

## Comparative Analysis between Hybrid and Conventional Vertical Axis Wind Turbines Performances

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### ABSTRACT

*Emission of carbon and other hazardous pollutants resulting from burning of fossil fuels pose a great danger to the environment and therefore need to be reduced or eradicated as a result of their negative effects to the globe. This can be done by effectively harnessing alternative sources of energy that are environment friendly, under which wind energy falls and can be tapped with the aid of wind turbines. To come up with a solution to the aforementioned problem a hybrid vertical axis wind turbine (VAWT) was designed, fabricated and its performance explored. The turbine (hybrid VAWT) design was carried-out using Google sketch-up software solid tools and fabricated with locally available materials. The fabricated hybrid VAWT was tested in laboratory using ventilation fans, by changing position of the turbines from the fans between distances of 100 and 115 cm. The rotation per minute (RPM), wind speed, rotational speed, tip speed ratio, experimental power, mechanical power, coefficient of power, experimental torque and coefficient of torque were determined experimentally. The results showed that the maximum coefficient of power ( $C_p$ ) values for hybrid VAWT increased at separation distances 100, 105, 110, and 115 cm, by 91.67, 71.3, 9.97, and 66.67%, respectively, in comparison to Conventional VAWT. Correspondingly, the maximum coefficient of torque ( $C_t$ ) for hybrid VAWT was increased by 83.3, 183.3, 5.88, and 23.53% respectively within the same experimental conditions. The percentage increment showed that hybrid vertical axis wind turbine has significant improvement in performance than that of conventional vertical axis wind turbine. The coupling of ice-wind rotor (Savonius Rotor) with hybrid VAWT yield results in greater self-starting and higher performance in the measured parameters compared to the Conventional VAWT.*

### 1. INTRODUCTION

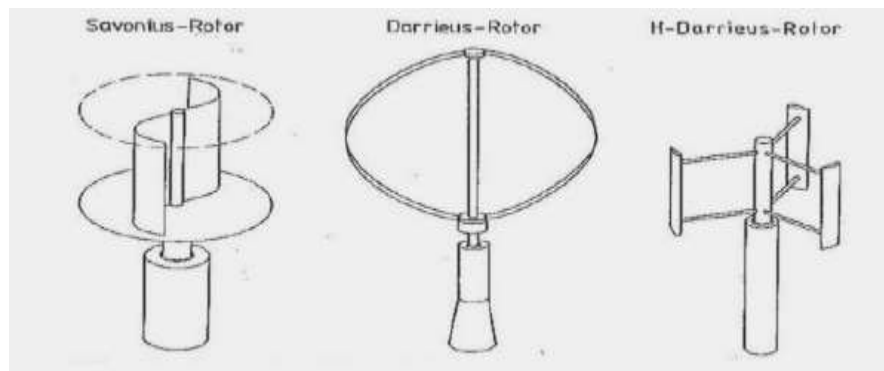
The major tool for development of any nation is the energy resources; it has forever been a crucial and essential contributor toward achieving the economic obligation of the present-day society. Indeed, it serves Buhari *et al.*: Comparative Analysis between Hybrid and Conventional Vertical Axis Wind Turbines Performances

as the inspiring strength of industrialization (Sambo, 2005). It is also regarded as an influential parameter of fiscal and societal prospective; there is no country that has developed without ensuring least contact to energy resource beyond a survival economy for a wide section of its populace (Newsom, 2012).

The Darrieus turbine has insufficient lift to produce the force that is able of overpowering the inertial and strength sequence confrontation and therefore failing to stimulate the spin at low wind speeds. In Darrieus wind turbine, torque can only be produced by lift force at low wind, an earlier research supported the above report with wind tunnel testing and field experiment. To overcome the predicament of little lift force, with savonius rotor, a drag force can produce torque at low wind speed. Savonius rotor has advantage in operation over the Darrieus turbine in feeble wind flow. Thus, hybrid wind turbine is suitable, but power coefficient decrease at high Tip Speed Ratio is inevitable as shown in a previous study (Kumar *et al.*, 2017). There are various types of wind turbines but this paper focuses on comparative analysis between hybrid and conventional wind axis wind turbines performances.

### Vertical Axis Wind Turbines

Unlike HAWTs, VAWTs allow the mounting of equipment at ground level, which eases access and reduces cost. However, they are generally less efficient than traditional HAWTs. Improvements in blade design and the introduction of control mechanisms to allow the rotor speed vary with wind speed have increased their efficiency (DeCoste *et al.*, 2016). There are two types of VAWT: Savonius and Darrieus wind turbines (Figure 1). According to Sunny and Kumar (2016), VAWTs have some advantages over HAWTs which are appropriate for very little wind speed location, appropriate for small amount of power generation, they withstand bad weather situation such as snow, ice, etc, they have lower construction and installation costs, lighter weight, causes of injury to the wild life are less, has generating ability of power annually in comparison with Horizontal Axis Wind Turbines, Maintenance culture such as service, repairs can be done easily as the gear box, generator, and other major components are placed close to the ground (Darhmaoui and Sheikh, 2017).



