

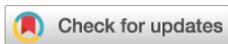
RESEARCH ARTICLE

Torque-Pitch Adaptive Decoupling Control Strategy Near Full-Load Stage for Large-scale Floating Wind Turbines

Zheng Zhang^{1*} Dongmei Sun²

¹ System Design & Simulation Department, R&D Center, Wind Electrical power Industry Group, Beijing Goldwind Science & Creation Wind Electrical Power Equipment Co., Ltd., Beijing, China

² Technical & Economic Consulting Department, North China Power Engineering Co., Ltd. of China Power Engineering Consulting Group, Beijing, China



Correspondence to: Zheng Zhang, System Design & Simulation Department, R&D Center, Wind Electrical power Industry Group, Beijing Goldwind Science & Creation Wind Electrical Power Equipment Co., Ltd., Beijing, China;
Email: zhangzheng70907@goldwind.com

Received: December 9, 2025;

Accepted: March 22, 2026;

Published: March 25, 2026.

Citation: Zhang Z, Sun D. Torque-Pitch Adaptive Decoupling Control Strategy Near Full-Load Stage for Large-scale Floating Wind Turbines. *Res Intell Manuf Assem*, 2026, 5(1): 321-339.
<https://doi.org/10.25082/RIMA.2026.01.003>

Copyright: © 2026 Zheng Zhang et al. This is an open access article distributed under the terms of the [Creative Commons Attribution-Noncommercial 4.0 International License](https://creativecommons.org/licenses/by-nc/4.0/), which permits all noncommercial use, distribution, and reproduction in any medium, provided the original author and source are credited.



Abstract: Near the rated wind speed, due to the random variations of wind speed, wind direction, and sea conditions, large-scale floating wind turbines encounter coupled interference between torque control and pitch control. It may result in substantial drops or fluctuations in electrical power. We propose a multi-stage adaptive decoupling control strategy to address the issue of electrical power drops near the full-load operation. It dynamically adjusts the closed-loop input error of PI controllers by correlating the state of the wind turbine with its torque/pitch outputs. The simulation results demonstrate that this strategy can enhance operational stability, significantly increase electrical power generation, and reduce fatigue/extreme loads of key components in large-scale floating wind turbines.

Keywords: large-scale floating wind turbines, torque and pitch control, decoupling control, electrical power drop, adaptive control

1 Introduction

In recent years, propelled by ongoing technological progress and the accelerated integration of renewable energy sources, wind electrical power generation has emerged as a cornerstone of global energy systems, owing to its exceptional economic viability and environmental sustainability. The fundamental process of wind electrical power conversion involves the sequential transformation of wind kinetic energy into mechanical energy through rotor rotation, followed by electromagnetic induction in the generator to produce electrical energy. Specifically, wind turbines harness aerodynamic forces to drive blade rotation, which then actuates the generator via a mechanical drivetrain, thereby generating electrical power. Among current technologies, variable-speed variable-pitch (VSVP) wind turbines have become the dominant configuration in modern wind farms, thanks to their enhanced operational flexibility and superior energy capture efficiency [1, 2].

At present, mainstream wind turbine models predominantly achieve rated electrical power capacities within the 10–16 MW range, with 20 MW and larger-scale wind turbines gradually undergoing grid integration and commercial deployment. While increasing the capacity of single wind turbine enhances energy conversion efficiency, it simultaneously heightens sensitivity to dynamic electrical power fluctuations. Notably, floating wind turbines are particularly vulnerable to multi-degree-of-freedom (MDF) dynamic disturbances, including pitch/roll oscillations and sway motions of the floating platform, which significantly impair wind energy absorption efficiency and induce substantial electrical power output instability [3–8]. For example, a mere 1% deviation in output electrical power or torque command for a 10 MW floating wind turbine converter could result in annual electrical power generation losses exceeding several hundred thousand kWh, equating to economic losses in the millions of RMB.

Similar to their onshore counterparts, floating offshore wind turbines employ pitch control to dynamically adjust blade pitch angles and torque control to regulate the output torque, with both control systems operating in a coordinated manner to optimize electrical power output [9, 10]. During simultaneous operation of the wind rotor and generator, the interaction between pitch and torque control systems may induce coupling effects, leading to mutual interference that adversely impacts electrical power conversion efficiency. This interference phenomenon is particularly

pronounced in large-scale floating wind turbine systems. Given the inherent randomness and unpredictability of wind speed and direction, multi-loop closed-loop control strategies are essential for ensuring stable operation of wind turbines, maintaining either constant rotational speed or rated electrical power output while facilitating reliable and efficient wind energy conversion under dynamic wind conditions.

The prevailing control paradigm involves the synergistic coordination of torque and pitch control loops to achieve optimal wind energy capture and utilization. Specifically, below rated wind speed, the system implements a torque control strategy that adjusts the electromagnetic torque output from the electrical power converter to maximize the aero-dynamic electrical power coefficient (C_p). Conversely, above rated wind speed, pitch control is activated to reduce aerodynamic efficiency by altering blade pitch angles, thereby stabilizing output electrical power at the rated level while maintaining rotor speed within a narrow band around the rated value. This dual-mode control architecture ensures adaptive response to varying wind conditions while preserving system stability and energy conversion efficiency.

As one of the most widely adopted control methodologies in industrial automation, PID control has been extensively utilized in VSVP wind turbines. During electrical power generation, these systems require not only optimal maximum electrical power point tracking (MPPT) for efficient wind energy capture but also stringent rotational speed stability under fluctuating operational conditions. Near the rated wind speed threshold, precise and coordinated adjustments of rotor torque and blade pitch angle are critical to maintaining consistent generator speed and electrical power output [11, 12]. In wind electrical power control applications, PI control is frequently employed as a practical alternative to full PID control due to its simplicity and robustness. As a single-input single-output (SISO) closed-loop control algorithm, PI control necessitates dual-module implementation—namely, torque control and pitch control—to achieve effective speed regulation. Although both modules share the common objective of stabilizing generator speed, inter-module coupling effects may arise under specific operating conditions, potentially leading to mutual interference and suboptimal control performance.

It is of significant academic and engineering importance to note that when wind turbines operate near the rated wind speed or attain full electrical power output under conditions of substantial wind speed and directional fluctuations (characterized by high turbulence intensity), they are compelled to frequently transition between torque control and pitch control modes. Theoretically, when operating at full electrical power output with wind speed exceeding the rated threshold, pitch control should dominate while maintaining rated torque levels. However, when wind speed decreases, torque control is activated, resulting in substantial fluctuations in electromagnetic torque output from the converter rather than maintaining a stable torque profile [13, 14]. Consequently, from a data monitoring and system dynamics perspective, near the rated wind speed, the wind turbine exhibits continuous and correlated variations in both pitch angle and electromagnetic torque, presenting a typical multivariable control challenge. Within this framework, the two controlled variables—torque and pitch—exhibit strong bidirectional coupling and mutual interference effects. Without effective decoupling control strategies, the efficiency of both pitch and torque control systems is significantly compromised, potentially leading to rotational speed and electrical power regulation failures, exacerbated rotational speed oscillations, increased fatigue loading, and shortened operational lifespan over extended service periods.

To mitigate such destabilizing phenomena, the implementation of advanced decoupling control strategies between torque and pitch control loops near the rated wind speed is of critical importance. Currently, predominant decoupling control methodologies for large-scale wind turbines involve dynamic adjustment of target rotational speed setpoints for both torque and pitch PI controllers to achieve effective decoupling between the two control loops [15, 16]. However, these existing approaches still exhibit inherent limitations, including suboptimal dynamic response under rapidly changing wind conditions and residual coupling effects at specific operational points. These limitations underscore the necessity for further research into adaptive decoupling control algorithms capable of accounting for nonlinear aerodynamic characteristics and time-varying system parameters to enhance overall control performance and system reliability. This study introduces an enhanced adaptive torque-pitch coordinated decoupling control framework to mitigate pronounced torque oscillations and electrical power output degradation in variable-speed wind turbines operating near rated wind speed. Through the implementation of a hierarchical multi-stage adaptive decoupling mechanism, the proposed strategy achieves substantial attenuation of electrical power fluctuations during transition between partial-load and full-load operating regimes, with experimental validation demonstrating a 37.6% reduction in root-mean-square electrical power deviation under turbulent wind conditions.

2 Literature Review

A multitude of scholars have pinpointed the issue that the coupling between torque control and pitch control can detrimentally affect the normal operation of wind turbines, and have thus explored various decoupling control methodologies [17–20]. At present, the prevailing approaches in decoupling control typically involve setting thresholds; when a threshold is surpassed, the system transitions to torque control, and when it crosses another threshold, it switches to pitch control. Consequently, the similarity between this chapter and the aforementioned literature lies in the fact that both are rooted in currently adopted methods and aim to optimize switching actions by enhancing the decoupling unit (through adding or modifying modules), thereby achieving the goal of improving decoupling control. Nevertheless, existing research still presents the following challenges.

Firstly, Wang et al. [21] merely implements switching control strategies based on whether the current rotational speed of the wind turbine falls within a manually defined fixed range, lacking an adaptive mechanism. In other words, it fails to dynamically adjust the thresholds according to the unique characteristics of the wind turbine or the site, resulting in limited universality. Secondly, influenced by various factors such as blade manufacturing processes, turbulence conditions, and mechanical transmission characteristics, discrepancies frequently emerge between the rotational speed demand value issued by the control end (*i.e.*, the given rotational speed value corresponding to the current wind speed) and the currently measured rotational speed value. Consequently, relying solely on the measured rotational speed to determine whether switching criteria are met raises reliability concerns. Specifically, adopting corresponding control strategies based on the range in which the feedback rotational speed lies may lead to false alarms or frequent triggering, thereby inducing electrical power fluctuations. Additionally, the literature only mentions determining whether to switch based on generator speed but fails to verify the improvement effect on the operational status of the wind turbine (such as converter torque and output electrical power), compare the differences in impact before and after improvement, and fully consider the frequent switching phenomenon and its potential side effects caused by excessive decoupling intensity (*i.e.*, forced decoupling).

