DESIGN AND WIND TUNNEL TESTING OF A SAVONIUS WIND TURBINE INTEGRATED WITH THE OMNI-DIRECTION-GUIDE-VANE

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ABSTRACT

A novel omni-direction-guide-vane (ODGV) that surrounds a vertical axis wind turbine (VAWT) is designed to improve the wind turbine performance. A scaled model was constructed to simulate a Savonius VAWT enclosed by the ODGV on top of high-rise building for wind tunnel testing. Torque, rotational speed and power output were measured using a torque transducer with hysteresis brake applied to the rotor shaft. With the aid of the ODGV, the highest increment in rotational speed (11.4%) was achieved at a wind speed of 3 m/s (at free-running condition). The ODGV also increased the power coefficient, C_p of the VAWT at all tested wind speeds and the maximum (C_p = 0.26) was achieved at the tip speed ratio, *TSR* = 0.95 for a wind speed of 3 m/s. The highest increment of C_p (56.9%) was obtained at the same *TSR* and wind speed. With this design, the size of VAWT can be reduced for a given power output.

1. INTRODUCTION

Demand and usage of energy is increasing throughout the world every day causing the pollution level to increase and depleting the current energy sources. Thus, safe and secure long-term energy resources with no global or local pollution have encouraged private sectors and governments to invest in the green energy field. Although there are many renewable technologies commercially available, most of them are still at an early stage of development and not technically mature. Thus, there is an urgent call for researchers and innovators to come out with the best possible solutions for clean energy generation.

Wind energy is the fastest growing energy source in the world today. Wind power is the transformation of wind energy into electricity by using wind turbines [1]. As a matter of fact for many years, wind turbines, especially horizontal axis wind turbines have been used to provide green energy to transfer electricity to urban areas. In the year 2010, the worldwide wind capacity reached 196,630 MW, after 159,050 MW in 2009, 120,903 MW in 2008 and 93,930 MW in 2007 [2]. However, for regions that experience low wind speed, energy generation by using the conventional wind turbine is not suitable since they are designed for operation in high wind speed areas. Thus, many researchers have extensively studied the different types of wind turbine systems for low wind speed operation.

This paper presents an innovative device called the omni-direction-guide-vane (ODGV) for integration with a vertical axis wind turbine (VAWT) for on-site energy generation. It is designed to improve the performance of a wind turbine in terms of power output, rotational speed and self-starting behavior. Wind tunnel testing is performed to measure the effectiveness of the device to improve the performance of a drag-type VAWT, i.e. the Savonius turbine. The comparisons between the ODGV integrated VAWT and the bare VAWT will be further discussed in this paper.

2. FUNNELED OR SHROUDED WIND ENERGY GENERATION SYSTEM

Besides focusing on improving the performance of a wind turbine by the aerodynamic study of the turbine blades, increasing the on-coming wind speed before it interacts with the wind turbine also provides a significant result in power generation increment. The power in the wind is proportional to the cubic wind velocity approaching the wind turbine, which means that even a small increment in wind velocity gives a large increase in energy generation. Thus, over the decades, researchers had studied and reported different designs of ducted or funneled wind turbines which increase the on-coming wind speed hence increasing the efficiency and performance of conventional and unconventional wind turbines.

A funnel or shroud is designed to surround the wind turbine to act as a diffuser for mass flow augmentation. The basic function of the diffuser is to convert the kinetic energy of the flow downstream of the rotor into a pressure rise. This lowers the pressure level behind the rotor, and makes it possible for the rotor to capture airflow from a free-stream tube area that is greater than that of the rotor itself [3]. However, the key problem in diffuser-augmented converters is to compensate at the outlet the pressure drop created by the turbine's energy extraction inside the duct [4]. According to Bussel [5], such mass flow augmentation can be achieved through two basic principles, i.e. increase in the diffuser exit ratio and/or by decreasing the negative back pressure at the exit. Thus, to offer more output per unit rotor area, this fundamental change in stream tube configuration enables practical rotor designs to operate even at very low wind speeds.

