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WIND ENERGY USING SPECIALLY DESIGNED VERTICAL-AXIS TURBINES

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ABSTRACT

The paper presents a study on obtaining energy from wind power by using vertical-axis turbines (VAWTs) with a special construction. The operating principles of vertical turbines, their advantages over horizontal-axis turbines, and their energy efficiency under various wind conditions, are analyzed. The special construction represents an overall solution proposed to optimize the capture of air flow, reduce noise in operation, and increase resistance to strong wind gusts. Based on specific numerical analysis methods, the optimized parametric model of the turbine rotor is established. The obtained results indicate an increased potential for wind energy conversion, which can be adapted for both urban and rural areas, including residential and agricultural applications. This potential contributes to the development of renewable and sustainable energy sources with major implications for environmental protection by reducing dependence on fossil fuels energy production.

KEYWORDS: renewable energy, wind power, vertical axis turbines, rotor assembly

1. INTRODUCTION

The intensifying demand for electrical energy, coupled with the urgent need to mitigate greenhouse gas emissions, has accelerated the global transition towards renewable energy systems. Among available renewable resources, wind energy has emerged as one of the most mature and economically viable technologies for large-scale and distributed power generation.

Conventional wind energy conversion systems are predominantly based on horizontal-axis wind turbines (HAWTs), which achieve high aerodynamic efficiency under steady, high-speed wind regimes.

However, their performance limitations in turbulent, low-altitude, and highly variable wind conditions, which are typical for urban and semi-urban environments, have stimulated renewed interest in alternative configurations, represented particularly by vertical-axis wind turbines (VAWTs).

Vertical-axis wind turbines offer several intrinsic advantages over their horizontal counterparts, including omnidirectional wind acceptance, simplified yaw control requirements, lower center of gravity, and improved suitability for installation in complex terrains and built environments.

Furthermore, VAWTs demonstrate enhanced operational stability in turbulent flow fields and can be more readily integrated into distributed energy systems serving residential, commercial, and agricultural applications.

Despite these advantages, conventional VAWT designs often suffer from comparatively lower aerodynamic efficiency, dynamic torque fluctuations, and structural challenges under extreme wind loads. These limitations necessitate advanced design methodologies and structural innovations to improve their overall performance and economic viability.

Recent developments in computational modeling, parametric optimization, and numerical simulation techniques have enabled more precise characterization of aerodynamic behavior and structural response in wind turbine systems [1-5].

By employing computational fluid dynamics (CFD), finite element analysis (FEA), and multi-parameter optimization strategies, it

is possible to systematically refine rotor geometry and turbine architecture to enhance energy capture efficiency, reduce aero-acoustic emissions, and increase mechanical resilience to gust-induced loads [8-12].

Such approaches are particularly critical for VAWTs operating in heterogeneous wind environments where air flow separation, vortex shedding, and dynamic stall phenomena significantly influence performance.

In this context, the present study investigates a specially designed vertical-axis wind turbine featuring an integrated structural configuration. This is intended to optimize airflow capture, minimize operational noise, and improve resistance to strong wind gusts.

The research focuses on analyzing the operating principles of vertical-axis turbines, evaluating their comparative advantages relative to horizontal-axis systems, and quantifying their energy efficiency under various wind conditions [13-17].

A parametric rotor model is developed using specific numerical analysis methods to determine the optimal geometric and operational parameters that maximize power conversion performance.

The results demonstrate an increased potential for wind energy conversion through the proposed design, indicating its suitability for both urban and rural deployment scenarios.

By addressing aerodynamic efficiency, structural durability, and acoustic performance within a unified optimization framework, this work contributes to the advancement of distributed wind energy technologies.

Ultimately, the study supports the broader objective of accelerating the adoption of sustainable energy solutions and reducing reliance on fossil fuel–based power generation, thereby contributing to environmental protection and long-term energy security.