**Figure 1:** Types of VAWTs (Darhmaoui and Sheikh, 2017).

### Hybrid Vertical Axis Wind Turbine (VAWT)

The design comprises of the Darrieus and the Savonius in order to get each of their benefits. The Darrieus was designed to have high power coefficient and is typically more efficient when comparing it to other VAWT designs, but it is not capable of self-starting (Lane *et al.*, 2018). The Savonius is a design that has high starting torque which is capable of self-starting but its rotational speed and power coefficient is too low. The aim of hybrid designs is to produce a rotor that combines the advantages of the Darrieus and the Savonius, such as capability of self-starting, producing a high starting torque and enhanced efficiency. They are normally constructed as a Darrieus with a drag type blade in the middle, as seen in Figure 2. This can normally self-start, but after they have started, they are less efficient than a normal lift type due to the middle creating negative drag (Hammond *et al.*, 2014)



**Figure 2:** (a) Egg-bester Hybrid VAWT (Hammond *et al.*, 2014), (b) H-rotor with savonius in open configuration (Kumar *et al.*, 2017)

### Power of Wind

Having this information earlier to setting up a wind turbine site is very important. A simple equation (1) is used to calculate wind average power

$$P = \frac{1}{2} \rho A V^3 \quad (1)$$

Where (P) is power output of a turbine, (A) area of the rotor blades, wind speed (V), and ( $\rho$ ) is air density. Equation (1) shows the significance of wind speed in power generation, because wind power generation increases proportionally as wind to the third power (Deisadze *et al.*, 2013).

### Tip Speed Ratio (TSR)

Tip Speed Ratio defines as the ratio of the tip speed of the blade divided by the wind speed (Deisadze *et al.*, 2013). Equation (2) describes tip speed ratio:

$$\lambda = \frac{\Omega R}{V_u} \quad (2)$$

Where,  $\Omega$  is the rotor rotational speed in radians per second, R is the rotor radius in meters,  $\lambda$  is the tip speed ratio, and  $V_u$  is the wind speed (Deisadze *et al.*, 2013).

### Power Coefficient and Torque Coefficient

Percentage of power received by the wind turbine through the swept area of the turbine blades is referred to as the power coefficient shown in equation (3).

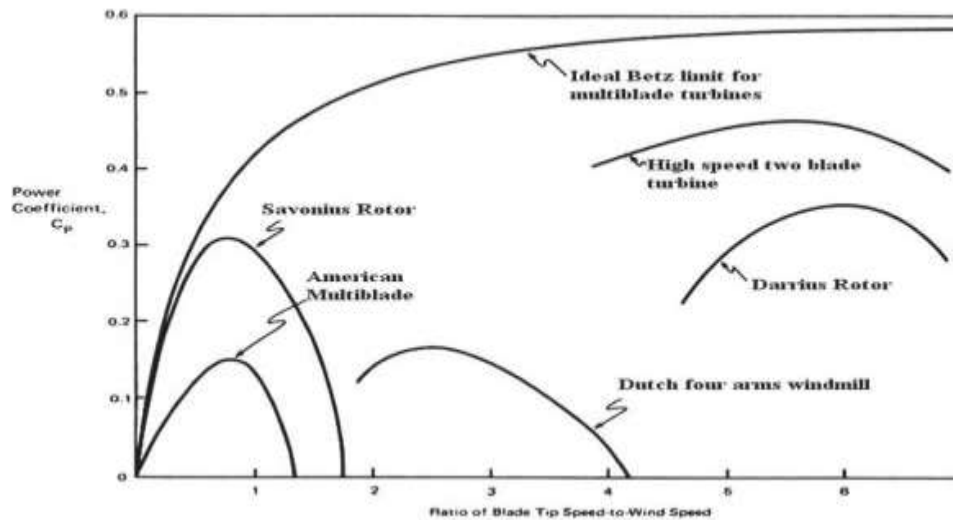
$$C_p = \frac{P}{0.5 \rho A V^3} \quad (3)$$

The Betz limit which is 0.593 is the maximum theoretically possible coefficient of power. Most Vertical Axis Wind Turbines has a range of power coefficient between 0.3 and 0.4 (Deisadze *et al.*, 2013)

The torque coefficient,  $C_t$ , is defined as:

$$C_t = \frac{C_p}{\lambda} \quad (4)$$

Where  $\lambda$  is the tip speed ratio and  $C_p$  is power coefficient (Hammond *et al.*, 2014).



