Effect of Overlapping Ratio, Blade Shape Factor, and Blade Arc Angle to modified Rotor Savonius performances

by Ida Bagus Alit

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Abstract

Savonius rotor has many advantages over other types of the rotor, such as simple construction, cheap, not dependent on the direction of the wind, and has good initial torque at low wind speeds. The Savonius rotor efficiency is strongly influenced by its geometric shape; therefore this study examines the effect of geometric shapes expressed by dimensionless numbers including overlapping ratios, blade shape factors, and blade arc angles. The results show that if the overlap ratio increases then the coefficient of rotor power decreases. Nevertheless, the best performance was obtained by the rotor configuration constructing of an overlap ratio 0.0, a blade shape factor of 0.5 and an angle arc angle of 110^{O}.

Keywords: Savonius rotor; overlap ratio; blade shape factor; blade arc angle

INTRODUCTION

The existence of vertical axis wind turbine (VAWT) becomes a new phenomenon in the development of wind technology. The advantages of VAWT that are not owned by horizontal wind turbine shafts (HAWT) give high interest to the researchers to conduct further study on this type of wind turbine. The Savonius turbine is one type of vertical wind turbine shaft. This turbine has many advantages over other types of turbines, such as: having a simple construction, low cost, not influenced by wind direction, and the generator can be placed under the tower. The operation of the Savonius turbine is particularly suitable for low wind speeds, Dhote [1]. This turbine spins because of the drag force which is the difference between the positive and negative moments that occur on each blade. The Savonius turbine usually consists of two or three blades, when viewed from above it looks like the letter S, Ali [2], see Figure 1.

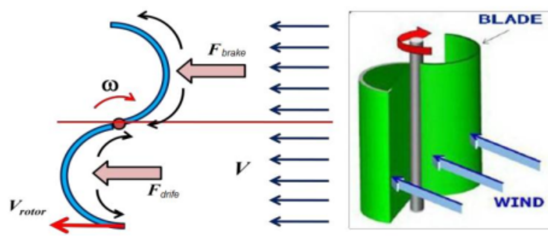

Figure 1. Force scheme on two blade Savonius turbine

Several studies have been undertaken to improve the performance of this turbine, such as the study of the effect of the number of blades, the use of rotor caps, and the overlap ratio of Savonius turbines on performance. The number of blades found is 2.3, and 4, whereas the ratio of overlapping variations is 0.0, 0.2, 0.25, 0.3, and 0.35. The result is that two blade Savonius rotor is more efficient than 3 or 4 blades. Moreover, the use of the rotor cap produces greater efficiency than without the rotor cap. The rotor without overlap ratio has a higher power coefficient than that with overlap ratios, Mahmoud et al. [3]. Rus [4] added a concentrator on the Savonius shaft to improve turbine performance. The concentrators were added with the aim of reducing the negative moments that occur on the blades. A similar study was conducted by Alit et al. [5]. They studied effects of adding concentrators on the performance of Savonius turbines. They concluded that adding the concentrator could increase the power coefficient.

Investigation on improving the Savonius turbine performance by modifying the rotor has been also done, e.g. Vaishali et al. [6]. They modified the blade by adding an arm. They tested their turbine at the wind velocities of 2 m/s to 8 m/s. Their Savonius rotor used 3 blades and on each blade they installed

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Deb et al. [8] examined the Savonius axis with a height of 60 cm and a diameter of 17 cm. The rotor model was helical Savonius with the blade twisted a 45°. Their results were compared to the conventional Savonius shaft. The similar work was also done by Damak et al. [9]. They rotated the blades at the angle of 180° with variations of the Reynolds number and overlap ratio. The results showed that twisting angles of 45° and 180° produced better performances. Gad et al. [10] conducted numerical studies using fluent software for modification of the Savonius V-blade turbine and polynomial blades. The revealed the polynomial beam resulted in the best performance.

Based on the above literature review, the aim of the research is to know the effect of overlap ratio, blade shape factor, and blade arc angle on the modified Savonius turbine performance.

