Experimental Study on the Performance of a Savonius-Darrius Counter-Rotating Vertical Axis Wind Turbine

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Abstract. This paper describes the study of a small vertical axis wind turbine (VAWT) with a combined design of Darrius and Savonius counter-rotating rotors. The main purpose of this study is to improve the extraction capabilities of a single-rotor VAWT by using two distinct rotor designs while adopting the counter-rotating technique. Given that the conversion capabilities and operational speed of the existing wind turbines are still limited, the current technique is used to enhance the efficiency and expand the operating wind speed range of the VAWT. The Darrius and Savonius counter-rotating rotors were exposed to a similar upstream wind speed using a centrifugal blower. It was found that the Savonius-Darrius counter-rotating rotor was able to operate effectively particularly at the low-speed wind. By looking at the individual performance of the rotors, it was observed that the conversion efficiency of the H-type rotor increases as the wind speed increases. However, in the case of the S-type rotor, it is higher at lower wind speed and tends to decreases as the operating speed increases. Thus, the maximum efficiency of the S-type rotor was achieved at low-speed, whereas the H-type rotor has achieved its maximum efficiency at the highest operating wind speed. The average efficiency of the present Savonius-Darrius counter-rotating rotor has been improved to reach almost 42% more efficiency in terms of torque.

1. Introduction
Today, wind energy is one of the most exploited and fastest growing sources of alternative energy globally. A global growth rate of approximately 16% was achieved in the last several years based on the sector presentation. According to the world wind energy association (WWEA), a total installed capacity of 539 GW was realised by end of 2017 last year compared to 487 GW in the year 2016 [1]. This has come as a result of the enormous number of wind turbines installed worldwide which has been manifested by
this great amount of power rise. In wind turbine industry, two dominant designs of wind turbine exist. They are characterized according to their axis of rotation as horizontal-axis wind turbine (HAWT) and vertical-axis wind turbine (VAWT). Nowadays, a renowned interest in developing wind turbines with vertical axis have emerged all over the world. The most popular designs of VAWT are the lift-type Darrius rotors and drag-type Savonius rotors. The straight-bladed H-type Darrius rotor and S-type Savonius rotor are among the widely used wind turbine rotors in the present days. This increased attentiveness could be owed to the fact that VAWTs have more advantages compared to HAWTs in terms of design, installation, operation and maintenance and overall cost [2], [3].

In essence, all wind turbines possess the ability to convert effectively the kinetic energy from the air into useful electrical energy or mechanical torque. However, in terms of application, each design is favourable at a particular site than another, depending on the strength of the wind at the site among other factors. While selecting an appropriate generator may be crucial, nevertheless, deciding suitable rotor of a wind turbine is of ultimate significance. This is due to the variations of the optimum working condition for different rotor type or design. Savonius rotors, for example, are typically found at sites where the wind velocity is low and high turbulent intensity such as the urban environment due to their lower cut-in speed and capability to cope well with turbulent wind. Moreover, they are also used when high starting torque is required such as grinding grain or pumping water [4]. On the other hand, the Darrius rotors are commonly found at sites where the wind strength is not an issue. This is because the Darrius rotors are renowned for their inherent characteristics to work more effectively and retain higher conversion efficiency at higher wind velocities. However, they generally face difficulty to self-start at low-speed wind and therefore external devices are sometimes used to resolve such issue [2], [5]. Thus, the two distinctive rotor-types are combined in the prototype of the current study in order to take advantage of inherent characteristics of both designs and to widen the application of the new counter-rotating concept in VAWT.

