Comparative Review of Pitch Control Strategies for Wind Turbine

Weidong Liu*

School of Electrical Engineering and Artificial Intelligence, Xiamen University Malaysia,
Sepang, 43900, Malaysia

*EEE2209298@xmu.edu.my

Abstract

Wind power generation is the core field of global energy transformation, and variable pitch control system is the key link to ensure the efficient and safe operation of modern wind turbine. This paper first describes the basic principle and system composition of pitch control. Then, the application and evolution of traditional control strategies and modern advanced strategies in pitch control are summarized. In the part of research progress, the latest achievements of advanced technologies such as intelligent optimization algorithm fusion and laser wind measurement feedforward control in recent years are mainly summarized. Finally, the paper looks forward to the development trend of "intelligent + feedforward" integration of pitch control in the future, in order to provide theoretical basis and technical reference for building a more safe, efficient and intelligent wind power generation system.

Keywords

Wind Power Generation; Pitch Control Strategy; Control System; Feedforward Control; Intelligent Algorithm.

1. Introduction

Wind power generation is leading the reform of renewable energy, constantly breaking records and promoting cleaner power production. According to the research report released by energy think tank ember in 2023, wind power generation increased by 10% year-on-year, accounting for 18% of the total electricity in the European Union, about 475 TWH, equivalent to the annual electricity demand in France, setting a record high. This is also the first time that the proportion of wind power generation exceeds that of natural gas.

With the rapid development of wind power technology, the pitch control system in modern wind turbines has become the core component to ensure the efficient operation of wind turbines because of its key role in capturing the maximum wind energy and dynamic load control. However, due to the complex operating environment and harsh working conditions, the pitch control system has become one of the components with the most frequent degradation and the highest failure rate in wind turbines. Pitch control strategy is the key to ensure the efficiency and reliability of the pitch control system under complex conditions. Aiming at the problem of wind turbine pitch control strategy, this paper summarizes the research status of related technologies at home and abroad, analyzes the control objectives, algorithms, prospects and other aspects, and looks forward to the development prospect of wind power control technology in the future.

2. Basic Concepts and System Characteristics of Wind Turbine Pitch Control

2.1 Working Principle and Control Objectives of Pitch Control

With the continuous expansion of the single unit capacity of wind turbines and the scale of wind farms, higher performance requirements are put forward for the operation control system of wind turbines. In this context, the pitch control system, as the core subsystem of modern high-power wind turbine, has key significance in improving the utilization rate of wind energy and ensuring the operation safety. Its basic function is to realize the dynamic optimal control of wind energy capture efficiency, power output and mechanical load level by adjusting the angle between the wind turbine blade and the incoming wind direction in real time, that is, the pitch angle. Especially in the area where the wind speed exceeds the rated value, pitch control is the key technical means to maintain the constant output of the generator, avoid overload operation and reduce structural fatigue.

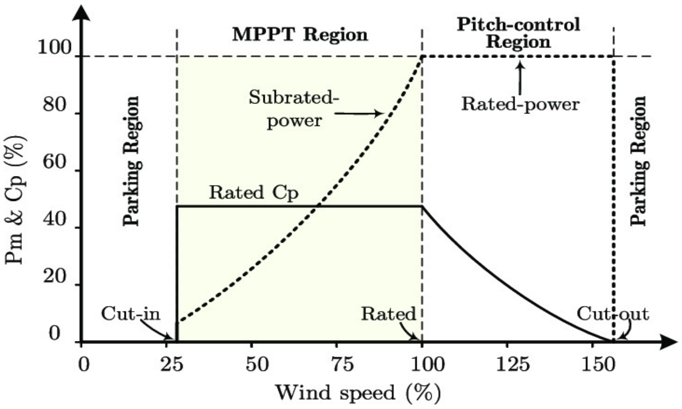

Figure 1. Operating regions of a typical wind turbine. Adapted from [1].

As shown in Figure 1, the operation of a modern wind turbine is typically divided into three main regions depending on the wind speed, as illustrated in [1]. These regions include: parking region (Region I), where the wind speed is cut into the rated wind speed; the maximum power point tracking (MPPT) control region (Region II), where the wind speed is close to the rated wind speed; and pitch control region (Region III), where the wind speed is higher than the rated wind speed. In region II, the control objective is to maintain the optimal tip speed ratio to achieve maximum MPPT, which mainly depends on the variable speed control strategy. In region III, as the wind speed continues to rise, the aerodynamic torque of the wind turbine increases significantly. It is necessary to adjust the pitch angle to reduce the angle of attack, so as to limit the output power and reduce the blade load synchronously, so as to maintain the output stability and prolong the service life of the unit.