EXPERIMENTAL SET UP

Modified Savonius rotor was tested in a wind tunnel with square nozzles, with the tunnel size of 450 mm x 405 mm x 1000 mm, see Figure 2. The air was flowed using a common commercial fan. Testing was done with wind speeds ranging from 2 m/s to 5 m/s. The wind speeds were measured using an anemometer JL-FS2 with a resolution of 0.1 m/s.

Figure 2. The schematic diagram of the experimental set up

Meanwhile, the rotational speeds of the rotor were measured with a digital laser tachometer model DT-2234C. The PMG 165-0.05 kW 300 rpm DC type generator was placed on the turbine shaft as the load of the Savonius turbine. The current and voltage outputs of the generator were measured by a digital multitester model DT-9205A.

Figures 3 - 5 indicate the modified Savonius turbine examined to know the effect of rotor geometries.

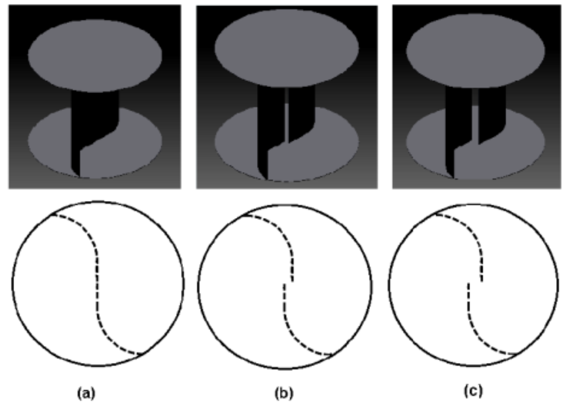

Figure 3. Overlap ratio variations; (a) 0.0, (b) 0.05, (c) 0.10

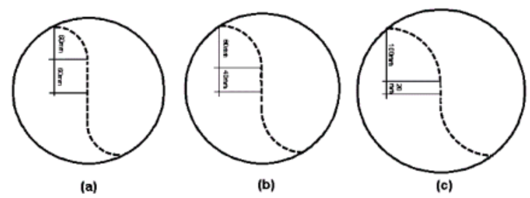

Figure 4. Blade shape factor variations; (a) 1.0, (b) 0.5, (c) 0.2

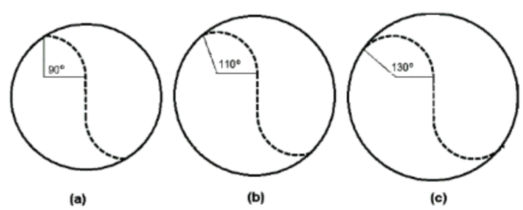

Figure 5. Blade arc angle variations, (a) 90^{O}, (b) 110^{O}, (c) 130^{O}

Modified Rotor Savonius. The geometric parameters of the Savonius rotor tested include aspect ratio (H/D), overlap ratio (m/D), blade arc angle (Ψ) and blade shape factor (p/q).

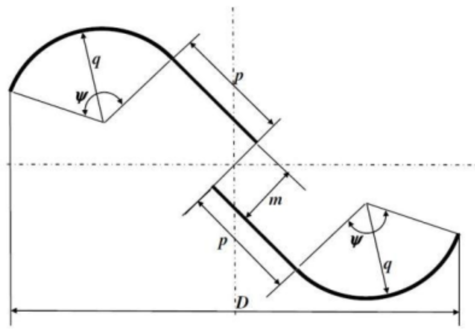

Figure 6. Modification basic concept of the Savonius rotor [11]

$$Aspect\ ratio = \frac{H}{D} \quad (1)$$

$$Overlap\ ratio = \frac{m}{D} \quad (2)$$

$$Blade\ shape\ factor = \frac{p}{q} \quad (3)$$

See Figure Where H is the rotor height (m), D indicates the rotor diameter (m), m is the overlapping gap (m), p is the arm length (m) and q is the blade radius (m).

Theoretically, the energy resulted by the wind turbine is a function of wind speed, air density, and swept area and formulated as [12]:

$$P_r = \frac{1}{2}\rho A_s C_p v^3 \quad (4)$$

$$A_s = HD \quad (5)$$

Where P_r is the wind power over the swept area (W), ρ represents the air density (kg/m³), A_s is the swept area (m²), C_p is the power coefficient, and v is the wind speed (m/s).

