Advanced Control Techniques for Wind Turbine Optimization: Challenges and Future Directions

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ABSTRACT

Wind energy is increasingly recognized as a crucial component of sustainable energy solutions due to its abundance and minimal environmental impact. However, optimizing wind turbine performance poses significant engineering challenges, including improving efficiency, stabilizing power output, maximizing energy production, and mitigating structural fatigue and vibrations. This survey paper provides a comprehensive classification and analysis of various control strategies and methodologies used in wind turbine systems. It focuses on advanced control techniques such as robust H∞ controllers, Genetic Algorithms, and PID controllers, detailing their principles, advantages, and limitations. The paper identifies key challenges in wind turbine optimization, including effective disturbance rejection and robustness against varying environmental conditions, and proposes potential solutions through these advanced control techniques. By evaluating recent advancements and practical implementations, this survey aims to guide future research and development efforts, contributing to the enhancement of wind turbine efficiency and reliability. The insights gained from this study are intended to support the ongoing evolution of wind energy technology, paving the way for more sustainable and efficient energy solutions.

KEYWORDS: Wind Turbine Optimization, Control Techniques, Wind energy, PID Controller.

1 INTRODUCTION

The utilization of wind as a renewable resource for the generation of alternative energy is considered both viable and practicable. Wind energy is widely recognized as a viable and efficient alternative to fossil fuels for meeting energy needs. Moreover, wind energy is characterized by its extensive accessibility, eco-friendliness, and ability to address the problem of global warming caused by the excessive use of air assistance in conventional combustion systems. The vertical axis wind turbine (VAWT) offers numerous advantages. When it comes to maintenance and organization on the ground, the larger parts are easier to handle. A Vertical Axis Wind Turbine (VAWT) is a versatile wind-harvesting device designed to efficiently capture wind energy from all directions [1]. The wind power system typically consists of an asynchronous generator that is directly connected to the electrical grid.

The consensus is that this particular style is considered to be one of the simplest and most fundamental options available. The following section presents the suggested models and control mechanisms for each area. The comprehensive presentation of the VAWT model provides an in-depth explanation of various phenomena, such as wind shear and tower shadow. The study and its findings have been validated using simulation and experimental data. The efficiency of this particular vertical axis wind turbine (VAWT) was found to be higher based on the results obtained from experiments conducted on various VAWT modifications. The text entered by the user is encapsulated within tags. The utilization of a wind turbine serves as an alternative means of generating electrical power in regions that lack access to the conventional electrical grid. Wind turbines can be classified into two main categories: vertical axis wind turbines (VAWTs) and horizontal axis wind turbines (HAWTs) [2]. The rotor assembly of a vertical-axis wind turbine is designed to enable rotation specifically along its vertical axis. The comparison between the vertical axis wind turbine (VAWT) and the traditional horizontal axis wind turbine highlights several advantages. The architecture of this system offers several advantages. The features of this wind turbine design include a lower level of acoustic noise, the ability to operate in any wind direction, the placement of rotating components near the ground for easier maintenance, and reduced gravitational disturbances caused by non-harmonic reversing stress at the base of the blades [3]. Extensive research has been conducted over the last three decades to advance the vertical axis wind turbine. Recently, there has been an increased focus on cost-effectiveness and power generation optimization in the field of vertical-axis wind turbines. The tip speed ratio is a critical factor that has a significant impact on the electricity generation capability of a wind turbine system. The optimal strategy for power control involves operating a wind turbine at its ideal tip speed ratio, which maximizes its power production. However, when the control is deactivated, it has the potential to result in avoidable losses within the system [4]. The Horizontal Axis Wind Turbine (HAWT) is widely recognized as the most popular configuration for power generation. Several rotor types have been developed and subjected to testing to evaluate their performance. The efficiency of a wind turbine can be increased and the minimum wind speeds required for rotation can be reduced by combining a Savonius vertical wind turbine with a Darrieus-type turbine. The objective of this research was to assess the power and torque coefficients of Curved Blades Vertical Axis Wind Turbines (CBVAWTs) about their operational parameters, specifically the tip speed ratio [5].

