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Feasibility and Experimental Investigation about Integration of Micro Wind Turbines in Marine Systems

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Abstract— ***There is an increasing demand for the use of sustainable and low-emission energy solution which has raised the need to create an alternative onboard power source. This study explores the feasibility of integration of a micro wind-turbine into marine systems to support auxiliary and emergency power requirements. The proposed design focuses on a hybrid configuration that combines Darrieus and Savonius rotors to achieve both efficient operation and reliable self-starting capability.***

The research involves a systematic approach involving conceptual design, 3D modelling using software, computational analysis, prototype fabrication and experimental testing. Key parameters such as blade geometry, rotor dimensions and aerodynamic performances were evaluated to optimize the turbine's functionality under controlled wind conditions similar to that of marine atmosphere. The computational analysis results indicate that the vertical axis hybrid turbine performs effectively with improved starting behavior at low wind speeds and stable operation across varying conditions. The system demonstrates consistent rotational behavior and low vibration levels.

This study highlights the potential of micro-Vertical Axis Wind Turbines (VAWT) as a sustainable solution for marine energy emergency needs. By reducing dependence on conventional fuel sources and lowering emissions, the proposed system contributes to cleaner and more energy-efficient maritime operations, aligning with current sustainable development goals in engineering and renewable energy adoption.

Index Terms— ***Auxiliary Power Supply, Marine Renewable Energy, Sustainability, Vertical Axis Wind Turbines***

I. INTRODUCTION

The growing demand for sustainable and low-emission energy solutions in the maritime sector has motivated the exploration of alternative auxiliary power sources. Marine vessels operate in environments with relatively consistent wind availability, making wind energy a promising supplementary resource. This project focuses on the development of a *micro–Vertical Axis Wind Turbine (VAWT)* intended for marine applications, particularly for emergency and low-load power requirements.

Unlike Horizontal Axis Wind Turbines, VAWTs offer advantages such as omnidirectional wind acceptance, compact configuration, and easier integration into shipboard systems. The present work aims to design, numerically analyze, fabricate, and experimentally test a micro VAWT. Key design parameters such as Savonius blade thickness, total rotor diameter, turbine stability, and direction of rotation are investigated to ensure reliable performance under *controlled wind conditions.*

II. LITERATURE SURVEY

Khaled M. El-Nenaey investigated the performance characteristics of a Hybrid Vertical Axis Wind Turbine (VAWT) combining different rotor concepts to enhance overall efficiency. The study addressed the common limitations of standalone VAWT designs, particularly low starting torque and reduced performance at varying wind speeds. The authors experimentally evaluated the hybrid configuration by integrating complementary rotor types to improve self-starting capability and power output. Performance parameters such as torque coefficient, power coefficient, and rotational speed were analyzed under different wind conditions. The results demonstrated improved startup behavior and enhanced aerodynamic efficiency compared to conventional single-type VAWTs. However, the study noted limitations related to prototype scale testing and controlled experimental conditions. Future work was suggested to include large-scale validation, structural optimization, and real-world marine or urban deployment analysis to assess long-term reliability and performance stability.

Ben Bacha, H. and El Ghali, S. E. B. (2020) examined the feasibility of utilizing wind energy to meet shipboard electrical power demands through a case study conducted on a Moroccan tanker. The study addressed the growing concerns of fuel consumption, greenhouse gas emissions, and rising operational costs in the maritime sector. Using a simulation-based approach, the authors assessed the integration of onboard wind turbines to supplement auxiliary power requirements under realistic wind conditions. Key performance indicators such as power generation potential, fuel savings, and emission reduction were evaluated. The findings indicated that wind energy could partially satisfy onboard electrical loads, leading to measurable reductions in fuel usage and environmental impact, particularly in regions with favorable wind availability. However, limitations included dependency on wind variability and practical constraints related to installation space and system integration. The authors suggested future research focusing on hybrid renewable systems, economic feasibility analysis, and large-scale implementation strategies for different vessel types.

