Advancements in Low-Speed Vertical Axis Wind Turbine Design: A Review

[1]Sardar Karanjeet Singh, [2]Prof. Pankaj Badgaiyan, [3]Prof. Dheeraj Jain

[1]Sardar Karanjeet Singh, M. Tech Scholar, Department of Energy Technology, Truba Institute of Engineering & Information Technology, Bhopal, MP, India.

[2]Prof. Pankaj Badgaiyan, Assistant Professor, Department of Energy Technology, Truba Institute of Engineering & Information Technology, Bhopal, MP, India.

[3]Prof. Dheeraj Jain, Assistant Professor, Department of Energy Technology, Truba Institute of Engineering & Information Technology, Bhopal, MP, India.

Email [1] karanjeetsingh5550@gmail.com, [2]pankajbadgaiyan33@gmail.com

* Corresponding Author: Sardar Karanjeet Singh

Abstract: *This in-depth analysis explores the most recent developments in Low-Speed Vertical Axis Wind Turbine (VAWT) design, showing the revolutionary potential of these turbines for the wind energy industry. These developments are positioned to increase the accessibility of clean and sustainable wind power by concentrating on utilizing wind resources in areas with lower wind speeds. The assessment looks at significant advancements in the fields of aerodynamics, materials, control systems, noise reduction, grid integration, scalability, environmental considerations, and economic viability. This review illuminates the low-speed VAWTs' bright future as an essential element of the renewable energy landscape by examining these developments.*

Keywords: *Low-Speed Vertical Axis Wind Turbine (VAWT), Design Transformative potential, Wind energy, Wind resources, Lower wind speeds, Clean energy*

1. INTRODUCTION

Several developing countries such as India and China have made significant efforts in adapting wind energy. Denmark, leading the wind industry, is the first country to be entirely powered by wind energy. By November 2013, Denmark even exported surplus power to neighbouring countries. Though the wind industry has witnessed rapid growth from 1996–2012, the history of the windmill dates back to the 7th century. Windmills in Persia (Iran) date back to 200 BC, with six to twelve sails made of cloths. These VAWTs are mainly used to pump water and to grind grains. Later in the 18th century, the first VAWT to generate electricity was created by James Blyoth, though the HAWT of Dutch windmill designs did exist in that period. It was in 1900, Finnish engineer Savonius created S-shaped blades called the Savonius turbine, which operates by the drag force. Innovative turbines are continuing to emerge to address the shortcomings of the original Darrieus design [1,2]. Because air pressure is not evenly distributed across the surface of the Earth, wind results. Air molecules travel from high-pressure places to low-pressure areas as a result of the pressure differential. With the exception of where it is directly applied at the equator, the Coriolis effect affects air flow. Normal classification of winds is based on the wind's strength and direction of origin. High-speed wind bursts that last only a short while are referred to as gusts, whereas squalls are longer-lasting, stronger winds. Depending on the strength and accompanying weather conditions, there are a number of names for winds that last for longer periods of time, such as breeze, gale, storm, and hurricane. For a variety of purposes, such as weather forecasting, it is essential to comprehend the mechanics and characteristics of wind.

The energy business is experiencing unprecedented profound changes as a result of the economic development of society and the advancement of science and technology. The operations and planning of power systems are becoming increasingly complicated as new types of energy sources become available [3]. In response to the global energy and environmental crisis, governments all over the world have stated that they want to establish a system that uses a large amount of renewable energy [4]. As a result of the revolution in power systems, power system planning studies face new challenges. Increased penetration of renewable energy in power systems, in particular, has resulted in significant uncertainty and fluctuation in power systems [5].

Electricity generated by wind energy differs significantly from that generated by traditional sources. The main distinction is that wind power is uncertain and intermittent [6]. The operation of the power system is made more uncertain by intermittent renewable energy sources. New energy production's growing effect in the power system puts new demands on planning and operation.

Wind energy and other new energy products now play a significant role in the modern power system. Despite the fact that the new energy power generation sector is rapidly expanding, it is difficult to address the issue of new energy power generation planning in the short term due to lack of planning, unstable development, and inadequate associated legislation. Therefore, it is critical to accurately evaluate new energy production efficiency, account for the rational allocation of new energy and conventional energy, increase unified planning and operation scheduling, and promote the industry's overall harmonious growth.