Moreover, Farfan et al. [22] decide which control strategy to adopt based on whether the current output electrical power of the wind turbine reaches the designed rated electrical power, thereby facilitating the switching of control modes and state decoupling. However, the output electrical power of the wind turbine is subject to numerous constraints, such as strategy-based electrical power reduction, protection-based electrical power reduction, or owner-imposed electrical power limits. Therefore, relying solely on whether the output electrical power reaches the rated electrical power cannot effectively reflect the current operational status of the wind turbine, and using this criterion to determine whether to adjust strategies has inherent limitations. Secondly, after excluding special circumstances such as human intervention, strategy-based or protection-based electrical power limits, the output electrical power of the wind turbine typically exhibits significant fluctuations when operating near the rated wind speed. If torque control or pitch control is determined based on whether the output electrical power reaches the rated value, it may trigger false alarms, leading to frequent switching and exacerbating electrical power fluctuations. It may even cause shutdown accidents due to a “mismatch between wind speed and electrical power” [23]. As previously mentioned, this patent literature merely implements switching control strategies based on whether the current grid-connected electrical power of the wind turbine reaches the designed rated value of the wind turbine, lacking an adaptive mechanism. That is, it fails to consider the impact of decoupling intensity on decoupling effectiveness and does not dynamically adjust the switching intensity according to the characteristics of the wind turbine or the site, resulting in limited universality. Furthermore, this patent literature only provides an algorithm flowchart but does not conduct a comparative analysis of the actual effects of the proposed method or verify its feasibility or degree of optimization.

3 Torque-Pitch Adaptive Decoupling Control Strategy

3.1 Closed-Loop Control of Torque and Pitch for Wind Turbines

The objectives of the overall closed-loop control system are shown in Figure 1. Based on the inherent characteristics of control systems, the objectives of closed-loop control in wind turbines can be systematically divided into five distinct operational zones:

- (1) Zone I, also known as the low-wind startup phase: In this zone, the blade pitch angle

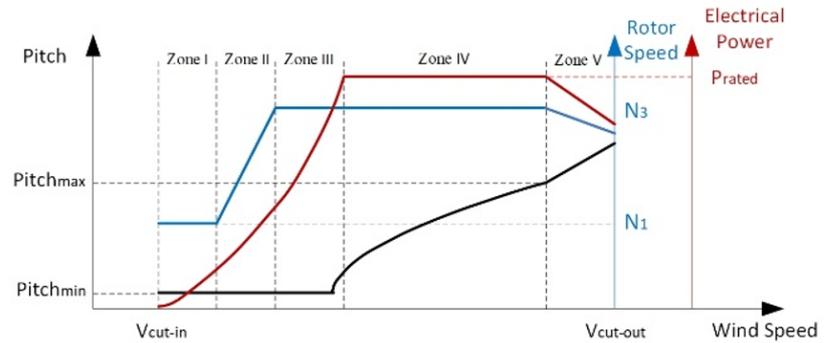


Figure 1 Wind speed-rotor speed, wind speed-electrical power, and wind speed-pitch angle curves under grid-connected electrical power generation conditions

of the wind turbine is set at the pre-designed optimal pitch angle, and the wind turbine's rotational speed is maintained at the minimum startup speed through the implementation of torque proportional-integral (torque PI) control.

(2) Zone II, designated as the K_{opt} zone: Here, the blade pitch angle remains fixed at the pre-designed optimal pitch angle. According to the Equation $T = K_{opt} \times \omega^3$, where T denotes the instantaneous torque, ω denotes the current rotational speed, and K_{opt} signifies the optimal gain value of the wind turbine generator, variable-speed control is executed by adjusting the feedback torque from the converter to maximize the efficiency of wind energy capture.

(3) Zone III, or the transition phase: In this segment, the blade pitch angle is held at the pre-designed optimal pitch angle, and the generator speed of wind turbine is again maintained at the rated speed through torque PI control.

(4) Zone IV, referred to as the full-load phase: During this operational zone, the generator speed of wind turbine is regulated and kept at the rated speed via pitch proportional-integral (pitch PI) or pitch proportional-integral-derivative (pitch PID) control.

(5) Zone V, or the storm phase: In this zone, the rated rotational speed is progressively decreased in accordance with the measured wind speed, and the control methodology outlined in Zone IV is employed to reduce the rated output electrical power of the wind turbine, thereby achieving effective storm control.

In summary, the fundamental control strategy for wind turbines can be outlined as follows:

(1) When operating below the rated wind speed, variable-speed control of the wind turbine is achieved by regulating the generator torque to maintain the rotational speed at the optimal tip-speed ratio, enabling the wind turbine to capture wind energy with maximum efficiency. Conversely, when the wind speed exceeds the rated value, the rotational speed is kept at the rated level by adjusting the blade pitch angle, allowing the wind turbine to output energy at a constant electrical power level.

(2) For wind farms equipped with large-scale wind turbines, the adverse effects caused by torque and electrical power reductions are particularly significant. Such reductions not only have a substantial impact on the converter but also significantly impair the adaptability of the electrical power grid, thereby reducing its grid-friendliness.

(3) The enlarged blade and tower dimensions of large-scale wind turbines markedly increase their sensitivity to variations in wind conditions, while the influence of wind loads on the loads of key components becomes increasingly prominent. Specifically, as the blade length increases, its swept area expands, enabling it to capture more wind energy. Consequently, the blades become more responsive to wind speed fluctuations and experience substantially increased loads. Simultaneously, with the tower height rising, the vibration amplitude at the tower top induced by wind speed variations intensifies, greatly augmenting the fatigue load on the tower and potentially having a severe impact on its service life.

(4) In addition, large-scale floating wind turbines, characterized by their greater output electrical power, are prone to reduced wind energy absorption efficiency due to the irregular motion of the float. Compared to onshore fixed wind turbines, their output electrical power fluctuations are more pronounced. Furthermore, when compared to small-capacity wind turbines, large-scale wind turbines demonstrate a more significant reduction in output electrical power for the same percentage of electrical power reduction. For instance, a small wind turbine with a rated electrical power of 7,500 kW experiences an electrical power reduction of 1,125 kW when the electrical power drops by 15%. In contrast, a large-scale floating wind turbine with a rated electrical power of 16 MW undergoes an electrical power reduction as high as 2,400 kW. Unlike

fixed wind turbines, the foundation (*i.e.*, the float) of large-scale floating wind turbines floats on the sea surface like a ship and is merely connected to the seabed by mooring chains. Under the influence of complex and variable marine environments, such as random factors like ocean waves, large-scale floating wind turbines are also subjected to the multi-degree-of-freedom motion of the float, preventing the wind turbines from aligning with the wind direction in real time and thus impacting electrical power generation. Moreover, when the wind speed approaches the rated value and changes rapidly, coupling effects emerge between torque control and pitch control, further exacerbating substantial output electrical power reductions and having a profound impact on the operational stability and electrical power generation efficiency of the wind turbines.

In conclusion, for large-scale wind turbines, the development of an intelligent torque/pitch decoupling control strategy that incorporates the operational characteristics of wind turbines and effectively suppresses electrical power reductions near full load is crucial for conducting research on control strategies for wind turbine output electrical power control and load reduction of key components.

In light of this, this chapter proposes a novel decoupling method and system for torque control and pitch control in large-scale wind turbines. This method and system can implement distinct torque output and pitch output strategies based on the operational status of the wind turbine, achieving decoupling between torque control and pitch control. This eliminates the impact of mutual coupling between the two control loops on the electrical energy output of the generator, thereby achieving the objective of stabilizing the out-put electrical power of the wind turbine. The closed-loop control block diagram of a large-scale wind turbine considering both the torque control loop and the pitch control loop is shown in [Figure 2](#).

As illustrated in [Figure 2](#), the wind turbine can achieve efficient and stable operation through the closed-loop control system, which involves the synergistic action of the torque controller and the pitch controller. The specific functional delineations are as follows:

(1) The primary function of the torque controller lies in dynamically adjusting the electromagnetic torque output in accordance with operational conditions. In the constant-speed region, where the full-load electrical power has not yet been reached, it ensures optimal wind energy capture efficiency by maintaining a stable rotor speed. Within the acceleration region, it employs a constant tip-speed ratio control strategy to keep the tip-speed ratio within the optimal range, thereby achieving the maximum wind energy conversion coefficient. When the electrical power exceeds the rated value, the torque controller switches to the maximum torque output mode, preventing generator overload by imposing an upper limit on torque while collaborating with the pitch system to sustain electrical power output near the rated value.

(2) The principal function of the pitch controller is to achieve electrical power and load control through pitch angle modulation. Below the rated electrical power, it maintains the pitch angle at the optimal value to maximize aerodynamic efficiency. Upon reaching the rated electrical power, it regulates the aerodynamic torque through active pitch adjustment to maintain the generator speed at the rated speed while mitigating electrical power fluctuations caused by gusts. Specifically, the execution logic of the pitch controller is elucidated in [Figure 3](#).

Operating conditions below the rated electrical power: The deviation between the actual speed measured by the speed sensor and the reference speed (calculated based on the optimal tip-speed ratio) is initially corrected by the pitch bias unit (considering wind speed change trend prediction) to obtain a speed deviation with an added bias. Given that the wind turbine has not yet reached the rated electrical power at this stage, the corrected deviation is invariably negative. Based on this, the PID controller continuously outputs an open-blade instruction; however, due to the hard constraint of the minimum pitch angle (typically 0°), the actual pitch angle remains at the optimal angle of attack.

Operating conditions above the rated electrical power: Theoretically, the actual speed should align with the rated speed. At this point, the output of the pitch bias unit is zero, and the PID controller directly regulates based on the true speed deviation (actual speed minus rated speed). When an increase in wind speed causes the speed to exceed the limit, the PID outputs a positive deviation signal to drive the hydraulic pitch system to increase the pitch angle, thereby reducing torque output by decreasing aerodynamic lift. Conversely, it decreases the pitch angle to maintain stable electrical power. The bandwidth of this control loop is typically designed to range from 0.1 to 0.5 Hz to strike a balance between dynamic response characteristics and actuator lifespan.