A lot of research works have been done to improve the performance of horizontal axis wind turbines. Frankovic & Vrsalovic [6] have designed a nozzle shaped ring with wings with its lower pressure side pointed towards the centre so that the lift force on each part of the wing is directed radially towards the centre. As a result, their nozzle augmented wind turbines were producing 3.28 times more energy than conventional turbines. Bet & Grassmann [7] have reported that by means of employing a wing structure placed at some distance around the turbine a field of low pressure is created behind the turbine. This effect slowed down and widened the air flow hence the corresponding loss in efficiency can be avoided. The wing structure can successfully increase the power of a wind turbine by a factor of 2.0.

The frustum-shaped diffuser for horizontal wind turbine as designed by Matsushima et al. [8] was able to increase the maximum wind speed by a factor of 1.7 with the selection of the appropriate diffuser shape as obtained by numerical simulations. Actual field tests has been conducted by using a real examination device with a diffuser and it was confirmed that the output power of the wind power generator increased by up to 2.4 times compared to that of a conventional turbine. A similar design of shrouded diffuser for HAWT has been studied and presented by Ohya and Karasudani [9]. The diffuser is equipped with a broad-ring brim at the exit periphery and a wind turbine inside it. The shrouded wind turbine with a brimmed diffuser has demonstrated power augmentation by a factor of about 2–5 times compared with a bare wind turbine, for a given turbine diameter and wind speed. This is because a low-pressure region, due to a strong vortex formation behind the broad brim, draws more mass flow to the wind turbine inside the diffuser shroud.

On the other hand, mass flow and power coefficient augmentation for the vertical axis wind turbine (VAWT) has also been studied extensively. The comparative studies on lift-based turbine have shown that VAWTs are advantageous to HAWTs in several aspects [10]. Looking at the structural aspects, low level of maintenance can be expected from the VAWT because it does not require any yaw mechanism, pitch regulation or gearbox and therefore, has few movable parts. In Japan, a study was conducted by Takao et al. [11] which showed that by adopting the guide vane row, the power coefficient of straight-bladed vertical axis wind (NACA 0015 airfoil) turbine (VAWT) was 1.5 times higher than a wind turbine which has no guide vane.

As for the drag type wind turbine, Irabu & Roy [12] employed a rectangular guide-box tunnel to adjust the inlet mass flow rate and improve the output power of the Savonius rotor. The power coefficient of the Savonius rotor was increased about 1.23 times and 1.5 times for a two bladed rotor and a three-bladed rotor respectively. Altan & Atilgan [13] also showed that the introduction of a curtain arrangement placed in front of a Savonius rotor prevents negative torque opposite the rotor rotation, and the maximum power coefficient of the Savonius wind rotor is increased to approximately 38.5%. Müller et al. [14] have made a box shape model of funnel to increase the theoretical efficiency of a drag type rotor to approximately 48%. The design was tested in an initial experiment, and it was shown that efficiency higher than 40% can be achieved.

3. DESIGN DESCRIPTION OF THE OMNI-DIRECTION-GUIDE-VANE

The initiative to promote clean energy generation continues in this paper with the patented device called the ODGV that integrates and optimizes several green elements; including urban wind turbine, solar array and rain water collector [15]. The ODGV is an innovative design to enhance wind power extraction by converting the free-stream wind into a speed-increased and directional-controlled air-stream. It is a revolution of the previous design called the power-augmented-guide-vane as thoroughly presented in the references [16, 17].

Fig. 1(a) and 1(b) shows the side sectional view and perspective view of the ODGV respectively. The ODGV consists of an upper wall duct, [A] a lower wall duct, [B] and guide vanes, [C]. Four pairs of guide vanes are arrayed uniformly and connected to the upper and lower duct around the cylinder. The vanes in each pair are tilted at angles of 20° and 55° respectively. The ODGV collects radial wind stream from a larger area through the guide vanes that form multiple flow channels, which are utilized to speed up the wind stream by creating a venturi effect and to guide the wind stream to the better flow direction of the VAWT. The VAWT is located at the center and surrounded by the ODGV with the radius of the ODGV greater than the radius of the VAWT. The center drive shaft of the VAWT is coupled with the generator, [D] through the power transmission shaft and mechanical drive system, [E] such as a gear system.