2. HISTORY OF VAWT

Beginning with the earliest of times, vertical axis wind turbines have been created. According to others, investment considerations, not technical advantages, account for why HAWTs are more widely used in commercial settings. A VAWT does not require a yaw mechanism because it is omnidirectional, which is one of the key advantages of employing VAWTs rather than HAWTs. Installing and maintaining the generator are made easier because it may be positioned at ground level. Additionally, compared to a HAWT, a VAWT should generate less acoustic noise. The "Darrieus wind turbine," as it was referred to by Darrieus in 1931, is the most popular VAWT. The Darrieus turbine was the subject of research in numerous nations in the 1970s and 1980s. Darrieus turbines were installed in commercial wind farms. The Darrieus turbine's disadvantages include the difficulty in manufacturing the blades and the fact that it is typically located very near to the ground, where wind speeds are lower and wind shear could lead to structural issues. Common names for the straight-bladed vertical axis wind turbine include "H-rotor," "straight-bladed Darrieus rotor," and "Giromill." The H-rotor's straight blades are typically fixed to the tower by one or more struts, whereas the Darrieus turbine's curved blades are fixed to the top and bottom of the tower. In contrast to a Darrieus turbine, the H-rotor can be mounted on a higher tower and is often farther from the ground. Although the H-rotor's bending moments on the blades are greater than those of the Darrieus rotor, it performs more aerodynamically well [7]. The straight blades of the H-rotor also result in a simpler structure, which lowers the cost and facilitates production.

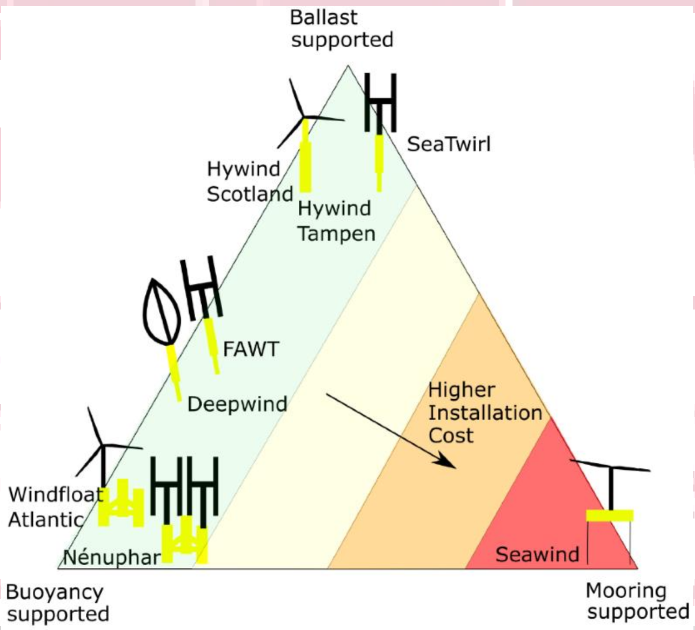

Fig. 1 Comparing Offshore VAWT and HAWT Concepts: A Stability Triangle of Foundation Types (Source: Arredondo-Galeana and Brennan [8])

Vertical axis wind turbines (VAWTs) and horizontal axis wind turbines (HAWTs) are two distinct concepts that have received a lot of interest in the offshore wind energy sector. With a focus on their distinctive qualities, benefits, and difficulties, this comparative analysis explores the key elements of various offshore wind turbine ideas.

Vertical rotor axis wind turbines (VAWTs):

VAWTs are distinguished by their ability to capture wind from any direction without having to follow the wind's course. Because of their innate omnidirectionality, VAWTs are excellent for regions with varying wind directions. Furthermore, VAWTs sometimes have more straightforward mechanical designs, which can lower maintenance expenses. They may, however, need higher initial wind speeds to generate power efficiently because they typically have lower energy conversion efficiencies than HAWTs.

