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Research Article

Unlocking the power of the wind: Innovations in smart hybrid vertical axis wind turbines

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Abstract. As global concerns about CO_2 emissions grow, the development of green energy sources like wind power has become increasingly important. Two significant strengths of vertical-axis wind turbines relative to horizontal-axis models are their capacity to initiate rotation under minimal wind conditions and their versatility to operate effectively regardless of wind direction. This paper explores the innovation of smart hybrid vertical axis wind turbines, which combine drag and lift principles for enhanced performance with a focus on rotor switching mechanisms to optimize performance across varying wind conditions. The methodology involves experimental investigations using a small hybrid Savonius-Darrieus model, with 14cm height and 10cm diameter. The data indicates that the optimal rotor switching occurs at a tip speed ratio of 1.7. The turbine is designed to operate in hybrid mode at tip speed ratios below 1.7 and switch to single Darrieus mode at higher tip speed ratios. Performance evaluation metrics include tip speed ratio, moment coefficient, and power coefficient. Results indicate that the smart hybrid model exhibits superior performance compared to traditional hybrid and single Darrieus configurations. Through empirical studies and computational analysis, the Smart Hybrid model shows significant enhancements, with a 175% increase in initial torque compared to single Darrieus model and a 12.12% improvement in maximum power coefficient compared to traditional hybrid configurations.

Keywords: Hybrid, moment coefficient, power coefficient, rotor switching, tip speed ratio, and vertical axis wind turbine.

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1. Introduction

The global emissions of CO_2 have exhibited a consistent upward trend annually (El Kenawy *et al.*, 2023). In the year 2022, these emissions reached a significant milestone at 36.1 $GtCO_2$, representing a noteworthy 1.5% escalation from the preceding year, 2021 (Liu *et al.*, 2023). In correlation with this trend, the development of renewable energy has been continuously advancing from 2010 to 2022 (Hassan *et al.*, 2024), aiming to mitigate the environmental repercussions stemming from the escalating CO_2 emissions (Ritchie *et al.*, 2024). Among all types of renewable energy, solar and wind energy have demonstrated particularly significant increases from year to year (Amjith & Bavanish, 2022; Ang *et al.*, 2022). However, in comparison to solar energy, global wind energy capacity surpassed by 1% in the year 2022 (Rahman *et al.*, 2022). The main factor driving this trend is the ability of wind turbines to continuously produce electricity, regardless of the time of day, as long as there is adequate wind (Cullen, 2013). This consistency in power output sets wind energy apart from solar energy, which is dependent on daylight hours for electricity generation (Gangopadhyay *et al.*, 2022).

Undoubtedly, vertical axis wind turbines (VAWTs) present a more auspicious prospect within the realm of wind energy when juxtaposed with their horizontal axis counterparts (HAWTs) (Micallef & Van Bussel, 2018). This assertion is underpinned by several noteworthy attributes: VAWTs necessitate lower installation heights (Micallef & Van Bussel, 2018), facilitate facile maintenance routines (Sefidgar *et al.*, 2023) and engender diminished levels of acoustic emissions (Al-Rawajfeh & Gomaa, 2023). However, the most notable advantage lies in their capability to commence rotation even in minimal wind velocities (Fazylova *et al.*, 2023) and to operate omnidirectionally (Cazzaro *et al.*, 2023). This attribute significantly expands the potential deployment of VAWTs across various environmental settings, particularly in regions with modest or inconsistent wind patterns.

In the realm of vertical axis wind turbines, two primary classifications exist based on their operating principles: drag-type and lift-type configurations (El-Zafry *et al.*, 2019). Drag-type Vertical Axis Wind Turbines operate by harnessing the drag created by wind against their blades (Mrigua *et al.*, 2022). The Savonius rotor, a prominent example of a drag-type VAWT, typically consists of curved blades arranged in a semi-cylindrical or S-shaped configuration (MacEachern & Yıldız, 2018). As the wind flows past these blades, a net torque is produced by the pressure differential that exists between concave and convex surfaces (Matsui *et al.*, 2020), causing the rotor to rotate (Rizk &

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Nasr, 2023). This design is characterized by its simplicity and ability to harness wind energy from various wind directions (Zemamou *et al.*, 2017), making it suitable for low wind speed environments (Dewan *et al.*, 2021). Lift-type VAWTs, exemplified by the Darrieus rotor, function on the aerodynamic principle of lift produced by the asymmetrical form of the turbine blades (Ghiasi *et al.*, 2021). These turbines typically feature airfoil-shaped blades arranged in a helical or eggbeater configuration (Ahmad *et al.*, 2023). As the blades rotate, the angle of attack varies, causing lift forces to be generated perpendicular to the wind direction (Rezaeiha *et al.*, 2017), thereby propelling the rotor (Fazylova *et al.*, 2023; Rudrapal & Acharya, 2023). Lift-type VAWTs are known for their higher efficiency (Hand *et al.*, 2021) and ability to operate at higher rotational speeds (Sun *et al.*, 2016) compared to drag-type VAWTs.