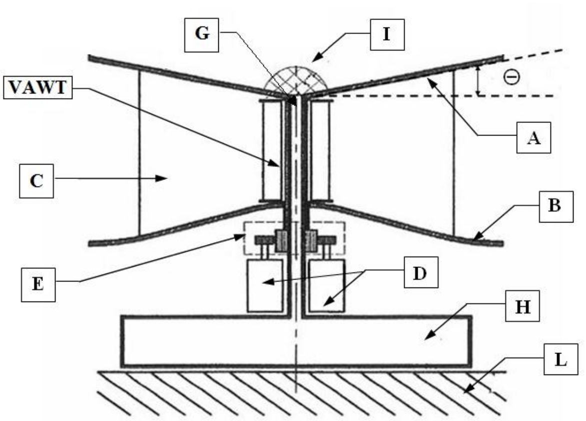

Fig. 1(a): Side sectional view of ODGV integrated VAWT for wind-solar hybrid renewable energy generation system with rain water collection feature

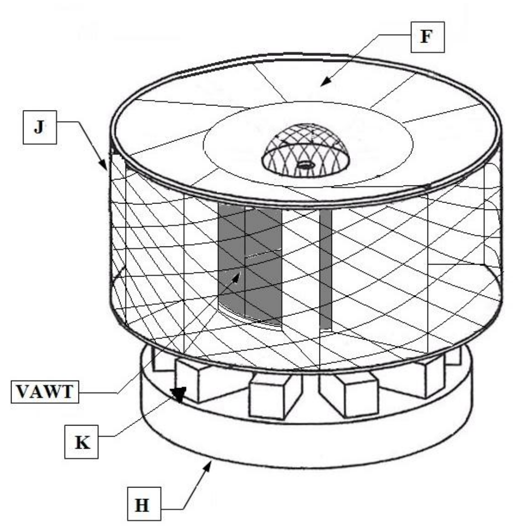

Fig. 1(b): Perspective view of ODGV integrated VAWT for wind-solar hybrid renewable energy generation system with rain water collection feature

The upper and lower wall ducts are inclined at an angle of 20° from the horizontal plane. The exterior surface of the upper wall of the PAGV provides the base for placement of solar panels (solar photovoltaic and/or solar thermal panel), [F] or solar concentrator system to harness solar energy from the sun. At the same time, the inclined solar panels also form the flow path for guiding the rain water towards the center of the system. The rain water then flows through the rain water passage, [G] in the middle of the system and is stored in the water storage compartment, [H] at the bottom. A rain water filter, [I] prevents the flow of foreign objects into the passage which can cause blockage of the passage. The mesh, [J] is mounted at the entrance side of the ODGV to avoid foreign objects from striking the VAWT. The power generated from the wind turbine and solar panel is stored in a battery bank, [K] or fed into the electricity grid line. A layer of thermal insulation, [L] is embedded into the bottom of the system to prevent heat transfer into the interior part of the building.

Since the VAWTs produce less noise and vibration compared to the horizontal axis wind turbines, the concerns on noise and vibration is minimized. In addition, the geometry of the system where the VAWT is surrounded by the ODGV causing the noise is further reduced. The large size of the wind turbine may be able to produce a higher amount of power, but when the wind speed is low, the turbine works much lower than its rated power. For this system, the ODGV will help the smaller size of the VAWT to spin close to its rated power even if the wind speed is low.

Besides all the mentioned features, the system is also designed by taking into account the installation and maintenance stages. Components of the VAWT and ODGV are fabricated in feasible-to-carry forms (easy to dismantle and assemble) and are easily transported to the top of a high-rise building. For maintenance purposes, the system is accessible from the interior of the building. To prevent the motion of the VAWT during maintenance works, a locking device can be installed. The maintenance cost is expected to be the same as the current operating VAWT. In order to adapt to the urban environment with minimum visual impact, the system can be of cylindrical shape or any shape of design, depending on the building architectural profile, such as in the shape of an ellipse, etc.