The performance of the wind turbine is shown by the magnitude of the speed ratio tip to the power coefficient. Tip speed ratio (t_{sr}) is the ratio of rotor tip speed to wind speed. The speed of the rotor tip has a nominal value that varies according to the wind speed. The matrices of T_{sr} can be calculated by the equation:

$$t_{sr} = \frac{\pi D n}{60 v} \quad (6)$$

Where n is the rotation speed (rpm). Each turbine rotor has different power coefficients on each speed ratio tip. Figure 7 shows the relationship of speed ratio tip with power coefficient for various turbine rotors.

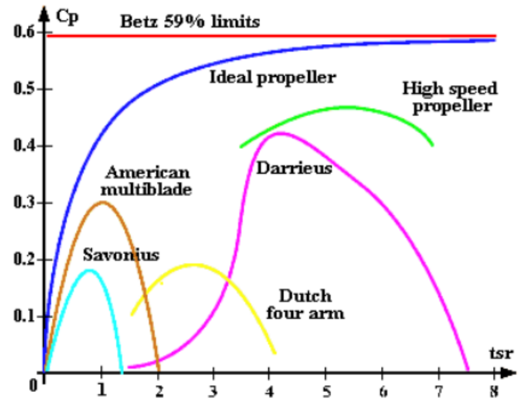

Figure 7. *Cp*-t_{sr} diagram for several turbine types [5, 13]

Modified Savonius rotor does not use a shaft between two plates (without central shaft between the two end plates). However, it uses two closing plates as the blade holder and these two closing plates can increase the turbine efficiency, [14]. The Savonius rotor in the study is made of the acrylic material with a thickness of 3 mm. At the top and bottom are covered with circular acrylic sheets according to the size of the rotor diameter. Parameters presented include the influence of overlap ratio, blade shape factor, and blade arc angle to turbine performance.

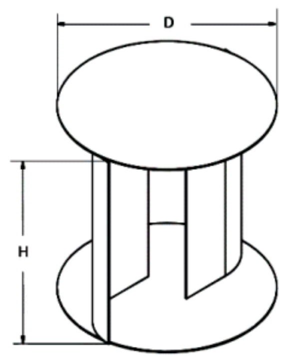

Figure 8. Modified Savonius rotor with two closing plates without a shaft between blades

Table 1. Configuration of the modified Savonius rotor

Overlap ratio (m/D)	Blade shape factor (p/q)	Blade arc angel (Ψ)
0.0, 0.05, 0.1	0.5	90°
0.0	0.2, 0.5, 1.0	90°
0.0	1.0	90°, 110°, 130°

RESULTS AND DISCUSION

The power coefficient is a function of the rotor shape and wind speed. The shape of modified Savonius rotor of this study is expressed in dimensionless numbers, including aspect ratio, overlap ratio, blade shape factor and blade arc angle. Some configurations were tested experimentally to get the optimum shape. Test results are presented through the relation of wind speed to the rotational speed of the shaft and tip speed ratio to power coefficient.

A. Effect of overlap ratio

The first test was performed on the overlap ratio variation. The rotor being tested has a blade shape factor of 0.5 and a blade arc angle 90°. The variations of the overlap ratio tested are 0.0, 0.05, and 0.10.

As seen in figure 9, increasing the wind speed raises the rotor rotation. This occurs for all overlap ratios. However, at the same wind speed, the rotor with the overlap ratio of 0.0 or without overlap ratio shows giving the better rotor rotations. In figure 10, it can be seen that raising the tip speed ratio elevates the power coefficient, however, at the tip speed ratios of more than 7, the power coefficient seems to be constant or even decreases. This finding was also found by Sharma et al. [15]. At the same tip speed ratio, the rotor without the overlap ratio presents the better power coefficients. The increased rotor rotation is due to the increase in the wind momentum pounding the turbine blades. The modified Savonius rotor without an overlap ratio yields the best performance. This finding was also found by Mahmoud et al. [3] and Kamoji et al. [11].