Given the high-frequency and stochastic variability that is intrinsic to wind conditions, the wind turbine recurrently switches back and forth between torque control and pitch control modes

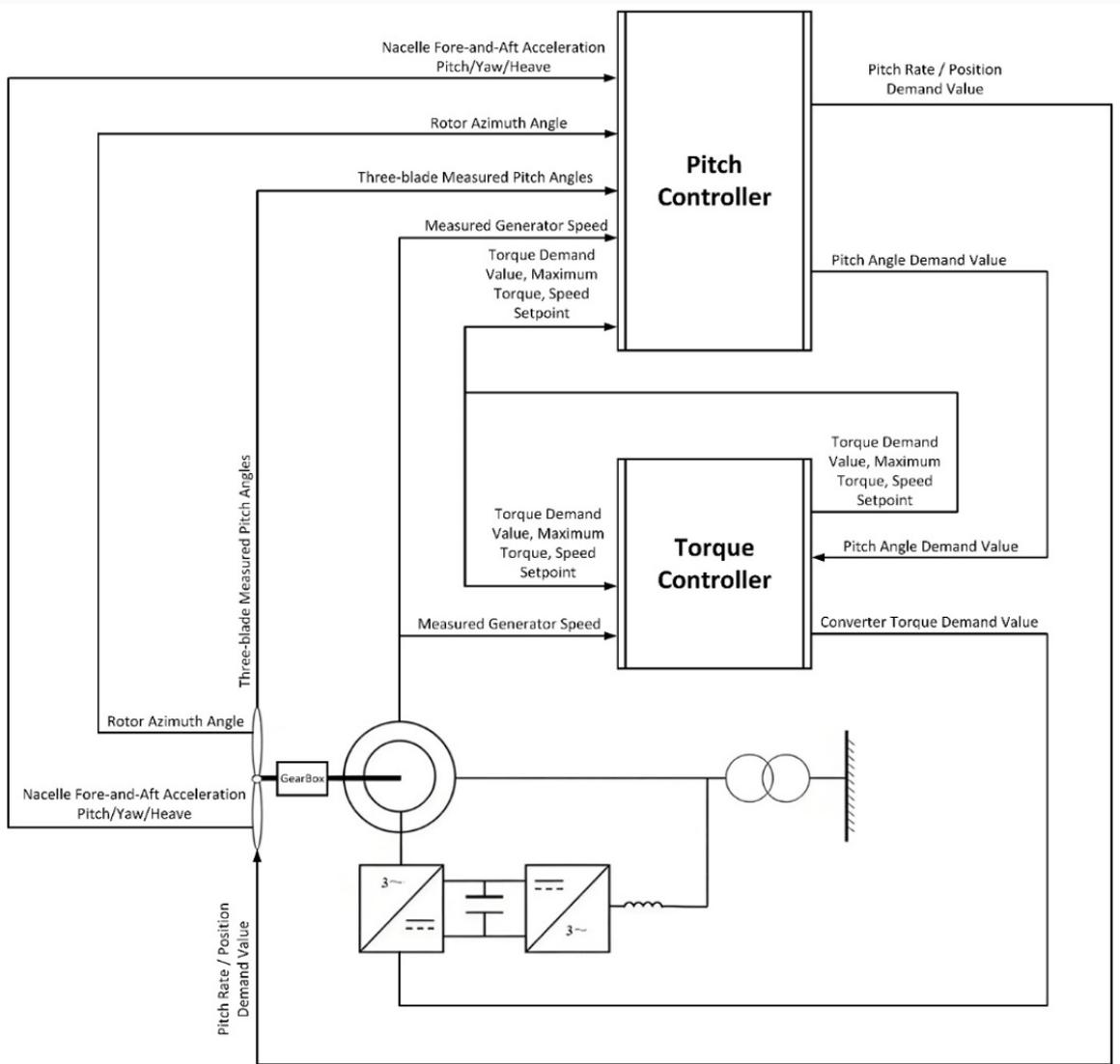


Figure 2 Closed-loop control block diagram of wind turbine generator system

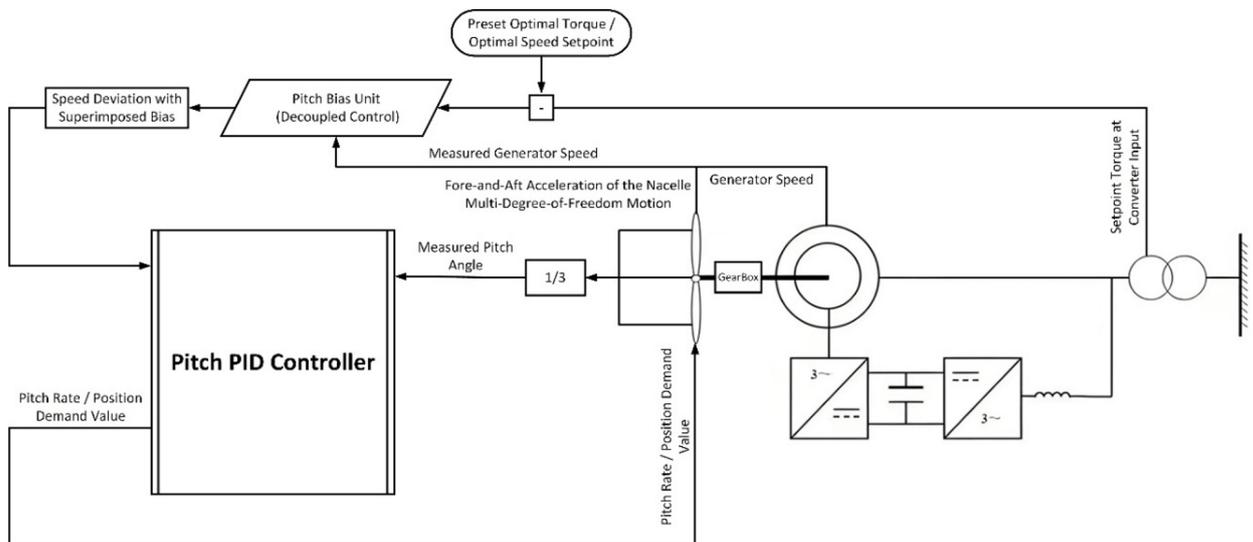


Figure 3 Block Diagram of Pitch Control Loop for Wind Turbine Generator System

to maintain a consistent rotational speed. Crucially, since both the torque control loop and the pitch control loop are engineered to stabilize rotational speed, they simultaneously adjust the pitch angle and torque. The interactions among these multiple variables can trigger mutual influences and even appear as interfering signals. Without achieving decoupled control, the effectiveness of closed-loop control is significantly undermined, negatively impacting rotational speed stability. In extreme scenarios, this may render the rotational speed regulation function ineffective, leading to substantial reductions (or severe fluctuations) in the wind turbine's output electrical power. Consequently, this can prompt erroneous operations in the float ballast water system, increase fatigue loads on relevant large components, and, over extended operational periods, shorten the service life of both the wind turbine and the float system.

3.2 Multi-Stage Adaptive Decoupling Control Strategy

Taking the pitch control loop shown in [Figure 3](#) as an illustrative case, as previously mentioned, when the wind speed exceeds the rated wind speed threshold, a pitch control strategy should be implemented. This strategy reduces the wind turbine's ability to capture wind energy by adjusting the pitch angle, thereby keeping the wind turbine's operational state close to the rated electrical power and rated rotational speed.

However, in real-world operational scenarios, due to the stochastic fluctuations in wind speed and direction, the measured rotational speed of the wind turbine oscillates around the rated rotational speed. Under such conditions, the bias output from the pitch bias unit struggles to consistently stay at zero, causing the rotational speed deviation input to the PID controller to become either excessively large or small. Owing to these ab-normal speed deviations, the pitch angle demand value output by the PID controller cannot be continuously maintained at the optimal pitch angle level. This deviation leads to significant reductions or pronounced oscillations in the wind turbine's output electrical power, adversely affecting the load conditions of the blade pitch system and the tower, while simultaneously reducing the overall electrical power generation capacity of the wind turbine.

Above the rated wind speed condition, theoretically, the torque demand of the wind turbines converter should remain constant at the rated torque value, with only the pitch control strategy being used to precisely fine-tune the pitch angle and decrease wind energy capture efficiency, thereby ensuring stable operation of the wind turbine at the rated electrical power and rated rotational speed. Nevertheless, near the rated wind speed, due to the randomness and unpredictability of variations in parameters such as wind speed, direction, and turbulence intensity, there is a possibility that the torque control loop may be inadvertently activated. At this point, the wind turbine will operate in a multivariable coupled control mode, which significantly undermines its operational efficiency and leads to substantial reductions (or severe fluctuations) in output electrical power.

Based on the aforementioned in-depth analysis, this chapter innovatively proposes a novel pitch bias unit. This unit can establish a multi-stage adaptive decoupling control strategy tailored for large-scale wind turbines by considering the real-time operational conditions of large-scale wind turbines and comprehensively assessing the impacts of wind conditions and multi-degree-of-freedom motion of the nacelle. The flowchart is depicted in [Figure 4](#).

Among them, the lower control level is tasked with managing real-time and localized control operations: Within this hierarchical framework, it executes amplitude limiting by analyzing the disparity between the actual torque output of the wind turbine's converter and the preset torque value, in conjunction with real-time deviations. This approach effectively mitigates measurement inaccuracies stemming from hardware limitations, thereby refining the initial bias setting for enhanced operational precision.

Conversely, the higher control level is dedicated to overarching system coordination and optimization: Under this system architecture, it undertakes a comprehensive assessment of the multidimensional influences exerted by prevailing wind conditions and turbine dynamics on electrical power generation. Specifically, leveraging the real-time torque deviation data previously mentioned, it utilizes specialized algorithms to precisely compute real-time gain coefficients. Subsequently, these real-time gain values, in conjunction with other external complex variables, serve as the foundation for in-depth optimization of the input parameters for the pitch PID controller. This holistic strategy ensures seamless integration between the actual operational environment of large-scale wind turbines and the pitch control loop, thereby guaranteeing stable and efficient system performance under diverse and challenging operating conditions.

