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IMPROVEMENT OF HYBRID VERTICAL AXIS WIND TURBINE PERFORMANCE FOR LOW WIND SPEED CONDITION

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*Corresponding author
mohdrashdan@gmail.com

Z Methal[1], Syahin AAT[1], Daniel HJ[2], Rahman MRA[1,3], Saad MR[1,3]*

[1]Department of Mechanical Engineering, Faculty of Engineering, Universiti Pertahanan Nasional Malaysia, Kem Perdana Sungai Besi, 57000 Kuala Lumpur, Malaysia
[2]Kulliyah of Engineering, International Islamic University Malaysia, Jalan Gombak, 51300 Selangor, Malaysia
[3]Centre for Defence Research and Technology (CODRAT), Universiti Pertahanan Nasional Malaysia, Kem Perdana Sungai Besi, 57000 Kuala Lumpur, Malaysia

zinnyrah93@gmail.com, asyahin92@gmail.com, daniel.hakim.jamaluddin@gmail.com, rosdzimin@gmail.com, mohdrashdan@gmail.com

ABSTRACT

Vertical-axis wind turbine (VAWT) as a power generator has shown great interest in research design to improve operational efficiency and enhance self-starting capability. Currently, Darrieus rotor is known for generating high torque at low wind speed condition from any direction indicating that Darrieus type wind turbine is excellent in electricity generator. However, Darrieus rotor suffers from poor self-starting capability and such wind turbine requires external power start-up. As a promising solution, dual stage Scoop Harmony combined with three-bladed NACA 0018 Darrieus rotor: D-rotor, H-rotor and Helix-rotor has been proposed to improve these limitations. Scoop Harmony is a drag-based turbine, assist to generate torque but received lesser attention compared to Savonius rotor. A proposed CAD wind turbine model was designed and fabricated using a 3D printer to study the effect of combined Darrieus and Scoop Harmony rotor on obtaining the tip speed ratio, torque and power coefficient, C_P. All rotors have a similar chord length, solidity, radius and height dimension. During test run, wind speed operation was varied from 0 to 8m/s, following the wind speed conditions in Malaysia. Results shows that D-rotor with Scoop Harmony gives the best performance compared to Helix rotor and H-rotor. The tip speed ratio for D-rotor can reach up to 12% higher than Helix-rotor and 53.5% higher than H-rotor at a wind speed of 8 m/s. For the torque rate, D-rotor has a 76% higher torque output than H-rotor and 25% higher than Helix-rotor. Meanwhile for C_P, D-rotor generates 23% and 75% higher compared to Helix rotor and H-rotor. However, D-rotor suffers from slower start-up compared to Helix-rotor when the starting torque occurred at 4 m/s compared to the Helix-rotor which is able to start up at only 3 m/s.

Keywords: *Vertical Axis Wind Turbine (VAWT), Power Coefficient (C_P), Tip Speed Ratio (TSR), Low Wind Speed.*

1.0 INTRODUCTION

The prospect development of wind energy in Malaysia remains vague [1]. Most failures from wind turbine generator project at Swallow Reef and Small Perhentian Island is a sign that wind energy in Malaysia faces a huge challenge and requires in-depth investigation to operate [2]. Being an equatorial country, Malaysia faces low and uneven wind speed condition throughout the whole year due to southeast and northeast monsoon. During the southeast monsoon, wind speed can be as low as 2m/s and reach up to 15 m/s during northeast monsoon especially in the east coast of Peninsular Malaysia [2]. This indicates that wind energy development in Malaysia requires extensive investigation to obtain an optimal wind turbine type configuration especially in an uneven and low wind speed conditions.