Thus far, the integration of drag and lift principles in turbine design holds considerable promise for enhancing the performance of VAWTs (Tripathi *et al.*, 2022). This innovation is widely recognized in scholarly circles as hybrid VAWT. As declared in the work by Lipiao JAC et. al (Lipiao *et al.*, 2022), hybrid VAWT configurations have the potential to enhance initial torque and facilitate self-starting of the turbine. Through experimental study, they combine three Darrieus blades as the external rotor and two stages of Savonius blades as the internal rotor. The results show that the hybrid model they proposed can commence rotation at low wind speeds, specifically 2 m/s.

Subsequently, Ahmad M and Zafar MH (Ahmad & Zafar, 2023) conducted improvement through a computational study of the hybrid VAWT model, utilizing a three-bladed Darrieus configuration as both the external and internal rotors. With a tip speed ratio of 3, an efficiency peak of 0.475 was achieved, outperforming the Savonius-Darrieus hybrid model. However, the power coefficient generated at an initial tip speed ratio is roughly 0.1, which is not much different from the conventional Savonius-Darrieus hybrid.

In our earlier study (Irawan *et al.*, 2023), we found that increasing the model's rotor radius ratio is one way to improve the combined model's power coefficient at the startling tip speed ratio. The hybrid VAWT with rotor radius ratios ranging from 0.1 to 0.5 were tested, indicating that the model with a rotor radius of 0.5 exhibited the best initial torque but the lowest maximum power coefficient. A detailed analysis of the study suggests that the best-performing hybrid VAWT model is distinguished by attaining the greatest maximum power coefficient when operating at high tip speed ratios, and by having substantial starting torque at lower tip speed ratios. Hence, this research addresses these challenges by introducing the Smart Hybrid VAWT. This innovative design enhances the field of VAWTs by aiming to improve the efficiency of conventional hybrid VAWTs through the implementation of a rotor switching mechanism.

2. Methodology

2.1 Model Specifications

The research employs a sophisticated compact hybrid wind turbine model that integrates both Savonius and Darrieus designs. The detailed specifications of this innovative hybrid model are comprehensively outlined in Table 1. This design approach aims to combine the advantageous features of both Savonius and Darrieus turbines to enhance overall efficiency and performance.

Table 1
Model specifications

Configuration	Feature
Savonius	
Number of blades	2
Number of stages	2
Radius (R_S)	5 cm
Height (h_S)	14 cm
Overlap (e)	0.2
Darrieus	
Number of blades	3
Radius (R_D)	10 cm
Cord length (c)	5 cm
Height (h_D)	15.4 cm

As seen in Fig. 1, the hybrid configuration uses the Savonius for the inner rotor and the Darrieus for the outer rotor. The overlap, defined as the relative distance between two adjacent Savonius blades (Rus *et al.*, 2018) at 0.2 times their total diameter, is implemented to achieve this distance of 2cm. The Darrieus blades are positioned with an angle of attack ($\boldsymbol{\alpha}$) of 0° respect to

