UNIABUJA Journal of Engineering and Technology
https://ujet.uniabuja.edu.ng/
ISSN: 2714-3236 (Online); 2714-3228 (Print)
Volume 2, Issue 2, 2025; 99-107

Design and Experimental Analysis of the Effect of Winglets on the Performance of a Hybrid Vertical Axis Wind Turbine

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ABSTRACT
This study investigates the effect of winglets on the performance of a hybrid Vertical Axis Wind Turbine (HVAWT) with a combined Savonius Darrieus configuration. Winglets, known for reducing aerodynamic drag in aeroplane were applied to the blades to assess improvements in efficiency, torque and power output. Comparative experiments were conducted on two configurations: one with winglets and another without winglets, under varying wind speeds (2 – 6 m/s). Results showed that the configuration without winglets achieved higher rotational speeds (about 10 rad/s) and torque (about 6 x 10^{-6} Nm). However, the turbine with winglets demonstrated superior self-starting ability at low wind speeds . The findings suggest that while winglets aid in low - speed operations, there is increase in drag, necessitating design optimization to improve overall efficiency.

Keywords: *Winglet, wind turbine, Savonius rotor, Darrius turbine, aerodynamics, power coefficient.*

1.0 Introduction

The quest for efficient and reliable renewable energy sources has intensified as the global community seeks to reduce reliance on fossil fuels and mitigate climate change. Wind energy, as a major contributor to this transition, has seen substantial advancements in turbine technology aimed at maximizing energy capture and efficiency. Vertical axis wind turbines (VAWTs) are gaining recognition for their unique advantages in various environmental conditions, especially in urban and decentralised settings, as they can capture wind from any direction and are compact. Wind turbine performance optimisation has been a key research area, driven by the need for increased efficiency and reduced costs in renewable energy generation. Vertical axis wind turbines (VAWTs) offer unique advantages, including compact design and omnidirectional wind capture, which make them suitable for urban and off-grid applications. However, improving their aerodynamic performance remains a challenge.

Early research on VAWTs, conducted by Mertens & Delft, (2002), Hand & Andrew (2015) and Takao et al., (2009), demonstrated the potential of VAWTs to improve energy generation in urban environments. This is because they can utilize wind from any direction. However, the performance of these turbines is often limited by high drag and low efficiency at certain wind speeds. Recent studies, such as those by (Altmimi et al., 2021 & Ahmad et al., 2022), have focused on optimizing VAWT designs, exploring blade profiles, and improving overall aerodynamic performance.

Generally, airfoils from the NACA 4-digit series are frequently utilized in VAWT research, with the NACA0012, NACA0015 and NACA0018 being the most notable examples (Yi et al., 2015; Zhang, L., Liang, Y., Liu, X., Jiao, Q., & Guo, 2013; Wenehenubun et al., 2015). In these studies the performance of Savonius wind turbines with 2, 3 and 4 blades was compared. The 4-bladed wind turbine generated higher torque than the rest. However, the 4-bladed wind turbine was seen to have greater drag force than the rest.

A hybrid vertical axis wind turbine (HVAWT) is designed by combining the Darrieus and Savonius vertical turbine types on a central shaft to enable it to operate in locations with low wind speeds. A very important advantage of this design is its ability to start at low wind speeds and achieving decent efficiency shortly after operation. A HVAWT was developed and experimentally tested for performance against Darrieus VAWT by (Dwiyantoro & Suphandani, 2017). The results demonstrate that the maximum efficiency of the hybrid vertical axis model surpasses that of the Darrieus. And the maximum coefficient of power (CP) of 43% was recorded at Tip Speed Ratio (TSR) of 0.95 for Hybrid model.