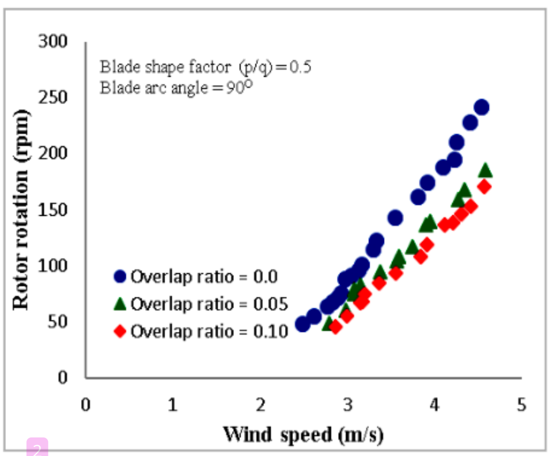

Figure 9. Effect of the overlap ratio on the rotor rotation speed

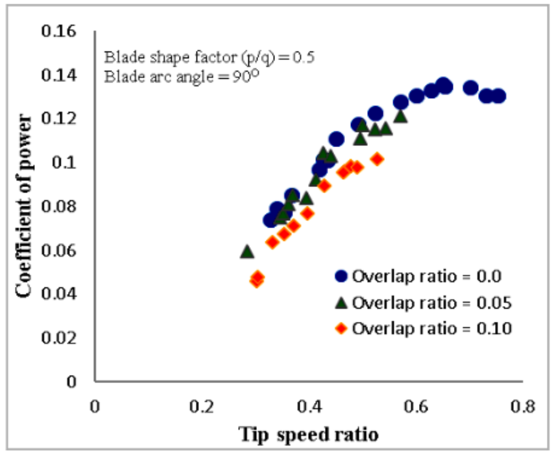

Figure 10. Effect of overlap ratio on power coefficient

B. Effect of blade shape factor

The second test looks for the effect of blade shape factor on turbine performance. The modified Savonius rotor is constructed with an overlap ratio 0.0, and a blade arc angle 90°. Variations of the blade shape factor tested were 0.2, 0.5, and 1.0.

The effect of wind velocity on the rotation of the rotor is clear, as the wind velocity increases the rotor rotation also increases. Nevertheless, at the same wind velocity, the effect of blade shape factor seems not clear, see figure 11. However, the blade shape factor 0.5 indicates giving better rotor rotations. Similarly, increasing the tip speed ratio increases the power coefficient for all blade shape factors, however, the blade shape factor 0.5 shows resulting in the higher power coefficient, see figure 12. Hence, the blade shape factor 0.5 produces higher rotor rotation and power coefficient than that of the blade shape factor 0.2 and 1.0. Therefore, the modified Savonius rotor with blade shape factor 0.5 has better performance than other blade shape factors.

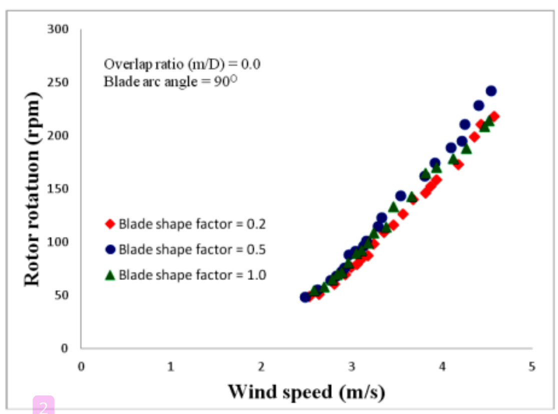

Figure 11. Effect of blade shape factor on rotor rotation

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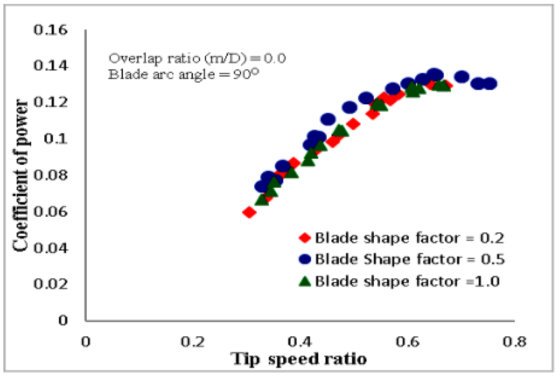

