82 m/s.

3. Rotor configurations

Various angular positions of rotor configuration of a conventional turbine with 0 overlap is shown in Fig. 4. The acronyms AB and RB represent advancing blade and returning blades respectively.

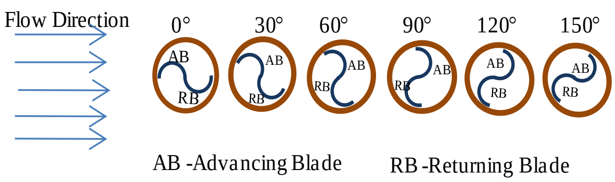
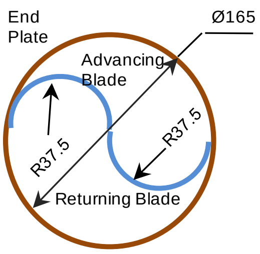
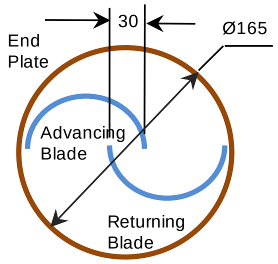


Fig. 4 Angular position of rotor

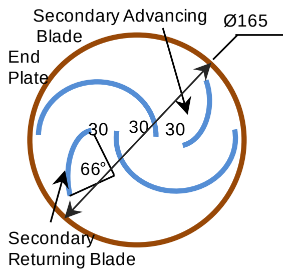
In this comparative experimental study, three types of Savonius rotors made of 1 mm steel sheets are used. Two rotors are of conventional Savonius types with an arc angle of 180° and overlap ratios of 0 and 0.2 respectively. Initially turbines with 0 and 0.2 overlap ratio configurations are tested in the canal and observed an improper rotation of rotors at certain angles. This reason may be due to negative torque experienced by the rotors as already reported in certain literatures. The starting ability of the conventional Savonius rotors is particularly poor between these angles.



(a) 0 overlap Savonius



(b) 0.2 Overlap



(c)Modified four blade Savonius

Fig. 5 Rotor Configuration of existing and modified Savonius turbine

The schematic of 0 and 0.2 overlap Savonius are shown in Figs. 5(a) and 5(b). The negative torque produced in the conventional turbines is found to be between 100° and 160°. To overcome this problem a modified four bladed Savonius rotor chosen was designed as shown in Fig. 5(c). In this modified design two blades (primary blades) are made similar to conventional Savonius with an overlap ratio of 0.2. The other two blades are positioned in front of the primary blades, is called as secondary blades. These secondary blades are designed to receive the fluid in the negative torque region of the conventional Savonius.

The geometric configuration of new four blade Savonius rotors with an arc angle of 99° and chord length of 6.5 cm shown in Fig 5(c). A small gap provided between the primary and secondary blades. To understand the effect of this gap, a space of 20 mm at one side and 30 mm at the other side of rotor is provided.

4. Results and Discussion

The performance of any water turbine is measured in terms of torque coefficient and power coefficient. The ratio between the actual torque developed by the rotor and theoretical torque available in the water is known as to *torque coefficient*, usually denoted by C_t, whereas the ratio of maximum power obtained from rotor and the total power available in the water is known as *power coefficient*, C_p. Coefficient of torque is the important parameter to decide the self starting ability of the rotor. There is no need of external starter to rotate the rotor if the rotor produces positive torque co efficient along the angular position of the rotor. The negative coefficient of torque indicates that the rotor won't start to rotate. Here classical Savonius rotor with 0 overlap shows negative torque in the angular region of 100°-160° and 280°-340° represented as blue line with filled circles as shown in Fig. 6. Between these angular positions the rotor simply oscillates, because of the drag force acts equally on both sides of the rotor.

Higher pressure difference must be required between the advancing blade and the returning blades to rotate the rotor continuously. From this negative torques, it is evident that the pressure difference between the advancing blade and returning blade is very less. The coefficient of torque increases from 0° - 40° than it reduces up to 160°. From the Fig.6, it can be seen that, the static coefficient of torque against the angular position appears to be sine curve.

