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Design and Performance Evaluation of a Prototype Vertical Axis Wind Turbines

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Abstract

Vertical axis wind turbines (VAWT) have recently attracted much attention as an efficient tool for harnessing wind energy. However, these wind turbine types face challenges affecting their overall performance. The Darrieus rotor has difficulty self-starting, while the Savonius rotor has low efficiency. We have designed and tested a novel solution, Hybrid VAWT, to address these issues. This system merges the Darrieus and Savonius rotors to generate high starting torque and enhanced efficiency. Our Research is significant in the context of the current state of wind energy technology as it presents a perfect solution to the performance limitations of conventional VAWTs. The turbine VAWTs were designed with Google sketch-up software solid tools and fabricated using locally available materials. The VAWTs were tested at four different wind speeds (V = 4.80 m/s, 4.50 m/s, 4.30 m/s and 3.90 m/s). The superior performance of the hybrid VAWT was demonstrated through a direct comparison with the conventional H-Darrieus VAWT under identical experimental conditions. The result revealed that experimental torque and mechanical power have an improvement on the same experimental conditions for hybrid VAWT as (87.4%, 8.8%, 5.6%, 21.61%) and (100%, 45.5%, 9.4% and 40.3%), respectively, compared to that of H-Darrieus

VAWT. The percentage increment showed that the hybrid vertical-axis wind turbine significantly improved performance compared to the conventional vertical-axis wind turbine. Coupling the Icewind rotor (Savonious Rotor) with H-Darrieus VAWT (hybrid VAWT) yields greater self-starting and higher performance in the measured parameters than the conventional H-Darrieus VAWT.

Keywords: Hybrid VAWTs, Darrieus Rotor, Savonius Rotor, Self-Starting, Efficiency

Introduction

Since the beginning of life, societies have depended on sunlight directly from sun radiations or indirect forms such as wind and hydro energies (Al-ghriybah et al., 2019). Burning natural fuel sources leads to increased greenhouse gas emissions, resulting in negative consequences such as climate change.(MAMEDOV et al., 2021). It, in turn, makes it essential to increase the share of humankind that uses clean energy sources. After the 1970s, energy from renewable resources such as solar radiation, hydropower, wind, and biomass started to dominate the energy sectors due to the depletion of conventional fuel resources (Abdalrahman et al., 2017). Globalization has become critical in increasing energy demand(Kumar & Agrawal, 2019). As the demand increases, a higher supply of energy needs to be available due to the barriers of using conventional resources, such as outdoor air quality and other environmental pollution, in addition to the high(Al-ghriybah et al., 2019). The current energy crisis and environmental damage caused by conventional thermal power plants are driving the development of efficient systems for harvesting renewable energy resources.(Antar et al., 2019). Renewable energy comes from natural resources like geothermal, biomass, sunlight, wind, and water, which are constantly replenished.(Abdulwahab & Mamuda, 2019). Wind energy has proven to be a cheaper alternative energy resource among these resources. Hence, extensive research efforts have been put into improving electricity generation technology through the wind (G. Mohammed et al., 2020).

A Wind turbine is a device used to transform wind's kinetic energy into a more beneficial electrical energy form. Inclusive research efforts were performed to improve electricity generation technology from wind turbines (El-Zafry et al., 2019). Based on their rotational axis orientation for the wind direction, wind turbines can be categorized as either vertical axis wind turbines (VAWT) or

horizontal axis wind turbines (HAWT).
(Al-ghriybah et al., 2019).

Literature Review

Horizontal axis (HAWTs) and Vertical axis (VAWTs).

Wind turbines are categorized as horizontal axis (HAWTs) or vertical axis (VAWTs). (Wang et al., 2019). HAWT is the most widespread type of wind turbine due to its high efficiency. Nevertheless, VAWT has featured over HAWT, such as lower construction and maintenance costs, lower noise level, and independent of the wind direction (Al-ghriybah et al., 2019).

HAWTs have become extremely common in the current market; they transform the wind's kinetic energy into electric energy by rotating a shaft with an axis parallel to the wind direction. Regarding VAWTs, the rotor axis has a vertical position, and they deal with the wind from any direction, so they do not need a yaw mechanism(El-Zafry et al., 2019).

