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Overview of wind turbine pitch angle adjustment model

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Abstract: Accurate adjustment of the wind turbine blade pitch angle is critical for optimizing energy capture, ensuring system stability, and avoiding excessive equipment fatigue. This paper reviews recent advances in control theory and methods for blade pitch angle regulation. Classical control theories such as PID control models and hysteresis compensation models have been widely used due to their simple structure and intuitive design; however, these methods exhibit limitations when dealing with nonlinearity and uncertainty. Modern control theories, including robust control models and fuzzy logic control models, enhance system robustness and adaptability, effectively improving the accuracy and stability of blade pitch angle regulation. Robust control models ensure stable operation under model uncertainties, while fuzzy logic control models, leveraging fuzzy set theory to mimic human decision-making, demonstrate good adaptability to complex environments. The application of intelligent algorithms in blade pitch angle regulation, such as neural network control models and genetic algorithm optimization models, shows great potential. Neural network control models, trained on large datasets, achieve precise control of nonlinear systems, and genetic algorithm optimization models, by simulating natural selection processes, significantly enhance control performance by finding globally optimal controller parameters. Despite higher design complexity, these intelligent algorithms significantly improve control performance, particularly in addressing the complex dynamics of wind turbines. In summary, research on blade pitch angle regulation models is transitioning from traditional control theories to modern control theories and intelligent algorithms, which contributes to enhanced power generation efficiency, stability, and reliability of wind turbines. Nevertheless, issues regarding real-time performance, explain ability, and model generalization of intelligent algorithms require further investigation. In the future, with advancements in deep learning, model predictive control, and other cutting-edge technologies, research on blade pitch angle regulation models will become more sophisticated, promising more efficient and intelligent wind turbine control.

Keywords: Wind Turbines; Pitch Angle Control; Control Theory.

1. Introduction

With the continuous growth of global energy demand and the urgent need for environmental protection, wind energy, as a clean and renewable form of energy, is becoming increasingly important. In the field of wind power generation, precise adjustment of pitch angle is crucial for optimizing energy capture, ensuring stable operation of wind turbines, and avoiding excessive fatigue of equipment. The development of wind power generation technology, especially the widespread application of horizontal axis wind turbines, has significantly increased the share of renewable energy worldwide. However, vertical axis wind turbines, with their unique structure and advantages such as simple maintenance and lower start-up wind speed requirements, have become the focus of researchers' attention. Although vertical axis wind turbines have shown potential in certain specific application scenarios, their wind energy utilization rate is lower than that of horizontal axis wind turbines, mainly due to limitations in their aerodynamic performance. By using variable pitch technology, which adjusts the pitch angle of the blades, the aerodynamic characteristics of vertical axis wind turbines can be effectively improved, thereby enhancing wind energy capture efficiency.

Traditionally, pitch control has mainly focused on solving dynamic stall problems at high angles of attack to ensure stable operation at high wind speeds. However, with the pursuit of wind turbine performance and efficiency, researchers have begun to focus on pitch angle adjustment at small angles of attack to optimize performance at low wind speeds, providing new ideas for developing smarter and more efficient control strategies. By utilizing intelligent control technologies such as multi sensory neural networks, it is possible to dynamically optimize the wind energy utilization rate of wind turbines under different operating conditions, marking a shift in control strategies from empirical rule-based to data-driven intelligent control.

Although some progress has been made, there are still challenges in implementing variable pitch control technology. Firstly, the complexity of the mechanical structure requires the pitch angle adjustment system to have high reliability. At the same time, the intelligence level of the control system itself urgently needs to be improved to cope with the complex and variable dynamic characteristics of wind turbines. In addition, computer numerical simulation plays an important role in research, but current simulations are often based on two-dimensional calculations, ignoring the effects of blade length, tip effect, and mechanical structure, which leads to a gap between simulation results and experimental data. Therefore, experimental research is crucial for verifying the accuracy of simulation results and evaluating the performance of control strategies, while experimental research on variable pitch vertical axis wind turbines is still relatively scarce.