A wind turbine is a mechanical device designed to convert the kinetic energy of the wind into mechanical energy through rotation [6]. A windmill is typically used to describe a machine that transfers its mechanical energy to other machinery, such as a pump or grinding stones, in a rapid manner. The process of converting mechanical energy into electrical energy is commonly known by various names, such as wind generators, wind turbines, wind power units (WPU), or wind energy converters (WEC) [7]. The wind turbine is a commonly used device for converting wind energy into electrical energy, which can then be distributed to meet various energy requirements. The turbine consists of three primary components. The wind turbine blades play a crucial role in the rotor as they are responsible for converting wind energy into low-speed rotational energy. The rotor component of the wind turbine represents approximately 20% of the total cost of the turbine [8]. The generator component constitutes approximately 34% of the total cost of the wind turbine. It consists of an electrical generator, control electronics, and, in some cases, a gearbox component.

The gearbox is an essential component required for power generation as it facilitates the conversion of low-speed rotation into high-speed rotation. The tower and rotor pointing mechanism are integral components of the wind turbine's structural support system, comprising 15% of the total cost.

The term "Changeables" refers to an idea or characteristic that can be modified or adjusted. The term "wind speed" is used to describe the measurement of the horizontal velocity of moving air. The measurement is typically expressed in units such as meters per second (m/s). The aforementioned element has a significant impact on the overall productivity of a windmill. The kinetic energy of the wind is utilized by the wind turbine to produce electrical power. The rotation of the generator's shaft causes the magnetic coils to sweep. The wind exerts a force on the axis, causing it to rotate and initiate the revolution. The rotation of the device generates an electric current [9]. The artificial wind source used for control, such as a regular electric fan or hair dryer, will remain unchanged.

The windmill blades are engineered to ensure a consistent distance and orientation from the wind source. The measurement of the distance between the two ends of the blade is referred to as the blade length. There is a direct proportional relationship between the swept area and the length of the blade. The increased blade diameters enable a greater amount of wind to be captured with each rotation due to the larger surface area covered by the blades. Furthermore, they can exhibit an augmentation in torque as a result. Adaptable management refers to the ability of a manager or leader to modify and adapt their approach and methods to effectively address and respond to changing events and circumstances. Adaptability is the term used to describe the capability to modify and manage behaviour following shifting circumstances [10]. The dimensions and form of the blades are determined by a single-blade design. Neither the breadth nor the length will change. The optimization of a wind turbine's blade form is crucial for maximizing its overall output. Design Limitations The dimensions and shape of an object dictate its physical size and form. The final design must adhere to height limitations to ensure stability and should not exceed a maximum diameter of approximately 3 meters. The objective of this study is to achieve the minimum weight possible to reduce the moment of inertia. It is imperative to consider this factor as a substantial event that will increase the necessary starting torque [11]. The self-starter should be designed to operate solely through mechanical means, without the need for any electrical components. The system exclusively relies on wind energy and does not provide support for any other alternative energy sources. The domains of human factors, ergonomics, and safety research and practice hold significant importance. The system can function normally without the need for direct human engagement. To optimize maintenance protocols, it is necessary to develop a brake mechanism that is capable of stopping the turbine when wind speeds surpass pre-determined safety thresholds [12]. The concepts of resilience and sustainability hold significant importance across various sectors of the economy. The term "resilience" refers to the ability of a system or entity to withstand unexpected events or disturbances and recover from them. The key to achieving sustainability in turbine construction lies in ensuring its ability to withstand extended periods of exposure to diverse weather conditions [13]. This includes enduring temperatures ranging from -20°C to +35°C, wind speeds of up to 30 m/s, and various forms of precipitation. The overall small size of the assembly enables convenient and effective operation.

However, there is no requirement to replace the shaft and blades. The replacement procedure has been designed to be user-friendly, ensuring that individuals can easily utilize it. To enhance the efficiency of the procedure, the assessment of the remaining sections has been simplified. The user submitted the input "Look" [14]. The primary objectives in turbine design should be to achieve an aesthetically pleasing appearance and minimize noise emissions. During operation, a generator will consistently generate noise. However, it is of utmost importance to ensure that the noise level remains within acceptable limits, especially in cases where the turbine is not located near densely populated areas.