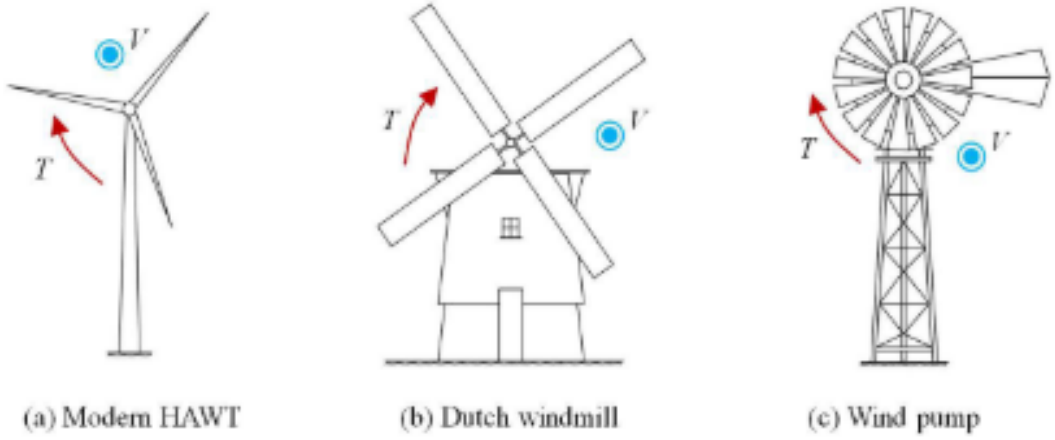


Figure 2.1: Typical Horizontal Axis Wind Turbine configurations (Du et al., 2019)

The early VAWTs are constructed based on the aerodynamic drag, whereas the reverse drag is eliminated by covering the advancing blade to generate net torque. Later, it was realized that the lift force is more efficient than drag, and in order to achieve sufficient lift, the blade shape has to be different on the top and bottom sides. Lift based Darrieus turbine was invented by G.J.M. Darrieus, a French aeronautical engineer, in 1925 (Palanisamy et al., 2019)

Due to the common perception that the VAWT is less efficient than the horizontal axis wind turbine (HAWT), extensive efforts have been made to improve the competitiveness and efficiency of the vertical rotor. Research has focused on the dynamic behaviour of fluid flow around the vertical rotor, blade-wake interactions, and exploiting unsteady tangential force components to improve the performance of

the VAWT, which has shown higher power output in highly turbulent urban wind conditions compared to the HAWT(Chong et al., 2019)

Savonius wind turbines are VAWT, in which the wind direction is ignored because the turbine will still rotate for all wind directions. This wind turbine is ideal for use in areas with erratic wind directions. However, Savonius wind turbines only have an efficiency of around 15%. It means that only 15% of the wind energy that hits the turbine turns into mechanical turbine energy. Turbine speed cannot rotate faster than wind speed. Darrieus wind turbines are VAWTs that can rotate faster than wind speeds up to several times due to Darrieus wind turbines producing smaller torque than Savonius wind turbines. This makes the Darrieus wind turbine more suitable as an electric generator than the Savonius wind turbine (Hidayanti et al., 2020).

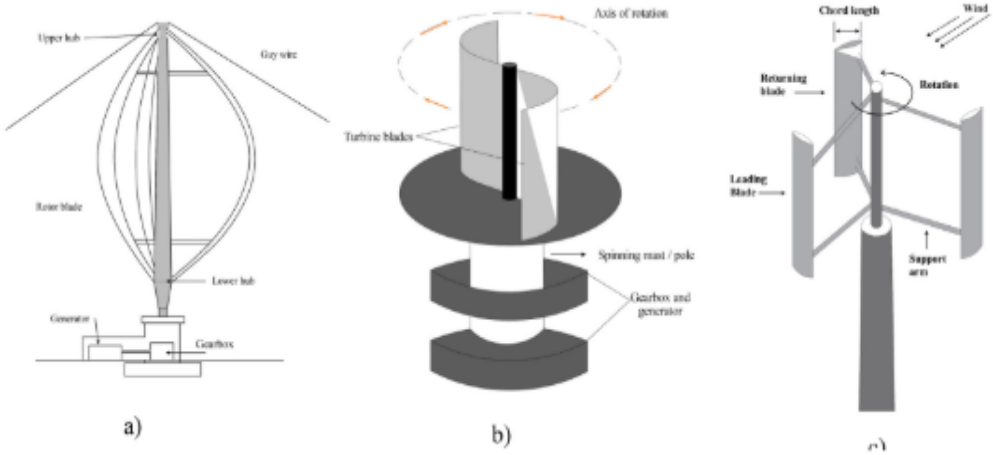


Figure 2.2: Diagrammatic representation of a) Darrieus VAWT, b) Savonius VAWT, c) H-Rotor (Tasneem et al., 2020)