In general, in order to meet the control requirements of different operating conditions, modern pitch controllers usually need to have the following three core functions: constant power control: when the wind speed exceeds the rated value, the control system needs to maintain the generator output power at the rated level; Load suppression control: in the face of gust, wind shear, tower shadow effect and other disturbances, the impact load is reduced by rapidly adjusting the pitch angle to reduce the structural burden; Safety protection control: in case of extreme wind conditions, emergency shutdown or system failure, the controller needs to rapidly rotate the blade to the "feather" state to minimize the windward force and ensure the safe operation of the unit.

2.2 Control System Structure and Actuator Type

A typical pitch control system architecture is illustrated in Figure 2, which consists of controller, sensor and actuator. The controller calculates and outputs the target pitch angle according to the running state of the fan and the control target; The sensor provides necessary measurement signals, such as wind speed, rotating speed and output power; The actuator is responsible for rotating the blade to the target angle.

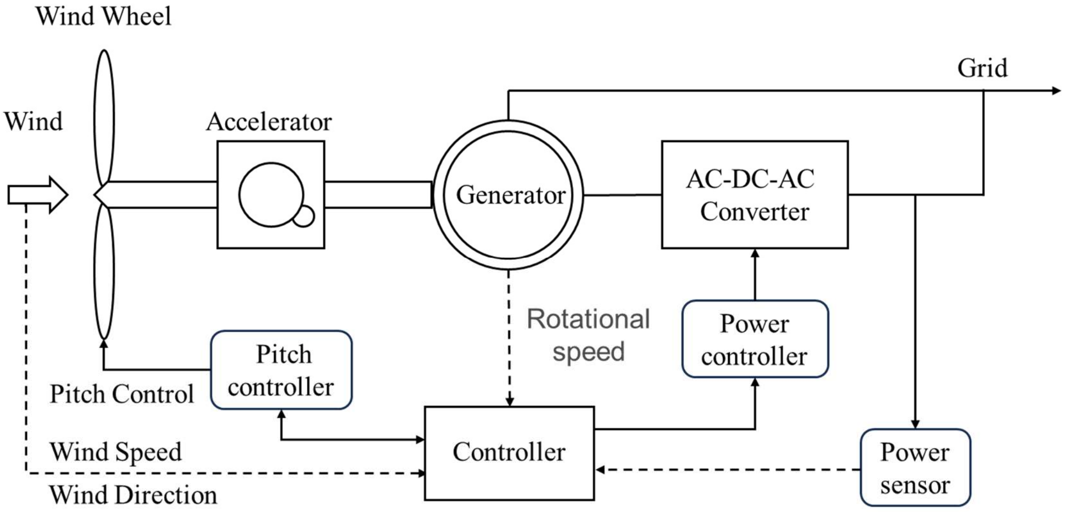

Figure 2. System architecture of a wind turbine pitch control system.

At present, the pitch drive system of wind turbines mainly consists of two types: electric and hydraulic. These systems differ significantly in their driving mechanisms, performance characteristics, maintenance requirements, and system reliability, as summarized in Table 1.

Table 1. Comparison of electric and hydraulic pitch.

Aspect	Electric Pitch System	Hydraulic Pitch System
Driving Mechanism	Motor + Gear mechanism	Hydraulic pump + Cylinder
Advantages	- Simple structure - High control accuracy - Easy maintenance	- High output torque - Fast response
Disadvantages	- Limited torque for high-power turbines - Requires UPS to avoid power failure issues	- Risk of hydraulic leakage - Complex maintenance
Transmission Mechanism	Pitch bearing + Gear rack or Gearbox	Pitch bearing + Hydraulic cylinder

The electric pitch system is driven by motor and gear mechanism, which has the advantages of simple structure, high control accuracy and convenient maintenance, so it has been widely used in modern wind turbines. However, in high-power fans, the electric system may have the problem of insufficient driving torque, so uninterruptible power supply (UPS) needs to be configured additionally to prevent control failure caused by power interruption and ensure the safe operation of the system.