Lou W. (2023) investigated the load characteristics and extreme structural responses of a straight-bladed floating Vertical Axis Wind Turbine (VAWT) using a fully coupled aero-hydro-servo-elastic model. The study addressed the complexity of accurately predicting turbine behavior under combined wind and wave conditions, particularly during startup and transient operations. By integrating aerodynamic, hydrodynamic, and structural dynamics into a unified simulation framework, the authors evaluated load distribution and platform motion under realistic offshore scenarios. The results revealed that aerodynamic loads during startup can significantly influence extreme structural responses, sometimes exceeding wave-induced effects. This highlights the necessity of considering strong multi-physics coupling in floating turbine design. However, the study acknowledged limitations related to computational intensity and the need for experimental validation. Future research was recommended to focus on control strategies, fatigue analysis, and large-scale experimental studies to enhance reliability and structural safety.

Lemmer, F. (2020) examined the influence of semi-submersible hull geometry on blade loads of floating wind turbines subjected to combined wind and wave excitation. The study addressed the challenge of excessive structural loads caused by platform motions in offshore environments. Using numerical simulations that coupled aerodynamic and hydrodynamic interactions, the authors evaluated different hull shape configurations and their impact on pitch motion and blade stress. The findings demonstrated that optimized hull designs significantly reduce platform motion, thereby lowering blade loads and improving overall structural stability. This emphasizes the importance of platform design in floating wind energy systems. However, the research was primarily simulation-based and required further experimental validation. Future work was suggested to explore advanced hull optimization, control integration, and real-scale offshore testing to ensure long-term performance and durability.

Su, Y. (2023) investigated the aerodynamic performance enhancement of Darrieus V-shaped blades through the incorporation of trailing-edge serrations. The study addressed the issue of flow separation and turbulence, which commonly reduce efficiency in vertical axis wind turbines. Using computational fluid dynamics (CFD) analysis, the authors examined how serrated trailing edges influence lift, drag, and overall power coefficient under varying operating conditions. The results showed that serrations effectively delayed flow separation, reduced wake turbulence, and improved aerodynamic stability, leading to enhanced turbine performance. The modification was found to be simple and cost-effective compared to complex structural redesigns. However, the study relied primarily on numerical simulations and recommended experimental validation for real-world applications. Future research was suggested to optimize serration geometry and assess performance under unsteady and low-wind marine conditions.

Ahmed, Y. (2015) conducted a comparative study between conventional and helical Savonius marine current turbines using Computational Fluid Dynamics (CFD). The research addressed the need for improved torque stability and efficiency in low-speed marine flow conditions. Through detailed numerical simulations, the authors analyzed flow behavior, torque characteristics, and power coefficients for both rotor configurations. The results indicated that the helical Savonius design produced smoother torque output and reduced pulsating loads compared to the conventional model, leading to better overall performance and structural stability. However, the study was limited to numerical investigation without extensive experimental validation. The authors recommended future work involving prototype testing, optimization of blade geometry, and evaluation under real marine current conditions to enhance practical applicability.

Sorensen, D. (2012) focused on the design and experimental performance evaluation of a small wind turbine rotor intended for low wind speed applications. The study addressed the challenge of efficient energy extraction in regions with limited wind availability. The authors developed a customized rotor design emphasizing blade geometry optimization, including airfoil selection, chord distribution, and twist configuration. Extensive experimental testing was conducted to evaluate power output, rotational speed, and efficiency under controlled low-wind conditions. The findings demonstrated improved startup capability and enhanced energy capture compared to conventional small rotors. However, the study was limited to small-scale testing and specific environmental conditions. Future work was suggested to explore large-scale implementation, advanced aerodynamic optimization, and long-term field performance assessment in varying wind environments.