The negative torque can be eliminated either by increasing the drag force on advancing blade or reducing the drag force on returning blade. Higher pressure difference between the blades also eliminates the negative torque. The negative torque coefficient is slightly improved with 0.2 overlap Savonius in comparison with 0 overlap configuration. The gap between the blades allows the fluid to strike the concave side of the returning blade. This overlap effectively used to increase the positive torque. It can be seen from the red line with filled squares in the Fig. 6.

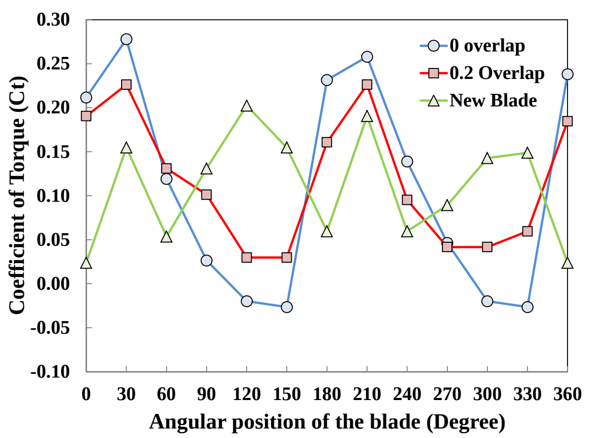


Fig. 6 Variation of coefficient of torque with angular position of rotor

The Coefficients of static torque against angular position obtained by the 0.2 overlap Savonius which is similar to 0 overlap Savonius except the negative torque region. Here an attempt is made to stabilize the Savonius static torque coefficient. Lack of fluid interaction with the rotor and high negative drag force are the major causes for the large torque variation. Large torque variation may increase the cyclic stress and reduce the reliability of rotor shaft. Conventional three and four bladed Savonius reduce the torque variation, at the same time it reduces the power coefficient.

In this work, a new four blade Savonius is designed to receive the fluid equally throughout the angular position in order to that the torque variation. From the results, it can be noticed that, an increase in torque value with the modified Savonius, in the angular region between 90°-160° and 260°-340° in comparison with the 0 and 0.2 overlaps of conventional types. The reason for the increased torque value is achieved due to the introduction of secondary blades in these angular positions.

However the torque values of modified Savonius is less than the classical Savonius (0 overlap) in the regions between 340°-60° and 180°-240°. It may be due to less quantity of fluid strike the blades and produces less drag force. The maximum coefficient of torque (0.20) is observed at the angle of 120° in the modified Savonius and this can be seen from Fig. 6. This value of torque is certainly a lesser value compared to conventional 0 overlap rotor whose torque coefficient is found to be 0.27. In spite of lesser torque coefficient with modified Savonius, the value of torque variation is very small and no negative torque is observed. For clear visualisation, a polar chart of static torque coefficient variation in relation with angular positions of rotor is given Fig. 7

The performance of Savonius turbine can also be expressed in terms of torque coefficient and power coefficient in relation with tip speed ratio (TSR) commonly denoted by λ. The tip speed ratio is the ratio between the blade speed to the water velocity.

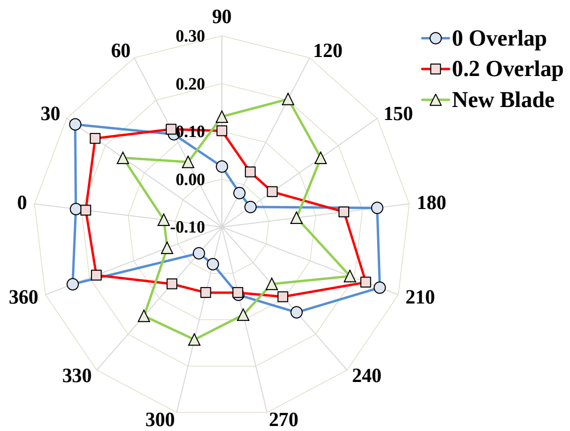


Fig. 7 Variation of coefficient of torque – Polar Frame

Many researchers have reported that, the conventional four blade and three blade Savonius highlights less torque variation along the angular positions of rotor and poor power coefficient compared to the two blade Savonius. The poor power coefficient in the turbine with more blades is resulted due to the reflection of fluid back to the previous blades. Fluid reflection and lack of fluid exit between the blades causes lower efficiency.