Figure 12. Effect of blade shape factor on power coefficient

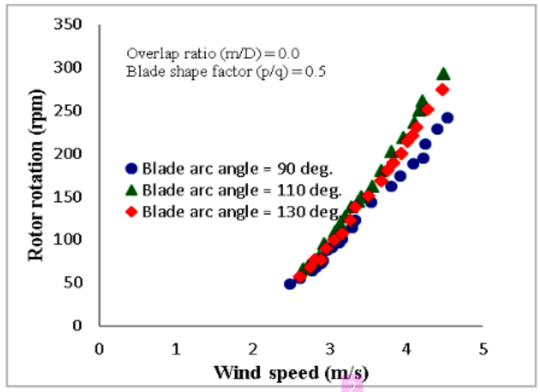

Figure 13. Effect of blade arc angle on the rotor rotation

C. *Effect of blade arc angle*

The third test of this research is to find the influence of the blade arc angle to turbine performances. The modified Savonius rotor is constructed with an aspect ratio of 1.0, an overlap ratio of 0.0, and a blade shape factor of 0.5. Variations of the blade arc angle tested were 90°, 110°, and 130°. The effect of wind speed on the rotation of the rotor and the influence of the tip speed ratio on the power coefficient for the three variations of the blade arc angle are shown in Figures 13 and 14. As the wind speed increases, the rotor rotation increases too for the three different blade arc angles. At the wind speeds of lower than 2.5 m/s, the effect of the blade arc angle is not significant, while at the wind speeds of more than 2.5 m/s, the blade arc angles affect the rotor rotation. In term of tip speed ratio, at the tip speed ratios less than 0.5, the blade arc angle does not affect the power coefficient, but at the tip speed ratios of more than 0.5 the effect of the blade arc angle is clear. At the tip speeds less than 0.7, the power coefficient increases with the tip speed ratio, while at the tip speed ratios more than 0.7, the power coefficient seems to decrease with the increase in the tip speed ratio. This finding agrees well with Figure 7 showing the relationship between tip speed ratio and power coefficient. Nevertheless, the rotor with the blade arc angle of 110° has a higher power coefficient than that of other blade arc angles. Kamoji et al. [11] found that the best blade arc angle was 124°. The results of this study in term of blade arc angle agree with that of Kamoji et al. [11] at the blade arc angles laying between 90° to 130°. Nevertheless, this study did not investigate the blade arc angle of 124°, but 110°. Kamoji et al. [11] used tip speed ratios of above 0.6, while in this study the tip ratios employed were less than 0.8.

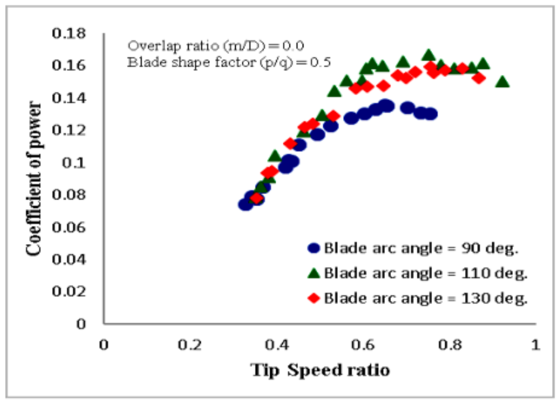

Figure 14. Effect of blade arc angle on the power coefficient

CONCLUSION

The performance of the turbine is strongly influenced by the wind speed and the geometrical shape of the modified Savonius rotor. Turbine performance can be seen from the amount of power coefficient generated. The magnitude of the power coefficient is a function of the tip speed ratio and rotor geometries. These geometries include aspect ratio, overlap ratio, blade shape factor and blade arc angle. The modified Savonius rotor without the overlap ratio has the best performance. Increasing values of the overlap ratio result in the decreased power coefficient. The best performance of the rotor configuration studied has an overlap ratio of 0.0 (without overlap ratio), a blade shape factor of 0.5, and a blade arc angle of 110°.

