Vertical Axis Wind Turbine for Low Wind Speed Environment: Effect of Scoop Harmony Blade

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Abstract. The wind condition in Malaysia is in the low-speed category with an average speed of 1 ms^{-1} to 4 ms^{-1}. Effect of ground level relies significantly on the wind speed distribution. Despite these conditions, it is less suitable for the development of horizontal wind turbine as an energy source. The obvious weakness is the lack ability to self-start and predict the wind direction thus affects the energy efficiency output. To overcome this problem, improvement of the vertical axis wind turbine design is observed to be the solution in replacing horizontal axis wind turbine. Hence, this study is to investigate a suitable type of vertical axis wind turbine bladedesign for the best performance RPM output in a low-speed wind environment. The investigationwas conducted in a Longwin LW-9300R subsonic wind tunnel at 0 ms^{-1} to 10 ms^{-1} wind speed condition from three wind turbine blades specified as Solid Harmony, Scoop Harmony and Conventional Savonius blade with angle of 90°, 135° and 180° to determine the highest RPM productivity. Result shows that Scoop Harmony blade delivers the highest RPM blade output while Savonius 180° is seen to have the highest self-start blade achieved at 64 rpm at 1 ms^{-1} wind speed. However, Solid Harmony shows an acceptable range TSR of 0.5 with difference of 23% lower than Scoop Harmony. This shows that both Scoop Harmony has a higher performance RPM but Solid Harmony still has the potential design to be applied at low-speed condition due to its low TSR output.

Keywords: VAWT, Savonius Blade, Harmony Blade, Low Wind Speed, Wind Energy.

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1 Introduction

According to Malaysian's Wind Speed analyst in 2015, wind speed distribution ranges from 1.4 ms^{-1} to 2.7 ms^{-1} [1,2], with a variation speed of 4.1 ms^{-1} detected specifically at offshores area [3]. Despite the fact, these are still considered as low wind speed in addition, to uneven geographical land which causes wind speed distribution to be unbalanced and divergent.

Unlike European countries where wind speed are considered high, wind energies has emerged in generating electricity [4] and assisting in water pumps [5,6] because of their high efficiency output in comparison to other natural resources. A convenient geographical location where wind shear level andsufficient wind speed are some of the key factors for wind turbines to deliver large amount of power generated. Instead, this suitability also depends on the type of wind turbine installed. Wide coastal areas, farms, in between mountains and offshores are more practicability for horizontal axis wind turbine (HAWT). It works by generating power from the rotating blade positioned horizontally or parallel to the ground. This is because HAWT generates a decent productivity at high wind speed condition, giving them a higher power output produced.

Nonetheless, HAWT has their own limitation. HAWT could not predict the wind direction with its fixed position as well as incapable to tolerate with turbulent wind flow [7]. Hence, this could affect the energy efficiency. One of the solutions to overcome this problem is by installing a device called yawing meter onto the mechanical system resulting in a higher consistency [8,9]. However, adding additional component contributes to larger, heavier, and further complexity to construct and maintain. After all, HAWT dominates the wind power industry through European countries and around the globe. Be that as it may, these type of wind turbines could not operate at low-speed wind condition and lack the ability to self-start. As a result, these wind turbines are not practical for Malaysian wind condition.

Therefore, vertical axis wind turbine (VAWT) is seen to be an alternative solution. This is proven bya study conducted by Saad and Magedi [8], revealing that, VAWT has an efficiency of 70% higher than HAWT despite its low-speed advantages. Chong et al. in their investigation found that, with the modification of VAWT blade to omni directed guide vanes (ODGV), the rotational speed can be increased up to 125% and a tip speed ratio (TSR) of 0.4 [10]. This has been proven through CFD simulation that ODGV is able gives the contribution factor to increase torque and power output for VAWT. Wong et al. [11] and Siregar et al. [12] supported findings by Magedi [8] where have ODGV has been proved to enhances the performance with good result.