A proposal on possibility of using the HVAWT for power generation for household applications in urban areas was made by (Kavade & Ghanegaonkar, 2017). Two, three and four-bladed Savonius rotors were compared using both experimental and numerical analysis. It was discovered that three-bladed rotor produced a higher power coefficient. Combining the three-bladed Savonius with Darrieus rotors proved to

Received: 01-03-2025 / Accepted: 06-05-2025 / Published: 14-06-2025

https://doi.org/10.70118/ujet.2025.0202.10

produce a higher coefficient of power at low wind speeds. Sun, et al., (2016) studied the aerodynamic characteristics of a hybrid vertical axis wind turbine. The results of their investigation indicated that the power coefficient of the hybrid VAWT declines when the distance between its Savonius blades and the centre of rotation of the turbine rotor increases. It went further to show that the starting torque can be significantly improved if the appropriate position is located for the savonius blade. This suggest that the Savonius blade's installation position is very crucial. The starting torque of the hybrid VAWT may not be enhanced if the Savonius blade is situated extremely close to the spindle. The need for further modification to enhance efficiency motivated the introduction of winglets.

Winglets have been widely studied in the context of fixed-wing aircraft and have been shown to reduce induced drag and improve lift-to-drag ratios. The pioneering work of (Whitcomb, 1976) and subsequent research by (Gavrilović et al., 2015) demonstrated significant improvements in efficiency through the integration of winglets in aviation. These findings suggest that similar aerodynamic principles could be applied to wind turbines to enhance their performance. The adaptation of winglet technology to wind turbines has been explored by a few researchers. For instance, (Johansen J, 2006); (Khlaifat et al., 2020) & (Mourad et al., 2020) investigated the effects of winglets on wind turbine blades (HAWTs), showing potential benefits in terms of increased efficiency and reduced noise. However, research that specifically focusing on VAWTs remains limited. Studies by (Moncef et al., 2023) & (Amir et al., 2024) have highlighted the potential of aerodynamic modifications, but the incorporation of winglets in VAWTs is yet to be thoroughly investigated.

Recent advancements in computational fluid dynamics (CFD) and wind tunnel testing have enabled more accurate predictions of aerodynamic performance. Researchers like (Johansen J, 2006); (Bora et al., 2023) & (Altmimi et al., 2021) have employed these tools to optimize turbine designs, including the integration of winglets. Their work underscores the importance of experimental validation in achieving reliable performance improvements, and real - life situation needs to be simulated under normal atmospheric conditions of the locality. The present investigation focuses on flows around a HVAWT with and without winglets. The research aimed at unveiling the impact of winglet on aerodynamic performance of the vertical axis wind turbine as a hybrid design.

2.0 Materials and Method

This study designed and built a HVAWT with combined Savonius and Darrieus blades. Two configurations were made: one with winglets on the Darrieus blades and another without. The profile used for Darrieus blade is DU06W200 airfoil profile shown in Figure 1. The solid model of the assembly of HVAWT with winglets is shown in Figure 2 while Figure 3 is the exploded drawing of the turbine. The blades were made from galvanised steel and assembled as shown in Plate 1.. The experimental setup consisted of a fan, an anemometer to capture wind speed, a tachometer to measure the turbine's rotational speed.

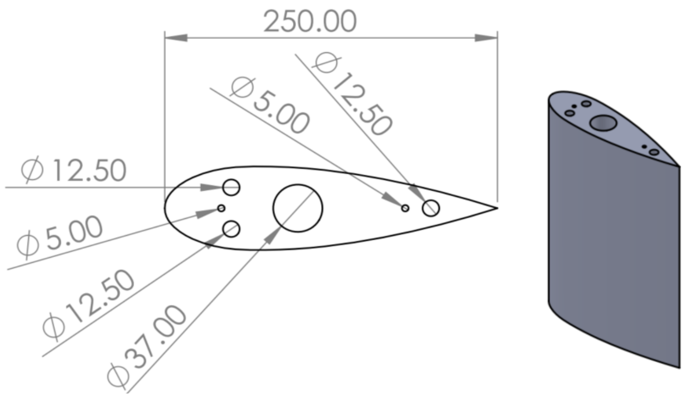


Figure 1: Design drawing of Darrieus blade profile

Received: 01-03-2025 / Accepted: 06-05-2025 / Published: 14-06-2025

https://doi.org/10.70118/ujet.2025.0202.10

Plate 1: Fabricated Darrieus blades

Tests were conducted at wind speeds of 2, 3, 4, 5, and 6 m/s. The turbine was evaluated on key performance parameters including angular speed, torque, and tip speed ratio. The performance of both configurations was measured and compared to assess the impact of winglets on the overall efficiency of the turbine. Data were collected at regular intervals during each test, and the performance metrics, such as power coefficient and tip speed ratio, were calculated for both configurations to determine if winglets provided any aerodynamic improvements.

