Performance investigation of the S-Rotors

B A Bhayo\textsuperscript{1}, H H Al-Kayiem\textsuperscript{1} and N Z Yahaya\textsuperscript{2}

\textsuperscript{1}Department of Mechanical Engineering, Universiti Teknologi Petronas, Bandar Seri Iskandar, 32610, Perak, Malaysia.
\textsuperscript{2}Department of Electrical and Electronics Engineering, Universiti Teknologi Petronas, Bandar Seri Iskandar, 32610, Perak, Malaysia.

E-mail: bilawal.bhyao@yahoo.com

Abstract. This paper presents and discusses results from an experimental investigation of three models of wind S-rotors. Models 1 is modified from conventional Savonius rotor with a single stage and zero offsets zero overlaps; model 2 is three blade single stage wind rotor; and model 3 is double stage conventional Savonius rotor. The three models were designed, fabricated and characterized in terms of their coefficient of performance and dynamic torque coefficient. A special open wind simulator was designed for the test. The optimum parameters for the models were based on previous studies. The results showed that the model 1, model 2 and model 3 has the maximum power coefficient of 0.26, 0.17, and 0.21 at the correspondence tip speed ratio (TSR) of 0.42, 0.39 and 0.46, respectively. Model 1 is further optimized in terms of the aspect ratio resulting in improved power coefficient by 24%. The maximum dynamic torque coefficient of model 1, model 2 and model 3 was found as 0.81, 0.56 and 0.67 at the correspondence minimum TSR of 0.28, 0.21 and 0.17, respectively. It was noted that the all three models have high torque coefficient because the models were tested at higher applied torque on the rotors.

1. Introduction

Wind energy is a clean renewable energy freely available on the earth surface in the form of kinetic energy of air. However, wind technology is a mature technology to exploit the wind energy for electricity generation [1]. According to Betz (1966) [2], a maximum of about 59% of wind energy can be transformed into mechanical energy. In pursuit of generating electricity using the wind as a clean and renewable energy for remote rural communities, the Savonius rotor (S-rotor) can be helpful [3].

The S-rotor is a simple and cheaper vertical axis wind turbine (VAWT). It can be installed near to living places because of less noisy and can accept the wind from any direction to drive it. Although the S-rotor is an inherently low efficient wind turbine, but its self-starting characteristics at the low cut in speed due to high torque makes it more attractive for the stand-alone power generation system [4, 5]. Thus, the S-rotor can be used for a self-driven stand-alone power system with very low adverse environmental effects. Since S-rotor has a poor coefficient of performance inherently because of negative torque at the convex side. Therefore, to increase the torque difference at positive and negative aspect; the geometrical profile and parameters should be optimized.

Akwa et al. [5] carried out the review to discuss the different geometrical parameters to enhance the performance of S-rotor. From the discussion, it was observed that the increase in an aspect ratio of the
rotor and the rotor with end plates can result in performance improvement. The S-rotor with two blades has higher coefficient of power \((C_p)\) than three blades rotor. Morshed et al. [6] have analyzed the effect of overlap ratio and Reynolds number on the aerodynamic characteristics of the three blade S-rotor with blade angle 120° apart and no central shaft between the end plates. In their experimental study, it was observed that the better static torque coefficient is at an overlap ratio of 0.12. However \(C_p\) is higher for the model without overlap ratio at low Reynolds number. Mahmoud et al. [7] have carried out study to test different Savonius wind rotors in a subsonic wind tunnel at wind speed of 13 m/s. It was concluded that the rotor with two blades, two stages, without overlap and with end plates has higher mechanical power. However the mechanical power increases with the increase of aspect ratio.