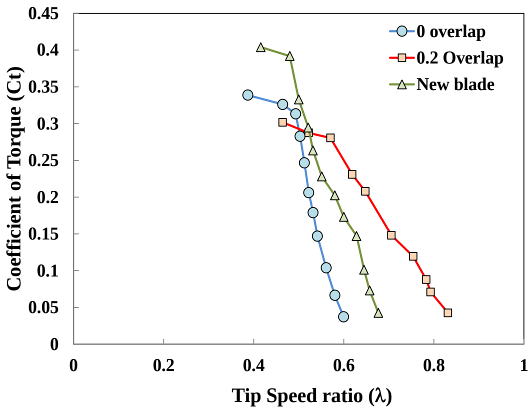


Fig. 8 Variation of coefficient of Torque with tip speed ratio

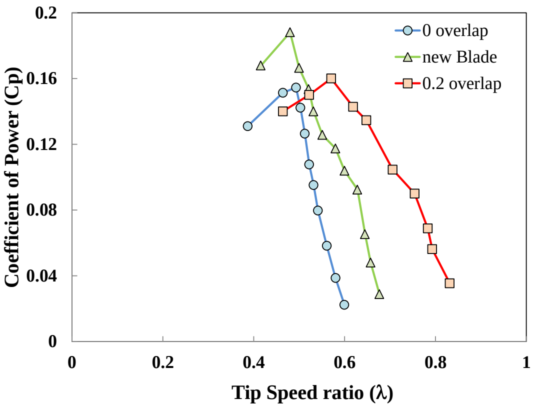


Fig. 9 Variation of coefficient of power with tip speed ratio

In order to mitigate the problem of poor efficiency, here in the modified design a 0.2 overlap is provided in the primary blades. The secondary blades are also provided a small overlap with the primary blades. Providing such an overlap is an attempt to reduce the variation in the torque production and improve the turbine efficiency compared to the conventional two rotor Savonius.

It is evident that secondary blades in the new design significantly increase the torque in the lower torque regions. This can be seen from the Fig. 6. An improved torque coefficient value of 0.42 can also be seen in comparison with 0 and 0.2 overlap turbines from the Fig. 8.

The conventional four blade turbine normally shows poor efficiency due to the experience of positive drag in the first half revolution and negative drag in the second half revolution of the blades. In the modified four bladed Savonius the secondary blades are placed in front of the primary blades, so that it does not experience the negative drag force. This is the reason new modified four blade Savonius shows 19% efficiency, which is higher than the two blade Savonius shown in Fig .9.

5. Conclusion

In this work, a modified Savonius turbine is designed, fabricated and tested, the performance characteristics are measured in comparison with conventional 0, and 0.2 overlap ratios Savonius turbines.

- Fluid which is pass through the overlap from concave side of the advancing blade to convex side of the returning blade reduces the reverse torque so that negative torque is eliminated in this region as well as the maximum pressure difference is maintained between the blades.
- The Savonius turbine with 0.2 overlap ratio shows better torque and power characteristics than the 0 overlap ratio turbine. The overlap not only eliminates the negative torque it also increase the speed of the rotor.
- Modified Savonius rotor does not show any negative torque along the angle of rotation, so its self starting.
- Static torque along the angular position is also improved, in comparison with the conventional Savonius.
- This modified Savonius shows less torque variations along the angular position of the rotor.
- Modified design produced maximum efficiency of 19% at the tip speed ratio of 0.5, which is higher than the two blade classical Savonius.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References

[1] Khan, M. J., Iqbal, M. T. and Quaicoe, J. E., “River current energy conversion systems: progress, prospects and challenges”, *Renewable and Sustainable Energy Reviews*, Vol. 12(8), pp. 2177-2193, 2008.

[2] Islam, M. S., Gupta, S. D., Raju, N. I., Masum, M. S., and Karim, S. A., "Potentiality of small-scale hydro power plant using the kinetic energy of flowing water of Gumoti & Surma river of Bangladesh: an energy odyssey" *International Journal of Renewable Energy Research*, Vol. 3(1), pp. 172-179, 2013.