The integration of automatic control systems is an increasingly important subject in the field of wind energy. The attention has been drawn to the potential impact of this problem on the dependability and efficiency of wind energy systems. The integration of automatic control systems enables real-time optimization of various parameters, such as power output, pitch angle, and turbine speed. Wind energy systems can optimize their performance and adapt to varying environmental conditions by implementing control systems. In addition, the utilization of automatic control systems enables the remote monitoring and administration of wind turbines, thereby improving their overall maintenance and operation. The integration of automatic control systems will be crucial in enhancing the effectiveness and efficiency of wind energy systems, as wind energy continues to expand as a sustainable and renewable energy source. The advancement of wind technology relies on the achievement of various control objectives and the enhancement of the turbine's energy efficiency. The objectives of the project are to minimize vibrations, mitigate fatigue in the structure, optimize energy production, and ensure that the output power remains at its nominal value. Wind energy is widely recognized as a highly promising and sustainable form of renewable energy. The utilization of Small to medium-sized Power Generation Systems (PGS) in conjunction with fixed-pitch wind turbines operating at variable speeds offers numerous advantages [15]. Permanent Magnet Synchronous Generators (PMSGs) are commonly utilized in Standalone Wind Energy Conversion Systems (WECS) due to their higher power density and user-friendly nature.

Researchers utilize hardware setups consisting of electromechanical devices to simulate wind climatic conditions for conducting studies in the field of wind energy. The Wind Turbine Emulator (WTE) is created by directly connecting an electric motor and the wind generator's shaft. The motor is powered by a speed drive that draws power from the laboratory grid. Permanent magnet direct current motors (PMDCMs) are commonly chosen for various applications due to their inherent advantages in control and regulation. The advancements in high-performance control calculators, faster switching times of power electronic components, and enhancements in Permanent Magnet Synchronous Generator (PMSG) design have collectively led to significant improvements in the controllability and power density of PMSGs. Permanent Magnet Synchronous Generators (PMSGs) have been observed to exhibit superior performance compared to induction generators in standalone systems [16].

Permanent magnet (PM) motors are commonly used in industrial control applications due to their affordability, high efficiency, and simple mechanical design. Plant models often encounter issues such as inadequate parameters or susceptibility to parameter variations. Modern robust control applications have the objective of minimizing the $H\infty$ norm of the closed-loop control system. This is done to enhance disturbance rejection, particularly in the context of fixed structure H-loop shaping control design.

The inclusion of a Genetic Algorithm (GA) into the PID controllers aims to enhance their performance by minimizing the integral of the time-weighted squared error (ITSE) performance metric. The H∞ controller is intentionally designed to optimize the rejection of disturbances. The process achieves this by utilizing various techniques of global optimization, such as Genetic Algorithms (GA) [17].

Robust control schemes are crucial for numerous applications as they offer precise monitoring and efficient disturbance rejection. To meet the robustness criteria, the typical PID controller has been enhanced with gain tuning through H∞ optimization. This is because the typical PID controller is not known for its resilience. Conventional methods often prove inadequate when it comes to effectively administering applications that rely on complex mathematical models. However, even though the PID framework is commonly taught and easy to comprehend, individuals with limited mathematical knowledge can still make use of it. The system can seamlessly incorporate additional features and effectively manage various control challenges. The presence of damped oscillation in control systems before reaching a stable state highlights the importance of employing appropriate control techniques to safeguard equipment and reduce the risk of potential damage. Significant overshoot results in an undesired increase in initial currents, particularly in machinery applications. PID controllers are designed to minimize the initial current and mitigate overshoot to maximize the performance characteristics [18].

1.1 Challenges encountered

Here are the key challenges encountered in optimizing wind turbine performance and control

- **Environmental Variability**

  Wind turbines operate in highly variable environmental conditions, including fluctuating wind speeds and changing weather patterns, which can significantly impact performance and efficiency. Developing control strategies that can adapt to these variations is crucial.

- **Efficiency Enhancement**

  Maximizing the energy extraction from wind resources while minimizing losses remains a significant challenge. Techniques need to be developed to ensure optimal tip speed ratios and minimize inefficiencies in power generation.

- **Disturbance Rejection**

  Wind turbines are subject to various disturbances, such as mechanical vibrations and electrical fluctuations. Effective disturbance rejection mechanisms are needed to ensure smooth and stable operation.

- **Computational Complexity**

  Advanced control methods, such as robust H∞ controllers and optimization algorithms, often require significant computational resources. Reducing the computational demands of these methods while maintaining their effectiveness is a critical challenge.

