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Research on the Application of PID Control Algorithm and Fuzzy Control Theory in the Field of Temperature Control

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Abstract: In the field of industrial automation control systems, PID control algorithms are widely used in various control fields such as temperature, speed and position. Among them, fuzzy PID control can improve control accuracy and stability, can significantly improve product quality and production efficiency, in food processing, chemical engineering, pharmaceutical and textile industries have a wide range of applications. Therefore, this paper comprehensively discusses the theory of fuzzy PID control algorithm and its application in the field of temperature control. The advantages of fuzzy PID control in complex industrial environments are emphasized through a comparative analysis with other temperature control methods as well as traditional linear PID control. The research indicates that by optimizing the control algorithm and hardware design, the fuzzy PID control algorithm can reduce the system overshoot and steady state error, thus improving the control accuracy and response speed. At the same time, the introduction of multivariable PID controllers or the use of advanced multivariable control strategies can achieve coordinated control of multiple variables, thereby improving the performance of the entire system. In addition, the integration of advanced energy management system and data analysis technology can comprehensively monitor and optimize the management of energy consumption, further improving the energy efficiency of the system.

Keywords: PID control, fuzzy control, automation control systems, temperature

1. Introduction

The PID control algorithm, known as the Proportional-Integral-Differential control strategy, originated in the 1930s to 1940s. It integrates three control components—Proportional, Integral, and Derivative—into a control strategy that is simple in principle, robust in performance, and widely adaptable, making it one of the most mature and extensively used control algorithms in continuous systems. In the field of industrial automation control systems, the PID control algorithm is broadly applied across various control domains such as temperature, velocity, and position. This algorithm is based on feedback control theory, which continuously compares the system's actual output with the setpoint and adjusts the controller's output to achieve stable system control [1].

As technology and industry have advanced into the modern era, the demands for control precision, response speed, system stability, and adaptive capabilities in the field of industrial production have been escalating. The subjects of industrial process control exhibit nonlinearity, time-varying characteristics, hysteresis, and specific dynamic properties, leading to significant uncertainties in

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internal control operations and disturbances from external environments. Traditional control methods can no longer meet the current demands of industrial process control. The application of classical fuzzy PID control theory, however, can greatly enhance the overall effectiveness of industrial process control. Fuzzy control theory is capable of comprehensively detecting and analyzing uncertain conditions and parameter disturbances in process control, and utilizes fuzzy reasoning to complete the online self-tuning of PID parameters, thereby further enhancing the flexibility, practicality, and precision of PID control.

2. Basic Principles of PID Control Algorithm

The PID control algorithm is composed of three fundamental components: Proportional (P), Integral (I), and Derivative (D). Its core principle involves a comprehensive consideration of the current error, the accumulation of past errors, and the rate of error change. By combining these three components, the system output is adjusted to achieve precise control of the target state [2-3]. When the structure and parameters of the controlled object are not fully understood or an accurate mathematical model cannot be obtained, PID control technology is the most convenient. It is suitable for situations where there is incomplete understanding of the system and the controlled object or where system parameters cannot be effectively measured.

Detailed Explanation of Specific Control Components of the PID Control Algorithm

2.1. Proportional (P) Control

Proportional control is the most fundamental method of control, characterized by maintaining a proportional relationship between the controller's output and the input error signal. However, relying solely on proportional control results in a steady-state error in the system output.

2.2. Integral (I) Control

In integral control, the controller's output is directly proportional to the integral of the input error signal. If a steady-state error persists in an automatic control system after it has reached a steady state, it is referred to as a system with an offset. To eliminate this steady-state error, an integral term must be incorporated into the controller. The error of the integral term accumulates over time, driving the controller's output to increase and gradually reducing the steady-state error to zero. Thus, a Proportional-Integral (PI) controller ensures no steady-state error post-steady state.

2.3. Derivative (D) Control

In derivative control, the controller's output is directly proportional to the derivative of the input error signal, that is, the rate of change of the error. During the regulation process of an automatic control system, oscillations or even instability may occur due to the presence of significant inertia or lag components. This is because the suppression of errors by these components always lags behind the changes in error. By introducing a derivative term into the controller, it can predict the trend of error changes.