4. METHODOLOGY

A wind tunnel testing on a scaled down ODGV integrated VAWT system was conducted at the Aeronautic Laboratory, Universiti Teknologi Malaysia. A Savonius VAWT with 0.5 meter rotor diameter and a height of 0.25 meter was used in the test (Fig. 2). The VAWT was supported by two bearings which are the tapered roller bearing and ball bearing.

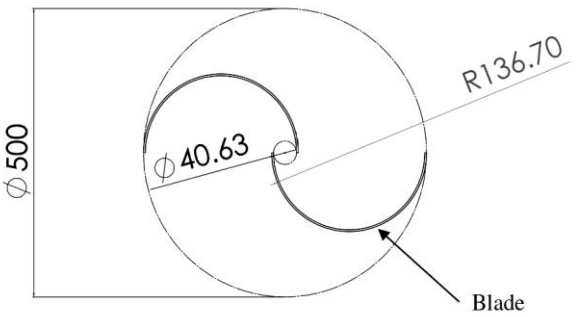

Fig. 2: Cross sectional view of a two-bladed Savonius VAWT (all dimensions are in mm)

The ODGV prototype was fabricated with a size 2 times larger than the wind turbine and its geometry and dimensions are shown in Fig. 3. The supporting structure of the system was built in a rectangular-shape to simulate a common high-rise building. The main purpose of the experiment is to compare the performance of the Savonius VAWT with and without the integration of an ODGV. Thus, the experiment was performed in two configurations as follows:

i. Bare VAWT on top of "building"
ii. VAWT enclosed by the ODGV on top of "building"

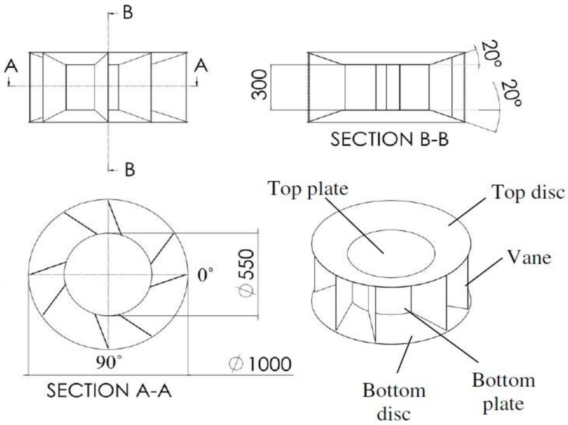

Fig. 3: General layout and dimensions of the ODGV (all dimensions are in mm)

Fig. 4 depicts an actual picture of the apparatus set-up for bare VAWT on top of "building" and Fig. 5 illustrates the schematic arrangement of the testing set-up for the VAWT enclosed by the ODGV on top of "building" in a wind tunnel test section. The rotational speed, torque and power generation were measured using a torque transducer which was connected in-line with the rotor shaft of the wind turbine. The free stream velocity in the wind tunnel was set via a wind tunnel control fan and sensed by a ceiling mounted pitot-static tube.

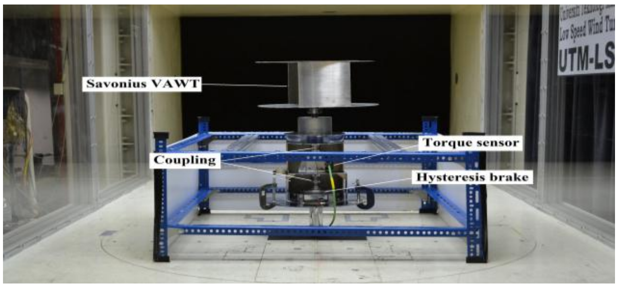

Fig. 4: Apparatus set-up for bare Savonius VAWT on top of "building" (view from the downstream side of the wind turbine)

The experiment was started with the wind turbine in free-running condition where only inertia and bearing friction were applied. At this moment, the maximum rotational speed of the VAWT with and without the wind turbine was measured. The following experiment was performed to compare the rotational speed, torque and power generated by the wind turbine with loading. The load was applied on the rotor shaft by adjusting the hysteresis brake. The maximum torque experienced by the rotor at the particular wind speed was recorded when the highest load was applied on the rotor and the rotor RPM had stabilized (able to maintain the rotor RPM).