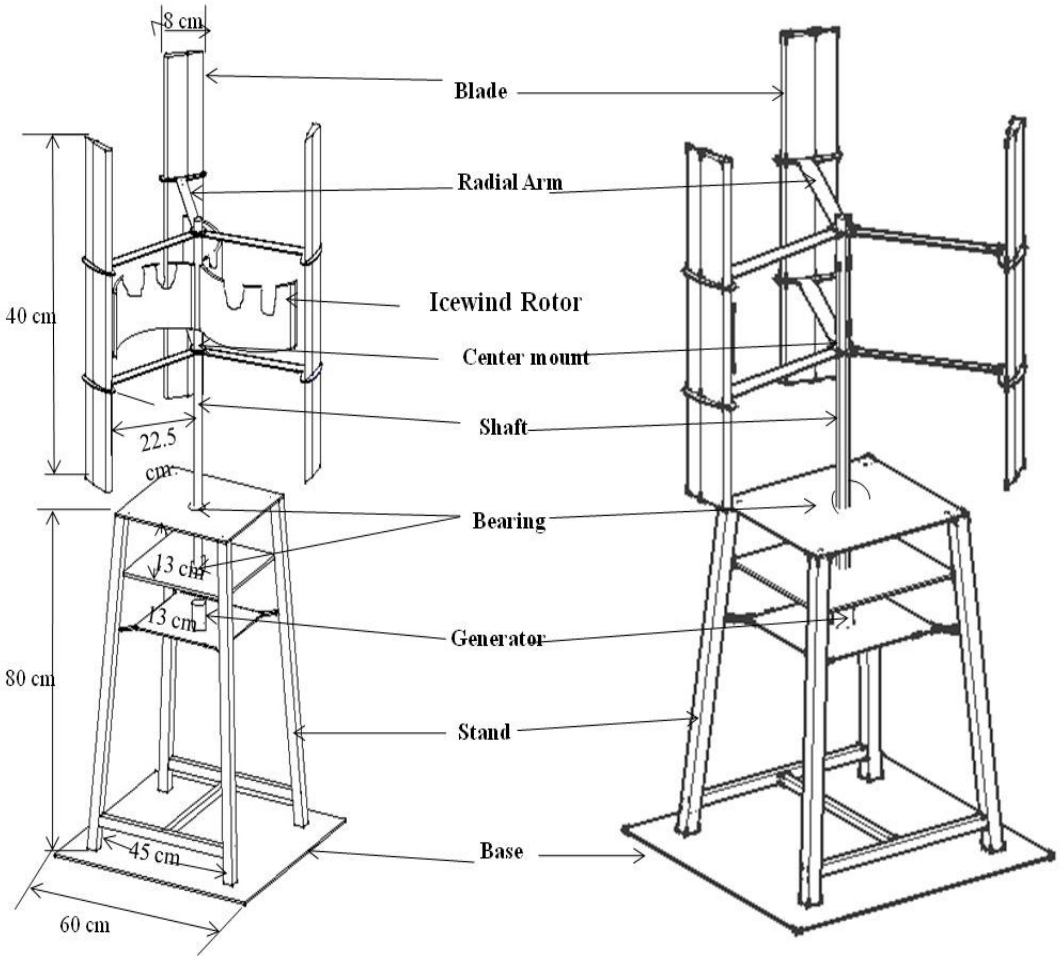
The design comprises the Darrieus and the Savonius to get each of their benefits. The Darrieus was designed to have a high power coefficient and is typically more efficient than other VAWT designs, but it cannot self-start (Mojica et al., 2019)(Lane et al., 2018). The Savonius design has high starting torque and can self-start but has low rotational speed and power coefficient. Hybrid designs combine aspects of the Darrieus and Savonius designs to achieve self-starting capability, high starting torque, and increased efficiency. Typically built as a Darrieus with a drag-type blade in the middle, this design is less efficient than a typical lift-type after starting due to the middle creating negative drag (Buhari et al., 2020)

Hybrid Wind Turbines In the development of VAWT, Hybrid wind turbines are the latest VAWT (Mohammed et al., 2022)(Debnath & Saeedifard, 2013). A hybrid wind turbine combines Savonius and Darrieus wind turbines in one vertical axis. This

turbine has two forces in its rotation, namely the drag force (drag force) of the Savonius wind turbine that functions as self-starting and the lift force (lift force) blade of the Darrieus wind turbine, which functions to accelerate the turbine rotation (Methal et al., 2022) (Abid, 2015).