2. THEORETICAL BACKGROUND AND OPERATING PRINCIPLES OF VERTICAL-AXIS WIND TURBINES

2.1 Fundamental aerodynamic principles

Wind energy conversion is governed by the kinetic energy available in a moving air stream. The theoretical upper limit of power extraction from wind is defined by the Betz limit, which establishes that no wind turbine can capture more than 59.3% of the kinetic energy in the undisturbed wind flow [18-20].

In practical systems, the actual power coefficient Cp is lower due to aerodynamic losses, mechanical inefficiencies, and generator constraints. The power extracted by a wind turbine is expressed as [11, 18]:

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

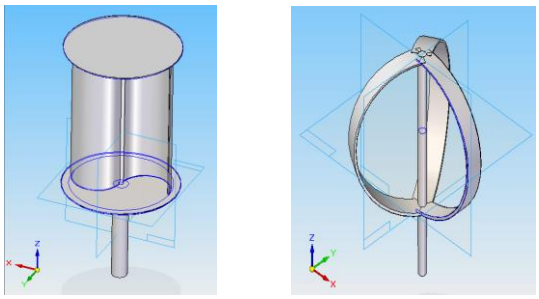
where ρ is the air density, A is the swept area, v is the free-stream wind velocity and Cp is the power coefficient. For vertical- axis wind turbines (VAWTs), the swept area is defined by the rotor height and diameter, which directly influence energy capture potential.

Unlike horizontal-axis wind turbines (HAWTs), where blades operate primarily under steady aerodynamic conditions relative to the incoming air flow, VAWT blades experience cyclic variations in angle of attack due to their rotational motion around a vertical axis. This leads to complex aerodynamic phenomena, including dynamic stall, vortex formation, and unsteady lift and drag forces. Proper understanding and control of these effects are essential for optimizing performance and ensuring structural reliability.

2.2 Classification of vertical-axis wind turbines

VAWTs are generally categorized into two main configurations:

- Lift-based turbines, such as the Darrieus-type rotor (Figure 1a), which utilize aerodynamic lift forces generated by airfoil-shaped blades;
- Drag-based turbines, such as the Savonius rotor (Figure 1b), which operate primarily on differential drag forces acting on concave and convex blade surfaces.



a) Savonius rotor b) Darrieus rotor

Fig. 1. VAWTs rotor models

The lift-based constructive configurations typically achieve higher rotational speeds and improved power coefficients, whereas drag-based systems provide superior self-starting capability and stable performance at low wind velocities. For these reasons, the hybrid

solutions combining both principles have been further investigated to enhance starting torque while maintaining high operational efficiency.

2.3 Comparative advantages over horizontal-axis turbines

Vertical-axis wind turbines exhibit several structural and operational advantages compared to horizontal-axis systems:

- Omni-directional operation, while VAWTs do not require yaw mechanisms to align with wind direction, reducing mechanical complexity;
- Lower installation height with effective operation at lower altitudes makes them suitable for urban, residential, and agricultural environments where wind flow is highly turbulent;
- Simplified maintenance as the generator and gearbox can be placed at ground level, facilitating inspection and servicing operations;
- Improved performance in turbulent air flows, as their configuration allows better adaptation to multidirectional and gusty wind conditions;
- Reduced visual and acoustic impact for properly designed VAWTs that can achieve lower tip-speed ratios, resulting in decreased noise emissions.

However, challenges remain in achieving optimal aerodynamic efficiency and mitigating cyclic mechanical loading effects, which can lead to fatigue and reduced lifespan if not properly addressed through structural optimization.

2.4 Energy efficiency under variable wind conditions

Wind regimes in urban and peri-urban areas are characterized by lower average wind velocities, high turbulence intensity, and frequent gust events. Under such conditions, turbine performance depends strongly on rotor geometry, blade profile, solidity ratio, and tip-speed ratio (TSR). The tip-speed ratio, defined as the ratio between blade tangential velocity and wind speed, is a critical parameter influencing aerodynamic efficiency and torque generation. The TSR equation formula is:

$$\lambda = \frac{\omega R}{v_w} \tag{2}$$

where

ω - is the angular speed of the rotor (rad/sec);

R - is the rotor radius;

v_w - is the wind speed.