3. Fuzzy PID Control in Industrial Process Control: Status and Application

The application of Fuzzy PID Control in the industrial process control has a positive effect on improving the overall performance of industrial process control. In practical research, it is necessary to start from the Fuzzy PID Control algorithm, understand the characteristics of Fuzzy Control, analyze the characteristics of industrial process control, grasp the difficulties in the process of industrial process control, and summarize the application characteristics of several Fuzzy PID Control

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algorithms, thereby deriving the process flow of Fuzzy Control algorithms for temperature control systems. Against the backdrop of modernization of science and industry, the requirements for control precision, response speed, system stability, and adaptive capacity in the field of industrial production are continuously increasing. In industrial process control, the control objects have nonlinearity, time-varying, hysteresis, and dynamic characteristics, which lead to strong uncertainty in internal control work and disturbance problems from the external environment. Traditional control methods can no longer meet the current needs of industrial process control. The use of classical Fuzzy PID Control theory can greatly enhance the overall effect of industrial process control. Fuzzy control theory can comprehensively detect and analyze uncertain conditions and parameter disturbances in process control, and use fuzzy reasoning to complete the online self-tuning of PID parameters. It fully exerts the advantages of traditional PID control, which is simple in principle and robust, and its flexibility, practicality, and accuracy will be more prominent.

4. Fuzzy Control and PID Control

4.1. Features of Fuzzy Control Theory

As one of the important contents of intelligent control, Fuzzy Control needs to combine the experience of operators with relevant theoretical knowledge in practical application, and transform it into control quantity, based on expert knowledge to imitate human thinking process, and perform uncertain reasoning on fuzzy information. This kind of Fuzzy Control algorithm can effectively deal with uncertain factors in the control system and can solve the control problems of multiple complex systems that cannot establish accurate mathematical models [4]. At present, Fuzzy Controllers have played a prominent role in various typical applications such as heat exchange processes, wastewater treatment processes, and automotive speed control. With the continuous development and application of Fuzzy chips and Fuzzy computers, it can further promote the development of Fuzzy Control and also lay the foundation for the further promotion of Fuzzy Control technology. In recent years, Fuzzy Control has played a role in the development of economy, industry, and medicine, and many Fuzzy technology products are more and more widely used in industrial and civilian fields. The main features of Fuzzy Control algorithms are manifested in the following aspects: 1) In the control system design process, there is no need to explicitly define the mathematical model of the controlled object. Fuzzy Control only refers to the relevant knowledge and experience of on-site operators or experts, and simulates and analyzes the entire control process through the system model. The system model is included in fuzzy operations and fuzzy rules, among which, fuzzy rules mainly complete the fuzzy processing of system status and variables, which can be fuzzy sets, and can also effectively connect with the output of the Fuzzy Controller. In the research process, Fuzzy Control is regarded as a comprehensive task of completing fuzzy modeling tasks and system control requirements, which can prevent complexity issues in the modeling process and affect the efficiency of modeling. (2) Fuzzy Control systems have strong robustness and low sensitivity to parameter changes. In the Fuzzy Control process, it is not binary logic, but a continuous multi-valued logic. Therefore, when system parameters change, the stability of the control system can be ensured.

4.2. Fuzzy PID Control Algorithms

At present, the application of hybrid fuzzy control theory in industrial process control is relatively widespread. Self-tuning fuzzy controllers, fuzzy PID control, fuzzy expert control systems, and fuzzy neural network control systems have all been developed based on this control theory. Therefore, this foundational theory has become quite mature and refined. In industrial process control, the application of control algorithms is increasing, yet the PID control algorithm holds a significant position due to its prominent advantages. This is primarily because the PID controller has a relatively simple structure, provides good control effects, and possesses strong stability and control precision, with a relatively complete theoretical analysis system. Currently, its application is widespread in fields such as metallurgy, petroleum, and chemical industries [5]. However, during the application of PID controllers, the set parameters are fixed, which cannot meet the control performance and precision requirements for control objects with strong time lags and disturbances in industrial process control. In this process, it is necessary to strengthen the effective integration of fuzzy control theory and PID control, which allows for an accurate and concise description of the research object, and enables online parameter adjustment without the need to establish an accurate mathematical model of the control object, ensuring that flexibility can meet control requirements. Therefore, effectively combining fuzzy control with traditional PID control is an important research content in the current field of industrial process.