METHODOLOGY

The analytical design parameters of the turbine were used to design the hybrid vertical wind turbine and its components using Google Sketch 2007 model solid tools to bring out the pictorial design with dimensions. The blade was first designed using Google Sketch-up software tools, and the shaft, ice-wind rotor and radial arm were designed after using the same software tools. Then, rotor support frames (stand) and generator were designed separately. Then, the shaft was inserted into the stand using a move-and-push tool. Also, radial arms were coupled to the shaft, and the blade was inserted in the hole proved in the radial arm; the Icewind rotor was put in the position between the upper and lower radial arm, where the assembled schematic drawing (diagram) became hybrid VAWT shown in Figure 3



(a) (b)

Figure 3: Schematic diagram of the (a) hybrid VAWT (b) H-Darrieus VAWT

3.1 EXPERIMENTAL SETUP: The experiment was set up with six electric Standing fans, and the VAWT was placed 100 cm from the fans, facing the fans in the same line and direction as shown in Figures 5 and 6. The distance between the blower and VAWTs was varied at a distance of 5 cm to vary the wind speed so that the VAWTs could be tested at different wind speeds. The wind speed was measured for different points, and the average wind speed was taken for each point.



Figure 5: Experimental setup

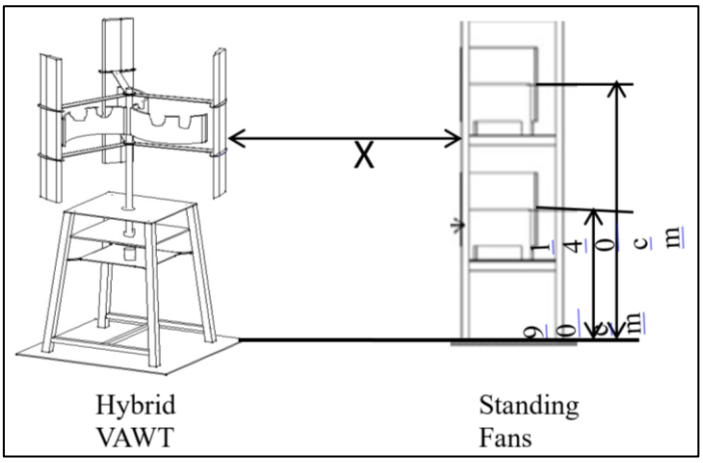


Figure 6: Symmetric diagram of the experimental setup with dimension

The setup arrangement of a 3x2 configuration of 100cm x 180cm downstream of the fans is shown in Figure 5. The average wind speed was taken using an anemometer on ten different positions on a straight line along the direction of the Fan's wind when the fans were on (4.77 m/s). Then, a horizontal distance between the Fan and the turbine position (X= 100 cm) was marked along the direction of the wind, and Hybrid VAWT was placed on the position marked as shown in Figure 6. The anemometer was used to measure wind speed, while a tachometer was used to measure RPM after the fans were activated. A 0.3W LED load was added, and the current and voltage were measured. The same procedure was repeated for each position by increasing the distance. The H-Darrieus VAWT was replaced, and the same experimental conditions were applied.

RESULTS AND DISCUSSION:

The two experiments were performed under the same experimental conditions, one for the hybrid VAWT and another for the H-Darrieus VAWT. The two turbines' horizontal

distance varied for four different wind speeds, i.e. V = 4.80 m/s, 4.50 m/s, 4.30 m/s, and 3.90 m/s, respectively.