Ahmed Farouk Abdel Gawad proposed a new and simplified blade-pitch control mechanism for small-size horizontal-axis wind turbines, aiming to improve operational safety and performance under varying wind conditions. The study addressed the complexity and high cost associated with conventional electronic or hydraulic pitch control systems. The author developed a mechanical centrifugal-governor-based mechanism that automatically adjusts blade pitch according to rotational speed, ensuring overspeed protection and efficiency optimization. Experimental evaluation demonstrated reliable pitch variation without requiring complex sensors or control units. The mechanism was found

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to be cost-effective, compact, and suitable for small-scale applications. However, the study acknowledged limitations regarding scalability and long-term durability under harsh environmental conditions. Future research was suggested to focus on structural refinement, fatigue analysis, and adaptation of the mechanism for larger wind turbine systems.

Yogesh Kumar, Sukanta Roga, and Nikhil Kishor Wanmali conducted an experimental investigation on a hybrid Vertical Axis Wind Turbine (VAWT) with a semi-cylindrical attachment added to the trailing edge. The study addressed the need to enhance aerodynamic performance and self-starting capability in hybrid VAWT configurations. By fabricating a prototype and testing it under controlled wind conditions, the authors evaluated parameters such as rotational speed, torque, and power coefficient. The semi-cylindrical attachment was introduced to modify flow behavior and improve lift generation while reducing adverse drag effects. Experimental results indicated noticeable improvement in power output and smoother operational characteristics compared to the conventional hybrid configuration. However, the analysis was limited to laboratory-scale testing and specific geometric dimensions. The authors suggested future work involving optimization of attachment size, numerical validation through CFD, and testing under real atmospheric wind conditions for broader applicability.

III. TURBINE DESIGN CONFIGURATION

The proposed design consists of a Hybrid Vertical Axis Wind Turbine combining a lift-based Darrieus blades rotor and Drag based Savonius rotor to enhance self-starting capability and aerodynamic feasibility under low and variable wind conditions.

This system consists of the following concept and parameters:

1) Hybrid Rotor:

The Darrieus rotor is designed to maximize aerodynamic lift and achieve higher power coefficients at moderate wind speeds. However, due to its poor self-starting characteristics, a Savonius rotor is integrated concentrically to provide high starting torque. The hybrid configuration ensures smooth startup and stable rotational behavior, particularly suitable for marine wind environments

2) Blade geometry and Parameters

The turbine design consists of variable parameters that aids in performance improvement.

- *Blade span*: Optimized to improve swept area and energy capture
- *Blade chord length*: Selected based on aerodynamic performance and structural strength
- *Number of blades*: Configured to balance power coefficient C_P and structural stability.

Darrieus blades airfoil profile = NACA0018

Savonius rotor uses semi-cylindrical profiles to ensure consistent drag generation.

3) Structural configuration

The turbine consists of a concentric hybrid configuration combining a central Savonius rotor and outer straight Darrieus blades. This arrangement improves self-starting capability while maintaining higher aerodynamic efficiency during steady operation.

3.1 Savonius rotor assembly

The central rotating unit consists of a vertical shaft mounted concentrically through upper and lower support plates. A semi-cylindrical Savonius rotor is integrated at the centre to provide high starting torque under low wind speeds. The rotor is enclosed between two circular end plates, which enhance pressure differential and improve aerodynamic efficiency while maintaining structural rigidity.

3.2 Outer darrieus blades

Straight vertical Darrieus blades are positioned symmetrically around the central shaft. These lift-based blades increase rotational speed and improve the power coefficient once the turbine reaches operational velocity.

3.3 Shaft and bearing system

A solid central shaft transmits rotational motion from the rotor to the output system. The shaft is supported at both ends by bearings mounted on the structural frame, ensuring proper alignment and minimizing friction losses. The dual-support arrangement prevents shaft deflection under aerodynamic loading.

3.4 Support frame

The support frame consists of solid central shaft that hold the bearings in alignment and transmits rotational motion from the rotor to the output system, ensuring proper alignment and minimizing friction losses. The dual-support arrangement prevents shaft deflection under aerodynamic loading.

3.5 Marine integration

The compact and symmetric structure allows omnidirectional wind acceptance and stable operation in fluctuating marine wind conditions. The configuration is suitable for deck-mounted or floating auxiliary power applications.