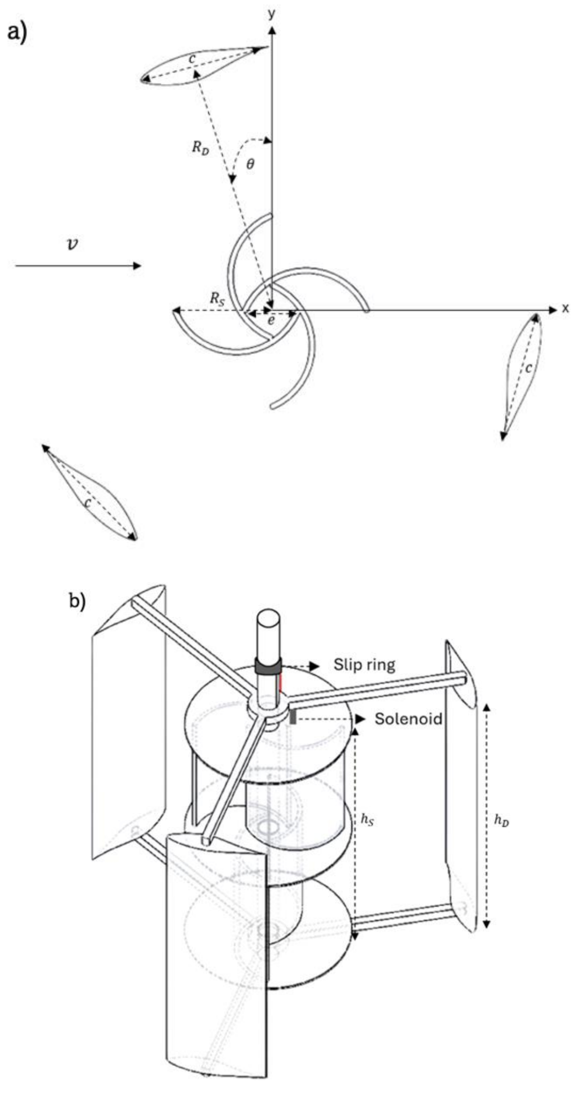

Fig. 1 2D (a) and 3D (b) views of hybrid model

the airflow, while they are incrementally angled (°) at 15° with respect to the Savonius component. The NREL S809 airfoil type Darrieus is employed due to its favorable performance characteristics at high wind speeds (Modi & Gilke, 2018).

Based on the literature review conducted, separating the rotation of the Savonius from the Darrieus when reaching high rotational speeds can enhance the efficiency of the hybrid turbine. A solenoid coil is employed for this purpose. The solenoid coil is utilized to combine and separate the rotation of the Savonius rotor from that of the Darrieus rotor. Consequently, to prevent any influence on the rotational dynamics of the main rotor, the solenoid is integrated with a slip ring mechanism. This arrangement ensures that the solenoid's operation does not impede the overall performance of the rotor system.

2.2 Experimental Arrangement

2.2.1 Model Performance Investigations

These experimental investigations are conducted within a wind tunnel featuring a cross-sectional area measuring 30x30 cm. Wind velocities are systematically varied across a range of 3-12 m/s to capture a spectrum of operating conditions. Concurrently, meticulous attention is paid to maintaining ambient conditions at a controlled temperature, achieved through the regulation of room temperature utilizing an air conditioning system to ensure the accuracy of the air density value for extracted power calculations (Jung & Schindler, 2019).

The power coefficient of the model can be analyzed using the circuit scheme depicted in Fig. 2. The circuit scheme in Fig. 2 (a) is employed at low rotational speeds. Subsequently, at higher rotational speeds, circuit scheme 2 (b) is applied. The utilization of circuit scheme 2 (b) serves the purpose of extending the measurement capabilities to encompass high tip speed ratios. This is achieved through the strategic injection of power into the model, thereby augmenting its rotational speed. The power injection is administered by providing a constant electric current (equivalent to the maximum current that the model can generate based on measurements using circuit scheme 2 (a)) while gradually increasing the voltage source until a gradual enhancement in the model's rotational speed is observed. Following this, the output current ($\boldsymbol{I_O}$) and voltage ($\boldsymbol{V_O}$) generated by the model or wind generator are measured by ammeter and voltmeter to be considered for calculating the power extracted ($\boldsymbol{P_O}$), moment coefficient ($\boldsymbol{C_M}$), and power coefficient ($\boldsymbol{C_P}$) and by the model.