Selection of wind turbine type is important for the wind energy development to enhance their respective turbine efficiency. At present, there are two types of wind turbine in operation: horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT). HAWT is well known compared to VAWT for its high efficiency and high-power generation of wind energy commercial product [3]. However, HAWT is only convenient at location with constant stream and wind direction [4]. Thus, the wind turbulent and skewed airflow at urban environment will interrupt the HAWT performance. In countries with uneven wind speed and wind direction, VAWT is more convenient to operate considering its capability to capture wind stream from any direction and speed [5]. Besides that, the absence of heavy components like generator, heavy blades, and gearbox at its supporting tower contributes to easy rotation although wind speed is relatively low [6].

VAWT consist of two main categories: Savonius and Darrieus. Savonius VAWT is simple in design, operates through aerodynamic drag, and has the ability to self-start at low wind speed condition. However, Savonius VAWT also has a lower efficiency and higher negative torque compared to conventional rotors, thus makes it only viable for small-scale applications [7]. For Darrieus VAWT, the blade is designed using airfoil shape and takes the advantage of aerodynamic lift to rotate its main shaft. There are three kinds of Darrieus VAWT: D-type, H-type and helix type [8]. Overall, Darrieus VAWT produces even a higher efficacy than Savonius VAWT, by means that it can rotate a faster rate even though wind speed is relatively low [4]. Nonetheless, Darrieus suffers from poor self-starting capability, as a consequence, they require external power source to start up [9].

A novel wind turbine design known as Scoop Harmony wind turbine (SHWT) has been introduced recently by Christopher Moore. Similar to Savonius rotor, SHWT uses aerodynamic drag to generate torque output with a slight modification. SHWT consist of a pair of scoop blade with each pair equitably aligned to 45°. The blades are assembled to a special handcraft generator which allows a high-power output at low start-up speed. Initially, the design is still in the preliminary stage. However, SHWT capability seems to be as equivalent to other conventional wind turbine. A numerical study of SHWT was done by Raut [10], investigating the effect of surface scoops on wind pattern around the blades at various wind velocity. Result shows that, blade harmonic arrangement can generate a power output of up to 18W at 7 m/s wind velocity. This shows a significant improvement on turbine efficiency from SHWT compared to other VAWT studies by Kalakanda and Nallapaneni[11], Sahisnu [12], Thomai [13] and Lap [14]. However, these studies associated with SHWT were unable to provide a clear explanation about the design effect on wind turbine performance, thus opening the opportunity for researchers to investigate this context thoroughly.

Soon, advance research on wind turbine energy was conducted, and a new term known as hybrid power system has started to grow[15][16][17]. The term wind hybrid refers to a combination of two or more wind energy resource in a single system, aim to enhance wind energy extraction and resolve self-starting problem in VAWT design. Numerous efforts were made to investigate the potential of Savonius-Darrieus hybrid turbine either through experimental or numerical studies. Rassoulinejad [18] experimentally investigates the potential of combining both Savonius and H-rotor in various wind velocity and gained improvement in self-starting ability and a higher power coefficient compared to a single H-rotor. Later, Kumar and Nikhade [19] developed various configuration of Savonius combined with eggbeater Darrieus, straight bladed and two stage Savonius and obtained a 10% of power improvement with low start-up torque. In addition, the arrangement of Savonius and Darrieus plays an important role to maximize the power output of the wind turbine. Siddiqui [20] attempts to investigate the of combination of Savoinus and Darrieus rotor with three different configurations and discovered a significant increase in power generation and coefficient performance when Savonius is located in between Darrieus rotor. Chawla [21] carried out CFD analysis to predict the pressure and velocity field distributions of Savonius and eggbeater Darrieus by placing Savonius at the center of each Darrieus and found out that this arrangement gave the best outcome out of others. Another study was performed numerically on dual-stage-two bladed Savonius combined with four blade D-rotor and the highest power coefficient were obtained by placing Savonius in the middle of D-rotor [22].

Therefore, as an initiative to identify the best potential of SHWT as a drag-based wind turbine combined with Darrieus rotor, this study was performed to investigate the capability of hybrid power system in affecting the tip speed ratio, torque and power coefficients, by explaining a detailed design of rotor and setup method for wind tunnel testing. The outcome of this paper will be expected to be used as a reference for new VAWT design in the future.