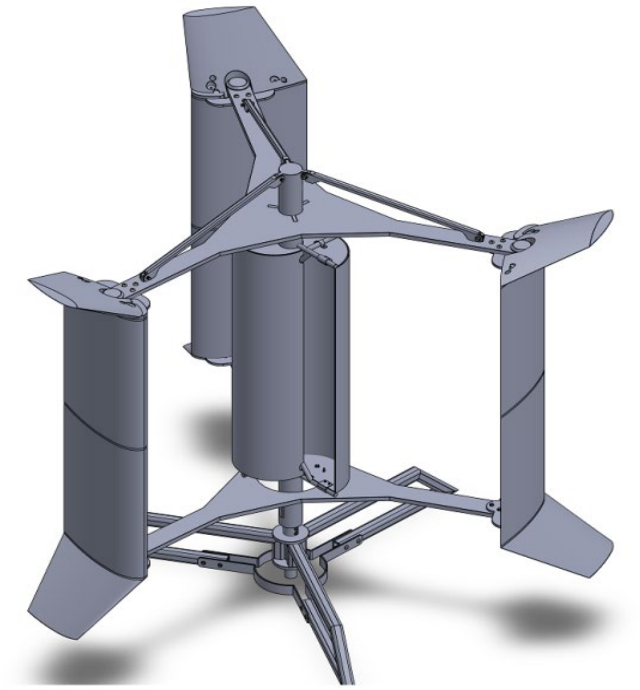
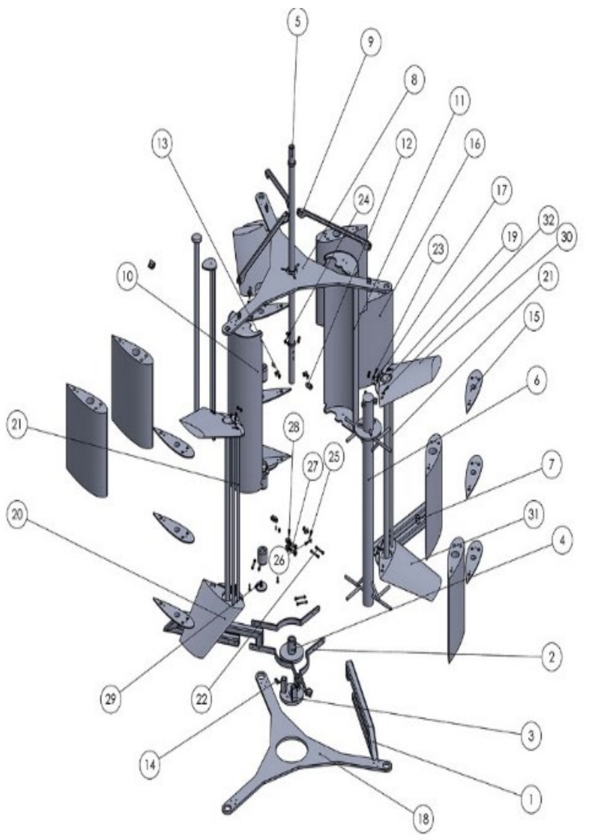