Counter-rotating wind turbine (CRWT) is a wind turbine system that involves the rotation of two rotors in a completely opposite direction to one another. The main difference between vertical-axis CRWT and horizontal-axis CRWT apart from the position of the rotation is that it involves the rotation of the generator together with one of the counter-rotating rotors in wind turbines with vertical axis. This is because one of the rotors is literally attached to the generator. Such innovative technique is also known as shell rotation. Counter-rotation is a recognized technique in enhancing the output of a single-rotor wind turbine system considerably. It has shown to work effectively and has the ability to improve the conversion efficiency of a wind turbine significantly in both wind turbine design with the vertical axis [6], [7] and horizontal axis [8]–[12]. Although the counter-rotation concept is widespread in HAWTs, only limited literature are recently starting to appear in VAWT applications. A recent experimental study performed by Didane et al. [6] indicated that an improvement of up to 43% and 40% of torque coefficient and power coefficient were respectively attainable using the counter-rotating technique in VAWT. A similar outcome was also achieved by Didane et al. [7] using a numerical simulation approach. Such significant improvement in the performance of the VAWT has motivated the current study. However, prior studies have revealed that the operation range of the CRWT with vertical-axis is still limited to moderate and higher wind speeds [6]. Therefore, this study is set out to expand the operating speed range in order to cover a lower operating speed by combining the Darrius and Savonius rotors while improving the performance of the single-rotor VAWT. This is also in an effort to respond to the fact that the average wind speed in many countries like Malaysia and Chad is less than 5 m/s and also the harnessing capabilities of a single-rotor VAWT is still low [13]–[16]. Thus, such appropriate design is needed in order to satisfy the need of such locations while enhancing the output of the single-rotor VAWT using the counter-rotating technique. The main objective of this study is therefore to enhance the performance of the single-rotor VAWT particularly at low-speed wind using the counter-rotating technique.
2. Experimental setup

The current prototype of the Savonius-Darrius CRWT is built by combining the Savonius S-type rotor and Darrius straight-bladed (H-type) rotor as shown in Figure 1. The S-type rotor shape was positioned on the top, where it is fixed to the shaft, while the H-type rotor shape was placed at the bottom side where it is fixed to the generator shell. Different materials were used to fabricate each rotor while paying attention to suitability and convenience in terms of design and fabrication. Thus, pinewood material was selected to fabricate the H-type Darrius rotor for its light, relatively strong, cheap and customizable characteristics. Meanwhile, galvanized steel is used for the S-type rotor shape for its capability to withstand a high vibration and shock. Moreover, the blade profile NACA0021 with 21 mm thickness was used as the aerofoil profile section for the rotor. A total of three wooden blades were fabricated and painted where the height of the blade is 50 cm and the chord length is 10 cm, as shown in Figure 2. However, in the case of the S-type rotor, a total of three blades were fabricated since the rotor is a three-blade rotor. Furthermore, the S-type rotor is designed with the dimension of 12 cm blade height and 27 cm blade length.

![Figure 1. H-type blade profile using NACA 0021 airfoil.](image)

![Figure 2. Dimension of S-type blade.](image)

On the other hand, a 1.2 cm cylindrical aluminium bar was used for central shaft material. In addition, the Darrius rotor is equipped with three semicircle polyvinyl chloride (PVC) tubes in an effort to assist the rotor to self-start. The diameter and length of each PVC is 10.5 cm and 23 cm, respectively while the
thickness is 2 mm. Moreover, the H-type rotor was predetermined to rotate in a counter-clockwise direction only whilst, the S-type rotor was fixed to rotate in a clockwise direction only. Such a mechanism was achieved with the help of single-direction bearings on top of the shaft and below the generator for the S-type rotor and H-type rotor, respectively.

The prototype design as shown in Figure 3 was set up and tested using a centrifugal blower with the capacity of 10 hp and 2880 rated rotational speed per minute (RPM) to generate the required airflow. The counter-rotating prototype was positioned at the blower’s outlet while testing.

3. Results and discussion

3.1. Rotational speed of the model

Figure 4 demonstrates the relationship between the rotational velocity of the two counter-rotating rotors and wind speed. The prototype has been tested with the range of wind speed starting from 2 m/s until 9 m/s. It has been noticed that the rotational speed of the rotors has a direct variation with wind velocity. The rotational speed of both rotors kept increasing as the wind speed increase as shown in Figure 4. Unlike the H-type rotor, the S-type rotor was able start to rotate from 2 m/s due to its inherent self-starting capabilities. However, the H-type was able to start rotating only from 5 m/s. Moreover, the RPM value for the S-type rotor is greater than the RPM value of the H-type rotor due to smooth rotation of the S-type rotor and absence of associated weight of the generator. The S-type rotor was attached to the shaft and not on the generator as the case with the H-type rotor which required less torque to spin this rotor. Moreover, since higher rotational speed means more power output, obvious increased performance in terms of RPM was realized from the two counter-rotating rotors as in Figure 4.