In an another case, VAWT is seen to be cheap and simple to operate [13]. VAWT is able to accept wind from any direction in a 360° angle. Instead of using normal propeller blade, VAWT works by rotating its rotor vertically [9]. This is more suitable in tight areas, tall buildings, where there is little wind speed supplied [14-16]. They are also capable to be mounted closely to the ground surface allowing the blade to overcome turbulence wind flow [16]. Consequently, VAWT is observed to be a safer operation compared to HAWT because it rotates at a slower speed, decreases the risk of bird's injuries and noise output [17].

Since then, studies have shown consistent improvement on the design of VAWT. Wakui et al. [18] has shown that VAWT can adapt with free-standing wind turbine generator system with several operating design rotor of Savonius type [19], Darrieus or Harmony. Savonius wind turbine has an S- shaped rotor, the blades are curved, twisted, and seen having a wind pocket (Scoop) [20]. Generally, the number, shape, vane angles and blade weight are several parameters needed to be considered in order to optimize the wind turbine performance [21]. Promdee et al. studied several wind angles from Savonius wind turbine and found out that more voltage at a wind angle of 17º to 38º produces the highest electricity output [22]. In this case, lift force is higher than the drag force which causes the blade to rotate freely [23] at an optimum angle relative to the wind direction [24]. In addition, scoops like shape helps the drag force to change wind energy to torque aiding the rotation of the wind turbine [20]. This creates a lesser drag when wind flows through the scoop and making consistent scoop spin regardless of wind direction. Hence, Savonius type is one of the simplest wind turbines existed [19]. Another in VAWT is Darrieus type. It has shapes of curved or straight, with a lift type device of rotor blade having an aerodynamic shape. With a TSR greater than one, Darrieus wind turbine can rotate faster than the speed of wind flowing across the blade [25]. Hence, this wind turbine is able to provide a higher torque to rotate faster than other wind turbine due to its a large centrifugal force [18]. In the same category,

Solid Harmony wind turbine arrayed in helix position and each blade is piled up at 120º apart. As seen from the physical configuration, obvious aerodynamic geometry towards a low wind motion, it could conceivably be hypothesized that Harmony type VAWT could deliver a better TSR and powercoefficient, Cp than Savonius and Darrieus, required that blade angle is taken into consideration.

Therefore, based on previous study, performance of VAWT can be increased by selecting the right type of wind turbine, weight blades and angle. Since there are no or very little research conducted on the Harmony type wind turbine, thus, seen to have the potential on harnessing more rotation speed anda better self-start capability on low wind speed case conditions, several scoop will be mounted at different angle on the Harmony VAWT to witness the performance of different scoop angle incomparison with Savonius type or also known as the baseline case in this study. The main objective of this study is to investigate the performance between the present of scoop blade on the wind turbine, specifically on the self-start, rotational speed (RPM) and TSR as a valuable contribution for VAWT at low wind speed condition. In this experiment, RPM and TSR will be evaluated to ensure a good performance of wind turbine as an optimum VAWT configuration.

2 Methodology

2.1 Design of VAWT

Three VAWT blade comprising of Solid Harmony, Scoop Harmony and Savonius type (baseline case)were used in this study (Figure 1). Height and diameter of all three blades are constant at 60 mm and 80 mm respectively.

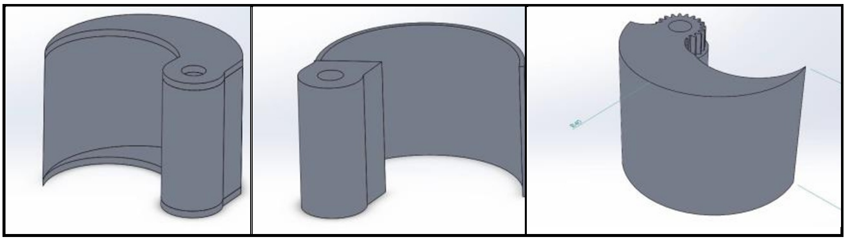

Fig. 1. Isometric view of VAWT Savonius [28] (left), Solid Harmony [29] (middle) and Scoop Harmony (right).

The design for Savonius blade design were acquired from Aymane et al. whereas Solid Harmony type was acquired from previous testing done by Christopher T. Moore.For further analysis, Scoop Harmony was added into this setup with modifications on the blade angle. Thus, all three VAWT was varied in three angle configurations, 90º, 135º and 180º between each layerblade.