Al-Kayiem and Ming [8] have experimentally investigated three different rotors and compared their performance in bounded flow, partially bounded flow and fully open flow. It was observed that the conventional S-rotor had higher power coefficient in the partially bounded flow. However Rotor 2, based on Kamoji and Kedare [9] and Rotor 3, a new design have maximum power and torque coefficient in the fully bounded flow. Kamoji et al. [9] have investigated the effect of geometrical parameters on single stage modified Savonius rotor in an open jet wind tunnel. It was found that the modified Savonius rotor (without shaft) has higher coefficient of power of 0.21 than that of conventional Savonius rotor (with and without shaft) and also with the modified Savonius rotor (with shaft). The optimum parameters for modified Savonius rotor were found as an overlap ratio zero, aspect ratio 0.7, blade arc angle 124° and blade shape factor 0.2. Hayashi et al. [10] carried out a study to minimize the negative torque coefficient, a three stage S-rotor with bucket stages angle 120° from each other was designed and tested in an open wind tunnel. During experimental testing, it was found that the three-stage rotor has an average and constant torque variation than that of one stage two-blade rotors. For the three stages rotor, the maximum power coefficient decreased by 25% relative to the single-stage rotor.

Menet and Bouraba [11] have designed and developed a small prototype of S-rotor for an off grid system. The optimum geometrical parameters were found as two-step rotor, with an end plate ratio of 1.1, aspect ratio of 4 and the overlap ratio of 0.15 to 0.3. Percival et al. [12] have carried out an experimental study to design and test S-rotor for domestic electricity generation. The optimum overlap ratio was found 0.2 after testing ten different configurations for overlap ratio in the range of 0.6 to 0.3 at a maximum wind speed of 10 m/s.

To improve the performance of S-rotor, this experimental study is carried out to investigate and compare the performance of three models. Also, the experimental comparative analysis of the designed wind rotor models with the conventional double stage Savonius rotor is carried out in this study. To do so, the models were designed, fabricated and experimentally tested in an open wind flow. The experiments were conducted to evaluate the performance coefficient and dynamic torque coefficient.

## 2. Experimental Expects

### 2.1. Design Concept of the Models

In this experimental analysis, three different wind rotor models were designed, fabricated and tested in an open wind flow. The main dimensions of wind rotor models are given in table 1. The models are named as Model 1, Model 2 and Model 3. All the models have an aspect ratio, AR \((H/D)\) equal to 2, end plate ratio \((D_0/D)\) of 1.1 and shaft diameter \((d)\) of 0.01 m. The geometrical parameters of simple Savonius rotor are taken optimum as suggested by [11].

| Model | \(H\) | \(D_0\) | \(D\) | \(A\) | \(AR\) | \(d\) |
|-------|-------|-------|-------|------|-------|------|
| Model 1 | 0.628 m | 0.302 m | 0.151 m | 0.1897 m\(^2\) | 2 | 0.01 m |

**Table 1.** The main dimensions of the wind rotor models.
2.1.1. Model 1. Refers to figure 1(a), Model 1 is a single-stage rotor, with zero overlap ratio (e/D) between the blades, the optimum blade arc angle is 124° and the shape factor (p/q) is set to 0.2 as recommended by [9]. Model 1 was designed in such a way that its blade diameter should be 150 mm.

2.1.2. Model 2. Refers to figure 1(b), Model 2 is a three bladed, single-stage rotor. The curvature ratio of rotor radius to the depth, (R/Y) is set to 2.5. However the skew factor (X/R), which is the ratio of the maximum depth location to a radius of the rotor is set to 0.75 as recommended by [13].

2.1.3. Model 3. Refers to figure 1(c), Model 3 is a two bladed, double stage simple Savonius rotor. The rotor is provided an overlap (e) between the blades with an overlap ratio of 0.2. The height to diameter ratio of the model 3 is same as of the model 1 and model 2. Since the rotor has two stages with phase shift angle of 90°, therefore it is expected to have optimum performance characteristics of the simple Savonius rotor [11, 14].

![Model 1](image1.png) ![Model 2](image2.png) ![Model 3](image3.png)

Figure 1. The schematic drawings of wind rotor models.

2.2. Fabrication of Models
The models blades were fabricated from 1 mm aluminum sheets because of its low weight and manufacturability. The 2 mm slot as per design was cut in 8 mm acrylic end plates, of 330 mm diameter, to fix the bended sheets easily. For bending the aluminum sheets to a particular profile, three wooden patterns for each model were made on five-axis CNC machine and the sheets were bended by using pattern and manual rolling machines. The rotors were assembled using super glue and bonding epoxies.
Two protruding shafts of mild steel at top and bottom with diameter 10 mm and height 150 mm were also assembled.