ACKNOWLEDGMENT

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The schematic diagram of the experimental set up Figure 3. Overlap ratio variations; (a) 0.0, (b) 0.05, (c) 0.10 Figure 4. Blade shape factor variations; (a) 1.0, (b) 0.5, (c) 0.2 Figure 5. Blade arc angle variations, (a) 90O, (b) 110O, (c) 130O Modified Rotor Savonius. The geometric parameters of the Savonius rotor tested include aspect ratio (H/D), overlap ratio (m/D), blade arc angle (Ψ) and blade shape factor (p/q). Meanwhile, the rotational speeds of the rotor were measured with a digital laser tachometer model DT-2234C. The PMG 165-0.05 kW 300 rpm DC type generator was placed on the turbine shaft as the load of the Savonius turbine. The current and voltage outputs of the generator were measured by a digital multitester model DT-9205A. Figures 3 - 5 indicate the modified Savonius turbine examined to know the effect of rotor geometries. Figure 6. Modification basic concept of the Savonius rotor [11] Aspect ratio ? H D Overlap ratio ? m D Blade shape factor ? p q (1) (2) (3) See Figure Where H is the rotor height (m), D indicates the rotor diameter (m), m is the overlapping gap (m), p is the arm length (m) and q is the blade radius (m). Theoretically, the energy resulted by the wind turbine is a function of wind speed, air density, and swept area and formulated as [12]: Pr ? ?AsCpv3 1 2 As ? HD (4) (5) Where Pr is the wind power over the swept area (W), ρ represents the air density (kg/m³), As is the swept area (m²), Cp is the power coefficient, and v is the wind speed (m/s). The performance of the wind turbine is shown by the magnitude of the speed ratio tip to the power coefficient. Tip speed ratio (tsr) is the ratio of rotor tip speed to wind speed. The speed of the rotor tip has a nominal value that varies according to the wind speed. The matrices of Tsr can be calculated by the equation: t sr ? ?6D0vn (6) Where n is the rotation speed (rpm). Each turbine rotor has different power coefficients on each speed ratio tip. Figure 7 shows the relationship of speed ratio tip with power coefficient for various turbine rotors. Figure 7. Cp-tsr diagram for several turbine types [5, 13] Modified Savonius rotor does not use a shaft between two plates (without central shaft between the two end plates). However, it uses two closing plates as the blade holder and these two closing plates can increase the turbine efficiency, [14]. The Savonius rotor in the study is made of the acrylic material with a thickness of 3 mm. At the top and bottom are covered with circular acrylic sheets according to the size of the rotor diameter. Parameters presented include the influence of overlap ratio, blade shape factor, and blade arc angle to turbine performance. Figure 8. Modified Savonius rotor with two closing plates without a shaft between blades Table 1. Configuration of the modified Savonius rotor Overlap ratio Blade shape factor Blade arc angel (m/D) (p/q) (Ψ) 0.0, 0.05, 0.1 0.5 90O 0.0 0.2, 0.5, 1.0 90O 0.0 1.0 90O, 110O, 130O RESULTS AND DISCUSION The power coefficient is a function of the rotor shape and wind speed. The shape of modified Savonius rotor of this study is expressed in dimensionless numbers, including aspect ratio, overlap ratio, blade shape factor and blade arc angle. Some configurations were tested experimentally to get the optimum shape. Test results are presented through the relation of wind speed to the rotational speed of the shaft and tip speed ratio to power coefficient. A. Effect of overlap ratio The first test was performed on the overlap ratio variation. The rotor being tested has a blade shape factor of 0.5 and a blade arc angle 90°. The variations of the overlap ratio tested are 0.0, 0.05, and 0.10. As seen in figure 9, increasing the wind speed raises the rotor rotation. This occurs for all overlap ratios. However, at the same wind speed, the rotor with the overlap ratio of 0.0 or without overlap ratio shows giving the better rotor rotations. In figure 10, it can be seen that raising the tip speed ratio elevates the power coefficient, however, at the tip speed ratios of more than 7, the power coefficient seems to be constant or even decreases. This finding was also found by Sharma et al. [15]. At the same tip speed ratio, the rotor without the overlap ratio presents the better power coefficients. The increased rotor rotation is due to the increase in the wind momentum pounding the turbine blades. The modified Savonius rotor without an overlap ratio yields the best performance. This finding was also found by Mahmoud et al. [3] and Kamoji et al. [11]. Figure 9. Effect of the overlap ratio on the rotor rotation speed Figure 