**Figure 3:** TSR vs. Power Coefficient for different blade types (Hammond *et al.*, 2014)

### Number of Airfoil Blade, N

For any design of VAWT, it is important to verify the number of blades the turbine should possess. For a 2-blade turbine, there is a situation when both blades are in a position that the wind does not support rotation. This is referred as the stall position, while for a 3-blade turbine, the stall condition is removed, and a model analysis conducted by same author established that the 2-blade turbine produces a smaller average torque than 3-blade (DeCoste *et al.*, 2005). However, the small scales for domestic use, vertical axis wind turbines, normally contain three blades which are the optimum number of blades (Hameed and Afaq, 2013). In consideration to the aforementioned literature, the turbine was chosen to consist of three (3) NACA 0012 blades.

### Diameter of the Turbine, D and Swept Area of a Turbine

According to DeCoste *et al.* (2005) for a VAWT, area depends on both the turbine diameter and turbine blade height (length). For H-type VAWT, the swept area was calculated using equation (5). Where H is the height of the turbine and D is its diameter

$$A_s = H \times D \quad (5)$$

### Chord Length of Blade, C

According to Brusca *et al.* (2014), the blade chord length (C) can be calculated using the solidity. The chord length is the length of the airfoil and is an important design variable because the generated torque changes with chord length. Using the previously described relationship for solidity, the chord length of the wind turbine blade can be calculated. The flow over the blade can be achieved by using longer chord length which provides an increased Reynolds, and thus, increase in lift. Large thrust forces involve a shorter airfoil length which will likely undergo a bend (Brusca *et al.*, 2014). The length of the chord for both hybrid and conventional vertical wind turbines was chosen as 8 cm = 0.08 m.

## 2. METHODOLOGY

### Description of Design: Analytical Method

The analytical design of the turbine parameters was carried out using the theories and equation as cited in the literature review for the calculation of the parameters that were utilized in the construction measurement of the turbine components. In consideration to the aforementioned literature, the turbine was chosen to

consists of three (3) NACA 0012 blades and the chord length, diameter and blade height of the chord for this hybrid vertical wind turbine was chosen as 8 cm, 45 cm and 40 cm, respectively. The swept area ( $A_s$ ) was determined using equation (2) and blades pitch angle ( $\beta$ ) for this turbine was fixed at a pitch angle of  $0^\circ$ . The power of the turbine (Generator power) was chosen to be 10 W because it is for small power generation.

**Table 1:** Design parameters of the Hybrid VAWT and Conventional VAWT

Parameter	Analytical Design Value
Air foil type	NACA 0012
Drag device type	Ice-wind rotor
Average Wind speed (V)	4.87 m/s
Air density ( $\rho$ )	1.23 kg/m <sup>3</sup>
Diameter of the turbine (D)	45 cm
Turbine Radius (R)	22.5 cm (0.225 m)
Blade height (length)	40 cm (0.40 m)
Chord length	08 cm (0.08 m)
Swept Area ( $A_s$ )	0.18 m <sup>2</sup>
Coefficient of performance ( $C_p$ )	0.39
Aspect Ratio	0.8889
Solidity ( $\sigma$ )	0.1689
Power of the turbine (P)	10 W
Span length (B)	0.07112 m
Shaft dimension	3x200 cm
Radial arm dimension	10x210 mm