The entire design was done using CAD software. Different angle arrangement was chosen to determine the optimum VAWT performance in respond to the low wind speed setting. Thus, there are a total of 9 configuration VAWT structure in terms of types and angles conducted in this study. These designs have already considered the safety margin of the wind tunnel test section which will be explain in section 2.2.

2.2 Fabrication of VAWT and Assembly Details

Design manufacturing of blades and connecters were done using Flash Forge Guide II 3D printer. The process used by a 3D printer, is an addictive manufacturing method called Fused Depositional Modelling (FDM), by means of forming layers of materials through bottom to top approach. It forms the model one thin layer at a time, starting from the bottom base until the end top layer via a 0.4 mm nozzle. In this case, Polylactic Acid (PLA) was used to eject the filament continuously. Guidelines to the 3D printer behavior is based on a STL format translated from the CAD software. Yet, after 3D printing is completed, all blades and connectors appear to have uneven surface roughness. Therefore, sanding process was a good way to smoothen the surface using P80, P120, P800 and P1200 grit type on all the complete printed models.

In order to assemble the components to a VAWT, a guide vane was attached to the bottom and top part of an 8 mm diameter and 350 mm length rod that also acts as a shaft. The blades are then attached to the shaft via a blade connector, allowing the blade to rotate in a circular motion alongside the vertical axis. The shaft also acts as a medium to transmit power from the blade to the generator. Two ball bearings are attached to the top and bottom shaft to ensure smooth rotation. Steel alloy was chosen for the shaft and ball bearing due to its light weight, strong and anti-rust properties. A connector then holds the two blades at the upper and lower part forming a pair of blades to rotate simultaneously on the same axis. 1mm diameter hole was drilled at the middle of the holder for the shaft to pass through the connector.

Next, frame support with a dimension of 30 mm (weight, height, and length) was built using T-slot aluminum extrusion to hold the VAWT firmly together in the test section as shown in Figure 2. This is done so that the wind speed does not disrupt any vibration or unwanted motion on the VAWT during testing.

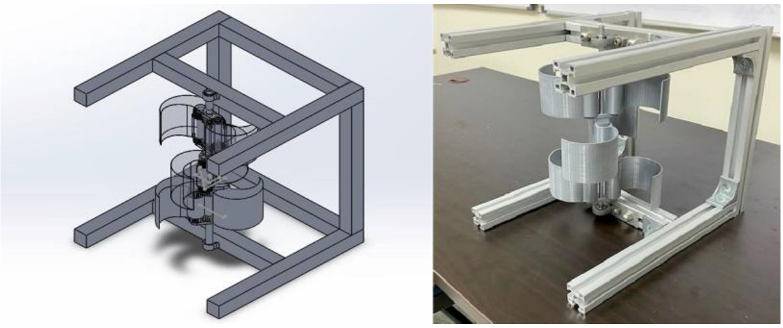

Fig. 2.: Full CAD Assembly of VAWT with frame support (left) and final VAWT assembled attached (right).

2.3 Low speed Subsonic Wind Tunnel

Data collection for the wind turbine were carried out in the LW-9300R subsonic open loop wind tunnel located at the Faculty of Engineering, National Defence University of Malaysia (UPNM) as shown in Figure 3. This is also an exact type used by Jumahadi et al. [28]. The open circuit wind tunnel has a test section fixed at 0.3m (width) x 0.3m (height) x 1.0m (length) with a transparent wall on each side except for the back side which is purposely made in black hue for visualization process. Falling under a suction mode type, the upstream air is sucked and aligned from a honeycomb mesh structure surrounded by a settling chamber at the front part of the wind tunnel. The purpose is to alignthe air entering the wind tunnel and reduces the flow turbulence upon reaching the test section.

Downstream of this section is equipped with three identical fan blades positioned together on the streamlines, generated by an AC220V-3-phase-60A, enclosed by a vent that passes the air out to the atmosphere. The wind tunnel is able to achieve a maximum air speed of 110ms^{-1} equivalent to Mach number of 0.3. Though, the air speed was set at 0 ms^{-1} to 10 ms^{-1} associated with the Malaysian wind speed suitability. The measurement technique used in this experiment is a handheld Fluke 940 DigitalTachometer system.