10. Effect of overlap ratio on power coefficient B. Effect of blade shape factor The second test looks for the effect of blade shape factor on turbine performance. The modified Savonius rotor is constructed with an overlap ratio 0.0, and a blade arc angle 90°. Variations of the blade shape factor tested were 0.2, 0.5, and 1.0. The effect of wind velocity on the rotation of the rotor is clear, as the wind velocity increases the rotor rotation also increases. Nevertheless, at the same wind velocity, the effect of blade shape factor seems not clear, see figure 11. However, the blade shape factor 0.5 indicates giving better rotor rotations. Similarly, increasing the tip speed ratio increases the power coefficient for all blade shape factors, however, the blade shape factor 0.5 shows resulting in the higher power coefficient, see figure 12. Hence, the blade shape factor 0.5 produces higher rotor rotation and power coefficient than that of the blade shape factor 0.2 and 1.0. Therefore, the modified Savonius rotor with blade shape factor 0.5 has better performance than other blade shape factors. Figure 11. Effect of blade shape factor on rotor rotation Figure 12. Effect of blade shape factor on power coefficient C. Effect of blade arc angle The third test of this research is to find the influence of the blade arc angle to turbine performances. The modified Savonius rotor is constructed with an aspect ratio of 1.0, an overlap ratio of 0.0, and a blade shape factor of 0.5. Variations of the blade arc angle tested were 90°, 110°, and 130°. The effect of wind speed on the rotation of the rotor and the influence of the tip speed ratio on the power coefficient for the three variations of the blade arc angle are shown in Figures 13 and 14. As the wind speed increases, the rotor rotation increases too for the three different blade arc angles. At the wind speeds of lower than 2.5 m/s, the effect of the blade arc angle is not significant, while at the wind speeds of more than 2.5 m/s, the blade arc angles affect the rotor rotation. In term of tip speed ratio, at the tip speed ratios less than 0.5, the blade arc angle does not affect the power coefficient, but at the tip speed ratios of more than 0.5 the effect of the blade arc angle is clear. At the tip speeds less than 0.7, the power coefficient increases with the tip speed ratio, while at the tip speed ratios more than 0.7, the power coefficient seems to decrease with the increase in the tip speed ratio. This finding agrees well with Figure 7 showing the relationship between tip speed ratio and power coefficient. Nevertheless, the rotor with the blade arc angle of 110° has a higher power coefficient than that of other blade arc angles. Kamoji et al. [11] found that the best blade arc angle was 124°. The results of this study in term of blade arc angle agree with that of Kamoji et al. [11] at the blade arc angles laying between 90° to 130°. Nevertheless, this study did not investigate the blade arc angle of 124°, but 110°. Kamoji et al. [11] used tip speed ratios of above 0.6, while in this study the tip ratios employed were less than 0.8. Figure 13. Effect of blade arc angle on the rotor rotation Figure 14. Effect of blade arc angle on the power coefficient CONCLUSION The performance of the turbine is strongly influenced by the wind speed and the geometrical shape of the modified Savonius rotor. Turbine performance can be seen from the amount of power coefficient generated. The magnitude of the power coefficient is a function of the tip speed ratio and rotor geometries. These geometries include aspect ratio, overlap ratio, blade shape factor and blade arc angle. The modified Savonius rotor without the overlap ratio has the best performance. Increasing values of the overlap ratio result in the decreased power coefficient. The best performance of the rotor configuration studied has an overlap ratio of 0.0 (without overlap ratio), a blade shape factor of 0.5, and a blade arc angle of 110°. ACKNOWLEDGMENT The research was funded entirely by the Ministry of Research, Technology and Higher Education through a grant of applied products with SP DIPA-042.06.1.401516 / 2017 contract number. REFERENCES [1] A. Dhote, "Design, analysis and fabrication of Savonius vertical axis wind turbine", International Research Journal of Engineering and Technology, Vol.2, No.3, pp. 2048-2054, 2015. [2] M.A. Ali, "Experimental comparison study for Savonius wind turbine of two & three blades at low wind speed", International Journal Modern Research IJMER, Vol. 3, No. 5, pp. 2978-2986, 2013. [3] N.H. Mahmoud, A.A. Haroun, E. Wahba, E., and M.H. 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