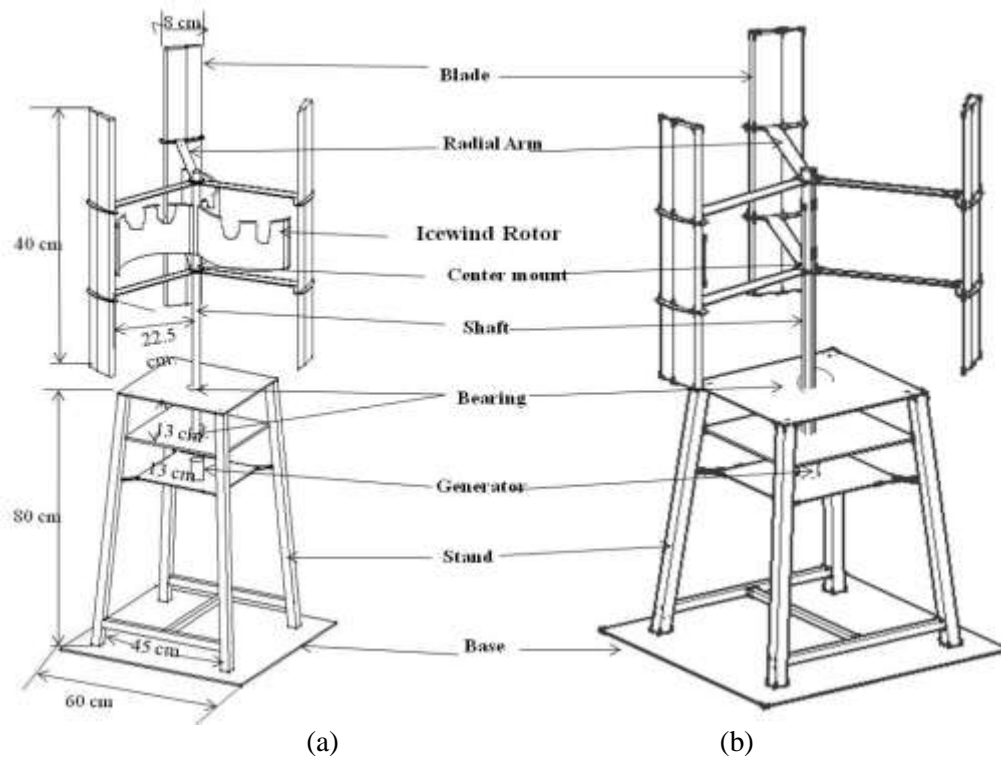
### Design of the Hybrid VAWT

The analytical design parameters of the turbine were used to design the hybrid vertical wind turbine and its components using Google Sketch up (2007) model solid tools to bring out the schematic design with dimensions. The rotor blade was first designed using Google sketch up software solid tools, rotor shaft, radial arm, and ice-wind rotor were designed using same software tools.

### Experimental Set Up

The experiment was set up with 6 electric Standing fans and the VAWT was placed at a distance of 100 cm from the fans, facing the fans in the same line and direction as shown in the plates 1 and 2. The position between the blower and VAWTs was varied at a distance of 5 cm to vary the wind speed so that the VAWTs can be tested at different wind speed. The wind speed was measured for different points and the average wind speed was taken for each points.





**Figure 4:** Schematic diagram of the (a) hybrid VAWT (b) Conventional VAWT



Plate 1: Experimental set up of Conventional VAWT



Plate 2: Experimental set up of Hybrid VAWT

### Data Collection and Evaluation

The rotational speed (rad/s) was evaluated by using the measured RPM and time in equation (2). The output power of the wind turbine was calculated from the measured current and voltage through Ohm's law. The measured wind speed (m/s) of the blade and rotational speed (rad/s) were used in equation (2) for evaluating TSR of the turbines. The measured rotational speed (rad/s) and torque (Nm) were used in determining the Mechanical power of the turbine in equation (3). Coefficient of power was evaluated using equation (3) by use of measured power output (W), air density ( $1.23 \text{ Kg/m}^3$ ), swept area ( $\text{m}^2$ ) of the turbines and wind speed (m/s).

### Data Analysis

The relationship between the evaluated parameters were carried out using excel 2007 Microsoft package in graphical representation. Coefficient of power against TSR for Hybrid VAWT and H-Rotor VAWT relationship was evaluated on graphical representation. Coefficient of torque against TSR for Hybrid VAWT and H-Rotor VAWT relationship was established on the graphs presented from the results on the same package.

## 3. RESULTS AND DISCUSSIONS

An experiment was performed with conventional VAWT and Hybrid VAWT at the testing laboratory. The two sets of experiment were performed under same experimental conditions, i.e one for the hybrid VAWT and the other for Conventional VAWT. The horizontal distance of the two turbines were varied for four different set of points i.e from  $X = 100$  to  $115 \text{ cm}$  with an increment of  $5 \text{ cm}$  for each case. The performance of the Hybrid VAWT and Conventional Turbines were evaluated based on the TSR, RPM and  $C_p$ . The Conventional and Hybrid VAWTs performance testing were carried out and evaluated by varying wind speeds for each change of distance of the turbines from the blower and the corresponding output variables of the turbine were recorded.