Fig. 3. Longwin LW-9300R Subsonic Wind Tunnel located at The National Defence University NDUM [29].

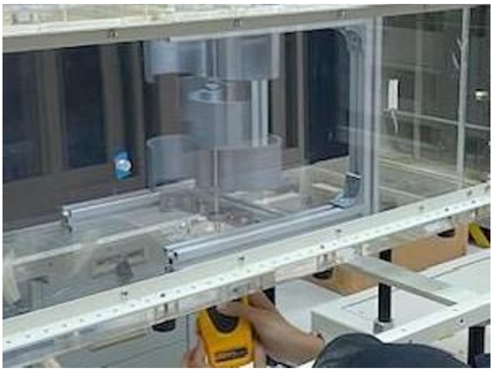

Fig. 4. Measuring rpm output reading from a Scoop Harmony VAWT [30].

Since the shaft length is purposely made to exceed the height of the test section, it is stretched out from a small slot at the test section base. Remaining spaces and gaps were sealed with a masking tape to ensure that there is no airflow leakage during the experiment. Exposed shaft at the base of the test section is then covered with a reflective mask so that rotation of VAWT model can be taken by the digital tachometer during experiment as shown in Figure 4.

The Digital Tachometer emits a small beam of light pointed out at the reflective mask at the tip ofshaft so that the rotation of the VAWT gives an rpm reading output as shown in Figure 5. This gives an advantage for no physical contact between the measuring tools and VAWT during testing. Despite obtaining the RPM, experiments were also done to calculate the self-start velocity and TSR as a vital element of power coefficient.

Fig. 5. Close view VAWT measurement using a Fluke 940 Digital Tachometer.

2.4 Vertical Axis Wind Turbine Equations

According to Manganhar et al. the energy produced from the wind turbine is influenced by the size of the wind turbine. A larger size area gives a bigger energy output. Factors that affect the output is the diameter and angular velocity of the wind turbine blade. This is also a dependent variable of tip speed ratio (TSR). TSR integrates the principle of aerodynamic effect on the wind speed and angular speed of the rotor. Dimensions from Savonius wind turbine was also conducted by Aymane et al.It is the ratio of blade radius to the angular speed of the rotor velocity relative to the wind direction.

TSR is calculated as:

$$TSR = \frac{V_{rotor}}{U} = \frac{\omega r}{U}$$

where, V_{rotor} and U are rotor blade speed and wind speed (ms^{-1}) respectively, ω is the angular speed(rads^{-1}) and r is the radius (m). The optimum TSR was obtained based on the angular speed.

3 Results and Discussions

Three experimental cases were conducted with each case has three different blade angles. Meanwhile,each case consists of three different angle configurations done in this investigation. Air flow condition that was supplied are the same for each case. Comparison of rotor speed and TSR discussed in this section.

3.1 Rotor Speed, RPM Performance

The rotor speed, RPM against wind speed (ms^{-1}) ranging from 1ms^{-1} to 10ms^{-1} are shown in Figure 6 to Figure 8 with a total of nine different variables. All the patterns were observed to have a linear graph against a higher wind speed. A slight difference can be observed by the self-start up of wind turbine. This can differ by adjusting the blade angle and blad type.

As seen in Figure 6, Solid Harmony with an angle of 90º seems to have a slower start up at 3ms^{-1}. Interestingly at 5ms^{-1}, all blade shows almost the same RPM with Scoop Harmony has an earliest start at 89 RPM. However, as wind speed increases, a large difference can be seen in the similar type of windturbine by overtaking other wind turbines. A reason behind this observation lies with a larger surface area increase turning speed. This statement also agrees with Wakui et al. [18]**.** As at 10ms^{-1}, Scoop Harmony seems to have a difference of 26% faster rotation compared to Savonius blade type.