2.0 METHODOLOGY

2.1 Design of Three-Blade Darrieus Rotor with Dual Stages Scoop Harmony

The hybrid VAWT type consisting of three-bladed D-rotor (Figure 1), H-rotor (Figure 2) and Helix-rotor (Figure 3) with each blade combined with a dual stage Scoop Harmony were designed using CAD Software. Three-blade Darrieus rotors were selected because of a higher coefficient performance [23] whereas dual stages Scoop Harmony promotes a better static and dynamic torque [24].

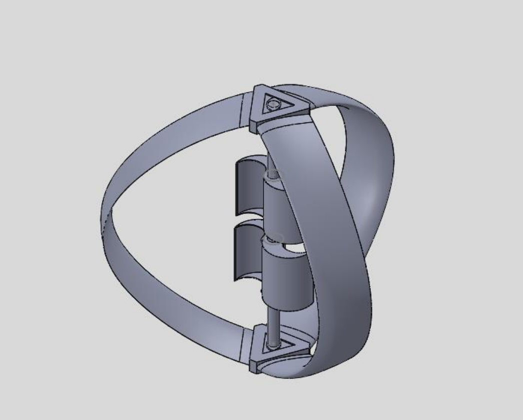

Figure 1 Hybrid D-rotor with Scoop Harmony

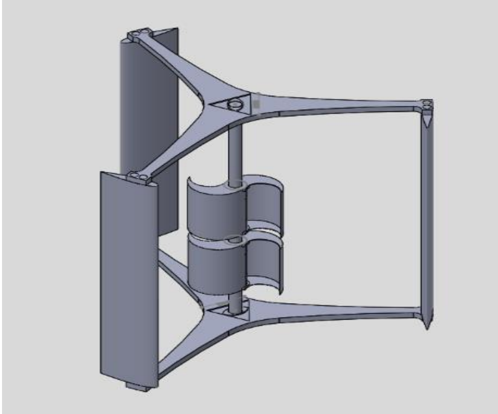

Figure 2 Hybrid H-rotor with Scoop Harmony

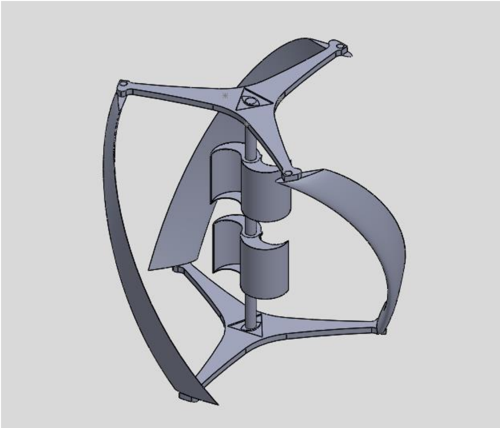

Figure 3 Hybrid Helix-rotor with Scoop Harmony

The dimension for all the wind turbine design were chosen carefully based on the wind tunnel test section capability. This is important to avoid any interruption during test run including any probability of the turbine blades colliding with the wall section or generating a lower power coefficient due to limited test section area. The test section has a cross sectional area of 0.09m^2 and 1m in length. The maximum allowable size for all Darrieus type were 0.15 m from the test section wall. Nonetheless, for safety precautions and tolerance consideration, it was set to approximately to 0.12 m. D-type, H-type and Helix-type have a height, h = 0.212 m and a twisted angle of 60° for D-type and Helix-type only. A maximum radius was kept constants for all Darrieus rotors of r_D = 0.120 m. The experimental setup was composed of a three-bladed NACA 0018 airfoil, with 0.04 m chord length (c) and solidity of (σ) of 0.5. NACA 0018 was chosen because it has a lower tip speed ratio and applicable for low wind speed testing [25]. For the solidity criteria (σ), Sagharichi [26] recommended a higher value of VAWTs rotor especially at Darrieus rotor to resolve initial self-starting ability.