3. Experimental Setup

3.1. Open wind simulator
The experimental setups consist of two sections, section 1 and two as shown in figure 2. Section 1 was an open wind tunnel, where a big propeller fan with variable RPM drive was used to blow the wind at different velocities. The propeller fan has a power capacity of 750 watts and can blow air up to 32000 m³/hr. The fan was placed at the inlet of wind tunnel section and wind was directed to the honeycomb of dimension 1 m x 1 m with each cell dimension of 0.2 m x 0.2 m to reduce the flow turbulence and swirl. At exit section of honeycomb flow convergent setup was attached with exit area of 0.8 m x 0.8 m to increase further the wind speed. Section 2 was a test rig to hold the models vertically for testing and data acquisition. The models extended shafts at ends were embedded to frictionless bearings to make the rotor rotate smoothly. While designing test rig, it was confirmed that the rotor end plates should also experience wind effect.

A brushed 24V, 135W DC generator was mounted with the setup to get the electrical power output. The timing belt and pulley system was also provided, to run the generator at a higher speed of about 3.75 times the wind rotor speed.

3.2. Experimental methodology
To test the models, the test rig was placed in such a way that the center of wind rotor models should be at 0.8 m downstream from the wind tunnel exit area. The propeller air fan was operated for variable wind velocities and the wind velocity was measured by using KIMO VT200 Vane Anemometer, which was held for 10 seconds at each of 6 different points and their mean was taken. The dynamic torque for the wind rotor models was calculated from the electric power output of a brushed 24 volts, 135 watts DC generator. The laser tachometer was also used to get wind rotor speed at a particular wind velocity. For every reading, the procedure was repeated four times to validate the readings. The variation of wind velocity from the concave side to convex side of the rotor is ±0.2 m/s.
4. Results and Discussion

To evaluate the performance of a wind rotor, the coefficient of power and torque should be determined. Hence, the electrical power output and rpm at a constant wind speed were measured. However, the dynamic torque was determined using mathematical relation of electrical power output and measured torque values. After the data had been acquired, the below provided mathematical formulations were used to identify performance parameters of the rotor.

Coefficient of Power,
\[
C_p = \frac{P_{\text{electrical}}}{\frac{1}{2} \rho V^3 A_{\text{rotor}} \eta_g}
\]  
(1)

Dynamic Torque,
\[
T = \frac{P_{\text{electrical}}}{\omega \eta_g}
\]  
(2)

Dynamic Coefficient of Torque,
\[
C_T = \frac{T}{\frac{1}{2} \rho V^2 A_{\text{rotor}} R}
\]  
(3)

Tip Speed Ratio (λ),
\[
TSR = \frac{\text{Rotar Tip Speed}}{\text{Wind Speed}}
\]  
(4)

or
\[
\lambda = \frac{\omega R}{V}
\]  

Reynolds Number (Re)
\[
Re = \frac{\rho V 2R}{\mu}
\]  
(5)

Where, \( \rho \) is the density of air (= 1.22 kg/m\(^3\)), \( V \) is the free stream wind velocity, \( A_{\text{rotor}} \) is the rotor area, \( R \) is the radius of rotor, \( \omega \) is the angular velocity of the rotor, \( T \) is the torque generated by the rotor, \( \eta_g \) is the generator efficiency and \( \mu \) is the air absolute viscosity (= 1.83×10\(^{-5}\) Pa·s at 20 °C). \( C_T \), is the dynamic torque coefficient.

4.1. Power Coefficient

Figure 3 represents the variation of power coefficient with the variation of tip speed ratio (TSR) for the model 1, model 2 and model 3. The magnitude of the power coefficient (\( C_p \)) at the minimum, optimum and maximum TSR with the corresponding Reynolds number (\( Re \)) for all three models is shown in Table 2.

For model 1, the minimum TSR observed is 0.28 at which power coefficient is 0.23 below this TSR rotor goes to stop rotating. The maximum power coefficient for the model 1 is noticed as 0.26 at the TSR of 0.42. The power coefficient decreases with the further increase of TSR. The percentage increase in power coefficient of Model 1 is about 24% than that of modified Savonius rotor by [9], which might be because of the positive effect of increasing aspect ratio from 0.7 to 2. The rise in performance with an increase in aspect ratio was also reported by [15, 16].