However, by observing the total output from the two rotors, it could be deduced that counter-rotating system is much more advantageous than a single-rotor VAWT. The performance of CRWT has been improved significantly in term of rotational speed due to the combination of the two rotors. In addition, the presence of S-type rotor has also enabled the CRWT system to generate power output as low as 2 m/s of wind speed which suggests a wider application of this concept in many sites including the urban environment.
3.2. Evaluation of mechanical torque

Figure 5 illustrates and brings together the performance of the two rotors with regard to torque against the whole operating wind speed range. It is clear that H-type rotor starts to rotate only from 5 m/s, unlike S-type rotor which was able to rotate from 2 m/s wind speed. The rotation of the two counter-rotating rotors is a result of pressure difference on the surfaces of the blades due to the incoming wind which was blown against the rotors. Moreover, although the rotational speed of the S-type rotor was high as seen in Figure 4, the total torque output obtained was low. This is because there is inverse variation between the torque and rotational speed. It was also revealed that compared to the H-type rotor, the torque output from the S-type rotor was low although the conversion efficiency of this rotor was better. Moreover, the rate of torque increment for the H-type rotor was significant with regard to the increase of the wind velocity. However, this rate has not changed much while the free-stream wind velocity increases. Nonetheless, the total output of the CRWT was increased considerably due to the presence of the H-type rotor in the system although it could not operate below 5 m/s wind velocity as shown in Figure 5.

While the current design has the advantage of operating at the wind speed of as low as 2 m/s, however, the significant contribution of this system appear at wind speed beyond 5 m/s. This is primarily attributed to the fact that H-type rotor could not contribute to the overall system at the wind speed below 5 m/s. However, the new concept has created a tangible benefit with regard to torque output as shown in Figure 5.

3.3. Evaluation of torque Coefficient

The conversion efficiency in terms of torque over the incoming wind velocity covered are presented in Figure 6. It shows a significant differences were found between the conversion efficiency of the Darrius rotor and Savonius rotor. As revealed in the figure, the total torque coefficient of the CRWT tends to have an inverse relation with the operating speed. Similarly, the S-type rotor was able to convert better at the lower wind speeds than higher wind speeds. However, unlike this trend, the conversion efficiency of the H-type rotor seems to increases with the wind speed. This is again due to the inherent characteristics of Darrius rotors to perform better in higher wind conditions. It is also interesting to note that the H-type rotor contributed less in the overall efficiency of system compared to S-type rotor. This because the current wind speed range involved is relatively low for the H-type rotor in which it was not able to start at 2, 3, 4 m/s wind speeds. It usually operate more efficiently at a tip-speed ratio that is greater than one. However, the current maximum wind speed (9 m/s) produces less than one tip-speed ratio. Therefore, it failed to start rotating at wind speed below 5 m/s. However, the collective conversion efficiency of the two rotors is still significant compared to a single-rotor system alone. Thus, an average conversion efficiency of almost 42% was achieved due to the combination of these two rotors as shown in Figure 7.
4. Conclusion

The performance of Savonius-Darrius CRWT model was evaluated using an experimental approach. The prototype was tested in the open air using a centrifugal blower of which wind speed ranging from 2 m/s to 9 m/s was generated. The Savonius-Darrius counter-rotating rotors have shown to work effectively at the entire wind speed range covered particularly at low-speed wind. The new concept was capable to improve the output of the single-rotor wind turbine substantially with an average conversion efficiency of almost 75\% in terms of torque. From the result obtained from the experiment, it shows the S-type rotor has good self-start with a high RPM at low wind speed. The S-type rotor was able to self-start at as low as 2 m/s while the straight-bladed H-type rotor started spinning only at 5 m/s wind speed. It was also demonstrated that the conversion efficiency of the H-type rotor increases as the operating velocity rises. However, in the case of S-type rotor, the conversion efficiency is high in lower wind speed conditions and tends to decreases as the operating speed increases. It is to be noted that the maximum efficiency of the S-type rotor was achieved at low-speed whereas the H-type rotor achieved its maximum efficiency at the highest operating wind speed.

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5. References

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