Optimizing VAWT performance requires careful balancing between maximizing lift-to-drag ratio, ensuring adequate starting torque, minimizing dynamic stall effects, and maintaining structural stability under taste loading.

Advanced numerical modeling techniques enable accurate simulation of these interacting phenomena, providing a framework for developing optimized rotor geometries tailored to specific wind environments. [1-5].

3. ROTOR CONCEPT AND NUMERICAL MODELING METHODOLOGY

The proposed vertical-axis wind turbine model is based on a specially engineered structural configuration intended to improve aerodynamic performance, acoustic behavior, and mechanical resilience under variable wind conditions. A proper design integrates a lift-based rotor architecture with geometric modifications aimed at enhancing airflow guidance and stabilizing torque generation throughout the rotational cycle.

The rotor consists of two main components represented by Darrieus and Savonius mounted in a single assembly, with vertically oriented blades mounted on a central shaft, supported by upper and lower structural arms to ensure torsional rigidity. The blade geometry is defined through a parametric airfoil profile, optimized to increase the effective lift-to-drag ratio while mitigating dynamic stall at moderate and high tip-speed ratios.

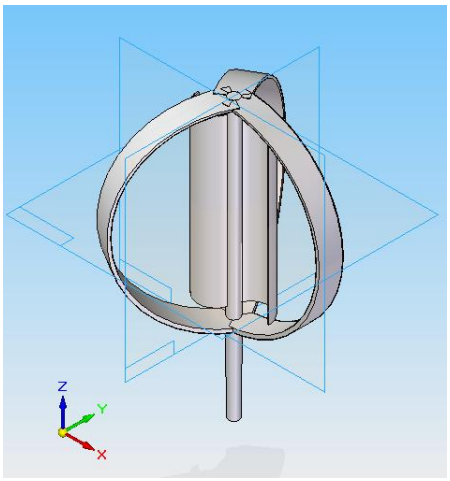


Fig. 2. VAWT hybrid rotor model

Particular attention must be given to the following structural parameters:

• Rotor diameter and height (defining the swept area);

• Blade chord length and curvature;

• Blade pitch angle;
• Number of blades and rotor solidity;
• Radial arm configuration and structural reinforcement elements.

The special construction introduces flow-guiding features that improve the effective capture of the incident air stream, especially in turbulent environments, while these features mainly contribute to aerodynamic losses reduction due to flow separation, smoother torque distribution during rotation, decreased aero-acoustic emissions, and increased structural resistance to extreme wind gusts.

The turbine's center of mass is positioned at a relatively low height, improving global stability and reducing bending moments at the foundation level. This configuration enhances operational safety and makes the system suitable for installation in residential, agricultural, and distributed generation applications.

The hybrid model geometry (Figure 2) corresponds to a hybrid blade vertical-axis wind turbine (VAWT) with three-blades enclosed by a circular support ring made so that it can obtain improved torque smoothness, reduced pulsations, and increased efficiency in turbulent wind compared with single Savonius and Darrieus rotor turbine blades.

For this specific assembly, the lift and drag forces are described and can be used to develop a numerical model simulation that provides improved performance predictions by incorporating blade correction, multi-blade interaction, dynamic azimuth discretization, and torque smoothing from the blade constructive solution.

$$F_l = \frac{1}{2}\rho v_r^2 c C_l$$
$$F_d = \frac{1}{2}\rho v_r^2 c C_d \quad (2)$$

To determine the torque acting on the vertical-axis rotor, we must focus on the tangential force component, as it is the only component of the total force that acts at a distance from the axis in order to produce rotation.

$$F_t = F_l \sin\phi - F_d \cos\phi$$
$$\phi = \tan^{-1}\left(\frac{v\cos\theta}{v\sin\theta + \omega r}\right) \quad (3)$$

Special constructive solutions represented by vertical axis wind turbine (VAWT) rotors, with Savonius or Darrieus component types, typically achieve maximum power coefficients (Cp) ranging from 0.26 to 0.42, with peak torque occurring at low-to-moderate tip speed ratios (TSR), often around 2.0 to 3.75, while performance is characterized by fluctuating torque due to rotation, with advanced designs reaching 40–43% efficiency.