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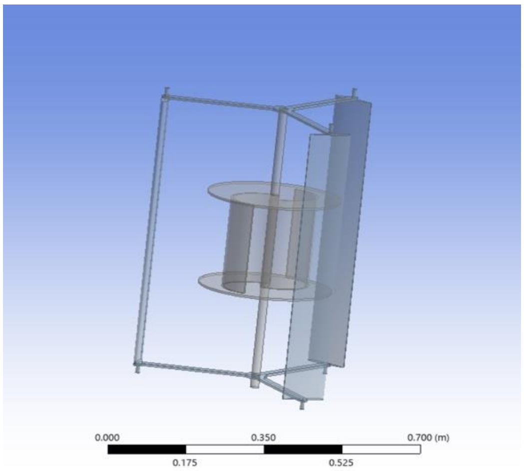

Fig. 1. Geometry design of Hybrid Vertical Axis Wind Turbine

IV. METHODOLOGY

This section describes the systematic procedure adopted for the design, numerical analysis, fabrication, and experimental evaluation of the proposed hybrid Vertical Axis Wind Turbine (VAWT). It outlines the geometric modelling process, parametric optimization strategy, computational fluid dynamics (CFD) setup, prototype development, and wind tunnel testing methods used to assess aerodynamic performance and structural stability under marine wind conditions.

A. Design modelling

The hybrid VAWT geometry was first developed using 3D CAD modelling software. The model included a central Savonius rotor and outer straight Darrieus blades connected through link arms. Design parameters such as blade span, chord length, rotor diameter, and blade angle were defined based on low-wind marine conditions.

B. Parametric optimization

Key geometric parameters were varied to study performance improvement. These included blade height, Darrieus blade inclination angle, and number of blades. The objective was to enhance start-up torque, improve power coefficient, and ensure structural stability.

C. Computational fluid dynamics analysis

The aerodynamic performance of the turbine was evaluated using CFD simulations.

Domain: A 2D/3D rotating domain was created around the rotor region.

Boundary conditions: Inlet wind velocity and pressure outlet conditions. A suitable turbulence model was selected to capture unsteady flow behavior.

Meshing: A refined mesh was generated near blade surfaces to capture boundary layer effects accurately. A rotating sliding mesh or moving reference frame approach was used for transient analysis.

Solver Setup: Time-step independence and mesh independence studies were conducted to ensure solution accuracy.

Torque, pressure distribution, and velocity contours were analyzed to compute the power coefficient (Cp) and torque coefficient (Ct).

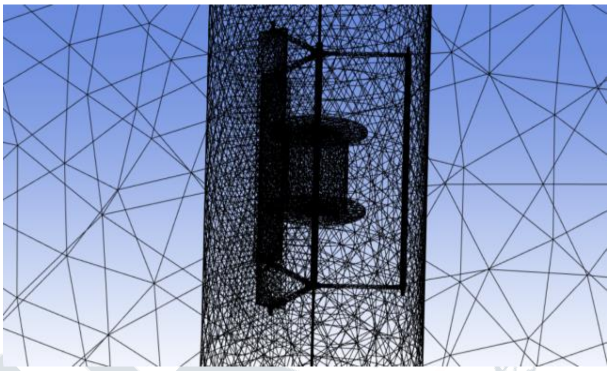

Fig. 2. Model meshing

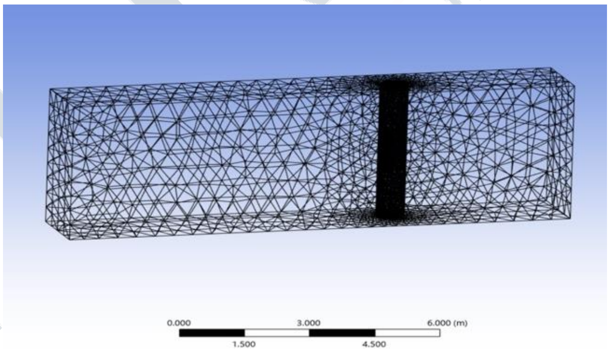

Fig. 3. Domain meshing

D. D. Prototype Fabrication

Based on optimized design parameters, a scaled prototype was fabricated using lightweight structural materials. The Savonius rotor, Darrieus blades, shaft, and support structure were assembled to replicate the numerical model.