In contrast, the hydraulic pitch system is driven by hydraulic pump station and oil cylinder, which has the advantages of large output torque and fast response speed, and is suitable for scenes with high requirements for pitch response speed. However, the hydraulic system also faces problems such as high risk of hydraulic leakage and complex maintenance, which may bring higher operation and maintenance costs.

In terms of transmission mechanism, the two systems usually adopt the combination of pitch bearing and gear rack/gearbox (electric system) or hydraulic cylinder (hydraulic system), which amplifies the output power of the actuator and then transmits it to the blade to realize its rotation around the shaft.

In order to enhance system redundancy, modern wind turbines are usually equipped with three sets of independent pitch drive systems, which control three blades respectively, and the systems are independent of each other, so as to effectively prevent single point of failure from affecting the operation of the whole machine.

2.3 Characteristics and Challenges of System Control

The pitch control system of wind turbine is facing multiple challenges, including strong nonlinearity and parameter uncertainty, large inertia and response lag, control target coupling, operation state switching and fault reliability. The aerodynamic and structural dynamic characteristics of wind turbine are highly nonlinear, and change significantly with wind speed, which limits the modeling accuracy.

At the same time, the external wind speed disturbance has strong randomness, which makes it difficult for the traditional linear control method to maintain excellent performance under all operating conditions. In addition, the blade and transmission system have large inertia, and the pitch actuator has response lag and transmission gap, which puts forward higher requirements for the rapidity and robustness of the controller. Due to the fact that the pitch control affects the unit output power and structural load at the same time, there is a significant trade-off between different control objectives, and there is a coupling relationship between the three pitch channels and the speed control, which needs to be effectively controlled through the coordination mechanism. The wind turbine needs to span multiple power control areas during operation, and the pitch strategy needs to realize smooth switching between maximum power tracking (MPPT) and constant power control to avoid dynamic impact caused by the switching process. On the other hand, the pitch control system itself is prone to degenerative faults, such as actuator failure and sensor drift, which further increases the demand for fault tolerance and adaptive ability of the control system.

Therefore, the construction of high-performance pitch control system needs to achieve collaborative innovation in the aspects of accurate modeling, state observation, optimal control and intelligent algorithm fusion, and form a multi-functional control system with stability, robustness and adaptive ability, so as to comprehensively meet the multiple challenges in the complex operating environment.

3. Traditional Control Strategy

3.1 Traditional PID Control

In the early stage of wind power pitch control, the proportional integral derivative (PID) controller, as the most widely used traditional control method, adjusts the pitch angle in real time through the feedback of wind speed or speed error, so as to realize the effective adjustment of output power. Due to its simple structure, convenient implementation and rich engineering application experience, PID controller has become the mainstream technology in collective pitch control (CPC) system. However, in the face of complex operating conditions such as dramatic changes in wind conditions, significant nonlinearity of the system and frequent switching of operating points, the traditional PID control has performance bottlenecks such as delayed response, serious overshoot and large steady-state error.

3.2 Active Disturbance Rejection Control (ADRC)

Active disturbance rejection control (ADRC) is a control method that does not depend on the exact model. It estimates the uncertainty and external disturbance of the system in real time through extended state observer (ESO), and actively suppresses it through feedback compensation, so as to realize the robust control of "total disturbance". This method is especially suitable for systems with large model uncertainty, and has good disturbance rejection performance and robustness.

An improved ADRC strategy for wind turbine pitch control is proposed. The gray wolf optimization algorithm is used to set the key parameters, which significantly improves the power regulation accuracy and anti-interference performance of the system [2]. This method shows the control advantages of "model free" and "strong robust", has strong adaptability, and can quickly converge to steady-state output at high wind speed. A wind turbine pitch controller based on Linear Active

Disturbance Rejection Control (LADRC) is further proposed in [3]. By establishing a discrete LADRC framework including an extended state observer and a state feedback control law, a double loop structure was designed to simultaneously suppress the tower load and stabilize the speed. The simulation results show that the controller can effectively maintain a constant output power under the disturbance of step wind, gust and turbulence, and significantly reduce the vibration load in the front and rear directions of the tower, so as to delay the process of structural fatigue.

In the practical application of wind turbine, the improved ADRC can not only achieve stable control under the conditions of high wind speed and large disturbance, but also effectively suppress the fluctuation of structural load and prolong the service life of blade and spindle system.