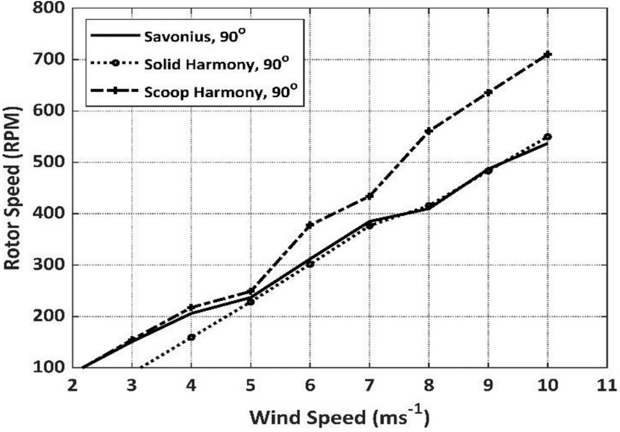

Fig. 6. Rotor Speed (RPM) performance against Wind Speed (ms^{-1}) for 90º blade

For the wind turbine at 135º blade angle shown in Figure 7, Scoop Harmony dominantly over the remaining two wind turbine. Only at 3ms^{-1} that Scoop Harmony was observed to underperform its efficacy. Though, at 10ms^{-1}, Scoop Harmony achieves 13% higher RPM then Savonius. However, unlike 90º blade, Savonius performs slightly better at this maximum speed range with 5% closer velocity against Solid Harmony.

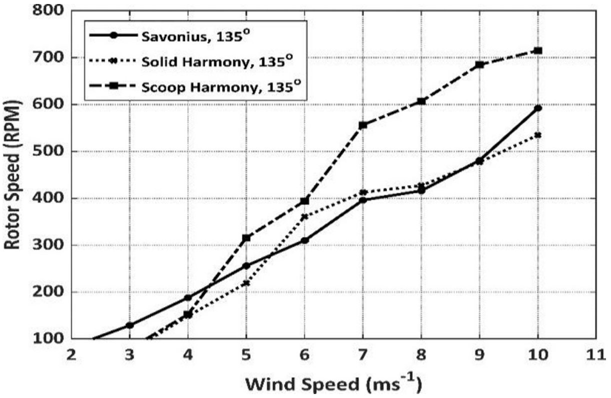

Fig. 7. Rotor Speed (RPM) performance against Wind Speed (ms^{-1}) for 135º blade

For 180º blade angle variation (Figure 8), Scoop Harmony maintains the best performance overcoming both Savonious and Scoop Harmony blade almost entirely with the highest wind tunnel operating speed of 10ms^{-1} for an output of 783 RPM. Nevertheless, a slower start was obtained at 2ms^{-1} having about similar RPM as other type blade. This result in Solid Harmony is seen to have the heaviest blade with a weight of 80g correspond to a higher surface area, compared to Solid Harmony and Savonius. The momentum of scoop pushes further by giving a higher output. However, if the wind turbine rotor rotates at a slower rate, most of the wind will pass through the blade gap having no effect entirely. Though if the rotor spins too fast, the blades will vibrate and act like a solid wall to the wind. This is because rotor blades create turbulence as they spin through the air. This needs to be consider with the 180° type blade although the maximum wind speed against RPM is yet to be investigated.

Since wind speed in Malaysia is observed from 3 ms^{-1} to 4 ms^{-1} . Therefore, this is seen that Scoop Harmony blade 180° is the having the most RPM at an average of 32.25% higher between 2 ms^{-1} and 4 ms^{-1} with a maximum 268RPM at 4ms^{-1}, 3.95% higher rpm than Savonius blade. This is understood that the geometry of the blade curvature is considered to start at a low velocity wind while achieving an allowable rotor speed.