### Coefficient of Power ( $C_p$ ) against TSR ( $\lambda$ )

The horizontal distance of hybrid VAWT and Conventional VAWT were varied along the direction of air flow from  $X = 100 \text{ cm}$ ,  $V = 4.77 \text{ m/s}$  to  $115 \text{ cm}$ . Figures 5-8 compare the values of  $C_p$  for the hybrid VAWT and that of Conventional VAWT at turbine for  $X = 100, 105, 110$  and  $115 \text{ cm}$ . The results show similar trend irrespective of the position of  $X$ . Figure 5 shows the coefficient of power against the TSR of the hybrid VAWT and Conventional VAWT placed at  $X = 100 \text{ cm}$ ,  $V = 4.77 \text{ m/s}$ . Reference to result recorded in Figure 5, the hybrid VAWT attained a maximum  $C_p$  value of  $0.023$  at a TSR ( $\lambda$ ) of  $2.12$ . The maximum  $C_p$  of the Conventional VAWT placed at the same position and subjected to same experimental conditions was  $0.012$  at a TSR ( $\lambda$ ) of  $1.95$  as shown in Figure 5. The result shows that the maximum  $C_p$  of the hybrid VAWT has an increase of  $91.67\%$  compared to that of Conventional VAWT for  $X = 100 \text{ cm}$ ,  $V = 4.77 \text{ m/s}$ . Figure 6 compares the  $C_p$  values between the hybrid VAWT and that of the Conventional VAWT placed at  $105 \text{ cm}$  position. The result showed that the maximum  $C_p$  recorded by hybrid VAWT at a distance of  $105 \text{ cm}$  was  $0.031$  at a TSR ( $\lambda$ ) of  $2.16$  which was higher than that of Conventional VAWT maximum  $C_p$  whose values was just  $0.0181$  at TSR ( $\lambda$ ) of  $1.71$ . The result at  $X = 105 \text{ cm}$ ,  $V = 4.50 \text{ m/s}$  shows that the hybrid VAWT has outperformed the Conventional VAWT by  $71.3\%$ . The increase in  $C_p$  performance is attributed to ice-wind rotor which increases the speed of the turbine.

Figure 7 presents the  $C_p$  value of the hybrid VAWT and Conventional VAWT for a distance of  $X = 110 \text{ cm}$ ,  $V = 4.29 \text{ m/s}$ . It was observed that hybrid VAWT had high  $C_p$  performance than that of Conventional VAWT. The results showed that the maximum  $C_p$  value attained by the hybrid VAWT and Conventional VAWT were  $0.032$  at a TSR ( $\lambda$ ) of  $1.80$  and  $0.0291$  at a TSR ( $\lambda$ ) of  $1.05$ . In comparison, the maximum  $C_p$  value for the hybrid was  $9.97\%$  higher compared to the maximum  $C_p$  value of the Conventional VAWT. Similarly, the presented result in Figure 8 for  $X = 115 \text{ cm}$  indicates that the  $C_p$  value of hybrid VAWT

increased by 66.67% compared to the Conventional VAWT under similar experimental settings. The highest  $C_p$  value recorded by the hybrid VAWT and Conventional VAWT at  $X = 115$  cm were 0.029 at a TSR of 1.39 and 0.0174 at TSR of 1.17. The  $C_p$  values were evaluated by equation (4).