3.3 Sliding Mode Control (SMC)

Sliding mode control is a robust control strategy suitable for nonlinear systems. By introducing switching control terms, the system state is approached and maintained along the preset sliding mode surface, so as to achieve high robust control of system uncertainty and external disturbance. This method has less dependence on the system model, and has inherent invariance and robustness. It can still maintain stable control performance under complex conditions such as wind speed fluctuation and parameter perturbation. The key mechanism is to make the system state quickly approach and stably remain on the sliding mode surface under the condition of allowing limited chattering, so as to achieve the robust control of the steady-state target.

Simulation results show that the sliding mode control can significantly suppress the speed overshoot when the wind speed changes suddenly, and the overall control performance is better than the traditional PI control method [4]. In order to alleviate the inherent chattering effect of sliding mode control, researchers proposed a variety of improvement strategies, such as exponential reaching law, terminal sliding mode, adaptive sliding mode, and gradually applied them to the wind turbine pitch control system. By introducing smooth switching mechanism or adjusting the reaching rate, these methods effectively reduce the oscillation amplitude of the system and further improve the accuracy and response performance of the control system.

In general, the application of sliding mode control in wind turbine pitch control system highlights its robustness advantage, and can realize the stable operation of the system in the presence of parameter disturbance and environmental uncertainty. However, the high-frequency chattering in sliding mode control has a potential threat to the life of the actuator, so in engineering practice, low-pass filtering or continuous approximation methods are usually combined to suppress the chattering effect.

3.4 Model Predictive Control (MPC)

Model Predictive Control (MPC) is a feedforward control method that uses a system model to predict future behavior and generates control inputs through rolling optimization strategies. Its main advantage lies in its ability to explicitly handle multi constraint and multi variable coupling problems, especially suitable for complex systems such as wind power pitch control with strong nonlinearity, multi-objective coupling, and actuator constraints.

A multi model predictive control framework is proposed, which divides the operation of the wind turbine into multiple wind speed intervals, establishes a linear model for each interval, and uses a one-step rolling optimization strategy to determine the control law to effectively suppress blade load fluctuations [5]. The adaptive model predictive control (MPC) method is further introduced, and the dynamic state estimation is carried out by combining Kalman filter, which significantly improves the robustness and real-time performance of the control system in dealing with wind speed disturbance and modeling error [6].

Although MPC has foresight and strong constraint handling capabilities, its high computational complexity places higher demands on algorithm efficiency and solver performance for real-time control. To solve this problem, researchers have proposed in recent years to combine neural networks with MPC or simplify models to achieve fast solutions, thereby meeting real-time control requirements.

4. Progress and Prospects of Intelligent Control Research

4.1 Application of Intelligent Optimization Algorithm in Variable Pitch Control

With the development of computational intelligence, various intelligent optimization algorithms have been widely used for parameter optimization and strategy design of wind turbine pitch control. Traditional controller parameters (such as PID gain, filter coefficients, etc.) often rely on empirical adjustment, while intelligent algorithms can automatically optimize through global search, improving control performance and robustness.

In recent years, many emerging algorithms have emerged, such as particle swarm optimization, genetic algorithm, grey wolf algorithm, sparrow search algorithm, whale optimization algorithm, etc. Researchers have also introduced them into pitch control. For example, the firefly algorithm is applied to optimize the pitch control strategy, and the distributed parallel firefly algorithm is introduced to coordinate the multi machine pitch control [7]. The simulation results show that the optimized controller can effectively suppress the speed fluctuation caused by wind disturbance and improve the performance of group control. The whale swarm algorithm is used to optimize the parameters of the PID controller [8]. By considering the system overshoot, stability time, phase margin and other factors, the control performance is greatly improved.

4.2 Neural Networks, Deep Reinforcement Learning

With the development of intelligent modeling technology, Artificial Neural Networks (ANN) have been widely used in the modeling and control of wind turbine pitch control systems due to their excellent nonlinear modeling and approximation capabilities. For example, a pitch controller based on adaptive continuous neural network is developed. Combined with Lyapunov stability theory, the online adaptive control of variable speed wind turbine pitch angle is realized. The method shows good system stability and convergence under various wind conditions [9].