- **Parameter Variations**

  - The performance of wind turbines can be affected by variations in system parameters over time. Control strategies must be robust enough to handle these variations and maintain optimal performance throughout the turbine's operational life.

- **Integration of Advanced Techniques**

  Incorporating machine learning and artificial intelligence into control systems presents opportunities for more adaptive and intelligent control but also introduces challenges related to data requirements, training, and real-time implementation.

1.2 Motivation

In the quest for sustainable and renewable energy sources, wind energy stands out as a promising solution due to its abundance and low environmental impact. Despite its potential, optimizing wind energy systems, particularly wind turbines, poses significant engineering challenges. These challenges include enhancing efficiency, stabilizing power output, maximizing energy production, and reducing structural fatigue and vibrations. This survey paper aims to address these challenges by focusing on the control strategies and methodologies that can significantly improve the performance of wind turbines. By exploring advanced control techniques, such as robust H∞ controllers and Genetic Algorithms for tuning PID controllers, this research seeks to provide solutions that ensure robust operation, effective disturbance rejection, and enhanced efficiency of wind turbines. This study also highlights the importance of developing controllers that can adapt to varying conditions and disturbances, ensuring reliable and efficient energy generation. Through a comprehensive review of current advancements and methodologies, this paper aims to contribute to the ongoing development of wind energy technology, paving the way for more sustainable and efficient energy solutions.

The contributions of this survey are:

- **Comprehensive Analysis and Classification**

  - The paper provides a detailed analysis and classification of various control strategies and methodologies used in wind turbine systems. This includes a focus on robust H∞ controllers, Genetic Algorithms, and PID controllers, highlighting their principles, advantages, and limitations.

- **Identification of Key Challenges and Solutions**

  The survey identifies critical challenges in the optimization and control of wind turbines, such as efficiency enhancement, disturbance rejection, and robustness against varying environmental conditions. It also proposes potential solutions to these challenges through advanced control techniques and methodologies.

- **Evaluation of Advanced Control Techniques**

  The paper evaluates the effectiveness of modern control techniques, such as the use of Genetic Algorithms for optimizing controller parameters and the application of robust H∞ control strategies. This evaluation provides insights into the practical implementation and potential improvements in wind turbine performance, contributing to the development of more reliable and efficient wind energy systems.

2 RELATED WORK

The development and optimization of control strategies for wind turbines have been extensively studied due to their critical role in enhancing the performance and reliability of wind energy systems. Numerous methodologies have been proposed to address challenges such as efficiency improvement, disturbance rejection, and robustness to environmental variability. This section reviews significant contributions in the field, including advanced control techniques like H∞ control, Genetic Algorithms, and sliding mode control. Additionally, the integration of machine learning approaches and the development of adaptive and model-free control strategies are examined. The aim is to highlight the strengths and limitations of existing methods and identify areas for future research to further advance wind turbine technology.

The rotor and stator experience significant attractive forces when Maxwell stresses are present, which increases the generator's structural mass. Claw-pole generators and transverse flux machines are two further instances of non-conventional generators [19].