Figure 2: 3D Model of the Hybrid VAWT



ITEM NO.	PART NUMBER	QTY.
1	BASE SQUARE PIPE	3
2	BASE SUPPORT	3
3	BASE SUPPORT B	1
4	BASE SUPPORT C	1
5	STATIC ROTOR SHAFT	1
6	MOBILE ROTOR SHAFT	1
7	BUSHING	1
8	TOP PLATE	1
9	CONNECTOR STRIP	3
10	BEARING	3
11	SAVONIUS BLADE	2
12	CLIP A	4
13	CLIP B	2
14	MIRRORCLIP B	2
15	DARRIEUS PLASTIC BLADE	9
16	DARRIEUS STYROFOAM BLADE	6
17	DARRIEUS BLADE LOCK	6
18	BOTTOM PLATE	1
19	DARRIEUS SHAFT	3
20	WASHER A	3
21	AIRFOIL ROD	3
22	ISO 4162 - M5 X 45 X 16-S	6
23	ISO 4162 - M5 X 25 X 25-S	24
24	ISO - 4161 - M5 - S	30
25	ISO 7045 - M2 X 12 - Z - 12S	24
26	ISO - 4032 - M2 - W - N	24
27	ISO 7046-1 - M10 X 60 - Z - 38S	2
28	ISO - 4161 - M10 - S	2
29	ISO 4162 - M10 X 25 X 25-S	3
30	TOP WINGLET	3
31	BOTTOM WINGLET	3
32	ISO 7045 - M5 X 20 - Z - 20S	12

Figure 3: Exploded view of the Hybrid VAWT

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2.1 Wind Turbine Theory

The performance of a Vertical Axis Wind Turbine (VAWT) is primarily evaluated using the **power coefficient** (C_p) which quantifies the effectiveness of the turbine in converting the kinetic energy of the wind into useful mechanical power. It is defined as the ratio of the mechanical power extracted by the turbine shaft (P_T) to the total power available in the wind (P_w).

$$C_p = \frac{P_T}{P_W} \quad 1$$

The maximum theoretical efficiency of any wind turbine is 59.3%; as earlier established by Betz law. C_p accounts for the aerodynamic efficiency of the turbine and as such, takes into account factors such as turbulence, environmental conditions and the physical properties of the wind turbine. Hence, in actuality, the efficiency of any wind turbine is practically lower than the Betz limit (0.59). It is important to note that C_p of the wind turbine varies with the changing tip speed ratio of the turbine.

The kinetic energy inherent in wind, which is directly proportional to air density, turbine swept area, and wind velocity, represents the substantial power that can be effectively captured and utilised. Mathematically, this power is defined by:

$$P_w = \frac{1}{2}\rho A V^3 \quad 2$$

The swept area *(A)* of a wind turbine is the entire surface area covered by the rotor blades as they rotate. It is the area swept out by the blades during rotation. The swept area is a pivotal factor in determining the turbine's ability to capture and convert wind energy into mechanical or electrical energy. The mechanical power generated by the rotation of the turbine's rotor within the shaft of a VAWT constitutes the power output of the wind turbine. This mechanical power is a direct consequence of the wind's kinetic energy being captured by the turbine blades, thereby converting it into rotational mechanical energy. Mathematically, the mechanical power (P_T) can be calculated as:

$$P_T = T\omega \quad 3$$

The **tip speed ratio (TSR)** is a key dimensionless parameter in wind turbine design, defined as the ratio of the blade tip's tangential velocity to the wind speed. The tip speed ratio (TSR) is a parameter used to describe the relationship between the rotational speed of a wind turbine's rotor and the speed of the wind at the outermost tip of its blades. It is given by:

$$\text{TSR} = \frac{\omega R}{V} \quad 4$$

2.2 Power Coefficient (C_p) and TSR (λ) curve

The C_p -TSR (Power Coefficient vs. Tip Speed Ratio) curve is a graphical representation that shows how the power coefficient (C_p) of a wind turbine varies with different tip speed ratios (TSR). This curve is a fundamental tool in the analysis and design of wind turbines, both for Horizontal Axis Wind Turbines and Vertical Axis Wind Turbines (VAWTs).