Nevertheless, the modified Savonius rotor is further optimized as rotor with zero overlaps having end plate ratio of 1.1, Aspect ratio (H/D) of 2, blade arc angle (\( \Psi \)) of 124\(^\circ\) and blade shape factor (p/q) of 0.2.

For model 2, the maximum power coefficient is recorded as 0.17 at the TSR of 0.39. The highest power coefficient of the model 2 was expected to be about double than the conventional Savonius rotor with same geometrical configuration [13]. However, the power coefficient of the model 2 from this
experimental study is 1.13 times the power coefficient of the three bladed simple Savonius rotor having an aspect ratio of 1.59 as reported by [14]. Thus, the power coefficient of Model 2 is about 43% less than the expected. This might be because of fabrication of wind rotor in a different way than that of reported by [13].

For model 3, the power coefficient of the model at lowest possible TSR of 0.17 is recorded as 0.12. The power coefficient increases with the rise of TSR to 0.46, where the maximum power coefficient is 0.21. The further increases of TSR cause to decrease power coefficient and at the highest TSR of 0.56, the power coefficient is 0.19. The maximum power coefficient of the model 3, double stage simple Savonius rotor is greater about 31% than the maximum power coefficient of a single stage two-bladed wind rotor from the referred study [10]. The highest power coefficient of the model 3 is also greater about 24% than the model 2, and the maximum power coefficient is less about 19% than the model 1.

![Figure 3. The power coefficient of the wind rotor models.](image_url)

4.2. Dynamic Torque

Figure 4 represents the variation of dynamic torque coefficient with the variation of TSR for the model 1, model 2 and model 3. The magnitude of the dynamic torque coefficient ($C_T$) at the minimum, optimum and maximum tip speed ratio with the corresponding Reynolds number ($Re$) for all three models is shown in table 2.

For model 1, the maximum dynamic torque coefficient is 0.81 at the minimum TSR of 0.28, and the torque coefficient decreases with the increase of tip speed ratio. The minimum torque coefficient can be seen as 0.32 at the TSR of 0.62. As there are larger variations in torque coefficient with small variations in tip speed, which can be because of the testing of the wind rotor models at a higher torque.

For model 2, the maximum dynamic torque for the wind rotor model is 0.56 at the minimum TSR of 0.21 and the torque coefficient decreases with the increase of TSR. The minimum torque coefficient of the model is 0.3 at the TSR of 0.47. The maximum dynamic torque coefficient of the model 2 is less than the maximum dynamic torque coefficient of the model 1. A reason for less torque coefficient of model 2 is that the model 2 is a three bladed rotor, which produce comparative less torque than a two bladed rotor. Also, the three blades rotor rotate slower than the two blades rotor, which is due to more area facing toward the wind and have more negative torque positions. The increases of negative torque positions cause the decrease of net torque produced by the rotor.
For the model 3, a double stage simple Savonius rotor. The maximum dynamic torque coefficient is noted as 0.67 at the minimum TSR of 0.17, and the torque coefficient decreases with the increase of TSR. The minimum torque coefficient is 0.33 at the higher TSR of 0.56. The maximum torque coefficient of the model 3 is 16% less than the maximum torque coefficient of the model 1. Moreover, the maximum torque coefficient of Model 3 is about 20% greater than the model 2. A reason for decrease of torque coefficient of the model 3 (double stage simple Savonius rotor) from the model 1 (a two-bladed single-stage rotor) is that the model 3 has become bulky due to two stages and the wind rotor loses some of its energy in rotating idle stage. The decrease of torque coefficient for such model was also reported by [14]. However, a reason for increase of torque coefficient of the model 3 than the model 2 is that a two stage, two bladed rotors produce more net torque than three bladed single-stage rotor [14].