Wind turbines with blades that revolve around a horizontal axis are known as horizontal axis wind turbines (HAWTs), and they are a familiar and well-liked sight in the wind energy landscape. These turbines are renowned for their outstanding energy conversion efficiency, making them a top pick for many offshore wind farms. Comparing comparable sized Vertical Axis Wind Turbines (VAWTs) to HAWTs, which are more versatile, the VAWTs are less effective in capturing wind energy throughout a wider range of wind speeds. They are more attractive for large-scale energy generation since they can produce more electricity. The need for tracking devices for HAWTs to align with the wind's direction adds complexity and expense to their overall design and maintenance, it is crucial to mention. Despite this drawback, their superior efficiency and power output make HAWTs a prominent player in offshore wind energy solutions.

The differences between horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs) are significant for a number of reasons. First, the design of HAWTs generally results in higher energy conversion efficiency. HAWTs are more suitable for regions with regular wind patterns, while VAWTs excel at adaptability to sites with variable wind directions. Furthermore, VAWTs frequently have more simple mechanical architectures, which can result in less frequent maintenance. The two types of turbines' construction and maintenance costs could differ from one another depending on the materials, size, and location. While HAWTs are known to begin power generation at lower wind speeds, giving them an edge in terms of starting wind conditions, VAWTs are considered to be more compact, making them suited for limited-space situations like urban surroundings. The importance of these factors is crucial in determining the most suitable choice for specific offshore wind energy projects.

Ultimately, the choice between VAWTs and HAWTs for offshore wind energy projects hinges on specific project requirements, environmental conditions, and economic considerations. This comparative assessment sheds light on the unique attributes of each concept, aiding in informed decision-making for offshore wind energy ventures.

3. EMERGING TRENDS – RELATED WORK

While traditional horizontal-axis wind turbines (HAWT) account for the majority of wind energy production today, their wake effects and noise requirements need huge rural regions. A portable, urban-friendly alternative has arisen in the form of vertical-axis wind turbines (VAWT). Lette, M., et al. [9] uses physical investigations and cost-effective small-scale prototyping to optimize twin-blade VAWTs. The authors used surrogate-assisted methodologies that effectively explore the design space utilizing anticipated means and uncertainties despite a constrained assessment budget and a multi-objective goal of maximizing rotational speed while decreasing mass. Results exhibit competitive, counterintuitive ideas, demonstrating the approach's potential for real-world design optimization with ramifications beyond VAWTs.

According to Ndaru Adyono et al. [10], the use of wind energy as a renewable resource has potential in Indonesia. It depends on the turbine's design whether this potential can be utilized. Residential areas characterized by weak and inconsistent winds are a good fit for Savonius vertical-axis wind turbines. Insights from analytical solutions can be used to optimize the horizontal and vertical sections of the turbine's structural design. The horizontal section's blade curvature and overlap ratio have a big impact on how well the turbine performs. According to the body of existing research, a two-blade turbine's ideal overlap ratio is 0.15. Turbine performance is improved by using semi-circular blades. The Savonius wind turbine design is theoretically appropriate for residential settings since narrowing the blades in the vertical part lowers the initial torque.

In order to harness renewable wind energy for the production of electricity, Ali, et al. [11] successfully constructed and tested a compact vertical-axis wind turbine (VAWT) that is mounted on building rooftops. Construction of the VAWT was specifically adapted to the region's unique wind patterns in Tabuk, Saudi Arabia, providing a long-term answer for meeting the region's energy needs and producing clean electricity. The VAWT's effectiveness was tested experimentally in a variety of wind conditions, and the results showed that it can produce at least 3 mw of power at 3 m/s and achieve the rated power at 9 m/s. The highest power coefficient ever observed was roughly 0.45 at a tip speed ratio of about 1.94. The turbine's resistance to shear stress and pressure was confirmed by computational fluid dynamics (CFD) simulations, with results that were remarkably consistent with those of the experiments. The robustness of the VAWT structure was confirmed, ensuring reliable performance even at high wind speeds.

under their study, Unsakul et al. [12] investigated the effects of design considerations on Vertical Axis Wind Turbines (VAWTs) under Thailand's low wind speed conditions. They examined elements like the type of wind turbine, the number of blades, the materials, height-to-radius ratios, and design modifications. They used Computational Fluid Dynamics (CFD) software to run computational studies on various VAWT models in a fake wind tunnel at various wind speeds. According to the kind of turbine, the number of blades, and the height-to-radius ratio, the study's performance curves for each VAWT demonstrated that materials had an effect on operating speeds as well as mechanical performance. With actual data supporting the CFD findings, the research aided in the creation of an optimized VAWT prototype for low-speed winds.