2.3 Experimental Procedure

Tests were carried out over five different wind speeds for winglet and non-winglet designs. The average wind speeds were measured with Anemometer while the angular speeds of the rotor shaft were measured using a tachometer. The measured data taken at successive time intervals of 20 seconds were used for calculations of various influencing parameters such as angular acceleration (α), torque and the Tip speed ratio at the time intervals.

$$\alpha = \frac{Change\ in\ angular\ velocity\ (\Delta\omega)}{Change\ in\ time\ (\Delta t)} \quad 5$$

$$Tip\ speed\ Ratio,\ TSR = \frac{Angular\ velocity\ (\omega) \times radius\ of\ turbine\ rotor\ (R)}{Wind\ speed\ (V)} \quad 6$$

With the angular acceleration, the instantaneous torque was computed using the relation:
Torque at turbine shaft, T = shaft's moment of inertia (I) × shaft's angular acceleration (a)

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The instantaneous power available in the turbine at time t is therefore calculated in equation 7:

$$P_T = Torque\ (T) \times angular\ velocity\ (\omega) \quad 7$$

At each wind speed, the power in the wind is calculated using the relation:

$$Power\ in\ the\ wind,\ P_w = \frac{1}{2}\ (\rho) \times swept\ area\ (A) \times\ (wind\ speed^2)(V^2) \quad 8$$

At each wind speed, the power coefficient, defined as the ratio of the power in the shaft to the power in the wind, was computed from equations (1) to (8). The input parameter is the wind speed.

3.0 Results and Discussion

The computed tip speed ratios and corresponding power coefficient at different wind speeds for the different hybrid VAWT configurations (with winglets and without winglets) are plotted as shown in Figures (4, 5 & 6). The curves show the behaviour of various parameters (such as angular speed, tip-speed ratio & torque) with time. The angular speed increases with time for all wind speeds examined and attained the maximum at 100 s. It is observed in Figure 4 that as wind speed increases the angular speed increases but remain constant thereafter, showing that steady state condition is attained when the wind stabilized. The hybrid VAWT configuration with winglet has maximum angular speed of 125 RPM and 50 RPM for local wind speed of 6 m/s and 2 m/s respectively.

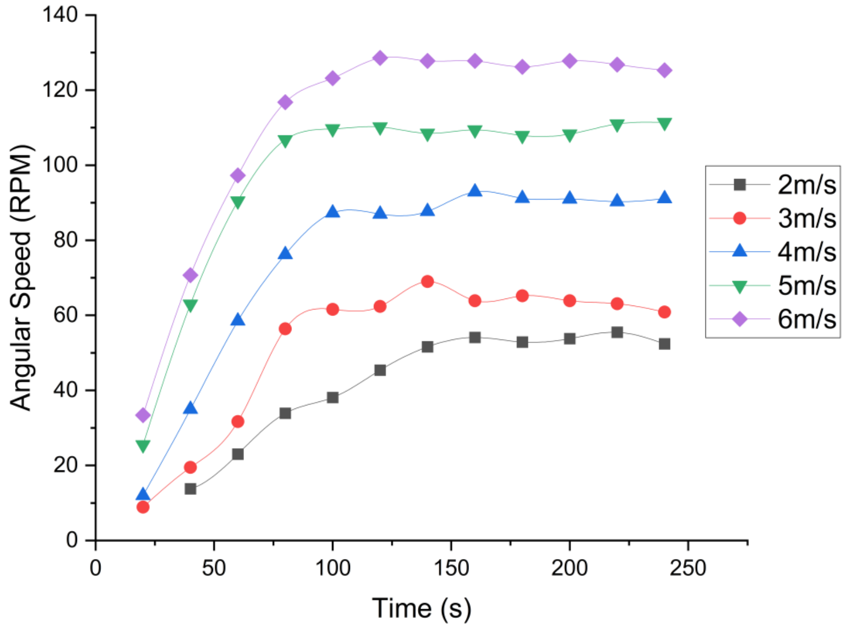

Figure 4: The angular speed at different wind speed (with winglet)

Figure 5 shows comparison of angular speed RPM at different wind speeds for hybrid VAWT without winglet. There is a small increase in angular speed when compared Figure 4 & 5, this implies that winglet addition to the design slightly reduce the angular speed perhaps due to increase in weight of the profile.