In the case of Scoop Harmony, it is located in between the Darrieus rotors with h = 0.045m while maintaining a radius, r_s = 0.03m from the central shaft, whereas the radius ratio from Scoop Harmony to Darrieus, r_{ratio} = 0.25. The aspect ratio (A_r) represents the height of Scoop Harmony (h) relative to its r_s given at A_r = 1.5. Khan [27] suggested that the selection of A_r needs to be larger by a factor of 4 for the best power coefficient. However, due to limitation of test section dimension, Jahangir Alam and Iqbal [28] agreed that $A_r > 1$ is also acceptable to achieve a better power coefficient performance.

2.2 Fabrication of Hybrid VAWTs model

All models were fabricated using a 3D printer machine employing a Polylactic Acid (PLA) filament material. After the printing process were completed, each part of VAWT rotors were smoothen using sandpapers from a coarse to smoother grit for better surface finishing as it significantly affects the model surface roughness. The parts were then assembled and attached permanently using super glue gel. A circular rod is positioned in between SHWT and Darrieus rotor via a bearing at each end to rotate turbine blade about the vertical axis.

2.3 Theoretical Calculation

2.3.1 Tip Speed Ratio (λ)

Tip speed ratio or TSR represents the ratio of tip speed blades over the wind speed and it is related to the efficiency of the blade design. TSR is calculated using:

$$\lambda = \frac{\omega r_D}{V} \qquad (1)$$

where ω is the angular velocity of the Scoop Harmony (rad/s), r_D is the radius of Darrieus rotors from the shaft (r_D = 0.120 m) and V is the wind speed (m/s).

2.3.2 Power Coefficient (C_P)

Power coefficient, C_P refers to the mechanical power of wind turbine relative to its theoretical power. It also represents the aerodynamic efficiency of the wind turbine rotor. C_P is given as follows:

$$C_P = \frac{\tau\omega}{\frac{1}{2}\rho AV} \qquad (2)$$

Where τ is torque (N/m), ρ is the density of air at temperature 32°C (kg/m^3) and A is Darrieus rotor swept area (m^2).

2.4 Wind Tunnel Testing

The experiment was done in an Open-Loop, LW-9300R Wind Tunnel model located at Universiti Pertahanan Nasional Malaysia (UPNM) as shown in Figure 4. The useable area of wind tunnel section is 0.3 m x 0.3 m x 1 m and wind operating speed ranges from 0 to 100 m/s.

Figure 4 LW-9300R Open-Loop Wind Tunnel

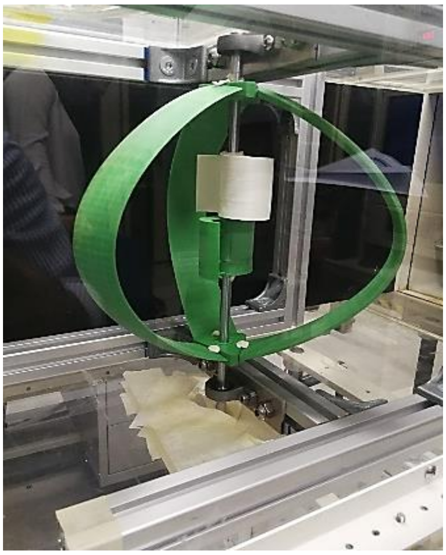

Figure 5 Hybrid D-rotor with Scoop Harmony (3D printed model)

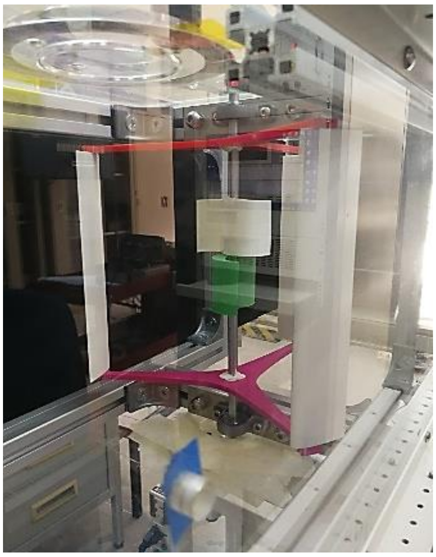

Figure 6 Hybrid H-rotor with Scoop Harmony (3D printed model)