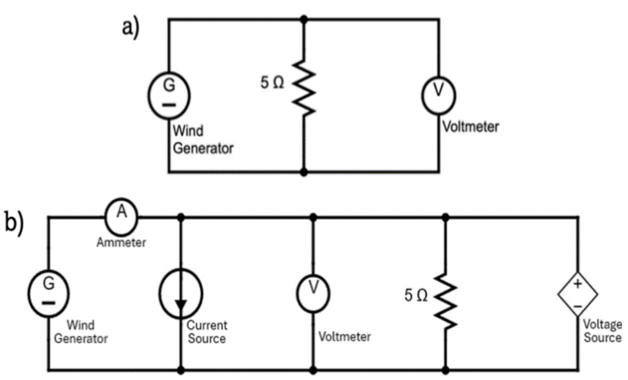

Fig. 2 Circuit scheme for low (a) and high (b) tip speed ratio

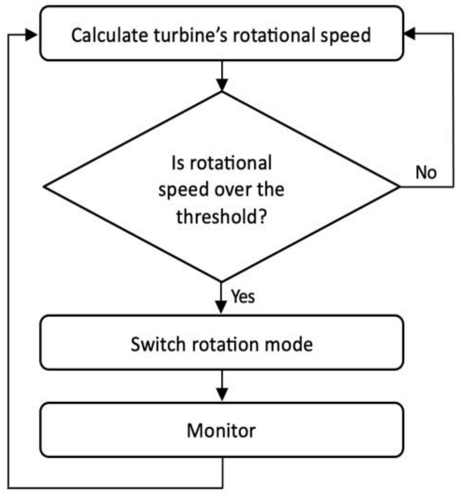

Fig. 3 Switching rotor scheme

2.2.2 Rotor Switching Design

To achieve optimal turbine performance across a range of operational conditions, a sophisticated rotor switching mechanism is employed as a smart hybrid model. This mechanism facilitates a seamless transition from the hybrid mode, characterized by the joint operation of the Savonius and Darrieus rotors, to the single Darrieus mode. This transition is guided by the operational paradigm outlined in the block diagram depicted in Fig. 3.

The turbine operation has two distinct modes based on the rotational speed condition, as follows:

- Hybrid mode: This mode is engaged when the rotational speed remains below the treshold. In this configuration, both the Savonius and Darrieus rotors collaborate to harness wind energy efficiently, leveraging the complementary characteristics of each rotor design.
- Single Darrieus mode: As the rotational speed surpasses the threshold, the turbine seamlessly transitions to the single Darrieus mode. Upon achieving high rotational speeds, the rotation of Savonius is made independent from that of Darrieus. In this mode, the operation is solely reliant on the Darrieus rotor. This mode is specifically optimized for higher rotational speeds, where the Darrieus rotor's design excels in extracting wind energy effectively.

The switching of the rotor configuration is orchestrated by precisely controlling the rotation of the Savonius rotor relative to the Darrieus. This control is achieved through a meticulously designed circuit configuration, as illustrated in the schematic depicted in Fig. 4.

The idea is to utilize a photoresistor to measure the turbine's rotational speed. The data collected is then processed by an Arduino, serving as the microcontroller. Based on this processing, the Arduino generates a response in the form of an output that either activates or deactivates the solenoid. So, this main mechanism is the utilization of a solenoid, a crucial element that makes it easier for the Savonius rotor to engage or disengage from the Darrieus rotor in accordance with operational demands. This precise control over the rotor configuration ensures that the turbine operates optimally across a wide range of wind conditions, maximizing its overall efficiency and performance.

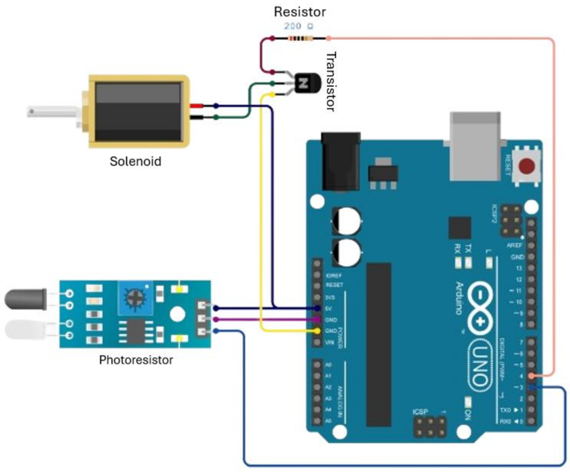

Fig. 4 Switching rotor circuit scheme

2.3 Parameters

The primary metric utilized for assessing the efficiency of the model lies in the power coefficient (C_P) (Castillo *et al.*, 2023), derived through the application of Equation 1.

$$C_P = \frac{2P_T}{\rho A v^3} \tag{1}$$

ρ is a density of air [1.225 kg/m^3], v stands for the wind velocity [m/s], and A represents the swept area of the turbine [m^2], is the result of multiplying the diameter of the rotor by its height. On the other hand, P_T, representing turbine's output power [W], is ascertained via empirical measurements conducted employing the methodology outlined in Fig. 2. However, it's imperative to acknowledge that P_T is subject to modulation by inherent loss factors intrinsic to the DC generator (Preecha & Dejvises, 2007) under consideration. Consequently, its determination necessitates recourse to Equation 2.