E. Experimental Testing

Wind tunnel experiments were conducted at controlled wind speeds. Rotational speed was measured using a tachometer, and torque output was calculated to determine experimental power coefficient. Results were compared with CFD predictions to validate numerical accuracy

F. Performance Evaluation

The performance of the hybrid VAWT was evaluated through both CFD simulations and wind tunnel experiments. Theoretical torque and power coefficients were obtained from numerical analysis. Experimental RPM measurements were used to calculate practical power output. A comparison between theoretical and practical results was performed to assess model accuracy. Minor deviations were observed due

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to mechanical and frictional losses. The close agreement validated the numerical approach and overall turbine design.

V. RESULTS AND DISCUSSION

The performance of the proposed hybrid VAWT is evaluated through detailed analysis based on its aerodynamic torque and power characteristics derived from Computational Fluid Dynamics analysis.

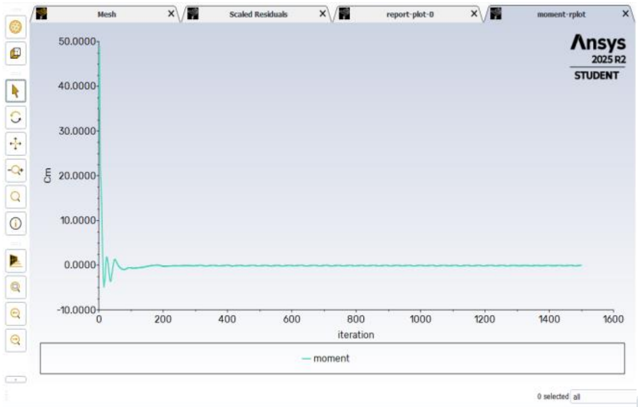

Fig. 4. Moment (torque) plot

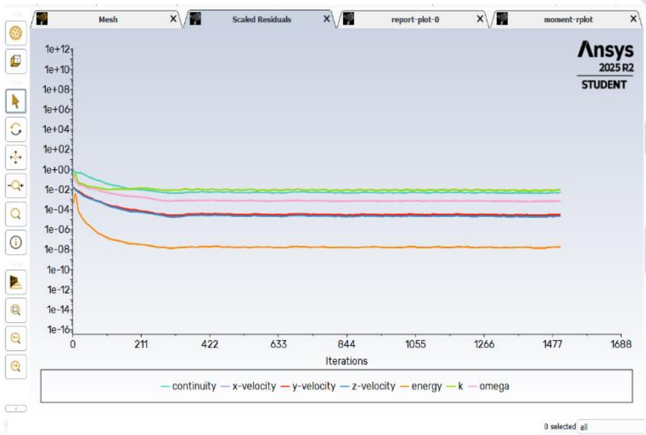

Fig. 5. Scaled Residuals

5.1 CFD Convergence and Solution Stability

The accuracy and reliability of the CFD simulation were verified through residual and moment convergence analysis. The scaled residuals demonstrated a rapid decrease during the initial iterations, followed by gradual stabilization. The velocity residuals reduced to the order of 10^{-5}, while the energy residuals reached approximately 10^{-8}, indicating a well resolved flow field, The continuity and turbulence factors stabilized within acceptable limits for rotating flow simulations.

In addition to residual convergence, the moment (torque) history was monitored. The moment plot showed an initial transient fluctuation followed by a steady and nearly constant value after sufficient iterations. This confirms that the aerodynamic forces acting on the turbine blades have stabilized, and the solution has reached a converged state. that the numerical results obtained are both *stable* and *physically reliable*, forming a strong foundation for further performance evaluation.