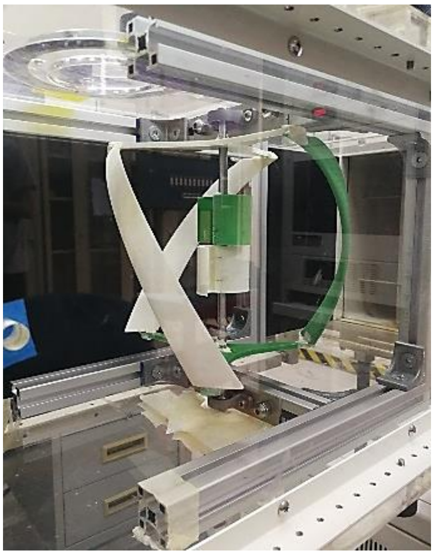

Figure 7 Hybrid Helix- rotor with Scoop Harmony (3D printed model)

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The L-shape metal frame was constructed to support the hybrid wind turbine during testing as shown in Figure 5 to 7. Width and height of L-shape metal frame was set close to the test section dimension to eliminate the wall effect. The RPM measurement reading output from this experiment was collected using a non-contact tachometer Fluke 930 as shown in Figure 8. The tachometer works by sending out a beam of light to the reflective tape attached on the bottom part of the rotating circular rod of the wind turbine and generating an RPM output. Each test run were repeated five times for every wind speed condition in between 0 to 8 m/s following the average wind speed in Malaysia.

Figure 8 Non-Contact Tachometer Fluke 930

3.0 RESULTS AND DISCUSSION

3.1 Effect of RPM and Torque towards Wind Speed

Result obtained for the rpm against wind speed for all hybrid wind turbines are shown in Figure 9. Its apparent that the rpm is highly dependent on wind speed where substantial increases were noticed as the wind speed increases. The D-rotor with Scoop Harmony surpassed the H-rotor and Helix-rotor giving a percentage difference of 53% for H-rotor and 12.3% for Helix-rotor with maximum rpm = 266 rad/min for D-rotor, 123.7 rad/min for H-rotor and 233.3 rad/min for Helix-rotor at 8 m/s. In terms of self-starting ability, based on Figure 10, Helix-rotor with Scoop Harmony managed to start up earlier at 3 m/s compared to 4 m/s for D-rotor and H-rotor. This study demonstrates that developing a hybrid VAWT by using SHWT as a drag-based type wind turbine increase the RPM and start-up torque even at low wind speed condition. Therefore, D-rotor is convenient to operate at low wind speed as it can generate high RPM and torque compared to H-rotor and Helix-rotor. This statement was supported by Liu [29] who proved that D-rotor can generate high rpm and high torque due to the advantage of the design having a short connection between the shaft and rotor as well as generating insignificant bending stress which was offset by higher centrifugal stress at higher RPM. However, if the location has a very low average minimum wind speed (v = 2 m/s), Helix-

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rotor design is seen to be more acceptable to use for a better start up. This is because the degree of twist in the helix design allows more air to be captured by the airfoil thus improving the self-start ability [30].