This strategy provides a useful instrument for enhancing VAWT design using computer simulations prior to physical construction.

4. CURRENT CHALLENGES

Expanding the use of wind energy, especially in areas with lower wind speeds, is very likely because to improvements in low-speed vertical axis wind turbine (VAWT) design. To fully utilize the promise of this technology, a number of critical obstacles need to be overcome:

Efficiency Improvement: The main difficulty facing low-speed VAWTs is improving their efficiency. These turbines frequently operate at lower wind speeds, which may restrict their capacity to capture energy. To enhance power generation in these circumstances, design advances and aerodynamic advancements are required.

Low-speed wind situations are frequently characterized by unpredictable and changeable wind profiles. Consistent energy production depends on the development of adaptive control techniques that enable VAWTs to quickly react to changing wind directions and speeds.

Structural Integrity: Low-speed VAWTs require strong and dependable structures to withstand mechanical stress and wind loading, particularly in turbulence. A significant problem is ensuring the structural integrity of these turbines over the long period.

Noise reduction: VAWT noise can be an issue, particularly in residential areas. Designing quieter turbines while maintaining their efficiency is a challenge that needs attention.

In order to overcome these obstacles, engineers, researchers, and industry stakeholders must continue to conduct study, innovate, and work together. To fully utilize low-speed VAWTs and spread the usage of wind energy throughout a wider range of geographic regions, these obstacles must be removed.

It's an exciting development in the field of wind energy because Low-Speed Vertical Axis Wind Turbines (VAWTs) design is continuing to advance. By greatly increasing the potential for wind energy production, these customized VAWTs are designed to efficiently capture wind resources in areas with relatively low wind speeds. This field is progressing thanks to a few crucial developments:

Improvements in aerodynamics Progress in low-speed VAWT design has been primarily driven by inventive blade arrangements and enhanced aerodynamic profiles. Optimizing blade forms and profiles is a major focus of research to increase energy capture effectiveness at lower wind speeds.

future-oriented materials In order to increase the reliability and robustness of VAWTs, cutting-edge materials are being used in their construction.

Reduced maintenance requirements and longer turbine lifespans are both a result of the use of lightweight yet durable materials. Smart Control Systems: Cutting-edge control technologies are being created to enable low-speed VAWTs to dynamically adjust to varying wind conditions. This entails using adaptive rotor mechanisms and variable pitch control to optimize energy absorption. Operating at a lower noise level: Noise emissions from wind turbines have sparked controversy, particularly in residential areas. To make low-speed VAWTs more environmentally benign and socially acceptable, researchers are actively developing noise-reduction solutions. One of the main goals is the smooth integration of low-speed VAWTs into the electrical system. A reliable power supply and grid resilience are being ensured by the development of grid-compatible control algorithms and energy storage systems.

Scaling for Broad Use: Although several low-speed VAWT The problem is to scale up these ideas for commercial applications even though many low-speed VAWT systems are still in the experimental or prototype stages. On a broader scale, the goal is to retain efficacy and cost-efficiency.

Environmental Concerns: Low-speed VAWT environmental effect evaluation and mitigation, particularly in environmentally sensitive areas, continue to be high priorities. Research is still being done on how to preserve habitats while still interacting with birds and other creatures.

Economic viability: For low-speed VAWT systems to be widely adopted, they must become cost-competitive. Reduced manufacturing, installation, and maintenance costs while increased energy capture efficiency are the goals.

Together, these developments are changing the wind energy environment, making it a practical and sustainable option in areas where wind resources were previously underutilized. As research and development efforts continue, low-speed VAWTs are poised to revolutionize the accessibility and effectiveness of clean wind power on a global scale.