The experiment was repeated twice, for both configurations, i.e. bare Savonius VAWT and Savonius VAWT with ODGV to compare the performance of the Savonius VAWT with and without the application of the ODGV. Losses due to bearing friction were calculated by an online software provided by the bearing manufacturer, SKF [18].

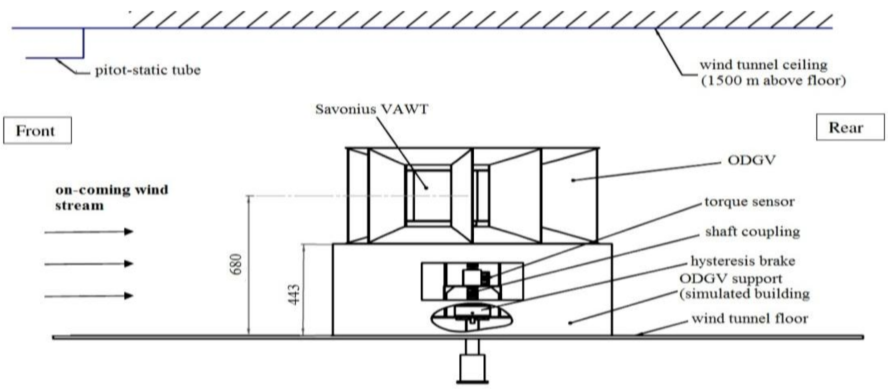

Fig. 5: The schematic of the testing unit and test rig for the VAWT enclosed by the ODGV on top of "building" in wind tunnel test section

5. RESULT AND DISCUSSION

5.1 Wind Tunnel Testing at Free-running condition

The experiment was first started in free-running condition (without load application) with the wind-stream velocity in the range of 3 m/s to 7.5 m/s. The stable VAWT rotational speed at each wind velocity is tabulated in TABLE 1.

TABLE 1: SUMMARY OF STABLE ROTATIONAL SPEED OF SAVONIUS VAWT ON TOP OF BUILDING AT FREE RUNNING CONDITION

Wind velocity (m/s)	Stabilized free running rotational speed (RPM)		Rotational speed increment percentage (%)
	ODGV integrated S-rotor	Bare S-rotor	
3.0	170.6	153.2	11.4
4.5	239.2	229.7	4.2
6.0	307.0	305.0	0.7
7.5	382.4	382.0	0.1

At a wind velocity of 3 m/s, an increment of 11.4% on stable free-running rotational speed of the S-rotor was achieved with the aid of the ODGV. However, the rotational speed increment was gradually reduced with increasing wind velocity until only 0.1% increment at 7.5 m/s of wind speed. On the other hand, it is clear that the peak power increment is decreasing while wind speed is increasing. The ODGV device also has acted as an angular speed limiter to the VAWT. Referring to TABLE 1, at a wind velocity 7.5 m/s, the free-running RPM for the case of with and without the ODGV are almost equal at about 382 rpm. This suggests that the ODGV has acted as an angular speed regulator which can possibly save the cost for adding in a breaking mechanism for high wind speed condition which is usually to avoid VAWT structural failure due to strong winds.

The result shows that, the presence of the ODGV that is integrated with the Savonius VAWT helps to improve the performance of the VAWT especially at low wind speed. It means that the VAWT has more capability to couple with higher load, hence producing higher power at the same on-coming wind speed. Thus, at an identical wind velocity, the ODGV integrated VAWT is expected to generate more power compared to the bare Savonius VAWT.

5.2 Wind Tunnel Testing with Load Application

Wind tunnel testing with load application to the power transmission shaft was performed at the free-stream wind velocities of 3 m/s, 4.5 m/s, 6 m/s and 7.5 m/s, and the results are shown in Fig. 6(a) to Fig. 6(d) respectively.