### COEFFICIENT OF POWER ( $C_p$ ) AGAINST TIP SPEED RATIO ( $\lambda$ )

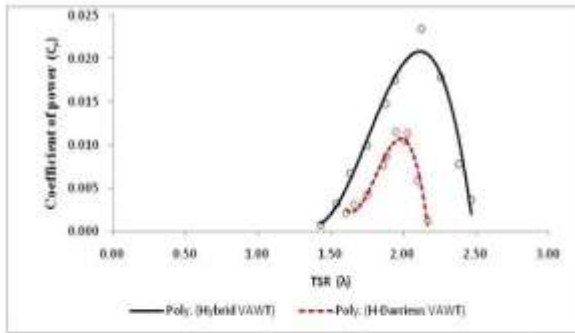


Fig. 5: 100 cm (91.67%)  $V = 4.77$  m/s

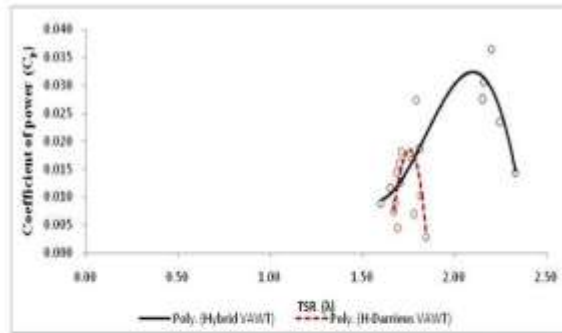


Fig. 6: 105 cm (71.3%)  $V = 4.50$  m/s

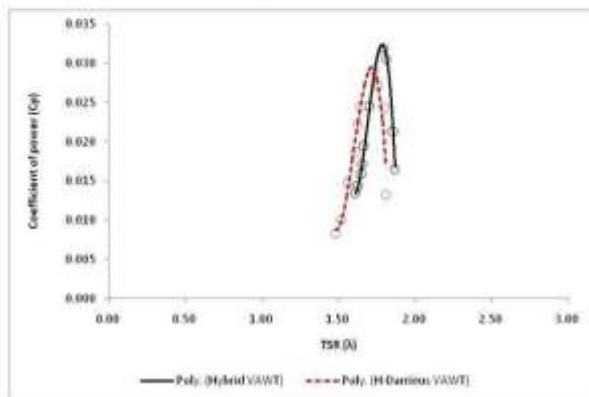


Fig. 7: 110 cm (9.97%)  $V = 4.29$  m/s

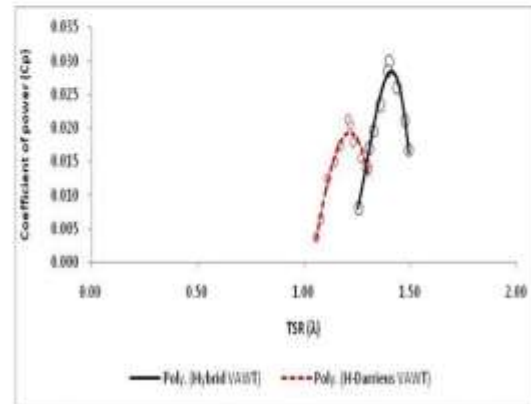


Fig. 8: 115 cm (66.67%)  $V = 3.98$  m/s

Figures 5 - 8 are the relationships between the coefficient of power and tip speed ratio. The results of hybrid VAWT shows better performance for the coefficient of power than that of Conventional VAWT for all the configurations (100-115 cm). These significant improvements in coefficient of power in percentage values of the hybrid VAWT are attributed to the ice-wind rotor which enable it to operate in all directions of wind. These improvements in performance of hybrid VAWT are due to skewed flow effect that can lead to a reduction of the minimum cut-in speed, thus extending the operating range of the rotor and increasing the energy harvesting for the low-wind conditions. This low coefficient of performance of the Conventional VAWT is related to the radial arms of the turbine. The supporting struts (radial arms) of Conventional VAWT usually affect the power output of the turbine by adding an additional drag on the Figure.

### Coefficient of Torque ( $C_t$ ) against TSR ( $\lambda$ )

Figures 9-12 compared the values of coefficient of torque for the hybrid VAWT and that of Conventional VAWT for  $X = 100, 105, 110$  and  $115$  cm. The results showing similar trend were obtained for Figures 9-12. Figure 9 shows the coefficient of torque against the TSR ( $\lambda$ ) for the hybrid VAWT and Conventional VAWT placed at a position of 100 cm. Based on the observed and recorded result in Figure 9, the hybrid VAWT attained a maximum value of coefficient of torque as 0.011 at TSR ( $\lambda$ ) of 2.12. The maximum coefficient of torque of the Conventional VAWT placed at the same position and subjected to same experimental conditions was 0.006 at a TSR ( $\lambda$ ) of 1.95. The result shows that the maximum coefficient of

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torque for the hybrid VAWT has an increase of 83.3% compared to that of Conventional VAWT for  $X = 100$ .

Figure 10 compares the coefficient of torque values between the hybrid VAWT and that of the coefficient of torque recorded by hybrid VAWT at a distance of 105 cm and obtained 0.017 at a TSR ( $\lambda$ ) of 2.20 is higher than that of Conventional VAWT maximum coefficient of torque whose values is 0.006 at TSR ( $\lambda$ ) of 1.79. The result at  $X = 105$  cm,  $V = 4.50$  m/s shows that the hybrid VAWT has outperformed the Conventional VAWT by 183.3%. The increase in coefficient of torque is attributed to ice-wind rotor which increases the speed of the turbine. Figure 11 presents the coefficient of torque value of the hybrid VAWT and Conventional VAWT for a distance of  $X = 110$  cm,  $V = 4.29$  m/s. It was observed that hybrid VAWT has high coefficient of torque than that of Conventional VAWT at values of 0.018 at a TSR ( $\lambda$ ) of 1.80 and 0.017 at a TSR ( $\lambda$ ) of 1.73 respectively. In comparison, the maximum coefficient of torque value for the hybrid is 5.88% higher compared to the maximum coefficient of torque value of the Conventional VAWT. Similarly, the presented result in Figure 12 for  $X = 115$  cm indicates that the coefficient of torque value of hybrid VAWT increases by 23.53 % compared to the Conventional VAWT under similar experimental conditions with experimental values of 0.021 at a TSR ( $\lambda$ ) of 1.40 and 0.017 at a TSR ( $\lambda$ ) of 1.22 respectively.