Particularly, Savonius types provide high starting torque but face fluctuating torque during rotation, while the hybrid design can achieve a maximum torque of 2.05 Nm.

The relationships that describe torque, power, and power coefficient are as follows [11-13]:

$$T(\theta) = r \cdot F_t$$
$$P = \omega \cdot T$$
$$Cp = \frac{P}{\frac{1}{2}\rho A v^3} \quad (4)$$

4. NUMERICAL RESULTS AND PERFORMANCE ANALYSIS

The aerodynamic performance of the proposed three-blade vertical-axis wind turbine was evaluated through numerical simulations using an aerodynamic model based on azimuthal discretization of the rotor motion. The analysis focused on the variation of the power coefficient, torque distribution during rotation, and power output as a function of wind velocity. These simulations allow a preliminary estimation of the turbine efficiency and provide insight into the operational behavior of the proposed configuration.

The numerical results indicate that the turbine achieves its maximum aerodynamic efficiency at a tip speed ratio (TSR) of approximately 3.7–3.8, where the calculated power coefficient reaches values of about

$Cp \approx 0.47–0.48$.

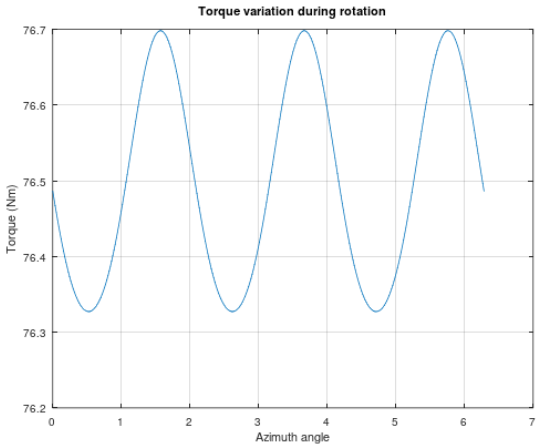
This efficiency range is close to the upper limits typically reported for optimized vertical-axis wind turbines and remains within the theoretical constraints imposed by the Betz limit. The obtained values suggest that the proposed rotor configuration can effectively convert wind energy into mechanical power while maintaining stable aerodynamic behavior.

The distribution of the aerodynamic torque as a function of the azimuthal angle was also investigated. The results show a relatively

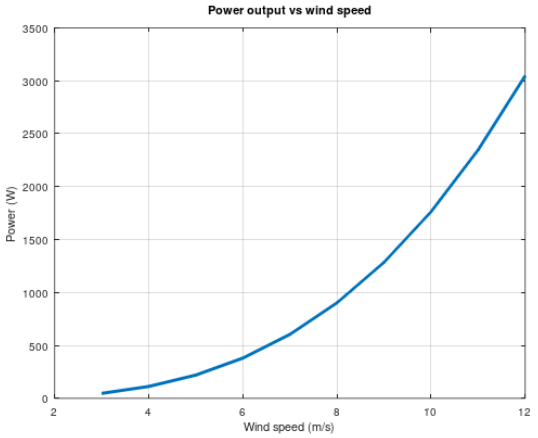
smooth variation of torque over the full rotational cycle, which indicates improved rotational stability of the rotor. The use of three-blades contributes to a more uniform torque profile, reducing oscillations that may occur in turbines with a smaller number of blades. This characteristic is beneficial for mechanical reliability and contributes to lower structural stresses during operation.