Reference [20] shows that the generators in issue have low power factors. Super-conducting direct-drive generators are presently under investigation, and their large torque densities are predicted. For marketing purposes, the development stage as it is now does not meet the requirements. Wind turbines may be divided into two categories: vertical-axis wind turbines and horizontal-axis wind turbines. The rotor's orientation determines the categorization. As evidenced by recorded examples of vertical axis wind turbines in the literature, axial flux generators have been proven to be very suited for these turbines [21]. Nonetheless, it is uncommon to find MW wind turbines on the market with low capacity factors and subpar performance. According to the investigation, there may be a need for the recommended generator, especially with horizontal axis wind turbines. Closed-loop iterative learning is suggested as a method in reference [15] to handle the effect of system nonlinearity. It is crucial to remember that this approach may increase disruptions while concurrently decreasing aperiodic disturbances. According to [16], the suggested approach comprises creating a speed controller that takes into consideration the unique properties of the disturbance and target models. The control method, often called Control, is widely used in many different applications because of its remarkable capacity to handle complex control tasks. However, Control requires a significant amount of processing power and work to accomplish. This is mostly due to the challenge of effectively simulating disturbances, which show a high degree of frequency unpredictability. Both periodic and aperiodic disturbances are efficiently suppressed by the observer's feedforward adjustment of the disturbance torque. Because it can manage unexpected and time-varying disturbances in real-time, even in the absence of prior knowledge of the disturbances, the observer is well suited for engineering applications. Furthermore, the observer does this with the least amount of computing power required. The input entered by the user is shown as [22] the torque, location, and speed may all be measured by the full-order observer, as described in detail. Torque is converted into feedforward current by this technique. Often, controlling the speed of a permanent magnet motor does not require monitoring all state variables. The suggested method seeks to reduce the number of adjustable factors to improve the system. This is accomplished by reducing the full-order observer's functionality to just track speed and torque. The strategy also emphasizes enhancing the system's simplicity of use while preserving its anti-interference capabilities. In the study [23], it is discussed how to use decentralized H∞ controllers in linked AC grids to minimize frequency deviations and achieve optimal power sharing. This is accomplished by the synchronization of synchronous generators and MTDC converters. The work uses a dynamic model of hybrid MTDC-linked grids, taking decentralized control inputs and outputs into account as well as model parameter uncertainty. Robust optimization problem formulation and solution are pursued in this field. An approach to balanced truncation is used to reduce the order of the controller models. The method outlined entails removing uncontrollable and unobservable state factors while keeping the predominant response traits. The impact of grid measurements, degrees of parameter uncertainty, and communication time delays are the main subjects of concern in sensitivity and eigenvalue analysis. The goal of the paper's general robust controller design approach—detailed in reference [24]—is to reduce the impact of system uncertainty on stability and performance.

This work entails solving several problems, including steady-state error, rejection of disturbances, attenuation of high-frequency noise, and dynamic reaction speed. There are several steps in the process. These steps include reducing the order of the system, revaluating design goals, developing mathematical models to guarantee robust stability and performance, executing robust H∞ controller synthesis, choosing weighting functions to bound transfer functions across the entire uncertainty range, and using the multi-dimensional Pareto Front algorithm to choose an optimized controller. A revolutionary rotor design that incorporates optimally constructed flux barriers is presented in the work. This rotor's intended application is in combination with a conventional SRM stator. An optimization method is used to identify the ideal rotor shape. The suggested approach combines Genetic Algorithm (GA) and Finite Element Analysis (FEA) to maximize torque ripple and tangential vibration reduction while maintaining average torque. To evaluate the performance of the improved motor against a conventional Switched Reluctance Motor (SRM) of the same size, a comparative analysis is carried out. The principal topic covered in [25] concerns disturbance observer (DOB) remuneration. An analysis of the behaviour and stability of the classical disturbance observer (DOB) in combination with a proportional-integral-derivative (PID) controller was carried out. Both open and closed-loop designs were taken into account in the research. The experimental results show that independent of the setpoint tracking transfer function, the disturbance rejection of the DOB was optimum. By adaptively altering the convergence time, a switching mode disturbance observer (SMDOB) may identify the disturbance force influencing the slider trajectory. Through computer models and practical testing, the benefits of the SMDOB (Sliding Mode Disturbance Observer) on lowering control error have been demonstrated.

Model-based strategies are utilized to estimate and compensate for frictional forces during motor operation with increasing current. One of the methods used in this procedure is to measure the friction forces before starting the operation. Next, a mathematical model that successfully integrates and accounts for these forces is found. Several different applications use the Stribeck and LuGre models of friction. Among these models, the LuGre model is most commonly used because of its simple design and its ability to properly simulate both static and dynamic friction [12]. For PMDC motors, a popular model-free method in many sectors is the disturbance observer (DOB) or acceleration-based control method [13]. The solution uses a permanent magnet direct drive motor management mechanism to reduce speed fluctuations during low-speed operation. The suggested approach combines disturbance detection and rotor position tracking methods. The simulations have shown that robust stability and disturbance rejection are at odds when it comes to controlling rotor position tracking. A disturbance observer is used to make up for the feedforward current. This makes it possible to use a composite control strategy, which enhances the system's anti-interference performance and successfully reduces the deterioration of robust stability. To improve the performance of the traditional reduced-order observer, a differential connection is added. This change is intended to reduce any inherent delay and enhance dynamic estimating performance. The polynomial method, which has been extensively reported in several publications, is thought to be separate from the mainstream studies on H∞ control problems [17]. The suggested method effectively tackles a wide range of optimum H∞ control issues using a frequency domain-centered control strategy. The accomplishment is made possible by the coordinated simultaneous development of control aspects and solutions.