$$P_T = P_O + K_f\omega + K_c{I_O}^2 + K_i{V_O}^2 \tag{2}$$

P_O, I_O, and V_O denote the recorded power output, current, and voltage of the turbine, respectively. The DC generator employed exhibits specific loss factors (Lorimer & Lieu, 1999), including a friction loss coefficient (K_f) of 1x10^{-5}, a copper loss coefficient (K_c) of 4.131, and an iron loss coefficient (K_i) of 0.013.

Furthermore, the model's performance evaluation extends to the analysis of the tip speed ratio (TSR), computed utilizing Equation 3.

$$TSR = \frac{\omega R}{v} \tag{3}$$

In this context, ω symbolizes the turbine rotation in radians per second while R represents the outer radius of the turbine in meters. Finally, the model's effectiveness is further elucidated by the derivation of the moment coefficient (C_M) (Kamada *et al.*, 2008), achievable through Equation 4.

$$C_M = R \cdot \tau \tag{4}$$

$\boldsymbol{\tau}$ indicates the turbine's torque [N.m]. These four parameters will serve as benchmarks for evaluating the performance of the model.

3. Result and Discussion

3.1 Model's Original Performance

The original performance characteristics of the hybrid wind turbine model are effectively illustrated through detailed graphical representations. These graphs, as delineated in Fig. 5, showcase the variation of both the moment coefficient and the power coefficient under different operational conditions. By analyzing these graphical depictions, one can gain a comprehensive understanding of the model's efficiency and performance dynamics across a range of scenarios. The graphs are constructed based on calculations using Eq. (1) and (4). In Figure 5 (a), a detailed characteristic of the moment coefficient profiles for both hybrid and single Darrieus models is presented. Notably, the hybrid configuration demonstrates a substantial initial moment coefficient advantage over its single Darrieus counterpart, registering a remarkable 150% increase. This disparity in performance indicates the distinct aerodynamic characteristics inherent in hybrid turbine design.

Specifically, the hybrid model having a rotor radius ratio of 0.5 exhibits a notable augmentation in the initial moment coefficient. Its enhancement could be ascribed to the Its enhancement could be ascribed to the Savonius component's dominating effect in the hybrid arrangement. Conversely, a reduction in the rotor radius ratio leads to a commensurate decrease in the initial moment coefficient. This observation is in line with prior simulation findings (Irawan *et al.*, 2023), which indicated a rapid decline in moment coefficient for hybrid

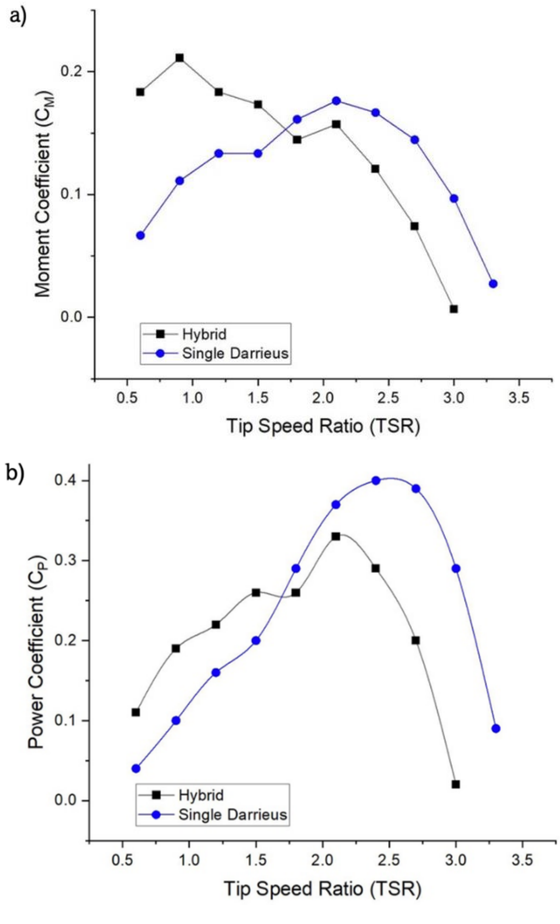

Fig. 5 Original moment (a) and power coefficients (b) of the model

models with varying rotor radius ratios post-TSR surpassing 1. Notably, the single Darrieus model continues to display a rise in moment coefficient even beyond a TSR of 2, highlighting the robustness and versatility of the single Darrieus setup under varied operational conditions.