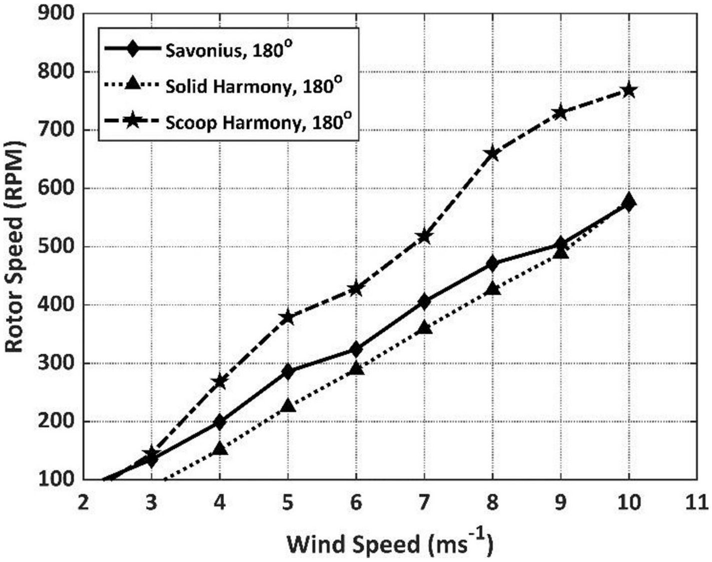

Fig. 8. Rotor Speed (RPM) performance against Wind Speed (ms^{-1}) for 180° blade

In summary, 180° blade for all three types of cases rotates at a faster speed than its lower blade angle. While Scoop Harmony 180° blade seems to gain the most wind surface increase, proportion tothe relative wind contact on the blade.

3.2 Tip Speed Ratio, TSR

Tip speed ratio is analysed to help maximize the power output and efficiency of your wind turbine. Asshown in Figure 9, the graph shows that Scoop Harmony blade 90° has the highest TSR at 0.6 at 700 RPM. This trend can be seen by other data as well. Previous results show a similar trend In their experimental study, they found that VAWT types with a blade has a good TSR output at 6ms^{-1} wind speed by obtaining a maximum of about 1.6 TSR.

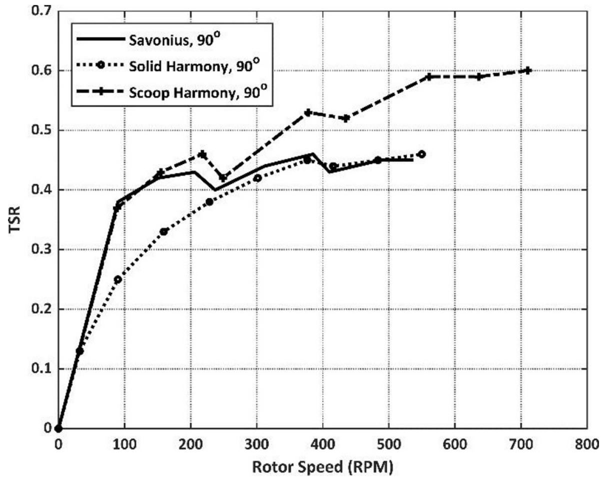

Fig. 9. TSR against Rotor Speed (RPM) for 90° blade

For the TSR at 135° shown in Figure 10, Savonius shows a favourable TSR at 0.4 with a wind speed of up to 2ms^{-1}. Although Scoop Harmony surpasses Savonius after 200 RPM. However, as stated by Saeidi et al. higher rotation does not mean higher TSR. because of a possibility of lower Cp. This statement also agrees by Antar and Elkhoury [19], as Scoop Harmony has the highest TSR, the optimize performance can be better with presence of scoop though maintain at lower RPM. Also, TSR value results in a relatively low over the theoretical calculation.