Figures 7-10 compare the Values of experimental torque between the hybrid VAWT and that of H-Darrieus VAWT at V= 4.80 m/s, 4.50 m/s, 4.30 m/s and 3.90. The results showing the same trend were obtained for Figure 7-10. Figure 7 shows the experimental torque against the TSR (λ) of the hybrid VAWT and H-Darrieus VAWT placed at V= 4.80 m/s. Based on the result observed and recorded in Figure 7, the hybrid VAWT has attained a maximum value of experimental torque of 0.006265 Nm at TSR (λ) of 2.12. The maximum experimental torque of the H-Darrieus VAWT placed at the same position and subjected to the same experimental conditions is 0.003344 Nm at TSR (λ) of 1.95, as shown in Figure 7. The result shows that the maximum experimental torque for the hybrid VAWT has an increment of 87.4% compared to that of H-Darrieus VAWT for V= 4.80 m/s; Figure 8 compared the experimental torque values between the hybrid VAWT and that of the H-Darrieus VAWT for V= 4.50 m/s, which is 0.008339 Nm at a TSR (λ) of 2.20 is higher than that of H-Darrieus VAWT maximum experimental torque whose values is 0.007664 Nm at TSR (λ) of 1.79. The result at V= 4.50 m/s shows that the hybrid VAWT has outperformed the H-Darrieus VAWT by 8.8%. The increase in experimental torque is attributed to the icewind rotor, which increases the speed of the turbine.

Figure 9 presents the experimental torque value of the hybrid VAWT and H-Darrieu VAWT at V= 4.30 m/s. It is observed that hybrid VAWT has a higher experimental torque than that of H-Darrieus VAWT, and results obtained showed that the maximum experimental torque value attained by the hybrid VAWT and H-Darrieus VAWT are 0.008150 Nm at TSR (λ) of 1.80 and 0.007720 Nm at TSR (λ) of 1.73 respectively. In comparison, the maximum experimental torque value for the hybrid is 5.6%, which is higher than the maximum experimental torque value of the H-Darrieus VAWT. Similarly, the presented result in Figure 10 for V= 3.90 m/s indicates that the experimental torque value of hybrid VAWT increases by 21.61 % compared to the H-Darrieus VAWT under similar experimental conditions with values of 0.008077 Nm at TSR (λ) of 1.40 and 0.006642 Nm at TSR (λ) of 1.21 respectively. Figure 7-10 shows the relationship between experimental torque and tip speed ratio; the results show higher performance of the hybrid VAWT, which is attributed to the icewind rotor. This was due to the high starting torque from Icewind (Savonious) blades, as shown in all configurations. Figure 7-10 shows the relationship between experimental

torque and tip speed ratio, which increased performance for hybrid VAWT attributed to the Icewind rotor.

✓EXPERIMENTAL TORQUE (τ) AGAINTS TIP SPEED RATIO (λ)

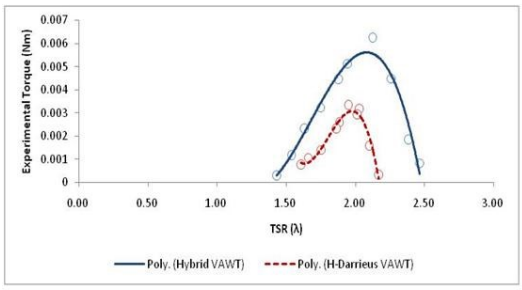


Figure 7: 100 cm, V 4.80 m/s (87.4%)

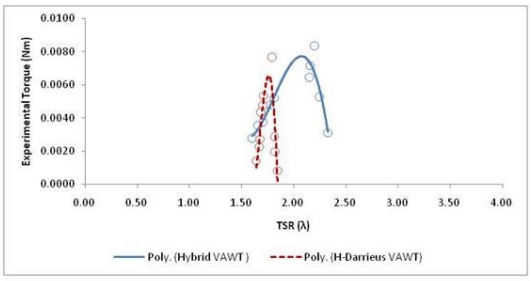


Figure 8:105 cm, V = 4.50 m/s (8.8%)

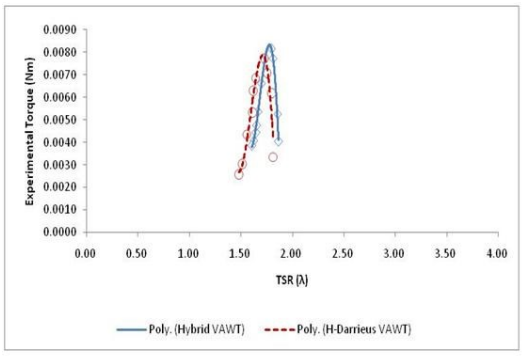


Figure 9:110 cm, V = 4.30 m/s (5.6%)