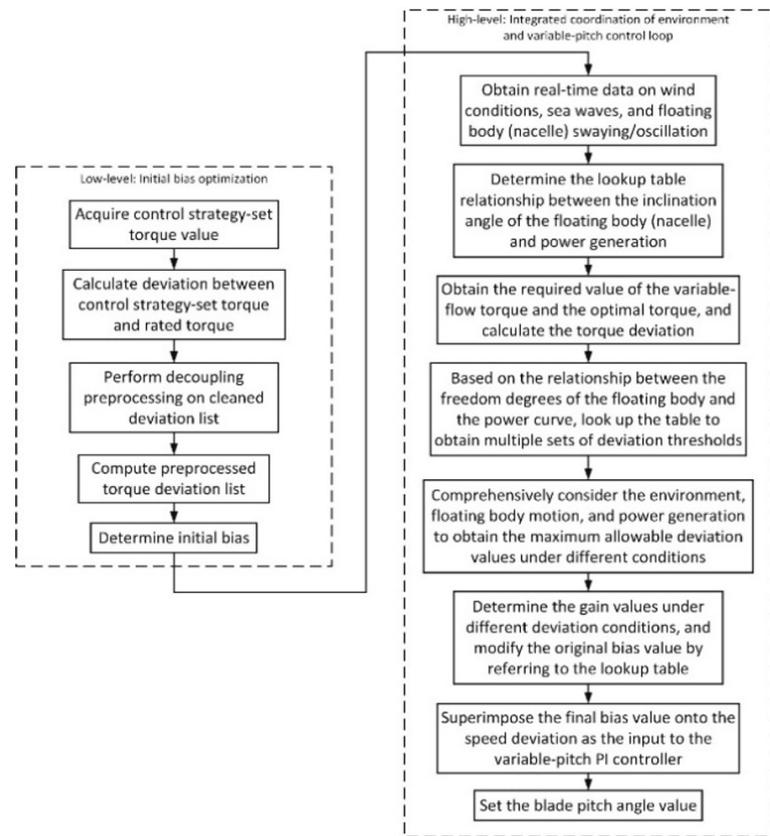


Figure 4 Flowchart of the multilevel adaptive decoupling control strategy

3.3 Adaptive Decoupling Control Strategy Based on Operating State

Through the implementation of the aforementioned multi-tiered optimization strategy, adaptive modulation of the output bias value is achieved in alignment with the operational status of the wind turbine, thereby effectively enhancing the stability of electrical power output characteristics. A detailed block diagram of the pitch bias unit, which employs an adaptive decoupling control strategy, is presented in [Figure 5](#).

The innovative features of the proposed methodology and its primary distinctions from existing technologies are delineated across the following three dimensions:

In-Depth Optimization and Enhancement of the Pitch Bias Unit: The proposed method introduces a comprehensive optimization and refinement of the pitch bias unit, as illustrated in [Figure 5](#). Traditional approaches typically rely on “external performance metrics (*e.g.*, rotational speed and output electrical power)”, which are susceptible to the interplay of various factors and form the basis for torque/pitch decoupling assessments. However, the stability and reliability of these parameters are often compromised. The proposed approach distinguishes itself by integrating more stable and reliable “internal transmission data (specifically, strategy-defined torque deviations)” into the evaluation index framework to enhance the precision of decoupling decisions.

Specifically, within the decoupling control process depicted in [Figure 5](#), the “direct deviation” between the demanded torque input value for the converter (or the torque setpoint directly output by the control strategy, which serves as the torque command received by the converter) and the rated torque (*i.e.*, the preset optimal torque) is initially computed with precision. Subsequently, saturation (or dead-zone) calculations are performed on this “direct deviation”, followed by a lookup table operation to derive the “raw deviation”, which serves as the initial reference point for decoupling.

Decoupling Preprocessing Grounded in Statistical Characteristics: In contrast to the conventional practice of directly executing decoupling control based on collected data, as observed

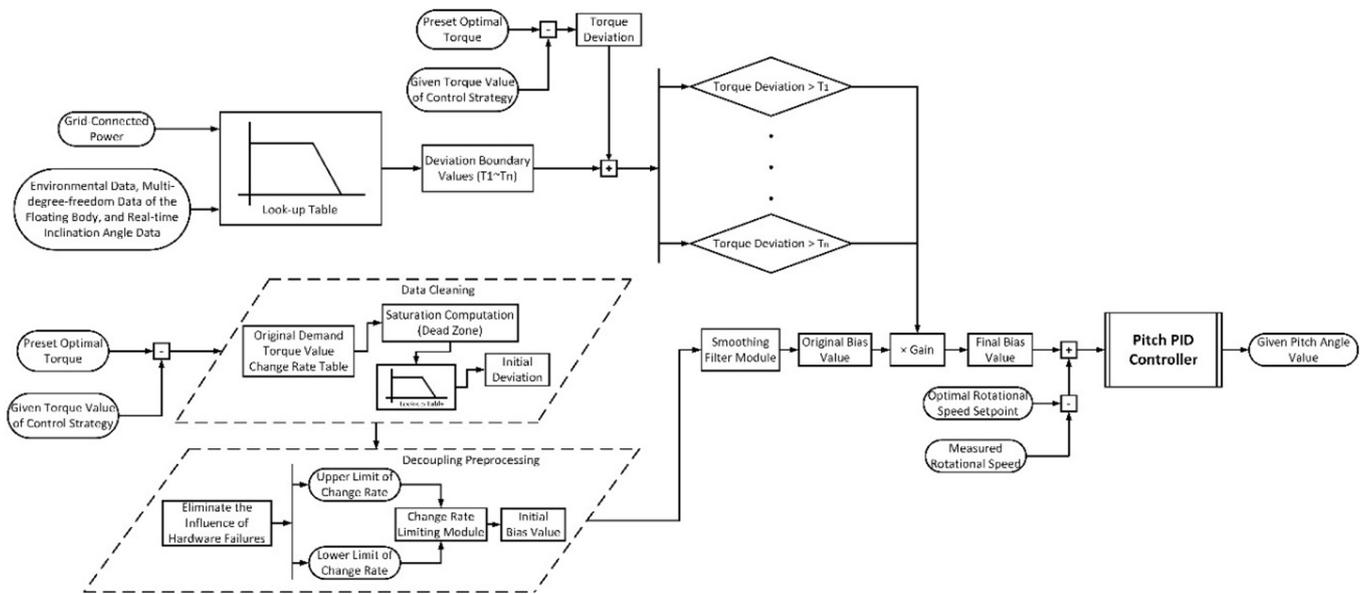


Figure 5 Block diagram of pitch bias unit (decoupling control)

in the aforementioned literature, the proposed method advances further. Beyond routine data cleansing (including filtering, saturation calculations, etc.), it undertakes decoupling preprocessing (*i.e.*, slew rate limiting) based on the fundamental statistical attributes of the deviation between the input torque demand value and the rated torque. The principal aim of this strategy is to comprehensively eliminate interference stemming from hardware factors and signal transmission processes, effectively preventing erroneous triggering of the control loop due to excessively large errors transmitted to the PID controller, thereby ensuring the stability and reliability of the control system.

The specific operational workflow is as follows: Following data cleansing of the “direct torque deviation”, the “initial deviation” is obtained. Subsequently, leveraging the time-series matrix of the “direct torque deviation”, its fundamental statistical outcomes are thoroughly computed to precisely filter out invalid data and scientifically establish the upper and lower bounds for slew rate limiting. After slew rate limiting, the “initial bias value” is derived, thereby overlooking torque surges or rapid drops induced by factors such as variations in wind speed and direction or measurement inaccuracies.

Comprehensive Consideration of Environmental Factors and Floater (Nacelle) Motion: The proposed method takes into full account the intricate impacts of environmental factors (*e.g.*, wind speed and direction) and floater (nacelle) motion on the output electrical power of wind turbines. Based on simulation outcomes from the model platform, the proposed method adaptively selects gain values and astutely incorporates them into the obtained bias values to accurately compute the optimal values, thereby enhancing the operational performance and output electrical power stability of wind turbines under diverse environmental conditions. The specific implementation steps are as follows: Initially, environmental data such as wind speed, waves, and floater inclination angles are correlated with the current electrical power generation to construct a correspondence table of environmental parameter/floater inclination angle-electrical power curves. Based on intervals of significant electrical power reductions, multiple sets of “deviation boundary thresholds” are defined, and “gain values” corresponding to these “deviation boundary values” are derived by comprehensively considering torque deviation factors. In accordance with the interval in which the torque deviation value resides, the “raw bias value” obtained in the previous step is adjusted to ultimately yield the “final bias value” with adaptive gain incorporated.

Subsequently, akin to the methodologies employed in other literature, the obtained “final bias value” is added to the corrected rotational speed deviation to form the input error for the pitch PID controller. This error is processed by the controller to derive the demanded pitch setting, which is then transmitted to the pitch actuator to achieve real-time dynamic adjustment of the pitch angle.

4 Case Studies

4.1 Verification of Output Bias Modification Through Parameter Adjustment

Based on the simulation outcomes for the 12 m/s sub-scenario within DLC1.3, targeted parameter adjustments were implemented to refine the output bias. By deliberately modifying the dataset to attenuate several prominent peaks in the bias time series, the rotational speed deviation input to the PID controller was consequently altered. The ensuing effects on pitch angle and electrical power output were meticulously verified, with the findings visually represented in the subsequent figures. The blue curve in each figure serves as the baseline for comparative analysis, whereas the red curve delineates the outcomes subsequent to parameter adjustment and modification.

Specifically, Figure 6 delineates the time-series comparison of pitch bias values prior to and following modification, offering insights into the alterations made to the bias dynamics. Figure 7 presents a time-series comparison of the ultimate rotational speed deviations input to the PID controller post-processing, highlighting the impact of bias adjustments on the controller's input parameters. Figure 8 displays the time-series comparison of the demanded pitch angles of the wind turbine, showcasing how parameter modifications influence the turbine's pitch control mechanism. Figure 9 illustrates the time-series comparison of the torque demands at the converter stage of the wind turbine, providing a perspective on how adjustments affect torque generation. Lastly, Figure 10 showcases the time-series comparison of the output electrical power of the wind turbine, ultimately demonstrating the effectiveness of parameter adjustments in optimizing electrical power output stability and performance.