In addition, a strategy combining back propagation (BP) neural network with PID control is proposed, and a BP-PID pitch controller is designed. This method uses BP network to adaptively adjust PID gain parameters according to real-time wind speed changes, which significantly overcomes the problem of performance degradation of traditional fixed gain PID controller under variable wind conditions [10]. The simulation results show that in the case of sudden changes in wind speed, the controller can effectively reduce the overshoot amplitude of the speed (over 80%) and minimize steady-state errors. The overall control accuracy and robustness are better than traditional PID schemes. From this, it can be seen that neural networks provide a control tool for wind power systems that combines nonlinear processing capabilities and adaptive characteristics.

Furthermore, the rise of Deep Reinforcement Learning (DRL) has expanded the application boundaries of neural networks in wind power control. This method approximates the optimal control strategy through deep neural networks, enabling dynamic control strategies to be obtained through interactive learning even in model free environments. On the one hand, deep networks can be used for wind speed time series prediction to assist feedforward pitch control strategies in obtaining more accurate ultra short-term inflow information; On the other hand, DRL can train agents to explore and optimize control strategies in simulation environments to maximize cumulative benefits.

A DRL-based robust variable pitch controller demonstrates strong stability in the face of random wind disturbances is proposed in [11]. The application of data-driven techniques, such as machine learning, for diagnosing faults in the pitch control system is delved by [12]. These techniques can effectively detect anomalies in pitch sensors and actuator failures, offering crucial support for system reliability assessment and proactive maintenance. In addition, a composite control approach that integrates reinforcement learning with traditional PID control is introduced by [13]. The simulation verification shows that the controller can adjust the pitch angle more quickly under sudden wind speed changes, reduce overshoot and errors, and improve the stability of output power and control response speed. Although DRL has shown significant advantages in handling high-dimensional strategy spaces and complex control problems, its lack of interpretability, unstable training process, and strong dependence on data still constrain its large-scale application in practical wind power systems.

4.3 Outlook on Feedforward Control Method for Laser Wind Measurement

Real time acquisition of incoming wind condition information is of great significance for improving the responsiveness and accuracy of wind turbine pitch control. With the development of LiDAR wind measurement technology, the practical application of feedforward control in wind power systems has gradually become possible. Laser wind radar can sense changes in incoming wind speed within a range of several hundred meters in front of the wind turbine, providing a second level preview window for the control system. At present, the feedforward control strategy based on laser wind measurement radar has become one of the hot research directions in the control of large-scale wind turbines.

Research was conducted on a control strategy that incorporates cabin feedforward signals, simultaneously introducing feedforward information into both the yaw and pitch control modules [14]. This approach allows for a more precise response to incoming flow disturbances. The experimental results show that after introducing feedforward control, the wind turbine can align with the wind direction more timely, the wind energy utilization efficiency is improved by about 2% -3%, and the instantaneous load impact caused by yaw and pitch lag is significantly reduced.

Building on this concept, a strategy that combines feedforward control with traditional feedback mechanisms is proposed in [15]. In actual unit tests, the composite control method reduced the amplitude of tower vibration by about 10%, further verifying the practical effectiveness of feedforward information in load suppression.

More recently, an incremental collective pitch feedforward control method that leverages LiDAR (Laser Wind Detection and Ranging) data is introduced by [16]. This method superimposes the incremental pitch value calculated from the incoming wind speed changes predicted by LiDAR on the traditional collective pitch controller, achieving a feedforward compensation mechanism for wind speed disturbances. The results of multi condition joint simulation and hardware in the loop (HIL) experiments show that when the predicted wind speed trend of LiDAR is consistent with the actual change, this incremental feedforward strategy can effectively suppress power and load fluctuations and achieve smooth output transition.

Combining feedforward methods such as laser wind measurement with intelligent control algorithms is one of the important directions for the future development of pitch control systems. For example, machine learning methods can be used to fuse multiple beams of LiDAR data, real-time correction of wind direction estimation bias and wind speed prediction lag, further enhancing the reliability of feedforward information. Predictive feedforward and deep reinforcement learning control strategies can also be integrated to enable the agent to simultaneously consider current errors and future wind conditions, in order to achieve dynamic performance superior to pure feedback control. The introduction of laser wind measurement feedforward control has transformed wind turbine pitch control from passive response to active predictive regulation, providing strong support for suppressing load impact and power fluctuations under extreme wind conditions. With the integration and development of wind measurement technology and intelligent algorithms, variable pitch control will achieve smoother, more efficient, and robust wind turbine operation control.