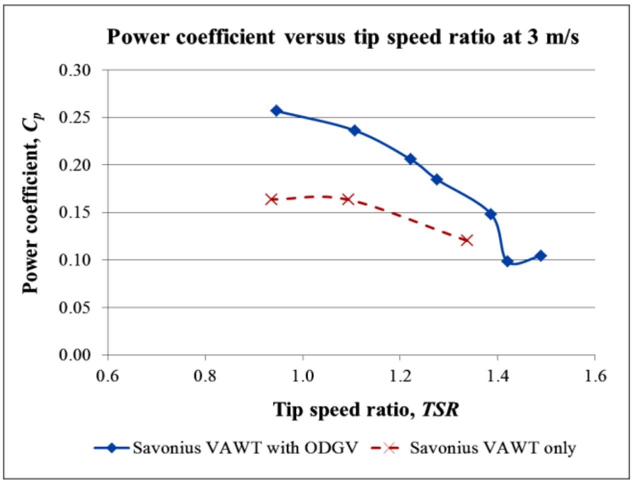

Fig. 6(a): Power coefficient, C_p against tip speed ratio, *TSR* at the wind velocity of 3 m/s for ODGV integrated Savonius VAWT and bare Savonius VAWT

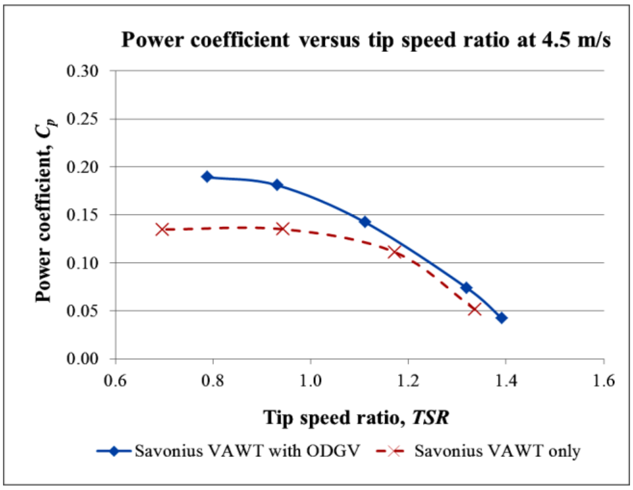

Fig. 6(b): Power coefficient, C_p against tip speed ratio, *TSR* at the wind velocity of 4.5 m/s for ODGV integrated Savonius VAWT and bare Savonius VAWT

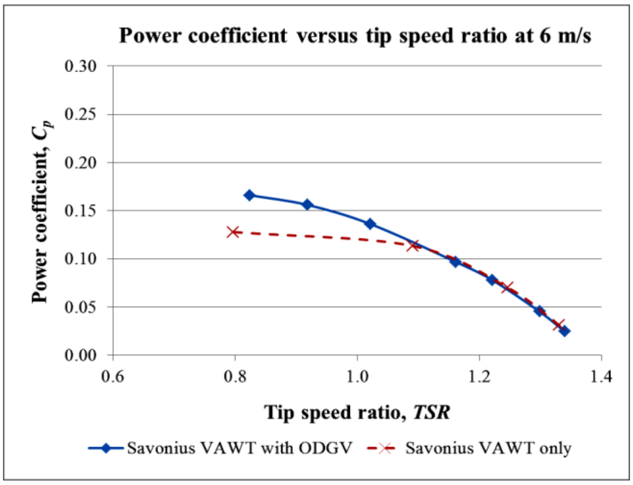

Fig. 6(c): Power coefficient, C_p against tip speed ratio, *TSR* at the wind velocity of 6 m/s for ODGV integrated Savonius VAWT and bare Savonius VAWT