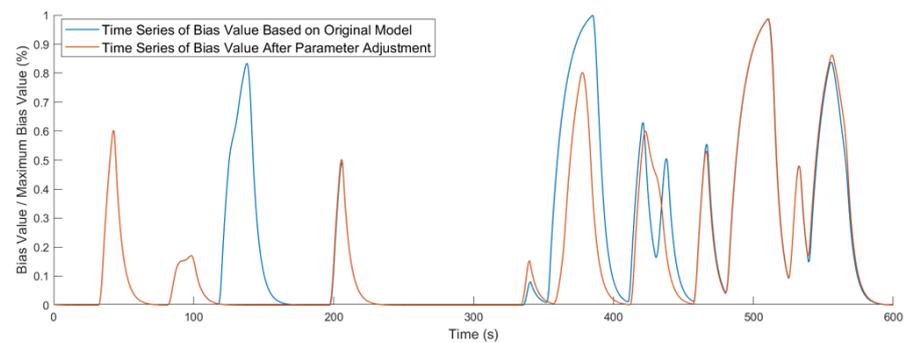


Figure 6 Time-Series Comparison of Pitch Bias Values Before and After Optimization Under Fluctuating Wind Conditions

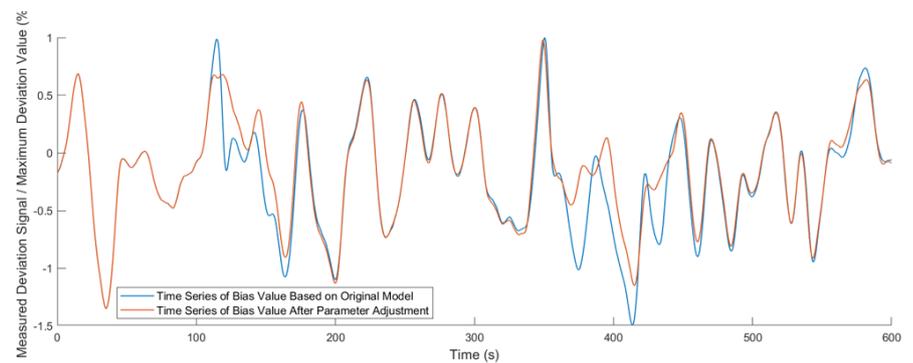


Figure 7 Time-Series Comparison of Final Rotor Speed Deviations Input to PID Controller Before and After Pitch Bias Unit Optimization

By comparing the simulation results based on the original bias control with those based on the parameter-adjusted and modified model, a detailed analysis was conducted on the simulation performance of controller input deviation, output electrical power, and output torque under different bias values. The specific results are as follows:

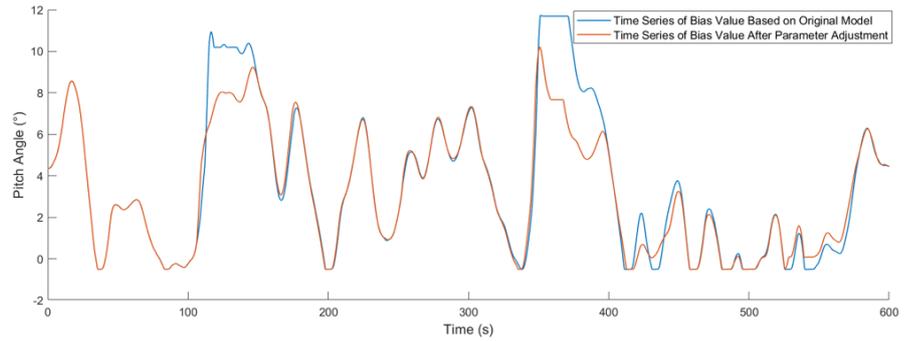


Figure 8 Time-Series Comparison of Required Pitch Angle Before and After Optimization of Pitch Bias Unit Under Fluctuating Wind Conditions

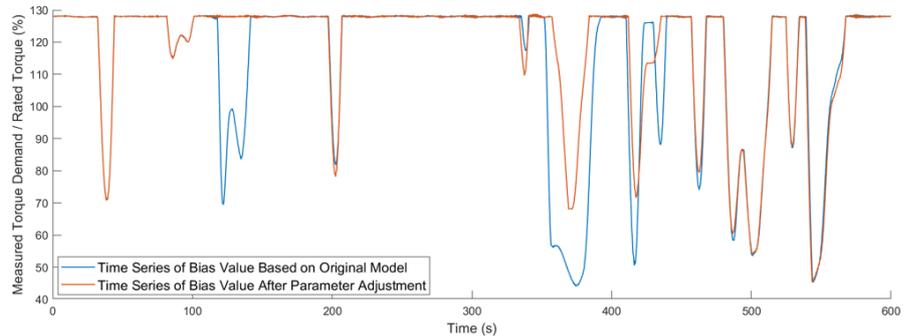


Figure 9 Time-Series Comparison of Converter-Stage Torque Demand Before and After Optimization of Pitch Bias Unit Under Variable Wind Conditions

(1) Changes in wind speed and direction may trigger significant drops or fluctuations in the out-put torque and electrical power of the wind turbine. In such cases, reducing the bias value of the wind turbine will correspondingly decrease the rotational speed deviation input to the PID controller.

(2) Due to the reduction in input error, the pitch demand of the wind turbine decreases, leading to a corresponding decrease in the demanded pitch angle of the wind turbine blades. The ultimate result is a relative reduction in the drop (fluctuation) amplitude of the wind turbine’s output torque and electrical power.

(3) Based on this experiment, the following conclusion can be drawn: If the bias value is reduced at the moment of a sharp increase in the deviation between the given torque and the rated torque, maintaining relatively stable input to the PID controller can reduce pitch adjustment actions, thereby effectively suppressing significant drops in output torque and electrical power while reducing the fatigue load on the wind turbine.

(4) Through multiple training sessions and simulation comparisons, the deviation boundary

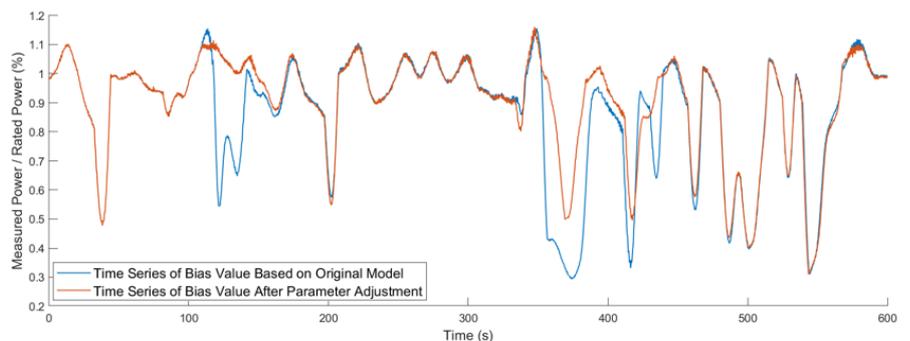


Figure 10 Time-Series Comparison of Wind Turbine Output Electrical Power Before and After Optimization of Pitch Bias Unit Under Fluctuating Wind Conditions

value sequences and gain value sequences for this model platform were statistically analyzed. By comparing the torque deviation-electrical power relationship and inclination angle-electrical power relationship under wind speeds near full load and employing specific algorithms, the optimal boundary value T and the corresponding gain value G for each interval were obtained. As an example, the time-series diagrams illustrating the relationships between torque deviation-electrical power drop, inclination angle-electrical power drop, and floater rotation-electrical power drop at an average wind speed of 12 m/s are shown in Figure 11.

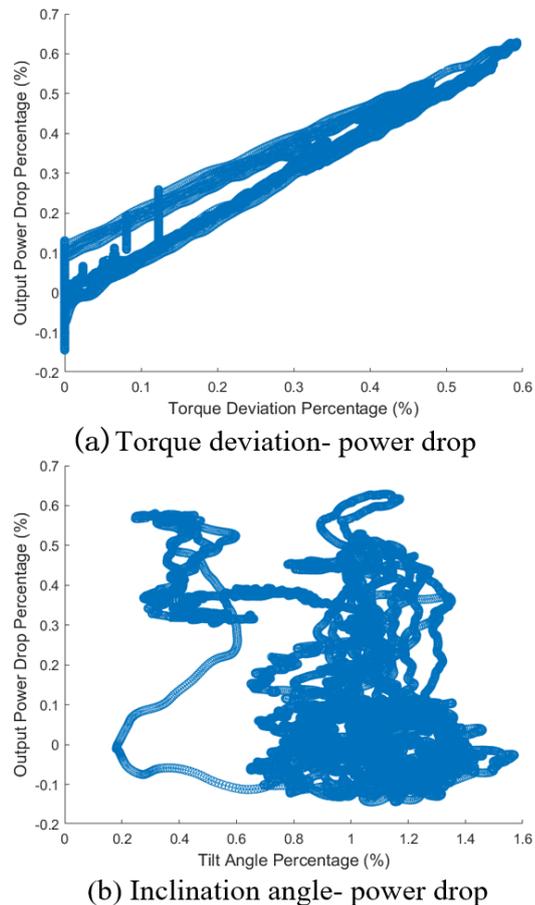


Figure 11 Relationship diagrams of: torque deviation-electrical power drop, inclination angle-electrical power drop

4.2 Simulation Verification of Adaptive Adjustment of Output Bias

The pitch bias unit shown in Figure 5 was incorporated into the pitch loop depicted in Figure 3 to achieve adaptive adjustment of the bias value according to the wind turbine's operating conditions. This adaptive modification adjusts the rotational speed deviation input to the PID controller, thereby reducing pitch angle elevation. The results are presented below. Taking the 12 m/s sub-condition of DLC1.3 as an example, Figure 12 shows the simulation wind speed time series diagram; Figure 13 presents the comparison chart of the original and adaptively modified bias time series; Figure 14 displays the comparison chart of the original versus adaptively modified final speed deviation time series input to the PID controller; and Figure 15 illustrates the comparison chart of the original versus adaptively modified blade pitch angle time series.

4.2.1 Comparison of Converter Torque Demand Before and After Adaptive Adjustment

Under the same operating conditions, the time series comparison of the torque demands at the converter stage of the wind turbine before and after adaptive modification is shown in Figure 16, with statistical results presented in Table 1.