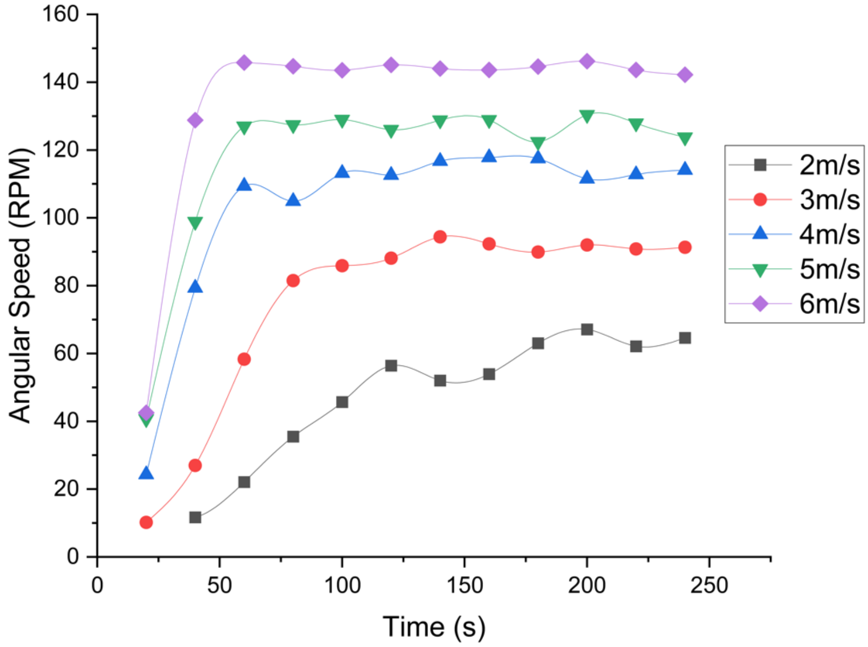

Figure 5: Angular speed obtained for different wind speed (without - winglet)

Figure 6 shows the behaviour of TSR with time for various wind speeds when the hybrid VAWT has winglet. The speed ratio attains a mximum of about 1.0 TSR for most wind speeds examined. Figure 7 is a similar result for hybrid VAWT that has no winglet. There is a significant difference between TSR for no-winglet design compared to winglet. This observation may be attributed to increase loading on the wing design due to the add-on.

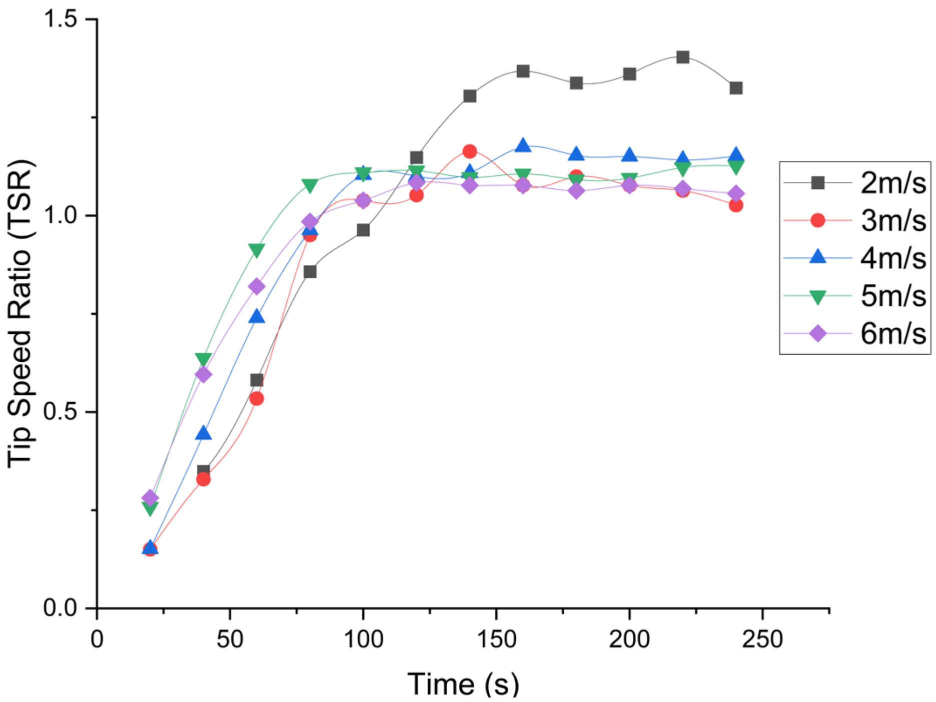

Figure 6: TSR-time graph of a hybrid vawt with winglets

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https://doi.org/10.70118/ujet.2025.0202.10