2. Application of Classical Control Theory in Pitch Angle Adjustment

2.1. PID Control Model

The PID (Proportional Integral Derivative) control model is the cornerstone of classical control theory, widely used for adjusting the pitch angle of wind turbines due to its simple structure, intuitive design, and ease of implementation. The PID controller in the pitch angle control system adjusts the pitch angle by calculating the error, error integral, and error derivative of the pitch angle, thereby achieving precise control of the wind turbine's capture of wind energy.

In the PID model, the proportional (P) term reflects the magnitude of the current error, that is, the difference between the front pitch angle and the expected pitch angle; The integral (I) takes into account the accumulation of past errors, which helps to eliminate steady-state errors and improve the stability of the system; The differential (D) term responds to the rate of error change, helping to suppress system oscillations and improve the speed of dynamic response. By adjusting the PID parameters (proportional gain, integral time constant, and derivative time constant), the performance of the controller can be optimized to meet the operational requirements of wind turbines under different working conditions.

The output u (t) u (t) u (t) of the PID controller can be expressed as:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t)$$

Among them, $e(t)$ is the system error, K_p is the proportional gain, K_i is the integral gain, and K_d is the differential gain. $K_p e(t)$, the proportional term, provides a control effect proportional to the current error; $K_i \int_0^t e(\tau) d\tau$, the integral term, is used to eliminate steady-state errors; $K_d \frac{d}{dt} e(t)$, the differential term, reflects the rate of error change and is used to predict and reduce the trend of error variation. The PID controller has the advantages of simple structure and easy implementation, and has been widely used in industrial control. However, PID control has limited performance in dealing with nonlinear and multivariable coupled systems, especially in situations where wind speed changes dramatically, and its response speed and control accuracy may not be ideal. In addition, the parameter tuning of PID controllers (the selection of K_p、K_i、K_d) has a significant impact on system performance and usually requires optimization through experimentation or adjustment algorithms.

In practical applications of pitch angle control systems, PID models are often combined with modern control theories such as model predictive control and robust control to enhance their adaptability to nonlinear systems and uncertain environments. However, the limitation of PID control models is that they typically assume the dynamic characteristics of the system to be linear and lack robustness to model uncertainties, which may affect control performance when faced with the complex and variable aerodynamic characteristics of wind turbines.

2.2. Lag compensation model

The lag compensation model is a correction method in classical control theory, which addresses the problem of performance degradation in PID control when dealing with system delays. It improves the dynamic performance of the system by introducing a compensation element. In the pitch angle adjustment of wind turbines, system delay mainly comes from the response time of mechanical mechanisms and the measurement delay of wind speed signals. The lag compensation model can offset the influence of system delay by predicting the future state of the system and adjusting the pitch angle in advance.

Lag compensation is often described using a state space model, where the relationship between the system's state variable x (t) and the input u (t) and output y (t) is:

$$\dot{x}(t) = Ax(t) + Bu(t - \tau)$$

$$y(t) = Cx(t) + Du(t - \tau)$$

Among them, A, B, C, and D are the system matrix and the τ is the lag time of the system. Lag compensation is achieved by designing an appropriate control law u(t) to ensure that the system output y(t) accurately follows the input signal.

The lag compensation model is usually based on the form of state space or transfer function, and constructs a corresponding compensation network by estimating the lag link of the controlled object. Compensation networks typically include one or more first-order or second-order lag elements, whose parameters are determined through system identification methods such as least squares or Kalman filtering. The output of the compensation stage is added to the output of the PID controller, which works together to adjust the pitch angle, thereby eliminating to some extent the adverse effects of system delay on control performance.

In the pitch angle control system, the lag compensation model can significantly improve the system's tracking performance and anti-interference ability. Especially for situations with significant measurement delays in wind speed signals, lag compensation can effectively reduce control lag caused by delays, thereby improving the efficiency of wind turbines in capturing wind energy under various wind conditions. However, the design and parameter adjustment of lag compensation models are relatively complex, requiring a deep understanding of the dynamic and delay characteristics of the system. In addition, the accuracy of compensation models largely depends on the quality of system identification. If there is a significant deviation between the model and the actual system, it may actually reduce control performance.