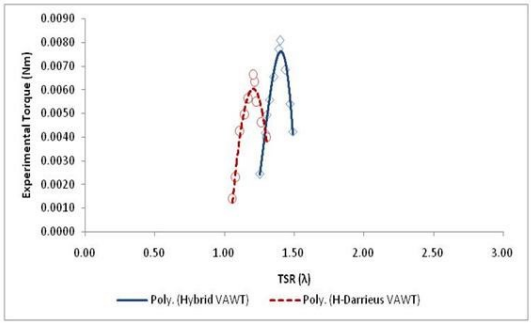


Figure 10:115 cm, V = 3.90 m/s (21.61 %)

Figures 11-14 compare the mechanical power values between the hybrid VAWT and that of H-Darrieus VAWT at V= 4.80 m/s, 4.50 m/s, 4.30 m/s and 3.90. The results show a similar trend in Figures 11-14. Figure 11 shows the mechanical power against the rotational speed (ω) of the hybrid VAWT and H-Darrieus VAWT placed at V= 4.80 m/s. Based on the result observed and recorded in Figure 11, the hybrid VAWT has attained a maximum value of mechanical power of 0.28 W at a rotational speed (ω) of 45.021 rad/s. The maximum mechanical power of the H-Darrieus VAWT placed at the same position and subjected to the same experimental conditions is 0.14 W at a rotational speed (ω) of 41.326 rad/s, as shown in Figure 11. The result shows that the maximum mechanical power for the hybrid VAWT has an increase of 100% compared to that of H-Darrieus VAWT for V= 4.80 m/s. Figure 12 compares the mechanical power values between the hybrid VAWT and the H-Darrieus VAWT, which is placed at V= 4.50 m/s position. The result showed that the maximum mechanical power recorded by hybrid VAWT at V= 4.50 m/s is 0.4 W at a rotational speed (ω) of 43.993 rad/s higher than that of H-Darrieus VAWT maximum mechanical power whose value is 0.275 W at rotational speed (ω) of 35.842 rad/s. The result at V= 4.50 m/s shows that the hybrid VAWT outperformed the H-Darrieus VAWT by 45.5%. As mentioned

earlier, the increase in mechanical power is attributed to the Icewind rotor, which increases the turbine's speed. Figure 13 presents the mechanical power value of the hybrid VAWT and H-Darrieu VAWT for a distance of V= 4.30 m/s. It is observed that hybrid VAWT has higher mechanical power than that of H-Darrieus VAWT. The results showed that the maximum mechanical power value attained by the hybrid VAWT and H-Darrieus VAWT are 0.279 at a rotational speed (ω) of 34.237 and 0.255 at a rotational speed (ω) of 20.068. In comparison, the maximum mechanical power value for the hybrid is 9.4% higher than the maximum mechanical power value of the H-Darrieus VAWT. Similarly, the presented result in Figure 14 for V= 3.90 m/s indicates that the mechanical power value of hybrid VAWT increases by 40.3 % compared to the H-Darrieus VAWT under similar experimental conditions. The maximum mechanical power values recorded by the hybrid VAWT and H-Darrieus VAWT at V= 3.90 m/s are 0.195 at a rotational speed (ω) of 24.174 and 0.139 at a rotational speed (ω) of 20.870.

✓MECHANICAL POWER (Pm) AGAINTS ROTATIONAL SPEED (ω)

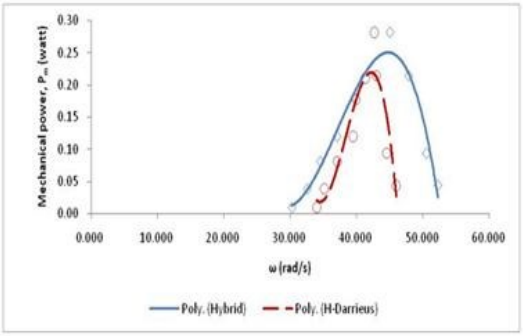


Figure 11: 100 cm, V = 4.80 m/s (100%)