Equation 4 shows how the moment coefficient and power coefficient of a turbine are closely connected. Through empirical observation in Fig. 5 (b), a discernible distinction emerges between the performance of single Darrieus and hybrid models. Notably, the single Darrieus model reaches a significantly higher maximum power coefficient, exceeding that of the hybrid model by 21%. This difference can be seen in the highest power coefficients that the single Darrieus configuration and the hybrid model attain, with the former reaching a maximum of 0.4 at TSR 2.4 and the latter peaking at 0.33 at TSR 2.1. The lift-based operation of the Darrieus configuration makes it particularly adept at harnessing wind energy at higher velocities. This allows the single Darrieus model to reach its maximum power coefficient at a relatively higher TSR, as observed in Fig. 5 (b). In contrast, the hybrid model, which combines elements of both Darrieus and Savonius designs, may exhibit a different performance profile due to the interaction between these distinct aerodynamic principles. However, compared to the computational fluid dynamics (CFD) research conducted by (Modi & Gilke, 2018), the NREL S809 should still be able to achieve a higher power coefficient, reaching 0.5 at a wind speed of 10 m/s.

The operational dynamics of the Darrieus turbine, predicated on lift force principles, render it particularly effective at higher wind speeds. In ideal circumstances, a single Darrieus turbine would typically reach its maximum power coefficient within the TSR range of 3-4 (Kumara *et al.*, 2017). However, the specific single Darrieus model utilized in this study, characterized by a solidity of 0.75, deviates from this ideal scenario (Aboufazeli *et al.*, 2019). The relatively high solidity introduces weight considerations that impact the turbine's performance, precluding it from attaining its maximum power coefficient within the typical TSR range of 3-4.

3.2 Rotor Switching

By combining the best features of single and hybrid Darrieus turbine designs, the rotor switching mechanism is a novel way to produce a hybridized model that optimizes the power generation and aerodynamic efficiency of vertical axis wind turbine. This method involves seamlessly blending the robust initial torque provided by the hybrid model with the high-speed operational efficiency of the single Darrieus configuration. The resultant model is distinguished by its high initial moment coefficient, which enhances startup capabilities, and its superior maximum power coefficient, which optimizes overall energy production at higher wind speeds.

A crucial component of this design approach is figuring out the exact timing to switch the rotor. It is based on a meticulous analysis of the power coefficient curves from extensive empirical data. Fig. 5 represents the energy efficiency of the hybrid and single Darrieus models across a range of operating conditions. The intersection of those curves indicates the most effective transition point where the combined benefits of both models are optimized, allowing for enhanced performance and efficiency.

The experimental results, illustrated in Fig. 5(b), are essential to our analysis. They provide a visual representation of the performance thresholds where the benefits of switching from the hybrid to the single Darrieus model are maximized. A technique for determining the rotor switching mechanism has been researched by (Hosseini & Goudarzi, 2018). He proposed the idea of switching rotors based on the moment value of the turbine. However, this approach is considered less straightforward in practice. Therefore, using the tip speed ratio as the parameter for rotor switching offers a simpler and more innovative solution.

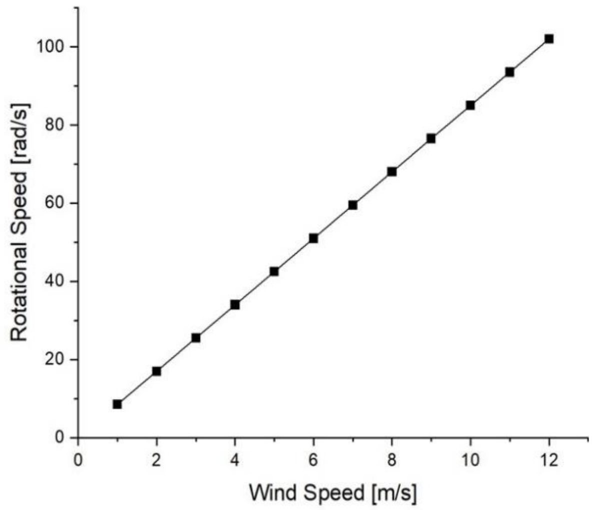

Fig. 6 Correlation between wind speed and rotational speed of the smart hybrid at a TSR of 1.7