3. Application of Modern Control Theory in Pitch Angle Adjustment

3.1. Robust Control Model

The application of robust control models in pitch angle adjustment aims to address the limitations of classical control theory in dealing with nonlinear systems and uncertainties. In wind turbines, due to the random variation of wind speed, the interaction between blades and wind, and the complexity of mechanical structure, the dynamic characteristics of the system are often difficult to accurately model. Robust control theory ensures the stability and reliability of system performance under various operating conditions by designing controllers that can resist model uncertainty, disturbances, and noise.

Robust control typically employs H(∞) control theory, where the objective is to minimize the maximum gain of the control system to ensure stable operation under all possible uncertainty conditions. The optimization problem can be expressed as:

$$\min_K \|T_{z\omega}(s)\|_\infty$$

Among them, $T_{z\omega}(s)$ is the transfer function from disturbance input ω to control output z, and $\|\cdot\|_\infty$ representing the maximum gain. By solving this optimization problem, a controller K with robustness to system uncertainty can be obtained.

In robust control of pitch angle, the controller is usually based on state feedback or output feedback, and calculates the optimal pitch angle adjustment by observing state variables such as wind speed, pitch angle, and tip speed. In order to further enhance robustness, robust controllers may combine sliding mode control, adaptive control, or hybrid control strategies to cope with the changes of wind turbines under different wind conditions. For example, sliding mode control utilizes a sliding mode function to force the system state to quickly slide onto a stable sliding surface, thereby ensuring rapid convergence of the system; Adaptive control continuously adapts to system changes and maintains control performance through online learning and parameter adjustment.

The application of robust control models in pitch angle adjustment significantly improves the robustness and adaptability of the system. It is not only suitable for linear systems, but also capable of handling complex nonlinear, time-varying, and uncertain systems such as wind turbines. However, the design of robust controllers is often complex and requires consideration of system uncertainty and disturbance range, which may result in a complex controller structure and high computational complexity. In addition, although robust control can ensure the stability of the system within a certain range of uncertainty, it cannot completely eliminate performance degradation, and further research is needed on robustness in extreme situations.

3.2. Fuzzy Logic Control Model

The fuzzy logic control model consists of four parts: fuzzification, rule base, inference engine, and deblurring. Firstly, the input signal (such as wind speed error) is transformed into a fuzzy set through fuzzification; Next, perform fuzzy reasoning based on the rule library; Finally, the fuzzy output is transformed into specific control instructions through deblurring.

Assuming the input variables are e and $\dot{e}$, the fuzzy rule can be expressed as: If e is A_i and $\dot{e}$ is B_j, then u is C_k

Among them, A_i, B_j and C_k are fuzzy sets of input and output variables, respectively. By using a fuzzy inference engine, the output control variable u can be calculated based on fuzzy rules.

In the context of pitch angle adjustment, the fuzzy logic controller first converts the actual input variables such as wind speed, wind direction, and pitch angle into fuzzy sets through a series of fuzzy rules. These sets reflect the semantic uncertainty of these variables, such as "low", "medium", and "high". Then, the fuzzy logic controller calculates a fuzzy output set based on these fuzzy sets and predefined fuzzy rules as the direction for adjusting the pitch angle. Finally, through fuzzy reasoning and deblurring processes, the fuzzy output is transformed into precise pitch angle adjustment values, thereby achieving control of the wind turbine.

The advantage of fuzzy logic control is that it can handle the fuzziness and uncertainty of input parameters, which is particularly important in wind turbine environments because the measurement of parameters such as wind speed and direction often involves uncertainty, and these parameters are crucial for adjusting the pitch angle. In addition, fuzzy logic controllers can adapt to different wind conditions and operating conditions by adjusting fuzzy rules and parameters, and have good adaptability.