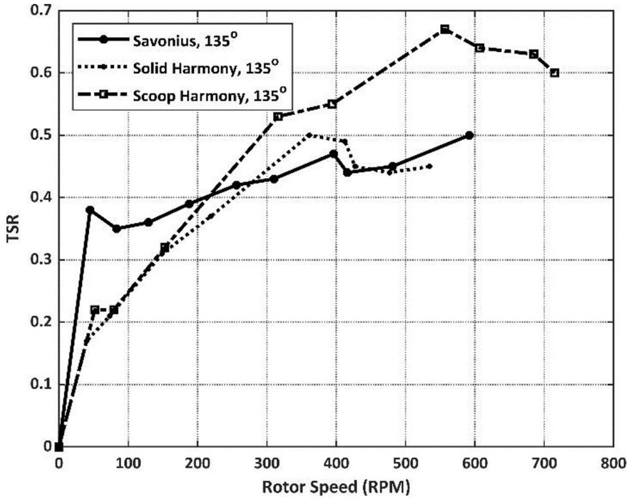

Fig. 10. TSR against Rotor Speed (RPM) for 135° blade

At 180° configuration from Figure 11, Solid Harmony is seen to have the lowest TSR at almost 0.5,at 504 RPM. This shows that the absence of scoop and weight factors gives a huge influence on the wind turbine efficiency especially the angular velocity. The weight of the turbine is lighter without a scoop shape, thus is able to affects the rotation and mechanical power of the turbine. By inspecting the RPM and TSR, Solid Harmony is the lightest blade entirely among others with its shape geometry, easing its gives the ability for the wind to energize the blade movement. The presence of scoops on each blade of wind turbine, gives an effect on the blade rotation speed but also on TSR although the absence of scoop on the blades experiences a higher drag effect. As a result, Solid Harmony wind turbine will not operate at its highest efficiency. Other factors such as mechanical loss in bearing of VAWT contributes to the inconsistency of data.

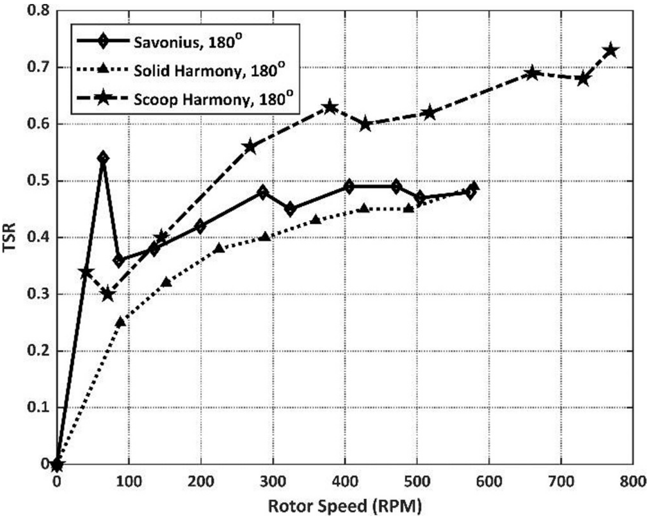

Fig. 11. TSR against Rotor Speed (RPM) for 180° blade

In summary, Solid Harmony blades has a noticeable difference in a lower TSR region where the blade is operating in median operating range than a dynamic range region. Longer operating hours can be expected with the lower start-up wind speed as demonstrated by the VAWT with the scoop assembly, comparably to lower wind speeds.
A similar study has been performed at high wind speed region where the revolution speed is considerably higher for all TSR values in a two and four blade arrangment[26]. The output shows that,the power coefficient (Cp) is mostly invariable to change in the number of blades for all TSR values. It can be considered that the power coefficient (CP) is insensitive to the change in the number of blades with in this case, a three amount of blade.
TSR value in important for turbine speed as a function of wind speed and output of generator has constant to changed in the TSR value. A rotor can be considered well designed if the power coefficient is relatively high for a longer range of TSR rather than having a very high value for only a fraction of the same range of TSR. Nevertheless, as mentioned by [27], very low tip speed ratio will not have enough energy to be extracted by the wind, consequently giving a low Cp. However, too high tip ratio can also result in a low Cp with an addition of tip to stress effect on the blades. Therefore, it is very important to have the optimal tip speed ratio, to maximize the efficiency.
Another considerations that needs to take is the physical shape or size. As mentioned by Hassan et al., the power coefficient of the Savonius wind turbine varies due to its physical shape These factors affect the rotor shaft speed (RPM(by giving out certain number of power coefficient values.

4 Conclusion

Based on the experiment, Scoop Harmony blades 180° wind turbine achieved highest rotor speed of 783 RPM at 10ms^{-1}, almost 31% than the conventional Savionius blade. Earliest self-start was at 1ms^{-1} which is about 18.7% faster than baseline Savonius blade. The performance of the Scoop Harmony contributed by the presence of scoop and weight factor and have blade angle that was increased by the wind momentum. For TSR efficiency, Solid Harmony shows an acceptable range TSR of 0.5 with difference of 23% lower than Scoop Harmony.

This shows that both Scoop Harmony has a better performance RPM although Solid Harmony 180º could still believe to obtain an optimum value forlow-wind speed condition due to low TSR output.

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