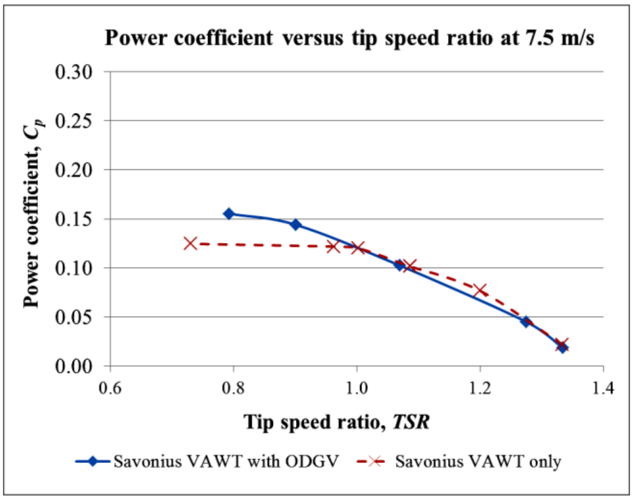

Fig. 6(d): Power coefficient, C_p against tip speed ratio, *TSR* at the wind velocity of 7.5 m/s for ODGV integrated Savonius VAWT and bare Savonius VAWT

From the figures, the most noticeable effect of ODGV integration with the VAWT performance was demonstrated at lower wind velocity. At the on-coming wind velocity of 3 m/s and 4.5 m/s the peak power coefficient of the Savonius VAWT with the application of ODGV was 56.86% and 40.10% respectively greater than the bare Savonius VAWT only. The highest peak power coefficient was achieved at the *TSR* of 0.95 and wind velocity of 3.0 m/s with C_p = 0.26. The power augmentations for the wind velocity from 3.0 to 7.5 m/s are summarized in TABLE 2.

TABLE 2 SUMMARY OF PEAK POWER COEFFICIENT INCREMENT AT VARIOUS WIND SPEED

Wind velocity (m/s)	Increment of peak power coefficient (%)
3.0	56.86
4.5	40.10
6.0	29.81
7.5	24.57

The results on the peak power coefficient increment show a good agreement with the free-running condition as discussed in section 5.1. The ODGV is proven to serve the purpose in improving the Savonius VAWT performance especially at low wind speed.

6. CONCLUSION

An innovative device called an omni-direction-guide-vane (ODGV) is introduced to be integrated with a VAWT. The ODGV surrounds the VAWT and is designed to improve the wind rotor performance and minimize safety concerns. The performance of the ODGV integrated VAWT system is optimized by increasing the on-coming wind speed, guiding the wind stream to a better flow direction of the VAWT and improving its starting behavior. For on-site energy generation in urban areas, the ODGV is recommended to be installed on the top of high-rise buildings with minimum negative visual impact and public concern on safety.

From the wind tunnel tests, the presence of the ODGV that is integrated with the Savonius VAWT improves the performance of the rotor. The highest increment of rotational speed (11.4%) was recorded at 3 m/s when the turbine was operated at free-running condition. When a load was applied (via hysteresis brake) to the power transmission shaft of the VAWT, the rotor recorded its highest power coefficient with C_p = 0.26 which was obtained at the *TSR* = 0.95 and wind speed of 3 m/s. The highest Cp augmentation of 62.5% was also obtained at the same condition (TSR = 0.95 and wind speed = 3 m/s). All these figures are obtained with the aid of the ODGV.

The results presented in this paper prove that the ODGV is capable to significantly improve the performance of the Savonius VAWT. It is also expected to improve other types of VAWT such as the H-rotor and Sistan rotor. In addition, this performance augmentation device can help to address the problem of low wind speed where the wind turbine can start producing energy at a lower wind speed. On top of that, the design of the ODGV not only focuses on the performance improvement of the rotor inside, but it also emphasizes on the safety, visual impact, bird strike and other concerns related to wind turbines. As a conclusion, the ODGV integrated VAWT is an ideal wind power generation system that optimizes the turbine performance and it has a great potential to be sited in urban areas for on-site and grid-connected power generation.

ACKNOWLEDGEMENT

The authors would like to thank the University of Malaya for the assistance provided in the patent application of this design (patent pending PI 2011700168), and the research grant allocated to further develop this design under the project RG039-09AET. Special appreciations are also credited to the Malaysian Ministry of Higher Education (MOHE) for the research grant (Fundamental Research Grant Scheme, FP071-2010A).

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