[3] Savonius, S. J., “The S-turbine and its applications”, *Mechanical Engineering*, Vol. 53(5), pp. 333–338, 1931.

[4] Alexander, A, J. and Holownia, B. P., Wind tunnel tests on a Savonius rotor, *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 3(4), pp. 343-351, 1978.

[5] Saha, U. K., Thotla, S. and Maity, D., "Optimum design configuration of Savonius rotor through wind tunnel experiments", Journal *of Wind Engineering and Industrial Aerodynamics*, Vol. 96(8), pp. 1359-1375, 2008.

[6] Zhao, Z., Zheng, Y., Xu, X., Liu, W. and Hu, G., "Research on the improvement of the performance of Savonius rotor based on numerical study" *IEEE conference on Sustainable Power Generation and Supply*, pp. 1-6, 2009.

[7] Alexander, A. J. and Holownia, B. P., Wind tunnel tests on a Savonius rotor. *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 3(4), pp. 343-351, 1978.

[8] Fujisawa, N., On the torque mechanism of Savonius rotors. *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 40(3), pp. 277-292, 1992

[9] Blackwell, B. F., Sheldahl, R. F., and Feltz, L. V., "Wind tunnel performance data for two-and three-bucket Savonius rotors". Springfield, VA, USA: Sandia Laboratories, 1977.

[10] Kacprzak, K., Liskiewicz, G., and Sobczak, K., "Numerical investigation of conventional and modified Savonius wind turbines", *Renewable energy*, Vol. 60, pp. 578-585, 2013.

[11] Sanusi, A., Soeparman, S., Wahyudi, S., and Yuliati, L., "Experimental Study of Combined Blade Savonius Wind Turbine", *International Journal of Renewable Energy Research*, Vol. 6(2), pp. 614-619, 2016.

[12] Roy, S. and Saha, U. K., "Wind tunnel experiments of a newly developed two-bladed Savonius-style wind turbine", *Applied Energy*, Vol. 137, pp. 117-125, 2015.

[13] Mahmoud, N. H., El-Haroun, A. A., Wahba, E., and Nasef, M. H., "An experimental study on improvement of Savonius rotor performance", *Alexandria Engineering Journal*, Vol. 51(1), pp. 19-25, 2012.

[14] Yaakob, O., Suprayogi, D., Ghani, M. A., and Tawi, K., "Experimental Studies on Savonius-type Vertical Axis Turbine for Low Marine Current Velocity", *International Journal of Engineering-Transactions A: Basics*, Vol. 26(1), pp. 91-98. 2012.

[15] Hayashi, T., Li, Y. and Hara, Y., "Wind tunnel tests on a different phase three-stage Savonius rotor", *JSME International Journal Series B Fluids and Thermal Engineering*, Vol. 48(1), pp. 9-16, 2005.

[16] Rus, T., Rus, L. F., Abrudan, A. C., Domnita, F. V. and Mare, R., "Experimental tests in equipping vertical axis wind turbines with electric Generator", *International Journal of Renewable Energy Research* Vol. 6(2), pp. 465-471, 2016.

[17] Jeon, K. S., Jeong, J. I., Pan, J. K. and Ryu, K. W., "Effects of end plates with various shapes and sizes on helical Savonius wind turbines", *Renewable Energy*, *79*, 167-176, 2015.

[18] Kamoji, M. A., Kedare, S. B., and Prabhu, S. V., "Experimental investigations on single stage modified Savonius rotor", *Applied Energy*, *86*(7), 1064-1073, 2009.

[19] Golecha, K., Eldho, T. I. and Prabhu, S. V., "Influence of the deflector plate on the performance of modified Savonius water turbine", *Applied Energy*, 88(9), 3207-3217, 2011.

[20] Lee, Jae-Hoon, Young-Tae Lee, and Hee-Chang Lim.,"Effect of twist angle on the performance of Savonius wind turbine", *Renewable Energy*, Vol. 89, pp. 231-244, 2016.

[21] Sahim, K., Santoso, D. and Sipahutar, R. "Performance of combined water turbine Darrieus-Savonius with two stage Savonius buckets and single deflector", *International Journal of Renewable Energy Research*, vol. *5*(1), pp. 217-221, 2015.