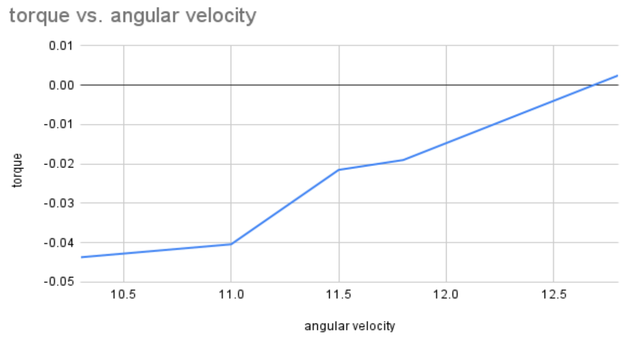

Fig. 6. Angular velocity (w) vs Torque (T)

5.2 Torque – Angular Velocity Characteristics

The variation of aerodynamic torque with angular velocity provides critical insight into the turbine's behavior. The results indicate that the turbine generates higher torque at lower angular velocities, with values reaching approximately **0.043-0.044. N-m** around **10-10.3 rad/s**.

As the angular velocity increases, the torque decreases smoothly and continuously, reaching approximately **0.0147 N-m at 12 rad/s**. This trend reflects the expected behavior of a drag-based Savonius turbine, where the effective drag difference between the advancing and returning blades diminishes at higher rotational speeds.

By extrapolating the torque curve, the torque approaches zero at approximately **12.6-12.7 rad/s**, which represents the free running bracketed no-load angular velocity of the turbine. At this point, the aerodynamic driving forces are balanced by opposing forces, and the rotor reaches stable equilibrium condition.

The smooth and consistent nature of the torque curve confirms that the turbine exhibits predictable aerodynamic behavior and that the CFD model accurately captures the underlying physics.

5.3 Power Output Analysis

The power generated by the turbine was calculated using the relation:

$$P = T\,\omega \text{ (Watts)}$$

The results indicate that the turbine achieves a maximum power output of approximately 0.45W at an angular velocity of 10.3 rad/s. This demonstrates that the turbine is capable of effectively converting wind energy into mechanical power within its operating range.

As the angular velocity increases beyond this point, the reduction and torque lead to a corresponding decrease in power output. Angular velocity approaching the free running speed (~12.6 rad/s), the torque approaches zero and consequently, the power output also becomes negligible.

The presence of a well -defined peak in the power curve confirms the existence of an optimal operating condition which is essential for practical energy extraction.

5.4 Efficiency and Energy Extraction

The efficiency of the turbine can be inferred from its ability to generate power across the range of angular velocity. The result clearly indicate that the turbine operates most effectively within the range of 10-11 rad/s, where the product of torque and angular velocity (power) is maximized.

At lower angular velocities, the turbine benefits from a strong drag differential between the concave and convex blade surfaces resulting in higher torque generation. As the rotational speed increases, the relative wind velocity acting on the blade decreases, leading to reduced aerodynamic effectiveness.

Despite this, the turbine maintains a consistent and stable performance profile, demonstrating its capability to extract energy efficiently with the defined operating window. This behavior is characteristic of Savonius turbine and highlights their suitability for low- speed wind environments**.**

VI. CONCLUSION

The results obtained from the CFD analysis confirmed that the proposed hybrid Savonius- Darrieus turbine design is *functionally successful and aerodynamically sound.*

The turbine demonstrates:

1. Strong self-starting capability, as indicated by significant torque at low angular velocity
2. A clear and well-defined maximum power point, confirming effective energy conversion
3. Stable and predictable aerodynamic behavior, validated through convergence and smooth performance and strengths
4. A physically consistent free running speed, indicating accurate modelling of real-world turbine dynamics.

The ability of the turbine to generate measurable power and maintain stable operations under the given conditions highlights its effectiveness as a small-scale wind energy harvesting system.

Overall, the prototype can be considered a successful implementation of a hybrid VAWT, particularly for applications such as emergency power support at low wind speed environments, where reliability and simplicity are of primary importance.

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