### COEFFICIENT OF TORQUE ( $C_t$ ) AGAINST TIP SPEED RATIO ( $\lambda$ )

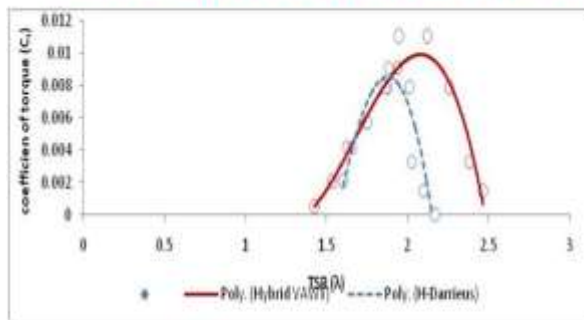


Fig. 9: 100 cm (83.3%)  $V = 4.77$  m/s

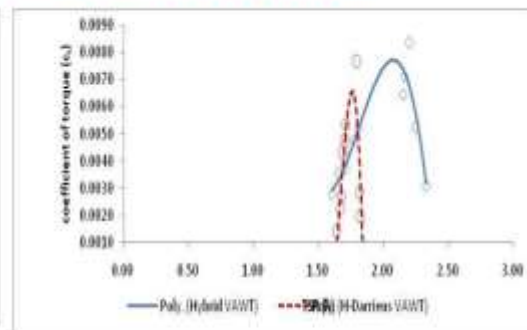


Fig. 10: 105 cm,  $V = 4.50$  m/s

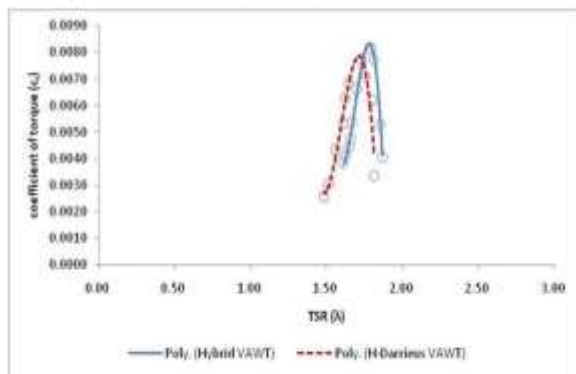


Fig. 11: 110 cm (5.88%),  $V = 4.29$  m/s

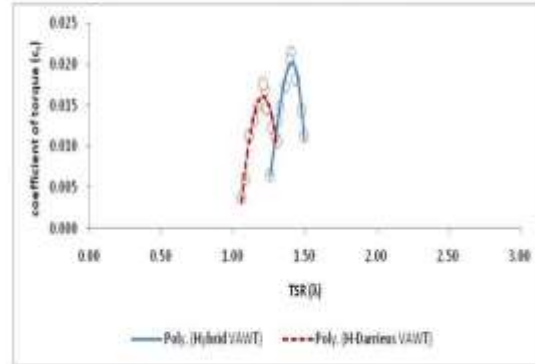


Fig. 12: 115 cm (23.53 %),  $V = 3.98$  m/s

**Figure 9-12:** Coefficient of torque against Tip Speed Ratio for Hybrid VAWT and H-Rotor VAWT for  $X = 100$  cm,  $V = 4.77$  m/s, 105 cm, 110 cm and 115 cm

Figures 9-12 show the relationship between coefficients of torque ( $C_t$ ) against tip speed ratio ( $\lambda$ ) resulted in increase of performance for hybrid VAWT which is attributed to the ice-wind rotor. In general, there are

two critical challenges Darrieus turbine is pebbledash nowadays, over speed regulation and wind speed low performance. These problems need immediate attention and practical solution. Attempts have produced feasible solution, but its difficulties is in exorbitant cost and its commercial application. These challenges can be overcome by developing boundary conditions such as minimal cost, ability to sustain the rotation, ability to control the rotational speed if the rotor spins beyond the rated rpm (Mangalam and Pfenninger, 1984). Furthermore, the reduction in previous lift is exacerbated by the high Angle of Attack (AoA) (Shigemi, 1993). Generating torque by lift force at low wind speed is not realistic for a Darrieus turbine and past finding strengthen the above assertion with wind tunnel and field test (Ai, 1979). To overcome the problem of low lift, reasonable drag force can be used to generate the torque at low wind speed such as Savonius turbine. The Savonius rotor creates drag and converts it to torque, which the magnitude depends on the difference between the drag force of concave and convex portion of the blade (Dobrev and Massouh, 2011). Turbine, thereby affecting the overall performance of the Conventional VAWT (Islam *et al.*, 2008).

#### 4. CONCLUSION

Hybrid VAWT has been designed, constructed and tested. The exceptionality of this design gives rise to its technical advantages over the Conventional VAWT wind turbines and can minimize or completely eliminate the disadvantages of the Conventional VAWT wind turbines. The technology of using ice-wind in the hybrid VAWT has improved rotational speed, power output and self-start behavior of the hybrid VAWT. The results showed that the coefficient of power ( $C_p$ ) of the hybrid VAWT improved momentarily compared to the Conventional VAWT at various distances separation. At  $X = 100$  cm,  $V = 4.77$  m/s, the maximum value of  $C_p$ , for hybrid VAWT increased by 91.67 % at a tip speed ratio ( $\lambda$ ) of 2.12 at a wind speed of 4.77 m/s compared to the Conventional VAWT under the similar experimental conditions. Similar improvement in performance of hybrid is also experiential for all conditions of distances, i.e.,  $X = 105$  cm,  $V = 4.50$  m/s, 110 cm, and 115 cm. similarly, there is an increase in performance in other parameters such as  $C_t$ , from the measured parameters. The closer the distance the better the wind speed as this resulted in better performance of  $C_p$ , and  $C_t$ .