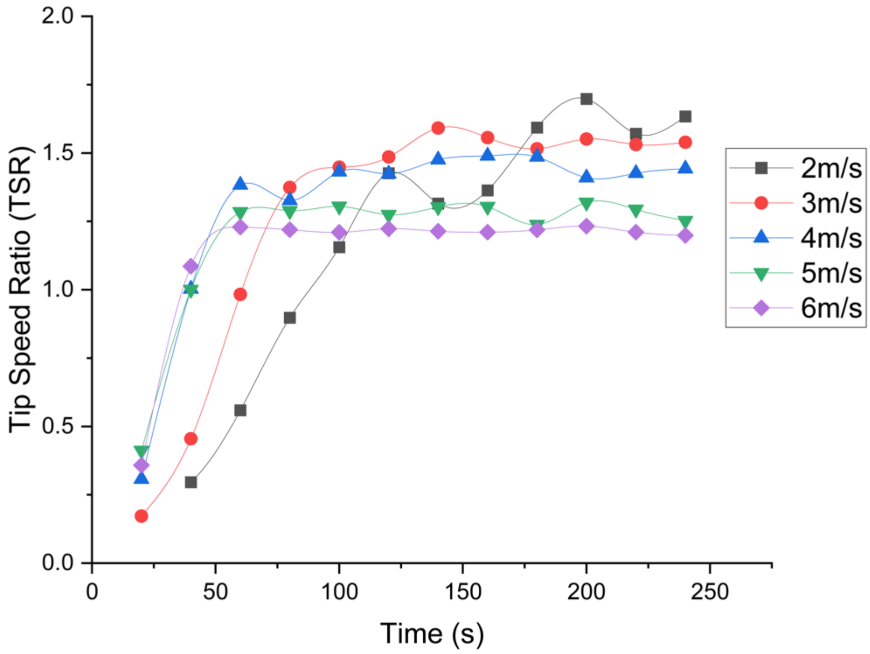

Figure 7: TSR-time graph of a hybrid vawt without winglets

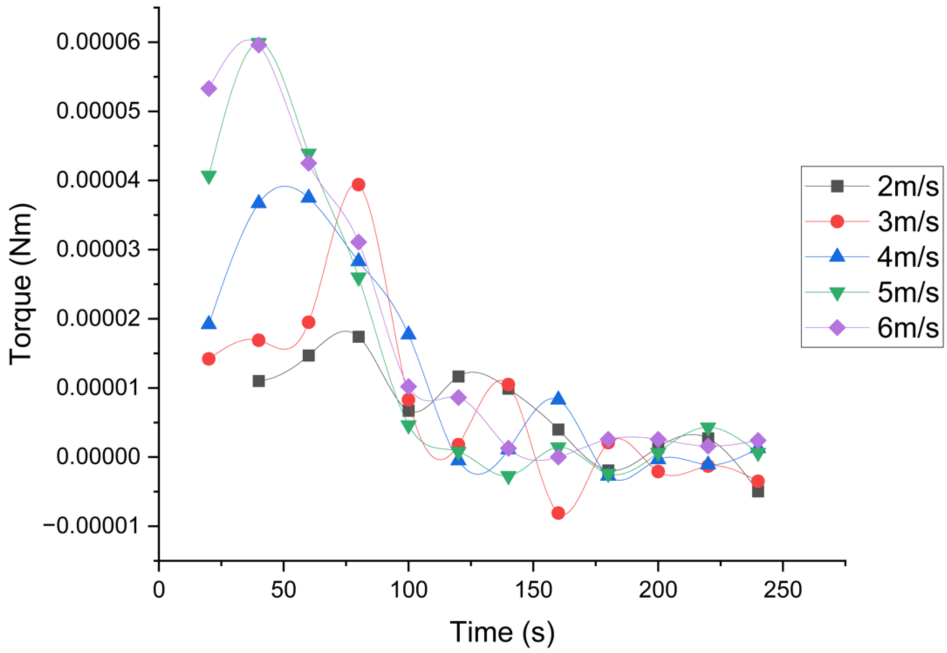

Figure 8: Torque-time graph of a hybrid vawt without winglets

Figure 8 & 9 show the relationship between Torque and time for different wind speeds. There is significant increase in torque for winglet hybrid VAWT compared to no - winglet design. The maximum torque was 6 x 10^{-5} Nm for the no-winglet design at 6 m/s wind speed, while the hybrid VAWT with winglet achieved a maximum of 14 x 10^{-5} Nm. This indicates that low wind speeds initiate turbine rotation, which is useful for regions with slow wind speeds.

Received: 01-03-2025 / Accepted: 06-05-2025 / Published: 14-06-2025

https://doi.org/10.70118/ujet.2025.0202.10

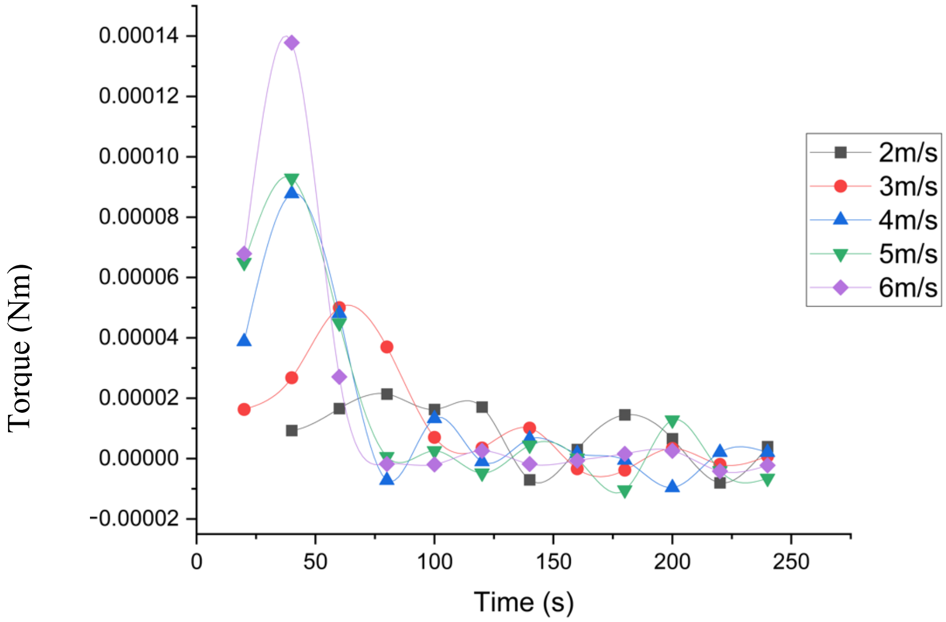

Figure 9: Torque-time graph of a hybrid vawt with winglets

Furthermore, it follows that the winglets improved the performance of the hybrid VAWT at lower wind speeds only and, as such, will be suited best for low/medium wind speed applications.

4.0 Conclusion and Recommendation

In this research, the aerodynamic performance of the hybrid VAWT with and without winglets were investigated. The HVAWT without winglets outperformed the HVAWT with winglets. These advantages includes rotational speed, increase in torque and overall efficiency. When considering the cost of design and fabricating the add-ons, non-winglet hybrid VAWT is economical, especially when the local windspeed is high. However, in an area with low - wind speed, addition of winglet can improve the self-starting ability of the wind turbine.

The study recommend further research on design optimizations using numerical simulation. Important parameters such as winglet size, shape, and the placement location should be carefully studied. Alternative tip devices such as endplates or shaklets should be explored.

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