5. CONCLUSION

The development of Low-Speed Vertical Axis Wind Turbine (VAWT) design represents a significant step forward in the effort to harness wind energy in areas with low wind speeds. These turbines are developing through careful research and invention to enhance energy capture efficiency, adaptability, and cost-effectiveness. The difficulties faced by low wind speeds are being overcome by these advancements, which range from improved aerodynamics to the incorporation of intelligent control systems and future-proof materials. Low-speed VAWTs are poised to fundamentally alter the wind energy sector by bringing the promise of clean and sustainable power to a larger geographical footprint, even if challenges still exist in scaling up and addressing environmental concerns. The future of wind energy is bright as long as research and development keep driving these major advancements.

REFERENCES

[1] Rezaeiha, A., & Montazeri, H. (2018). Towards optimal aerodynamic design of vertical axis wind turbines: Impact of solidity and number of blades. Energy, 165, 1129–1148.

[2] Pongchalat Chaisiriroj, N.T., & SaowapakUsajantragul. (2017). Experimental performance investigation of optimal vertical axis wind turbines under actual wind conditions in Thailand. Energy Procedia, 138(October), 651–656.

[3] Shortt, A., Kiviluoma, J., and O'Malley, M. (2013). Accommodating Variability in Generation Planning. IEEE Trans. Power Syst. 28 (1), 158–169. doi:10.1109/tpwrs.2012.2202925

[4] Kroposki, B., Johnson, B., Zhang, Y., Gevorgian, V., Denholm, P., Hodge, B.-M., et al. (2017). Achieving a 100% Renewable Grid. Ieee Power & Energy Mag. 15 (2), 61–73. doi:10.1109/mpe.2016.2637122

[5] Conejo, A. J., Cheng, Y., Cheng, Y., Zhang, N., and Kang, C. (2017). Long-term Coordination of Transmission and Storage to Integrate Wind Power. Csee Jpes 3 (1), 36–43. doi:10.17775/cseejpes.2017.0006

[6] Han, X., Li, T., Zhang, D., and Zhou, X. (2021). New Issues and Key Technologies of New Power System Planning under Double Carbon Goals. High. Volt. Eng. 47 (9), 3036–3046. doi:10.13336/j.1003-6520.hve.20210809

[7] Apelfröjd, S., Eriksson, S., & Bernhoff, H. (2016). A review of research on large scale modern vertical axis wind turbines at Uppsala University. Energies, 9(7), 570, doi:10.3390/en9070570

[8] Arredondo-Galeana, A., & Brennan, F. (2021). Floating Offshore Vertical Axis Wind Turbines: Opportunities, Challenges and Way Forward. Energies, 14(23), 8000. MDPI AG. Retrieved from http://dx.doi.org/10.3390/en14238000

[9] Lette, M., Rahi, K. H., Singh, H. K., & Ray, T. (2023, July). Vertical-Axis Wind Turbine Design Using Surrogate-assisted Optimization with Physical Experiments In-loop. In Proceedings of the Genetic and Evolutionary Computation Conference (pp. 1391-1399).

[10] Ndaru Adyono, Tria Puspa Sari, S. Sutiyono, Luluk Endahwati, Wahyu Dwi Lestari, Ahmad Khairul Faizin, Wiliandi Saputro, Radissa Dzaky Issafira; Design of Savonius vertical axis wind turbine for low speed wind field. AIP Conference Proceedings 2 March 2023; 2609 (1): 030002. https://doi.org/10.1063/5.0123835

[11] Ali, Malek, Gherissi, Abderraouf and Altaharwah, Yousef. "Experimental and simulation study on a rooftop vertical-axis wind turbine" *Open Engineering*, vol. 13, no. 1, 2023, pp. 20220465. https://doi.org/10.1515/eng-2022-0465

[12] Unsakul, S., Sranpat, C., Chaisiriroj, P. and Leephakpreeda, T. (2017) CFD-Based Performance Analysis and Experimental Investigation of Design Factors of Vertical Axis Wind Turbines under Low Wind Speed Conditions in Thailand. Journal of Flow Control, Measurement & Visualization, 5, 86-98. https://doi.org/10.4236/jfcmv.2017.54007