The data in Fig. 5 indicates that the optimal rotor switching occurs at a TSR of 1.7. This TSR is identified as the point where the turbine achieves a balance between low-speed torque and high-speed power output, enabling it to operate efficiently across a broader spectrum of wind conditions. However, to simplify the process of determining the switching conditions, using rotational speed is considered easier compared to tip speed ratio. Once it is understood that rotor switching needs to be performed at a TSR of 1.7 for this Smart Hybrid model, it can be converted into rotational speed based on wind speed conditions as illustrated by the graph in Fig. 6. The graph in Fig. 6 would typically illustrate how the rotational speed varies with wind speed to maintain the switching process, providing a visual representation of the turbine's operational strategy to maximize energy extraction under different environmental conditions.

3.3 Smart Hybrid's Performance

After implementing the rotor switching, the performance of the Smart Hybrid model can be demonstrated by Fig. 7. Fig. 7 (a) displays a comparison of the moment coefficient among three models: hybrid, single Darrieus, and Smart Hybrid. Prior to reaching this pivotal TSR, the Smart Hybrid model mirrors precisely the moment coefficient values of the hybrid model. This implies that the Smart Hybrid model initially presents a compelling advantage, boasting a moment coefficient that surpasses that of the single Darrieus model by 175%. Similarly, compared to the CFD research on improving hybrid VAWTs using double Darrieus conducted by (Ahmad *et al.*, 2022), the proposed improvement of the smart hybrid Savonius-Darrieus in this study has a superior initial moment up to a TSR of 2.

However, as the turbine transitions to TSRs immediately following the detachment of the Savonius component from the primary rotor, a discernible impact on the operational dynamics emerges. At this critical point, the power coefficient value of the

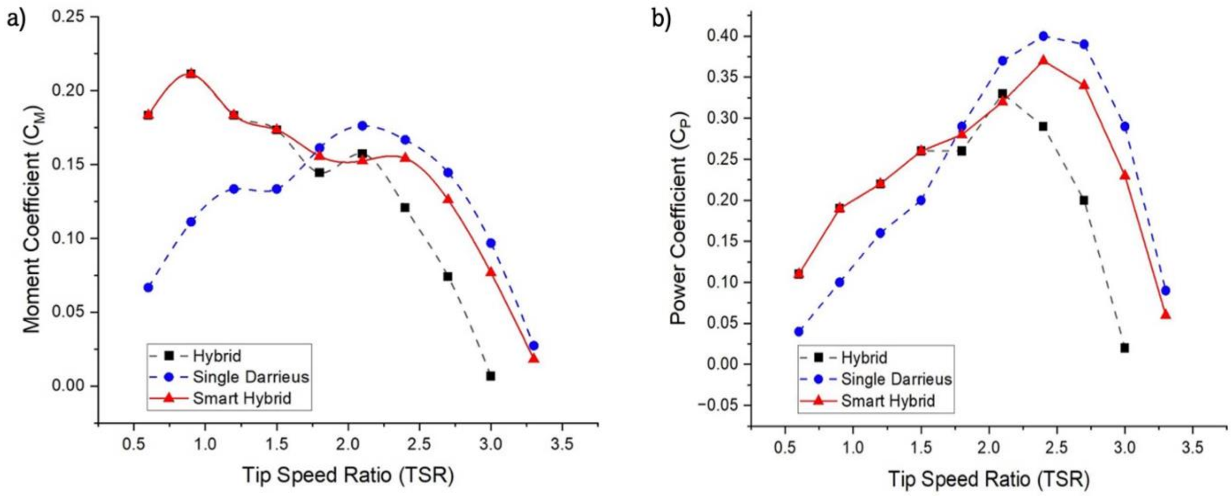

Fig. 7 Moment (a) and power (b) coefficients of the smart hybrid compared to other two models

Smart Hybrid model deviates slightly from the expected trajectory of the single Darrieus model. This shows similar characteristics to those observed in previous simulation studies (Irawan *et al.*, 2023). This deviation results in a marginal reduction of 8.11% in the maximum power coefficient generated by the Smart Hybrid model compared to the single Darrieus configuration. This phenomenon finds its roots in the independent rotation of the Savonius component positioned amidst the Darrieus blades. This can be elucidated through CFD studies, as demonstrated by the airflow contours in Fig. 8.