When carrying out industrial process control, the application of automatic control algorithms is relatively common. PID control algorithms based on traditional theory, and adaptive control, neural network control, and fuzzy control based on modern control theory all belong to automatic intelligent control methods. However, at this stage, the industrial process control site is mainly dominated by fuzzy PID control algorithms. These control algorithms are relatively simple and have high precision, which can greatly improve the overall performance of industrial process control. When analyzing the combination form of fuzzy control algorithms and traditional PID, and the differences in parameter tuning methods, the fuzzy PID algorithms used in industrial process control sites mainly include the following two types: (1) Fuzzy self-tuning PID control algorithm. This algorithm is developed based on the fuzzy derivation of PID parameters and online self-tuning. It can automatically adjust control parameters according to actual industrial control results and requirements, and can also ensure that control precision meets expectations to the greatest extent. In the specific use process, it is necessary to obtain the fuzzy relationships between the three parameters of PID and error and the rate of change of error. During control, dynamic real-time detection of the magnitude and direction of change of error and error change rate is required, and the three parameters of PID are online corrected according to fuzzy control theory. Master the specific requirements of industrial process control for PID parameters in different state control processes to ensure that the controlled object obtains good dynamic and static control performance. (2) Fuzzy-PI type fuzzy PID algorithm. This algorithm is a hybrid type of PID controller, mainly composed of a conventional integral controller and a general two-dimensional fuzzy controller with error and error change rate input in parallel. In practical application, the parallel structure can effectively combine control characteristics to ensure the control object achieves the best control effect. In the process of using this controller, in addition to having a good elimination effect on the residual difference caused by the discreteness of rules, it can also effectively eliminate the limit oscillation phenomenon near the zero point caused by input and output quantities, ensuring that the system becomes an error fuzzy control system with relatively good control performance. Temperature itself has the characteristics of nonlinear essence, therefore, in industrial process control, fuzzy PID controllers are mainly used to complete temperature control tasks [6].

5. Types of Temperature Control and Principles of Traditional Linear PID Control

In the early stages, temperature control systems primarily relied on mechanical and electrical control methods, such as honeycomb-style temperature controllers and thermocouple controllers, which were widely applied in industrial production. Starting from the 1970s, digital temperature control systems began to emerge, utilizing digital controllers and computer control technology to achieve more precise temperature control and facilitate integration into automated production lines. Contemporary temperature control systems have integrated microprocessors and intelligent algorithms, realizing even higher precision and stability in temperature control.

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The application advantages of PID control in temperature control are mainly reflected in the following aspects: Firstly, PID controllers can significantly enhance the accuracy and stability of temperature control, which is crucial for improving product quality and production efficiency. Secondly, the PID control algorithm is concise and easy to understand, making it easy to implement and suitable for various complex industrial environments and controlled objects. Currently, research on PID control in the field of temperature control has achieved remarkable results. Scholars at home and abroad have conducted in-depth studies on PID parameter tuning, adaptive PID control, and fuzzy PID control, and have obtained a series of important outcomes. For instance, the introduction of intelligent optimization algorithms such as genetic algorithms and particle swarm optimization algorithms has enabled the automatic tuning of PID parameters, enhancing the performance of temperature control systems. Adaptive PID control can automatically adjust PID parameters based on changes in the controlled object's parameters, enhancing the system's adaptability and robustness. Fuzzy PID control combines fuzzy control theory with PID control, achieving online adjustment of PID parameters through fuzzy reasoning, further enhancing the level of intelligent control. In industrial production, PID temperature control systems have been widely applied in various industries such as food processing, chemical engineering, pharmaceuticals, textiles, and glass manufacturing. They ensure the stability of the production process and product quality through real-time monitoring and temperature adjustment. Additionally, PID temperature control is also applied in laboratory environments for heat treatment, sintering, drying, and constant temperature and humidity conditions, providing strong support for scientific research.