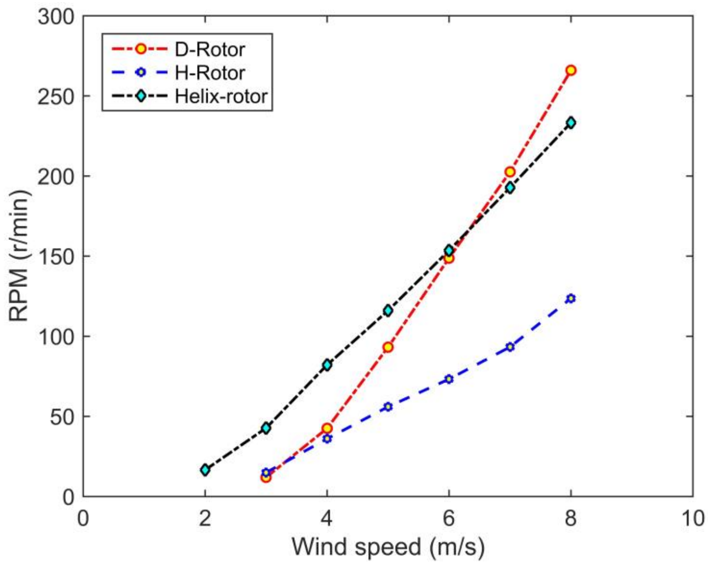

Figure 9 RPM with increasing wind speed for Hybrids wind turbines

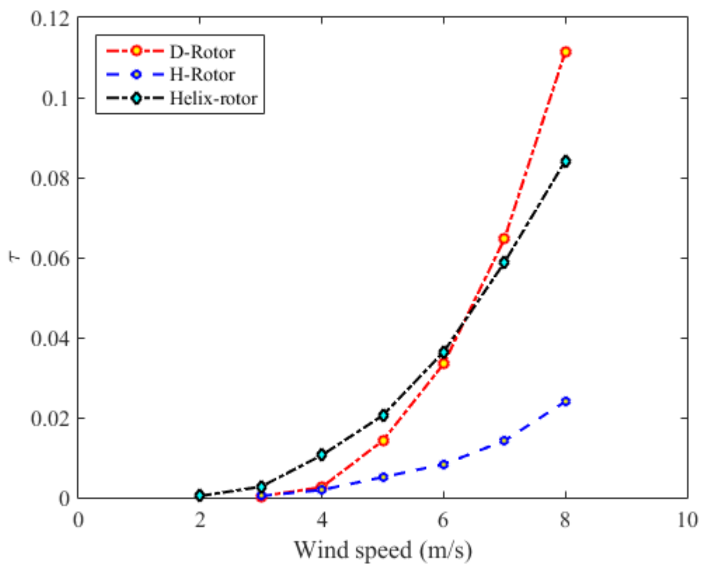

Figure 10 Torque with increasing wind speed for Hybrids wind turbines

3.2 Effect of Torque on Different TSR

Figure 11 presents the experimental data on theoretical torque value for different TSR. There is a significant improvement for torque when TSR increases. The maximum torque was determined at TSR = 0.418 with $\tau = 0.112$ Nm from the D-rotor with Scoop Harmony. In the case of H-rotor and Helix-rotor, the TSR recorded were 0.194 and 0.366 with $\tau = 0.024$ Nm and 0.0842 Nm respectively. The torque rate of D-rotor was 76% higher than H-rotor and 25% higher than Helix-rotor. This discrepancy could be attributed to a different swept area when D-rotor having a larger swept area compared to H-rotor and Helix-rotor. The relevance of this statement was clearly supported by Persico [31]. The large swept area forces more air to collide with the blade as more lift and drag force develops around the rotor. Consequently, the rotor spins faster and a high margin of torque is noticeable.