The power output of the turbine was further evaluated for wind speeds ranging between 3 m/s and 12 m/s, representing typical operating conditions for small-scale wind energy systems installed in urban or rural environments. The numerical simulations confirm the expected cubic dependence of the generated power on wind velocity, showing a significant increase in power production at higher wind speeds. These results demonstrate the capability of the turbine to operate efficiently across a broad range of wind conditions.

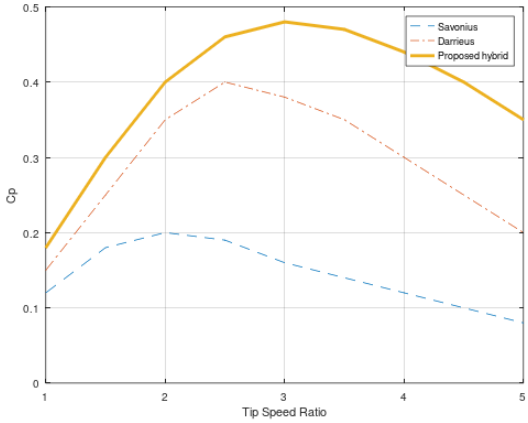
A comparative analysis with conventional vertical-axis wind turbine designs highlights the potential advantages of the proposed configuration. Classical drag-type turbines, such as Savonius rotors, typically reach power coefficients in the range of 0.18–0.22. Conventional straight-blade Darrieus turbines achieve values around 0.35–0.40. In contrast, the present model reaches efficiencies approaching 0.48. This improvement indicates that the proposed design may provide enhanced aerodynamic performance while maintaining the structural simplicity characteristic of vertical-axis wind turbines.



a) VAWT torque values function of azimuth angle



b) VAWT power based on wind speed values



c) Comparative analysis results between VAWT rotor types

Fig. 3 Numerical results for VAWT performance

Overall, the numerical investigation and results confirm that the proposed turbine configuration can achieve competitive aerodynamic performance and stable operation. The obtained results support the feasibility of the design for small-scale renewable energy applications, particularly in environments characterized by moderate and variable wind conditions.

5. CONCLUSIONS

The present study investigated the aerodynamic performance of a three-blade vertical-axis wind turbine using a numerical model. The simulations analyzed the variation of the power coefficient, torque distribution during rotor rotation, and the generated power under different operating conditions. The results show that the turbine reaches its maximum aerodynamic efficiency at a tip speed ratio of approximately 3.7–3.8, where the calculated power coefficient approaches $C_p \approx 0.47–0.48$. These values are consistent with the performance range reported for optimized

vertical-axis wind turbines and remain within the theoretical limits of wind energy conversion.

The analysis of torque variation indicates a relatively smooth rotational behavior, which contributes to improved mechanical stability and reduced dynamic loading of the turbine components. Additionally, the power output increases significantly with wind velocity, following the expected cubic relationship between wind speed and generated power.

The obtained results demonstrate that the proposed turbine configuration can achieve competitive aerodynamic performance while maintaining the structural advantages associated with vertical-axis wind turbines.

Consequently, the studied design represents a promising solution for small-scale wind energy applications in both urban and rural environments, contributing to the broader development of renewable and sustainable energy systems.

Future research will focus on extending the present numerical analysis through more advanced aerodynamic modeling and experimental validation.

In particular, the implementation of more detailed approaches, such as the double multiple streamtube (DMST) model or computational fluid dynamics (CFD) simulations, would allow a more accurate representation of the complex airflow patterns and dynamic stall effects occurring around the rotor blades.

Additional studies will also investigate the influence of key design parameters, including blade profile, chord length, rotor radius, and the number of blades, in order to further optimize the turbine performance.

The structural behavior of the turbine under variable wind conditions and gust loads will also be analyzed to evaluate mechanical stability and long-term reliability.

Furthermore, future work will include the development of a physical prototype and experimental testing under real wind conditions.

Such experimental investigations will enable the validation of the numerical results and provide valuable data for refining the aerodynamic model.

The integration of the proposed turbine into small-scale distributed energy systems, particularly for residential and agricultural applications, also represents an important direction for future research.

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