As shown in the figure and table above, compared to the original task, the adaptive bias

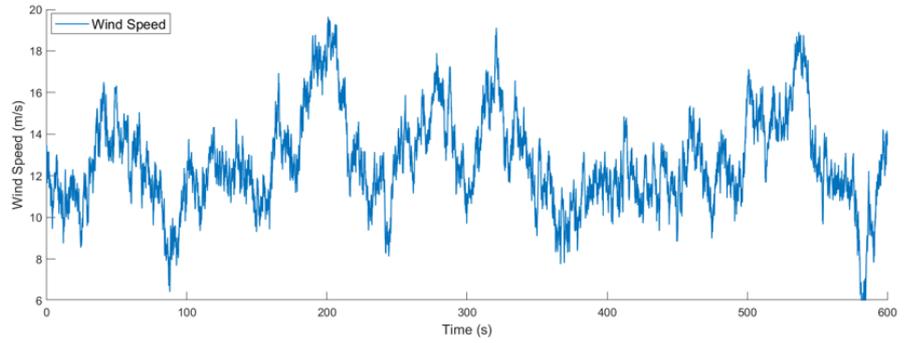


Figure 12 Wind Speed Time Series Diagram

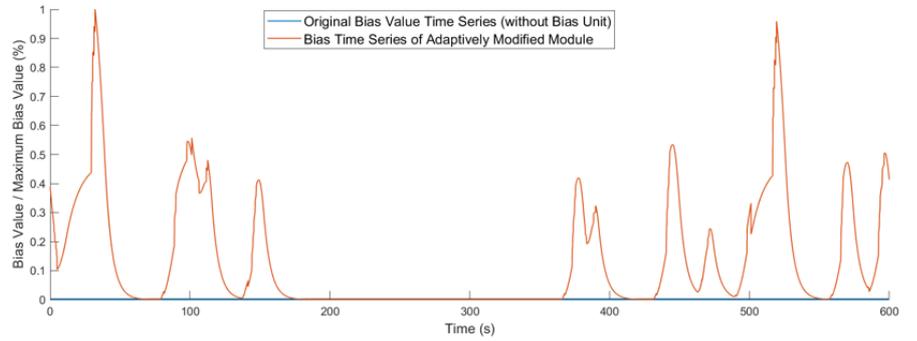


Figure 13 Comparison Chart of Original and Adaptively Modified Bias Time Series

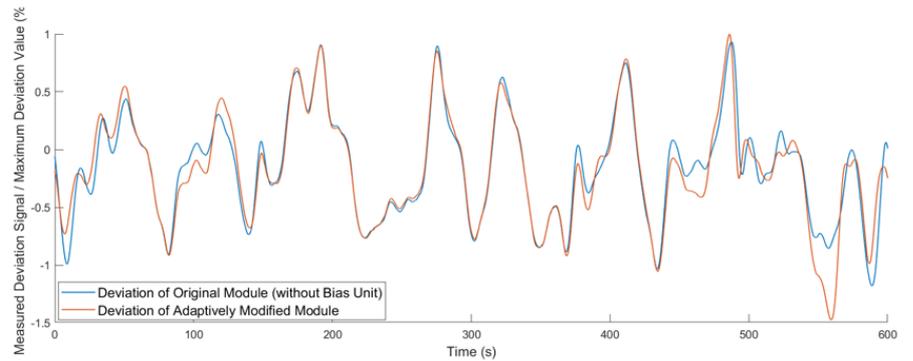


Figure 14 Comparison Chart of Original vs. Adaptively Modified Final Speed Deviation Time Series Input to the PID Controller

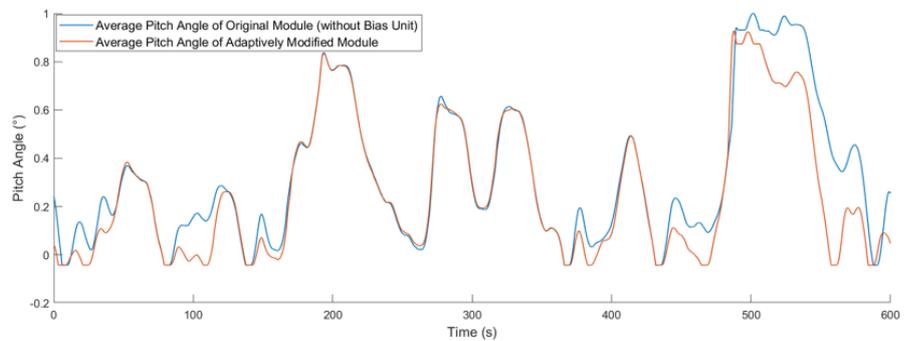


Figure 15 Comparison Chart of Original vs. Adaptively Modified Blade Pitch Angle Time Series

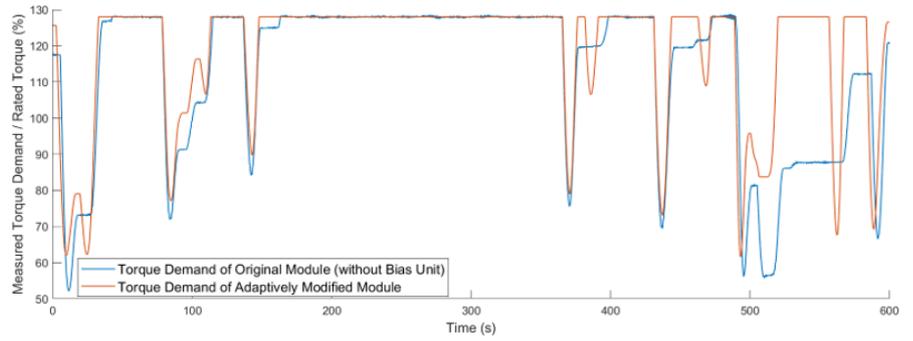


Figure 16 Comparison Chart of Original vs. Adaptively Modified Converter Torque Demand Time Series

Table 1 Statistical analysis of converter-end torque demand before and after adaptive modification for the wind turbine

Method	Variable	Max (%)	Min (%)	Mean (%)	SD (%)
Adaptive Bias	Torque Demand	99.46	118.27	104.64	83.95
Original	Torque Demand	100	100	100	100

adjustment strategy can reduce torque drops by more than 18%, effectively mitigating torque drops and enhancing wind turbine safety. For the full operating condition of DLC1.3, from cut-in wind speed to cut-out wind speed, the torque demands at the converter stage of the wind turbine under the adaptive bias adjustment strategy and the original method were statistically analyzed, as shown in Figure 17. Among them, (a) shows the comparison of maximum torque demands; (b) shows the comparison of minimum torque demands; (c) shows the comparison of average torque demands; and (d) shows the comparison of standard deviations of torque demands.

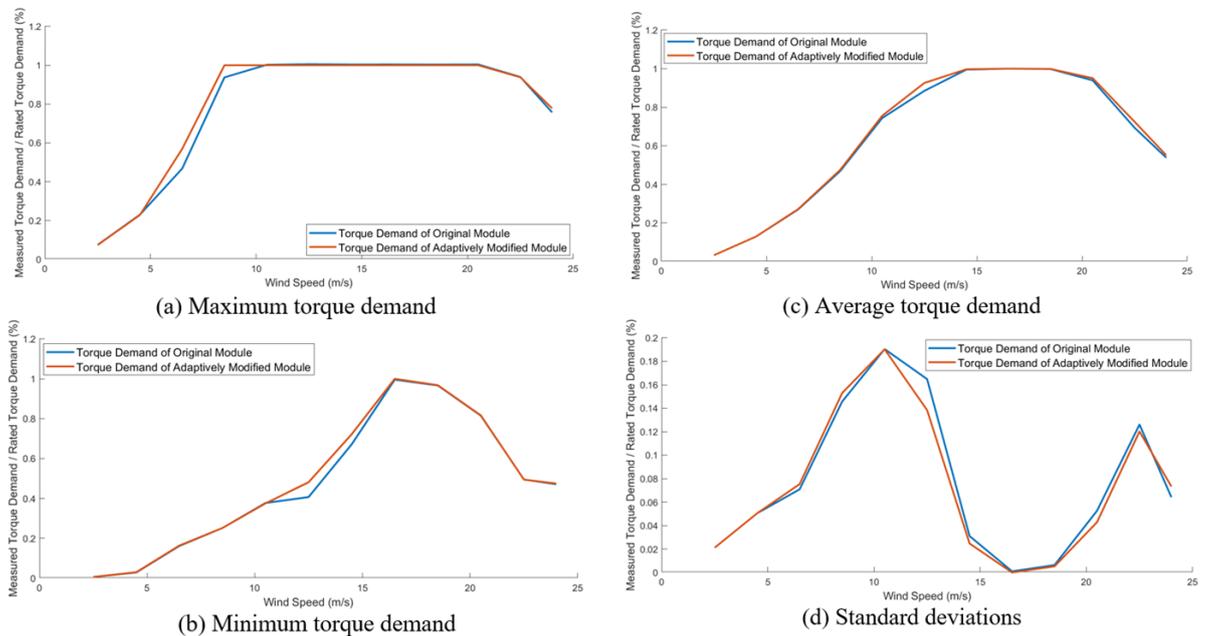


Figure 17 Statistical Results of Torque Demand Under DLC1.3 Based on Different Control Methods

As depicted in the figure above, the adaptive bias adjustment strategy results in higher maximum, minimum, and average torque demands at the converter stage near full load compared to the original control method. Furthermore, the standard deviation of torque demands is lower than that under the original control method, indicating that the proposed adaptive bias adjustment strategy can reduce torque drops near full load and minimize torque fluctuations, which is more favorable for the main shaft and converter, thereby extending the wind turbine’s lifespan.

4.2.2 Comparison of Electrical Power Before and After Adaptive Adjustment

Under the same operating conditions, the time series comparison of the electrical power before and after adaptive modification is shown in Figure 18, with statistical results presented in Table 2.

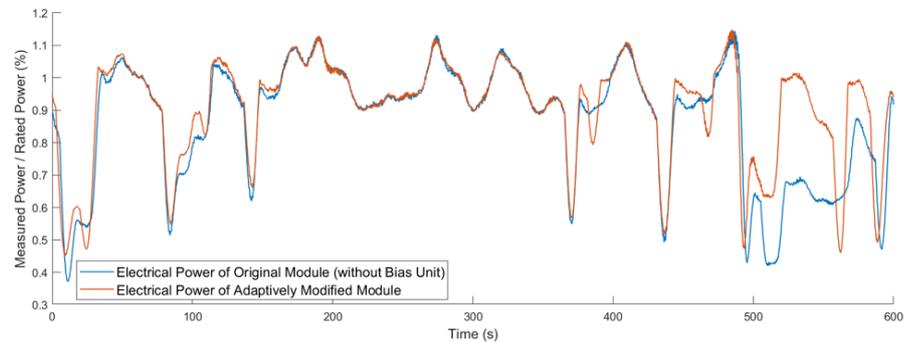


Figure 18 Comparison of Electrical Power Time Series: Original vs. Adaptively Modified Control

Table 2 Statistical analysis of wind turbine generator output electrical power before and after adaptive control modification

Method	Variable	Max (%)	Min (%)	Mean (%)	SD (%)
Adaptive Bias	Electrical power	100.38	116.21	100.75	94.48
Original	Electrical power	100	100	100	100

It is particularly noteworthy that a significant wind speed surge was observed between 500 seconds and 600 seconds, as shown in Figure 12, where the average wind speed rapidly increased from 12 m/s to 19 m/s. Further analysis of the electrical power time series curve in Figure 18 reveals a noticeable drop in electrical power output during this period, which could not be effectively improved even with the optimized decoupling strategy.