4. The specific application of 3 intelligent algorithms in pitch angle adjustment

4.1. Neural Network Control Model

Neural network control models typically consist of input layers, hidden layers, and output layers. If the input is wind speed v(t) and pitch angle θ(t), and the output is control signal u(t), then the output of the neural network can be expressed as:

$$\mathrm{u}(t) = f\left(\sum_{i=1}^{n} \omega_i \cdot \phi\left(\sum_{j=1}^{m} \omega_{ij} x_j + b_i\right) + b_0\right)$$

Among them, ω_i and ω_{ij} is the network weight, $\phi(\cdot)$ is the activation function, and b_i and b_0 is the bias term. By adjusting network weights and biases, neural networks can learn the control laws of the system and achieve intelligent adjustment of pitch angle.

The advantage of neural network control lies in its powerful nonlinear modeling ability, which can approximate the complex dynamic characteristics of wind turbines without relying on precise physical models. In addition, the adaptability of neural networks enables them to self adjust with environmental changes, providing more robust control in the face of wind speed fluctuations and uncertainties. However, this model also brings some challenges, such as long training time, the need for a large amount of data, the complexity of weight adjustment, and low interpretability of the model.

4.2. Genetic Algorithm Optimization Model

In genetic algorithms, each individual (solution) is represented by a chromosome vector, which is composed of several genes. Each gene corresponds to a parameter of the controller (such as K_p、K_i、K_d in the PID controller). Assuming the population size is N, the chromosome of the i-th individual in the k-th generation population is represented as:

$$x_i^k = \left[x_{i1}^k, x_{i2}^k, \ldots, x_{im}^k\right]$$

Among them, x_{im}^k represents the j-th gene of the i-th individual, and m is the chromosome length (i.e. the number of control parameters).

The core steps of genetic algorithm include:

Selection: Select individuals with excellent performance for reproduction based on the Fitness Function. The fitness function is $\mathrm{f}(x)$ usually designed based on the performance indicators of the control system, such as minimizing steady-state error, maximizing power output, etc.

Crossover: Generation of offspring from selected parental individuals, using single point or multi-point crossover operations to exchange chromosome fragments.

$$x_i^{k+1} = \left[x_{i1}^{parent1}, x_{i2}^{parent2}, \ldots, x_{im}^{parentm}\right]$$

Mutation: Randomly mutating newly generated individuals to introduce diversity and prevent the algorithm from getting stuck in local optima.

$$x_{ij}^{k+1} = x_{ij}^{k+1} + \delta$$

Among them, δ is a small random disturbance.

Through the above operations, the genetic algorithm gradually optimizes the population and ultimately finds the optimal combination of control parameters.

The advantage of genetic algorithm optimization models lies in their global optimization ability and adaptability. Since it does not rely on the initial guess of the problem, but seeks the optimal solution through a large number of attempts, it can effectively deal with non convex optimization problems and avoid falling into local optima. In addition, genetic algorithms have a certain degree of adaptability to environmental changes, that is, under different wind conditions, only the optimization process needs to be repeated to obtain controller parameters that are suitable for the new environment.

5. Conclusion

The development of theory and methods for pitch angle adjustment, as a key link in optimizing control of wind turbines, is of great significance for improving the performance, stability, and reliability of wind turbines. Classic control theories such as PID control and hysteresis compensation models dominate in practical applications due to their simple structure and intuitive design. However, their limitations in dealing with nonlinearity, uncertainty, and complex dynamic characteristics have driven the research of modern control theory, such as robust control models and fuzzy logic control models, which significantly improve the accuracy of pitch angle adjustment by enhancing the robustness and adaptability of the system. Intelligent algorithms, especially neural network control models and genetic algorithm optimization models, demonstrate the potential to surpass traditional control theory in complex environments. Neural networks, with their powerful nonlinear fitting ability, can adapt to the complex dynamic characteristics of wind turbines, while genetic algorithms improve control performance by finding the optimal controller parameters through global optimization strategies. However, the design complexity, real-time performance, and interpretability of intelligent algorithms still need to be addressed, which is a challenge for future research.

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