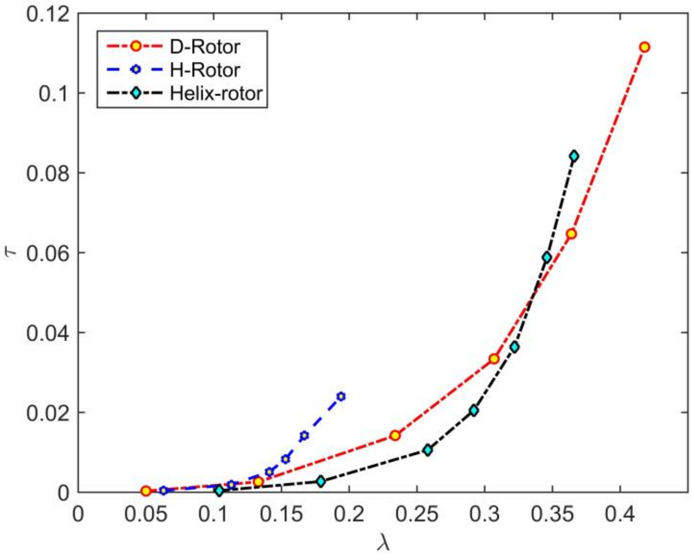

Figure 11 Variation of torque with different TSR for Hybrids wind turbines

3.3 Theoretical Power Coefficient

Figure 12 shows the variation of power coefficient (C_P) for hybrid wind turbines. It was observed that C_P value increases with TSR and there is only an insignificant difference in C_P were noticed for each hybrid VAWT. The D-rotor with Scoop Harmony outperformed the Helix-rotor giving a highest power coefficient with maximum values of $C_P = 0.233$ at $\lambda = 0.418$. The percentage difference of D-rotor with Helix-rotor was found to be 23% and 75% for H-rotor with $C_P = 0.179$ for $\lambda = 0.384$ and $C_P = 0.0583$ at $\lambda = 0.264$ respectively. The observed increase in C_P for D-rotor was also attributed to a bigger blade area. This conclusion was consistent with Hilewit [32] who found that smaller blade area will underperform the power coefficient of the turbine blade.

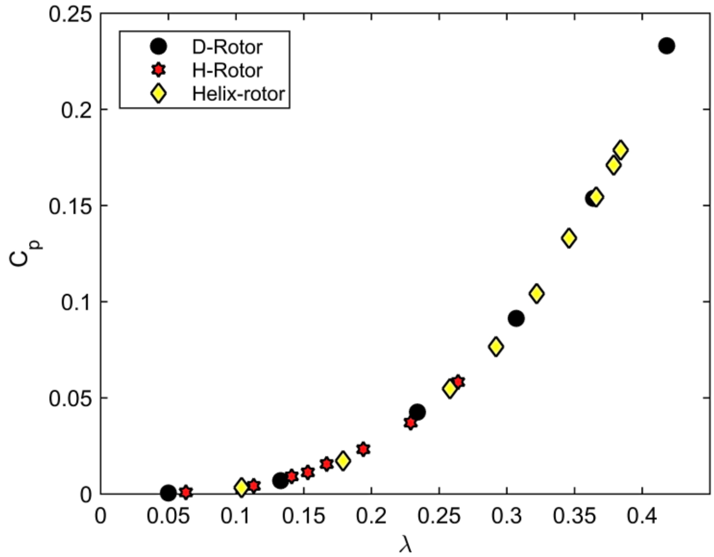

Figure 12 Variation of power coefficient C_P with different TSR for Hybrids wind turbines

4.0 CONCLUSION

Hybrid wind tunnel measurements with different wind speed range of 0 m/s to 8 m/s corresponding to the wind speed range in Malaysia were performed to investigate the tip speed ratio, torque and power coefficients of three-bladed D-rotor, H-rotor and Helix-rotor with each combined with dual stages Scoop Harmony. From the result obtained, it was determined that D-rotor with Scoop Harmony reveals the best performance in terms of RPM, torque and power coefficient compared to H-rotor and Helix-rotor. Tip speed ratio for D-rotor was 12% higher than Helix-rotor and 53.5% higher than H-rotor at a speed of 8 m/s. For the torque rate, D-rotor torque output was 76% higher than H-rotor and 25% higher than Helix-rotor. In addition, D-rotor generates 23% and 75% higher C_P compared to Helix rotor and H-rotor. Nevertheless, D-rotor faces a slower start-up in comparison to the Helix-rotor. This is believed that the slightly curving turbine blade like the Helix can increase the amount of wind energy captured. Consequently, the aerodynamic force around the blade increase resulting in higher torque.

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