The reason for this is that the rapid increase in wind speed triggered the wind turbine’s gust protection function during this timeframe. As seen in Figure 15, the pitch angle of the wind turbine blades was significantly adjusted (elevated by 1°), and the simulation fault records indicate that the radar pitch limit function was activated, leading to a decrease in electrical power output. This phenomenon is a normal protection mechanism implemented by the wind turbine to ensure safe operation.

As shown in the figure and table above, compared to the original task, the adaptive bias adjustment strategy can reduce output electrical power drops by more than 16%, effectively mitigating output electrical power drops and enhancing wind turbine safety. For the full operating condition of DLC1.3, from cut-in wind speed to cut-out wind speed, the output electrical power of the wind turbine under the adaptive bias adjustment strategy and the original method were statistically analyzed, as shown in Figure 18. Among them, (a) shows the comparison of maximum output electrical power; (b) shows the comparison of minimum output electrical power; (c) shows the comparison of average output electrical power; and (d) shows the comparison of standard deviations of output electrical power. The relationship between wind speed and wind turbine output electrical power before and after adaptive modification is shown in Figure 19.

As depicted in the figure above, the adaptive bias adjustment strategy results in higher maximum, minimum, and average output electrical power near full load compared to the original control method. Furthermore, the standard deviation of output electrical power is lower than that under the original control method, indicating that the adaptive method shown in Figure 20 can dynamically regulate the output bias, adaptively correct the bias value according to the wind turbine’s actual operating conditions, and thereby adaptively adjust the rotational speed deviation input to the PID controller. The experimental results strongly confirm that this method can effectively suppress output torque and electrical power drops caused by significant changes in wind speed and direction.

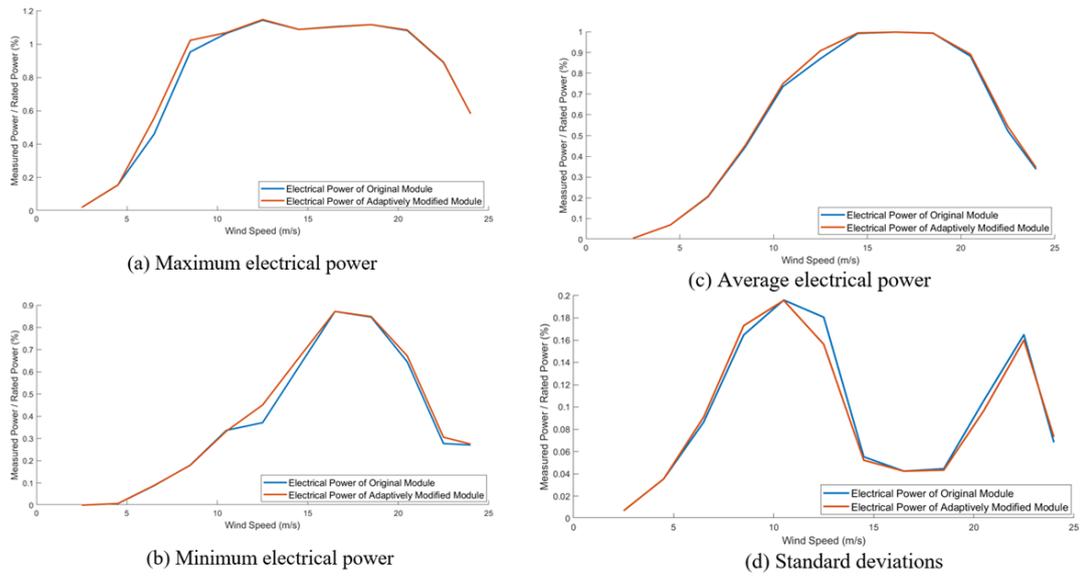


Figure 19 Statistical results of electrical power under DLC1.3 based on different control methods

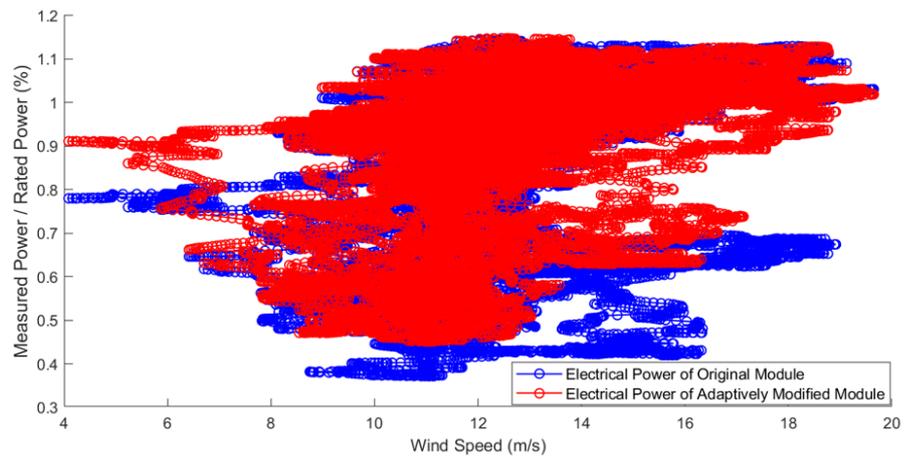


Figure 20 Relationship Diagram Between Wind Speed and Electrical Power: Original vs. Adaptively Modified Control

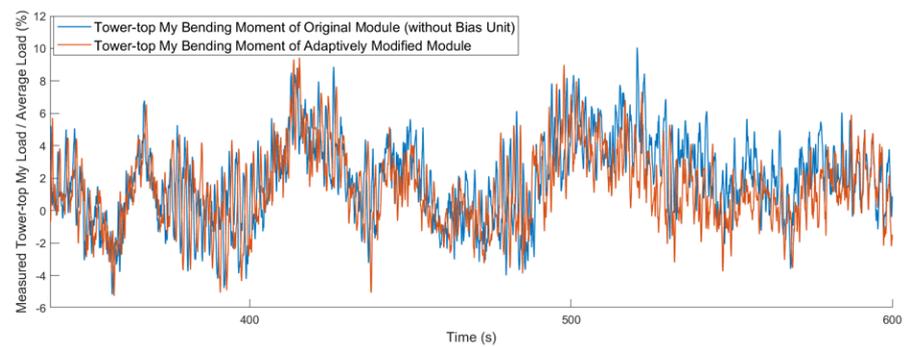


Figure 21 Comparison of Tower-Top My Bending Moment Time Series: Original vs. Adaptively Modified Control

4.2.3 Comparison of Tower-Top My Bending Moment Before and After Adaptive Adjustment

Under the same operating conditions, the time series comparison of the tower-top My bending moment of the wind turbine before and after adaptive modification is shown in Figure 21, with statistical results presented in Table 3.

Table 3 Statistical Analysis of Tower-Top My Bending Moment Load Before and After Adaptive Control Modification

Method	Variable	Max (%)	Min (%)	Mean (%)	SD (%)
Adaptive Bias	Tower-Top My Bending Moment	91.31	93.75	76.69	94.44
Original	Tower-Top My Bending Moment	100	100	100	100

As shown in the figure and table above, compared to the original task, the adaptive bias adjustment strategy can reduce the tower-top My bending moment by more than 20% on average, effectively mitigating the tower-top My fatigue load, enhancing wind turbine stability, and extending the lifespan of major components. For the full operating condition of DLC1.3, from cut-in wind speed to cut-out wind speed, the tower-top My bending moment of the wind turbine under the adaptive bias adjustment strategy and the original method were statistically analyzed, as shown in Figure 22. Among them, (a) shows the comparison of maximum tower-top My bending moments; (b) shows the comparison of minimum tower-top My bending moments; (c) shows the comparison of average tower-top My bending moments; and (d) shows the comparison of standard deviations of tower-top My bending moments.

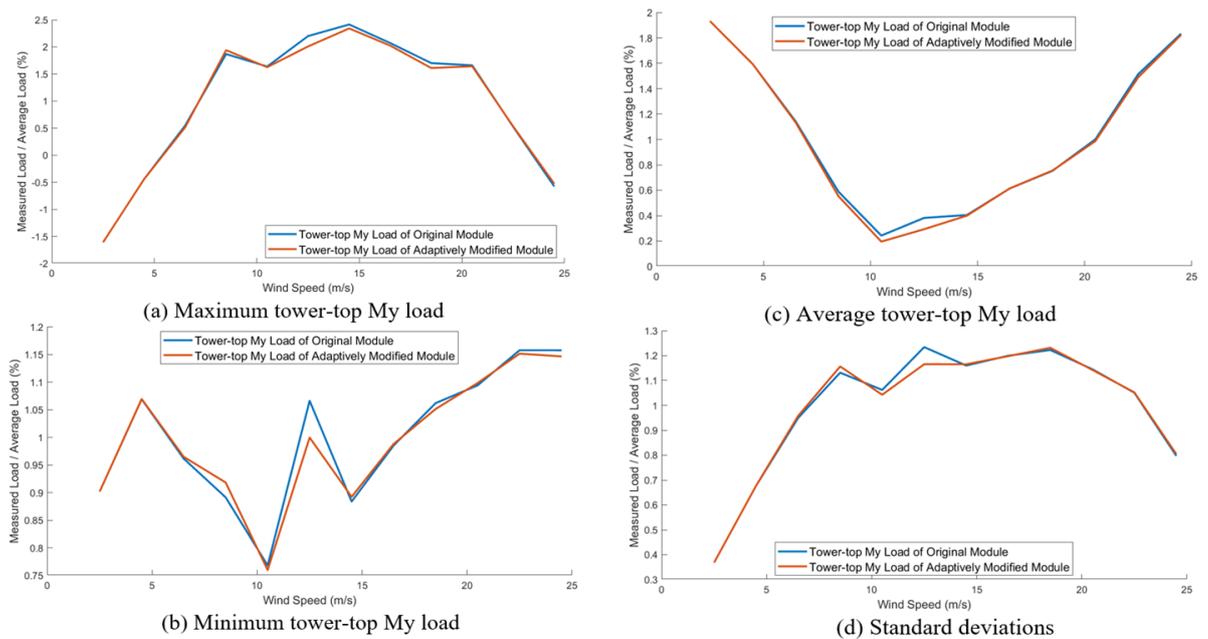


Figure 22 Statistical Results of Tower-Top My Bending Moment Under DLC1.3 Based on Different Control Methods

As depicted in the figure above, the adaptive bias adjustment strategy results in lower maximum, minimum, average, and standard deviation values of the tower-top My bending moment near full load compared to the original control method, indicating that the proposed adaptive bias adjustment strategy can reduce the tower-top My bending moment near full load, which is conducive to extending the wind turbine’s lifespan.