5. Conclusion

The pitch control strategy of wind turbines is gradually evolving towards intelligence and adaptability, and different control methods have their own advantages in performance characteristics and applicable scenarios, with strong complementarity. In engineering practice, it is often necessary to integrate the stability and reliability of classical control with the adaptive and optimization capabilities of intelligent control to better meet the comprehensive performance requirements of large wind turbines in complex operating environments. How to improve the performance of control systems while ensuring their safety and reliability will become a key challenge for future research and applications. With the continuous advancement of control algorithms, perception technology, and computing power, intelligent pitch control strategies are expected to be more widely validated and deployed in actual wind farms, providing solid technical support for further improving the power generation efficiency and operating life of wind turbines.

References

[1] Rezaei, M. M. (2018). A nonlinear maximum power point tracking technique for DFIG-based wind energy conversion systems. Engineering science and technology, an international journal, 21(5), 901-908.

[2] Song, W. J., Xie, Y., Huang, W. J., & Li, R. S. (2020). *Application of improved grey wolf optimization algorithm in variable pitch auto disturbance rejection control*. *Renewable Energy Resources*, *38*(7), 905–910.

[3] Tian, D., Huang, M., Tang, S., Deng, Y., Zhou, Q., & Deng, Y. (2023). *Output power and tower load control of large-scale wind turbines based on active disturbance rejection control*. *Journal of Solar Energy*, *44*(5), 466–472.

[4] Colombo, L., Corradini, M. L., Ippoliti, G., & Orlando, G. (2020). Pitch angle control of a wind turbine operating above the rated wind speed: A sliding mode control approach. ISA transactions, 96, 95-102.

[5] Abbasi, M., & Sadati, N. (2024). Multiple model predictive control for offshore wind turbines operating in the full-load range. Asian Journal of Control.

[6] Tian, D., Fang, J., Liu, F., Tang, S., & Deng, Y. (2022). *Design of model predictive individual pitch controller for large-scale wind turbines*. *Journal of Solar Energy*, *43*(4), 461–467.

[7] Shan, J., Pan, J. S., Chang, C. K., Chu, S. C., & Zheng, S. G. (2021). A distributed parallel firefly algorithm with communication strategies and its application for the control of variable pitch wind turbine. ISA transactions, 115, 79-94.

[8] Zeng, B., Huang, L., Peng, L., Zhang, S., Song, X., & Yang, X. (2020). *Parameter tuning method of PID individual pitch control based on Whale Swarm Algorithm*. *Ship Engineering*, *42*(S1), 550–553, 557.

[9] Yang, Q., Jiao, X., Luo, Q., Chen, Q., & Sun, Y. (2020). L1 adaptive pitch angle controller of wind energy conversion systems. ISA transactions, 103, 28-36.

[10] Ren, H., Hou, B., Zhou, G., Shen, L., Wei, C., & Li, Q. (2020). Variable pitch active disturbance rejection control of wind turbines based on BP neural network PID. IEEE Access, 8, 71782-71797.

[11] Chen, P., Han, D., Tan, F., & Wang, J. (2020). Reinforcement-based robust variable pitch control of wind turbines. IEEE Access, 8, 20493-20502.

[12] Li, H., Wang, X., Wang, D., Chen, N., & Pan, W. (2022). *Research progress on fault diagnosis of wind turbine electric pitch system*. *Equipment Management and Maintenance*, *(9)*, 154–158.

[13] Sierra-Garcia, J. E., Santos, M., & Pandit, R. (2022). Wind turbine pitch reinforcement learning control improved by PID regulator and learning observer. Engineering Applications of Artificial Intelligence, 111, 104769.

[14] Wang, J., Xu, G., & Zang, C. (2023). *Laser wind radar-based feedforward control of wind turbine nacelles with wind power performance study*. *Advances in Energy and Power Engineering*, *11*(3), 79–85.

[15] Loew, S., & Bottasso, C. L. (2022). Lidar-assisted model predictive control of wind turbine fatigue via online rainflow counting considering stress history. Wind Energy Science, 7(4), 1605-1625.

[16] Wang, Q., Du, Z., Chen, W., Zhang, J., Lin, Y., & Liu, H. (2023). Incremental feedforward collective pitch control method for wind turbines. Frontiers in Energy Research, 11, 1326248.