The Savonius component's independent rotational dynamics introduce subtle aerodynamic perturbations within the airflow region proximal to the Darrieus blades, causing minor airflow obstructions. The presence of the Savonius rotor within the Darrieus turbine configuration induces a flow disturbance that affects the downstream Darrieus blades. This disturbance is visually depicted by the intense blue shading observed in the velocity contours of Fig. 8 (a), indicating the formation of a wake region behind the Savonius rotor. Within this wake region, the airflow velocity is significantly reduced, resulting in decreased dynamic pressure and weaker aerodynamic forces acting on the Darrieus blades positioned downstream. Consequently, the Darrieus blades situated directly behind the Savonius rotor experience a diminished pressure differential between their upper and lower surfaces, leading to a reduction in lift force generation. This reduced aerodynamic lift has a negative impact on the turbine's overall reliability since it lessens the torque applied to the rotor shaft, which in turn reduces the turbine system's power generation. However, acording to research conducted by (Ali *et al.*, 2020), this weakness can be avoided by positioning the Savonius and

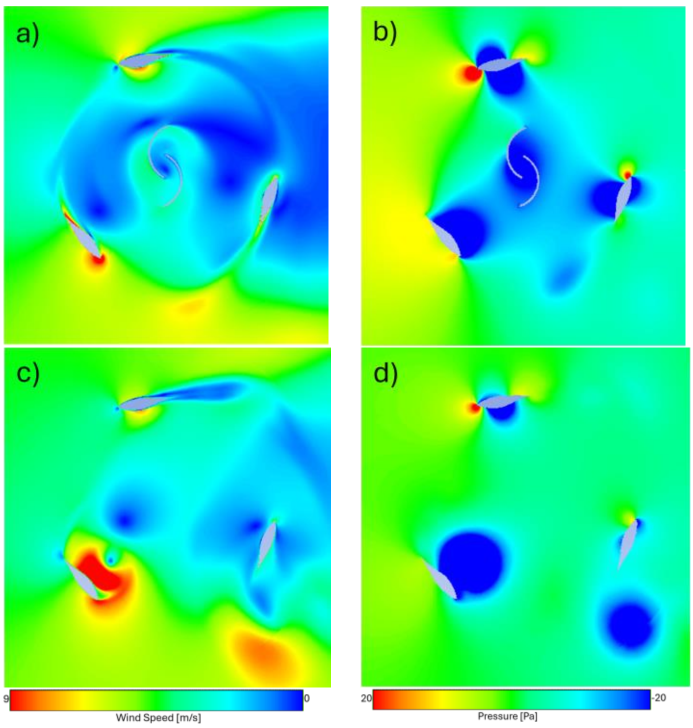

Fig. 8 Velocity (a) and pressure (b) contours of hybrid model vs. velocity (c) and pressure (b) contours of single darrieus model

Darrieus turbines in a parallel, top-and-bottom arrangement, thereby mitigating the wake effect caused by the internal rotor.

Despite this deviation, the Smart Hybrid model still maintains a notable maximum power coefficient superiority of 12.12% when juxtaposed against the hybrid model. Furthermore, the operational versatility of the Smart Hybrid model is highlighted by its extended range of operation in terms of TSR, surpassing a threshold of 3.3. This stands in stark contrast to the limited tip speed ratio capabilities of the hybrid model, which is capped at a maximum tip speed ratio of 3. This strategic switching not only improves the turbine's adaptability to varying wind speeds but also enhances its overall reliability and energy output, marking a significant advancement in VAWT technology.

4. Conclusion

In conclusion, the Smart Hybrid VAWT presents a promising solution for enhancing renewable energy generation by integrating drag and lift principles in turbine design. The implementation of a sophisticated rotor switching mechanism enables seamless transitions between hybrid and single Darrieus modes, optimizing turbine performance across varying wind conditions. Through empirical investigations and computational analyses, the Smart Hybrid model demonstrates notable improvements in both initial torque (175%) and maximum power coefficient (12.12%) compared to traditional hybrid configurations. Despite minor deviations in power coefficient at certain TSR ranges, the Smart Hybrid VAWT maintains a competitive edge over conventional hybrid models, offering enhanced reliability and energy output. However, future research should consider utilizing a stacked hybrid turbine configuration to avoid reducing the maximum power coefficient.

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