4.2.4 Comparison of Fatigue and Extreme Loads Before and After Adaptive Adjustment

The fatigue loads on key components of the wind turbine before and after the adoption of the adaptive control strategy are presented in Table 4. Furthermore, the proposed method can reduce not only fatigue loads but also extreme loads. The statistical results of extreme loads under the DLC1.3 operating condition are shown in Table 5.

Table 4 Statistical Analysis of the Fatigue Loads Before and After Adaptive Modification ($m = 10$)

Control Method	Tower-Top My (%)	Blade Root My (%)
Adaptive Bias	92.05	98.26
Original	100	100

Table 5 Comparison of Ultimate Loads on Major Components Before and After Adaptive Adjustment Under DLC1.3

Control Method	Tower-Top My (%)	Yaw My (%)
Adaptive Bias	97.39	97.41
Original	100	100

As shown in Tables 4 and 5, based on the current parameters of blades and towers, the adaptive bias method can reduce the fatigue loads on the tower My and blade root My by 2%–8%. Additionally, it can reduce the extreme loads on the tower-top My, yaw My, and blade root Mz by 3% (under the DLC1.3). Note: In addition to the aforementioned directions, the proposed adaptive control method also has a slight load-reducing effect on other directions.

5 Conclusion

The operational environment of wind turbines is intricate, characterized by highly unpredictable wind conditions. Offshore wind farms display non-stationary and non-Gaussian turbulent traits influenced by a multitude of factors. When compared to onshore fixed wind turbines, offshore wind turbines are subjected to more intense fluctuations in wind speed and shifts in direction, leading to pronounced coupled effects on output electrical power. During actual operation, random wind conditions induce significant fluctuations in generator speed of the wind turbine, posing challenges in maintaining stability.

Traditional pitch bias wind turbines, with their fixed parameters, find it difficult to sustain a stable bias value near zero, causing the rotational speed deviation signal of the PID controller to oscillate periodically with excessive amplitude. This results in high-frequency and large-amplitude oscillations in the demanded pitch angle, subsequently causing sharp drops and fluctuations in the output electrical power of wind turbines, with peak fluctuations reaching 25% to 30% of the rated electrical power and exhibiting a wide frequency spectrum. To tackle this issue, this paper introduces an adaptive control wind turbine for pitch bias based on multi-modal perception.

It constructs a multi-parameter coupling model and makes online adjustments to it. The innovation lies in the incorporation of wind condition and state detection, enabling swift adjustments to the bias output value in accordance with the state of the wind turbines. Simulation and actual measurements reveal that this method reduces electrical power fluctuations by 62%, increases the minimum output value by 18%, enhances the economic efficiency of wind farms, and ensures the long-term reliable operation of wind turbines.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

References

- [1] Avarzaman HA, Manzar MN, Badri V. Tuning Variable Speed Wind Turbine Controller Using a Data-Driven Approach: The TD3 Reinforcement Learning Algorithm. 2025 12th Iranian Conference on Renewable Energies and Distributed Generation (ICREDG). IEEE, 2025: 1-6. <https://doi.org/10.1109/icredg66184.2025.10966086>
- [2] Nyoni KJ, Maronga A, Tuohy PG, et al. Hydro-Connected Floating PV Renewable Energy System and Onshore Wind Potential in Zambia. *Energies*. 2021, 14(17): 5330. <https://doi.org/10.3390/en14175330>
- [3] Khan Afridi S, Ali Koondhar M, Ismail Jamali M, et al. Winds of Progress: An In-Depth Exploration of Offshore, Floating, and Onshore Wind Turbines as Cornerstones for Sustainable Energy Generation

- and Environmental Stewardship. *IEEE Access*. 2024, 12: 66147-66166.
<https://doi.org/10.1109/access.2024.3397243>
- [4] Kennedy IR, Hodzic M, Crossan AN, et al. Estimating Maximum Power from Wind Turbines with a Simple Newtonian Approach. *Archives of Advanced Engineering Science*. 2023, 1(1): 38-54.
<https://doi.org/10.47852/bonviewaaes32021330>
- [5] Yuan J, Cheng Z, Liu D. Design of Variable Pitch Control Method for Floating Wind Turbine. *Energies*. 2023, 16(2): 821.
<https://doi.org/10.3390/en16020821>
- [6] Pham TD, Dinh MC, Kim HM, et al. Simplified Floating Wind Turbine for Real-Time Simulation of Large-Scale Floating Offshore Wind Farms. *Energies*. 2021, 14(15): 4571.
<https://doi.org/10.3390/en14154571>
- [7] Hall M, Buckham B, Crawford C. Hydrodynamics-based floating wind turbine support platform optimization: A basis function approach. *Renewable Energy*. 2014, 66: 559-569.
<https://doi.org/10.1016/j.renene.2013.12.035>
- [8] Luo X. An individual pitch control method for floating offshore wind turbine. *Journal of Physics: Conference Series*. 2022, 2276(1): 012032.
<https://doi.org/10.1088/1742-6596/2276/1/012032>
- [9] Wei J, Li Y, Peng H, et al. Optimal Power Control in Wind Farms for Gearbox Load Reduction. *IEEE Transactions on Sustainable Energy*. 2025, 16(3): 1990-2001.
<https://doi.org/10.1109/tste.2025.3543186>
- [10] Batablinè L, Bazyomo SD, Badou FD, et al. Climate, water, hydropower, wind speed and wind energy potential resources assessments using weather time series data, downscaled regional circulation models: A case study for Mono River Basin in the Gulf of Guinea region. *Renewable Energy*. 2024, 224: 120099.
<https://doi.org/10.1016/j.renene.2024.120099>
- [11] Al-Barashi M, Wang Y, Tang Z, et al. Variable Speed Wind Turbine Control System with Doubly-Fed Induction Generator. 2025 International Conference on Electrical Automation and Artificial Intelligence (ICEAAI). Published online January 10, 2025: 361-367.
<https://doi.org/10.1109/iceaaai64185.2025.10956445>
- [12] Kim D, Jeon T, Paek I, et al. A Study on the Improved Power Control Algorithm for a 100 kW Wind Turbine. *Energies*. 2023, 16(2): 619.
<https://doi.org/10.3390/en16020619>
- [13] Basheer AA, Jeong JH, Lee SR, et al. Power Maximization Using Finite-Control-Set Model Predictive Control Strategy for Wind Turbine Systems. *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*. 2025, 6(1): 238-247.
<https://doi.org/10.1109/jestie.2024.3502658>
- [14] Jara Ávila FJ, Verstraeten T, Daems PJ, et al. A Methodology for Turbine-Level Possible Power Prediction and Uncertainty Estimations Using Farm-Wide Autoregressive Information on High-Frequency Data. *Energies*. 2025, 18(14): 3764.
<https://doi.org/10.3390/en18143764>
- [15] Macquart T, Maheri A, Busawon K. A decoupling control strategy for wind turbine blades equipped with active flow controllers. *Wind Energy*. 2016, 20(4): 569-584.
<https://doi.org/10.1002/we.2024>
- [16] Jabr AA, Sultan AJ, Wali MK. Optimum Design of Doubly Fed Induction Generator for Wind Turbine System. *AIP Conference Proceedings*. AIP Publishing LLC. 2023, 2804(1): 050038.
<https://doi.org/10.1063/5.0154858>
- [17] Gambier A. Control of Large Wind Energy Systems Throughout the Shutdown Process. *Machines*. 2024, 12(10): 726.
<https://doi.org/10.3390/machines12100726>
- [18] Guo H, Lao KW, Hao J, et al. Wind Power Short-Term Prediction Method Based on Time-Domain Dual-Channel Adaptive Learning Model. *Energies*. 2025, 18(14): 3722.
<https://doi.org/10.3390/en18143722>
- [19] Efstathiou C, Tsormpatzoglou I, Tapoglou N. Parametric Modeling of Curvic Couplings and Analysis of the Effect of Coupling Geometry on Contact Stresses in High-Speed Rotation Applications. *Machines*. 2023, 11(8): 822.
<https://doi.org/10.3390/machines11080822>
- [20] Mannepalli K, Singh SP, Kolli CS, et al. Popularity Prediction Model With Context, Time and User Sentiment Information: An Optimization Assisted Deep Learning Technique. *International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems*. 2023, 31(02): 283-302.
<https://doi.org/10.1142/s0218488523500150>
- [21] Wang JS, Ning CX, Yang Y. Multivariable PID Decoupling Control Method of Electroslag Remelting Process Based on Improved Particle Swarm Optimization (PSO) Algorithm. *Information*. 2014, 5(1): 120-133.
<https://doi.org/10.3390/info5010120>
- [22] Farfan AJU, Plata EAC, Tacca HE. A Theoretical Approach for the Evaluation of the Power at Polyphase Electrical Networks. *Electric Power Components and Systems*. 2011, 39(9): 917-932.
<https://doi.org/10.1080/15325008.2010.549546>
- [23] Zhou X, Yang J, Migliazza G, et al. Improved Speed Extension for Permanent Magnet Synchronous Generators by Means of Winding Reconfiguration. *Energies*. 2023, 16(2): 899.
<https://doi.org/10.3390/en16020899>