Types and Principles of Traditional Linear PID Control in Temperature Regulation

According to relevant information, there are several main control methods currently applied in temperature control: 1. Traditional Linear PID Control: Commonly found in industrial control and process industries, this method achieves faster, more accurate, and more stable control objectives by adjusting the three parameters of PID (proportional gain, integral gain, derivative gain). However, it has the issue of being unable to regulate precisely in real-time. 2. On-Off Heating Control: The principle is that when the actual temperature falls below a set minimum, the system begins heating; when the actual temperature exceeds a set maximum, heating is stopped. Its shortcomings include slow response, low accuracy, and high energy consumption. Fuzzy Logic Control: A control algorithm that relies on computer digits, fuzzy linguistic variables, fuzzy set theory, and fuzzy logic reasoning, characterized by simplifying complex systems, facilitating human-machine dialogue, and possessing strong robustness and adaptability. Model Predictive Control: An advanced control algorithm with continuous cyclic optimization, showing significant effects in control scenarios with large lags, but it has the problems of high difficulty and cost. Intelligent Digital PID Control: A control algorithm that combines artificial intelligence control algorithms with traditional PID control, reflecting the traditional control advantages of "fast, accurate, and stable" to the greatest extent, and capable of timely regulation. With the development of artificial intelligence technology, this kind of control is applied more and more in production, among which the Backpropagation (BP) neural network algorithm is one of them.

6. Current Status of Secondary Network Temperature Control Systems in Heat Exchange Stations and Application of Fuzzy Control

In the current secondary network temperature control systems of heat exchange stations, the most commonly used controllers are based on traditional PID control algorithms. In practical applications, due to the controlled equipment only requiring incremental output values, the incremental PID control algorithm is applied [7]. However, centralized heating systems are susceptible to interference from weather, pipeline transportation, and coupling effects, causing controlled parameters to deviate from set values and affecting system stability. Given the time-varying and complex nature of heating

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systems, their mathematical models change with system characteristics, and traditional PID control algorithms perform poorly in terms of anti-interference and adaptability to time-varying systems.

Fuzzy control algorithms can effectively compensate for the shortcomings of traditional PID control algorithms in centralized heating systems [8]. Fuzzy adaptive PID control algorithms not only retain the high precision and rapid response of traditional PID control but also have the strong robustness of fuzzy control and the ability to self-tune parameters, thereby achieving better control quality and energy saving.

Fuzzy control relies on the accumulation of expert experience to form specific fuzzy control rules [9], which can effectively control complex controlled objects, giving it a significant advantage in the automatic control of complex systems.

7. Conclusion

This paper provides a comprehensive exploration of the PID control algorithm, fuzzy control theory, and their applications in the field of temperature control. It initially presents the fundamental principles and advantages of the PID control algorithm, including the roles of the proportional (P), integral (I), and derivative (D) control components and their collective contribution to system stability. Subsequently, the paper discusses the limitations of traditional PID control when dealing with nonlinear, time-variant, and objects with specific dynamic characteristics, highlighting the significance of fuzzy PID control as an effective solution.

The paper delves into the diversity and specific applications of fuzzy PID control algorithms, such as the fuzzy self-tuning PID control algorithm and the Fuzzy-PI type fuzzy PID algorithm, which enhance the flexibility and precision of PID control through online self-tuning via fuzzy reasoning. In terms of temperature control, fuzzy PID control not only improves control accuracy and stability but also has broad applications across various industries including food processing, chemical engineering, pharmaceuticals, and textiles, significantly enhancing product quality and production efficiency.

Furthermore, the paper examines other methods of temperature control, such as on-off heating control, fuzzy logic control, model predictive control, and intelligent digital PID control, comparing them with traditional linear PID control and underscoring the advantages of fuzzy PID control in complex industrial environments. Specifically, regarding the current state of secondary network temperature control systems in heat exchange stations, the paper analyzes the shortcomings of traditional PID control and points out the effectiveness of fuzzy adaptive PID control algorithms in addressing the system's time-variability and interference resistance.

With the increasing demands for precision and response speed in industrial temperature control, scholars are actively exploring new control strategies and technologies to enhance the performance of PID temperature control systems. By optimizing control algorithms and hardware design, system overshoot and steady-state errors can be reduced, thereby improving control accuracy and response speed. In the complex industrial production process, temperature often interacts with other variables (e.g., pressure, flow rate), making multivariable coupling control issues a focus of research attention. The introduction of multivariable PID controllers or the adoption of advanced multivariable control strategies can achieve coordinated control of multiple variables, thus enhancing the overall system performance.

Amidst the intensifying global energy crisis and heightened environmental awareness, research on optimizing energy efficiency in PID temperature control systems has garnered significant attention. By precisely controlling the power and operating times of heating or cooling equipment, energy consumption and production costs can be effectively reduced. Moreover, the integration of advanced energy management systems and data analytics technologies enables comprehensive monitoring and optimized management of energy consumption, further enhancing the system's energy efficiency.

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