![Figure 4. Dynamic torque coefficient of the wind rotor models.](image-url)
Table 2. Power coefficient and torque coefficient at the correspondence minimum, optimum and maximum tip speed ratio

| Model #  | λ   | Re   | \(C_p\) | \(C_T\) |
|----------|-----|------|---------|---------|
| Model 1  | 0.28| 90041| 0.231   | 0.81    |
|          | 0.42| 104980| 0.260  | 0.62   |
|          | 0.62| 149799| 0.197  | 0.32   |
| Model 2  | 0.21| 104980| 0.118  | 0.56   |
|          | 0.39| 129206| 0.167  | 0.43   |
|          | 0.47| 149799| 0.141  | 0.30   |
| Model 3  | 0.17| 104980| 0.115  | 0.67   |
|          | 0.46| 129206| 0.206  | 0.44   |
|          | 0.56| 149799| 0.187  | 0.33   |

5. Conclusion

Three models of wind rotors have been tested in an open wind flow. The power coefficient of model 1 determined to be higher than the power coefficient of model 2 and model 3. The power coefficient of model 1 is also found to be higher about 24% than that of previously referred study of the same rotor because of the positive effect of changing the aspect ratio to 2. The maximum power coefficient for model 1, model 2 and model 3 is noted as 0.26, 0.17 and 0.21 at their respective tip speed ratio of 0.42, 0.39 and 0.46. The power coefficient of model 3 was observed higher than the power coefficient of the mode 2, a reason of this is model 3 is a two bladed, double stage rotor. Whereas, model 2 is a three bladed single-stage rotor therefore it can be concluded that the double stage two-bladed rotors have higher performance. However, the blade profile design also contributes to performance coefficient therefore it is needed to test the design of model 2 as a two bladed, double stage rotor.

The dynamic torque coefficient of all three models decreases with the increase of tip speed ratio. The maximum dynamic torque coefficient of the wind rotor models is at the minimum tip speed ratio. Dynamic torque coefficient of model 1, model 2 and model 3 is 0.81, 0.56 and 0.67 respectively at the correspondence minimum tip speed ratio of 0.28, 0.21 and 0.17. The models in this study have larger variations in torque coefficient with smaller variations in tip speed, which can be because of the testing of the wind rotor models at higher applied torque.

Acknowledgment

The authors acknowledge Universiti Teknologi PETRONAS (UTP) for supporting the work financially and technically under the International research agreement with University of Stavanger – Norway, grant URIF 22/2013.

References

[1] Panwar N L, Kaushik S C, Kothari S 2011 Renewable and Sustainable Energy Reviews 15 1513-24
[2] Betz A 2014 Introduction to the theory of flow machines Elsevier)
[3] Borhanazad H, Mekhilef S, Saidur R, Boroumandjazi G 2013 Renewable Energy 59 210-9
[4] Sathyajith M 2006 Wind energy: fundamentals, resource analysis and economics Springer Science & Business Media
[5] Akwa J V, Vielmo H A, Petry A P 2012 Renewable and Sustainable Energy Reviews 16 3054-64
[6] Morshed K N, Rahman M, Molina G, Ahmed M 2013 *International Journal of Energy and Environmental Engineering* **4** 1-14

[7] Mahmoud N, El-Haroun A, Wahba E, Nasef M 2012 *Alexandria Engineering Journal* **51** 19-25

[8] Al-Kayiem H H, Ming G J 2011 *World acad Sci, Eng and Tech* **60** 144-9

[9] Kamoji M A, Kedare S B, Prabhu S V 2009 *Applied Energy* **86** 1064-73

[10] Hayashi T, Li Y, Hara Y 2005 *JSME International Journal Series B* **48** 9-16

[11] Menet J L 2004 *Renewable Energy* **29** 1843-62

[12] Percival M, Leung P, Datta P, The development of a vertical turbine for domestic electricity generation. European Wind Energy Conference London; 2004.

[13] Vanderhye R A, Dexter M H, Aldrich A L, Rotsky B A, Hascup J R, inventorsThree bladed Savonius rotor. U.S. patent 7,314,346 B2. 2008.

[14] Saha U, Thotla S, Maity D 2008 *Journal of Wind Engineering and Industrial Aerodynamics* **96** 1359-75

[15] Blackwell B F, Sheldahl R F, Feltz L V 1977 *Wind tunnel performance data for two- and three-bucket Savonius rotors* (Sandia Laboratories)

[16] Alexander A J, Holownia B P 1978 *Journal of Wind Engineering and Industrial Aerodynamics* **3** 343-51