A proportional-integral-derivative (PID) controller and a back-propagation (BP) neural network are combined to create the variable pitch controller (BP-PID), which is the suggested solution. To optimize the combinations of PID parameters, the Proportional-Integral-Derivative (PID) parameters are dynamically adjusted in real time using the Backpropagation (BP) neural network. The procedure is carried out by continuously observing changes in the rotor's speed. Using the BP-PID algorithm, the active disturbance rejection pitch controller was created. The research considers various disturbance kinds and variations in the mechanical component characteristics of wind turbines. To improve a hybrid microgrid system's frequency responsiveness, a cascade Proportional Integral-Fractional Order proportional-integral derivative (PI-FOPID) controller is advised [19]. The Gorilla Troops Optimizer (GTO), a unique metaheuristic optimization approach, is used to optimize the optimal gains for the proposed controller. The table 1 shows the survey table.

Table 1 survey table

Method	**Advantage**	**Disadvantage**	**Research Gap**
Robust H∞ Controllers	High robustness to disturbances	High computational complexity	Reducing computational demands while maintaining robustness
Genetic Algorithms (GA)	Optimizes control parameters effectively	Requires large datasets and computation time	Improving efficiency and reducing training time
PID Controllers	Simple, intuitive, and widely used	Lacks robustness in complex environments	Enhancing robustness and adaptability
Sliding Mode Control (SMC)	High accuracy and robustness to parameter variations	Inherent chattering phenomenon	Reducing chattering while maintaining control of performance
Adaptive Control	Adjusts to changing conditions automatically	Increased computational burden due to high-order terms	Simplifying adaptive algorithms to reduce computational load
Fuzzy Logic Control	Handles non-linearities well	Complex design and tuning	Simplifying design and improving tuning methods
Model Predictive Control (MPC)	Predicts future states to optimize control actions	Requires accurate models and high computational resources	Developing efficient algorithms that work with less precise models
Machine Learning-Based Control	Intelligent and adaptive control strategies	Requires extensive training and large datasets	Integrating real-time learning capabilities

2.1 Research gap

- **Robustness Against Environmental Variability**
  Develop control strategies that can maintain optimal performance and stability under varying environmental conditions, such as fluctuating wind speeds and changing weather patterns.

- **Enhanced Efficiency and Power Output**
  Innovate methods to further enhance the efficiency and power output of wind turbines, ensuring maximum energy extraction from available wind resources while minimizing losses.

- **Advanced Disturbance Rejection**
  Create advanced control techniques that can effectively reject both periodic and aperiodic disturbances, ensuring smooth and stable operation of wind turbines under diverse conditions.

- **Optimization of Control Parameters**
  Improve optimization algorithms for tuning control parameters, particularly focusing on Genetic Algorithms and other metaheuristic approaches, to achieve more precise and reliable control settings.

- **Integration of Machine Learning Techniques**
  Explore the integration of machine learning and artificial intelligence techniques in control systems to enable adaptive and intelligent control strategies that can learn and adjust to changing conditions in real time.
- **Simplified Implementation and Maintenance**
  Design control methodologies that are not only effective but also simple to implement and maintain, reducing the complexity and cost associated with wind turbine control systems.
- **Comprehensive Validation and Testing**
  Conduct extensive validation and testing of proposed control strategies in real-world conditions to ensure their practicality, reliability, and scalability in large-scale wind energy installations.

3 CONCLUSION

In conclusion, this survey paper has provided a thorough examination of control strategies and methodologies for optimizing wind turbine performance. By systematically categorizing and analyzing advanced techniques such as robust $H\infty$ controllers, Genetic Algorithms, and PID controllers, the paper has highlighted both their advantages and limitations. Key challenges, including enhancing efficiency, stabilizing power output, maximizing energy production, and mitigating structural fatigue and vibrations, have been identified and addressed with potential solutions. The evaluation of recent advancements in these control techniques underscores their potential to significantly improve the reliability and efficiency of wind turbines. This survey aims to guide future research and development efforts, ultimately contributing to the advancement of wind energy technology and supporting the global transition to sustainable energy sources.

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