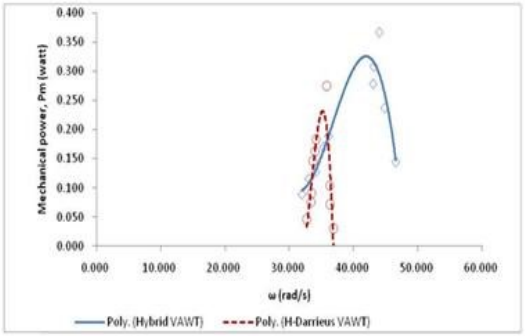
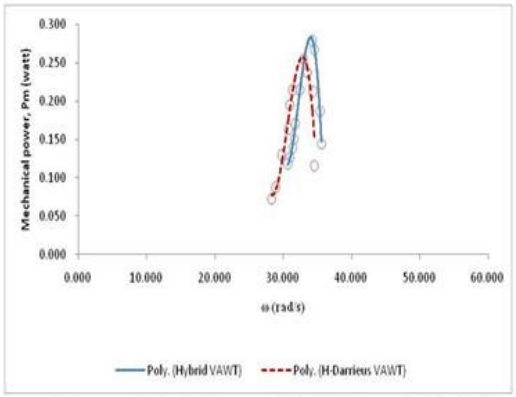


Figure 12: 105 cm, V = 4.50 m/s (45.5%)



(Figure 13: 110 cm, V= 4.30 m/s (9.4%)

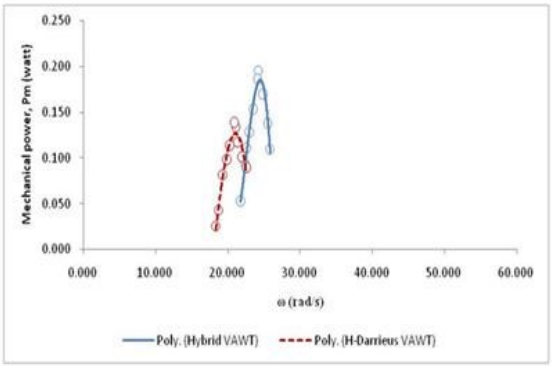


Figure 14: 115 cm, = 3.90 m/s (40.3 %)

Figures 11-14 show the relationship of Mechanical power and rotational speed of the VAWT. The increase in performance for the hybrid VAWT is attributed to the Icewind rotor coupled to the turbine. The low CP output of the H-Darrieus VAWT is attributed

to the radial arms (supporting struts) of the H-Darrieus VAWT. The supporting struts of the H-Darrieus VAWT have affected the power output of the turbine by adding additional drag (parasitic drag) on the turbine, thereby affecting the overall performance of the H-Darrieus VAWT(Mohammed et al., 2021) (Ramkissoon & Manohr, 2013).

The Darrieus turbine faces two critical challenges today: poor performance at low wind speed and overspeed regulation. These imperative problems require immediate attention and implementable solutions. The previous attempts yielded a solution, but the complexity and cost limit its application in commercial quantity. When addressing these challenges, "Consider low cost, increased starting torque at low wind speeds, sustained rotation, and the ability to control the rotational speed of the rotor exceeds the rated RPM.". (Kumar et al., et al., 2019)(Mangalam & Pfenninger, 1984). The decrease in the lift is further exacerbated by the high Angle of Attack(Ismail et al., 2020) (AoA) (Shigemi, 1993). The inadequate lift cannot generate the torque to overcome the inertial and drive train resistance (Moreira et al., 2020) (Bati & Luk, 2015), thus failing to incite the rotation at low wind speeds. Generating torque only by lift force at low wind speed is impractical for a Darrieus turbine. Past studies bolster the above statement with wind tunnel experiments and field tests (Shahzad et al., 2022) (Ai, 1979). To circumvent the problem of low lift, considerable drag force can be used to generate the torque at low wind speed, such as the Savonius rotor. The Savonius rotor creates drag and converts it into torque, in which the magnitude depends on the difference between the drag force of the concave and convex portion of the blade (Saad et al., 2021).

CONCLUSIONS

In this paper, VAWTS has been designed, constructed and tested. The result revealed that experimental torque and mechanical power have an improvement on the same experimental conditions for hybrid VAWT as (87.4%, 8.8%, 5.6%, 21.61%) and (100%, 45.5%, 9.4% and 40.3%), respectively, compared to that of H-Darrieus VAWT. The percentage increment showed that the hybrid vertical-axis wind turbine significantly improved performance compared to the conventional vertical-axis wind turbine. Coupling the Icewind rotor (Savonious Rotor) with H-Darrieus VAWT (hybrid VAWT) yields greater self-starting and higher performance in the measured parameters than the conventional H-Darrieus VAWT.

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