#### References

- Ai, D. (1979). Low Cost Darrieus Vertical-Axis Wind Turbine Design. Terrestrial Energy Systems Conference held at Vancouver, BC, Canada, 6–10 June 1979.
- Brusca, S., Lanzafame, R. and Messina M. (2014). Design of a Vertical-Axis Wind Turbine: How the Aspect Ratio Affects the Turbine's Performance. *International Journal Energy Environ Engineering*. 5(1): 333–340
- Darhmaoui, H. and Sheikh, N. (2017). Savonius Vertical Wind Turbine : Design, Simulation, and Physical. (Unpublished) M.Sc. Dessertation, Al Akhawayn University. 70p.
- DeCoste, J., Denise McKay, B. R. and Shaun Whitehead, S. W. (2016). Self-Starting Vertical Axis Wind Turbine. (Unpublished) M.Sc. Dessertation Dalhousie University. 99p.
- Decoste, J., Mckay, D., Robinson, B., Whitehead, S. and Wright, S. (2005). Vertical Axis Wind Turbine. (Unpublished) B.Sc. Design Project MECH 4010. Department Of Mechanical Engineering, Dalhousie University. 35p.
- Deisadze, L., Digeser, D. and Dunn, C. (2013). Vertical Axis Wind Turbine Evaluation and Design. (Unpublished) M.Sc. Dessertation, Worcester Polytechnic Institute. 66p.
- Dobrev, I. and Massouh, F. (2011). CFD and PIV investigation of unsteady flow through Savonius wind turbine. *Energy Procedia* 6(II): 711-720.
- Hameed, M. and Afaq, S. (2013). Design and Analysis of a Straight Bladed Vertical Axis Wind Turbine Blade Using Analytical and Numerical Techniques. *Ocean Engineering*, 57: 248–255
- Buhari *et al.*: Comparative Analysis between Hybrid and Conventional Vertical Axis Wind Turbines Performances

- Hammond, O., Hunt S. and Machlin, E. (2014). Design of an Alternative Hybrid Vertical Axis Wind Turbine, (Unpublished) M.Sc. Dessertation, Worcester Polytechnic Institute, 70p.
- Islam, M., Fartaj, A. and Cariveau, R. (2008). Analysis of the Design Parameters related to a Fixed-pitch Straight Bladed Vertical Axis Wind Turbine. *Wind Eng*, 32, 491–507.
- Kumar, M. P., Anbazhagan, S., Srikanth, N. and Lim, T. (2017). Optimization, Design, and Construction of Field Test Prototypes of Adaptive Hybrid Darrieus Turbine. *International Journal of Advance Engineering and Research Development*, 4(3): 774-778.
- Lane, J., Lynn, T., Rafieck, S. and Rossen, M. T. (2018). Vertical Axis Wind Turbine for Remote Power Generation, (unpublished) Ph.D thesis, Worcester Polytechnic Institute. 80p.
- Mangalam, S. and Pfenninger, W. (1984). Wind-Tunnel Tests on a High Performance Low-Reynolds Number Airfoil. 13th Aerodynamic Testing Conference held at Domas, Serang, Banten, In-donesia. 3040-3040.
- Newsom, C. (2012). Renewable Energy Potential in Nigeria: Low-Carbon Approaches to Tackling Nigeria's Energy Poverty. *International Institute for Environment and Development*, 2: 5-9.
- Sambo, A. S. (2005). Renewable Energy for Rural Development. The Nigerian Perspective. *ISESCO Science and Technology Vision*, 1, 12-22.
- Shigemi, M. (1993). Numerically Simulated Flow Separation on Airfoil of High Angle of Attack. Fluid Dynamics of High Angle of Attack. In:Kawamura R. Aihara Y. (Eds) Fluid Dynamics of High Angle of Attack. International Union of Theoretical and Applied Mechanics. Springer, Berlin, Heidelberg, 978-3-642-52462-2, 109-120
- Sunnya, K. A. and Kumar, N. M. (2016). Vertical Axis Wind Turbine: Aerodynamic Modelling and its Testing in Wind Tunnel, 6th International Conference on Advances in Computing and Communications, ICACC 2016, held at Cochin, India 6-8 September 2016 (Online) retrieved from [www.sciencedirect.com](http://www.sciencedirect.com)