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Enhancing Building Temperature Control Systems Using Advanced Fuzzy PID Algorithms

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Abstract. The performance of traditional building temperature control systems is often suboptimal due to the inherent complexity of the control objects and the challenges associated with establishing accurate mathematical models. These traditional systems frequently result in energy inefficiency and compromised comfort levels for occupants. Addressing these shortcomings requires an innovative approach to temperature regulation. After a thorough review of existing indoor temperature regulation systems both domestically and internationally, it is evident that there is significant room for improvement. Combining insights from control theory with advanced algorithms, this study proposes the use of a fuzzy PID (Proportional-Integral-Derivative) algorithm to establish a more effective temperature control system. The fuzzy PID algorithm integrates the robustness of PID control with the adaptability of fuzzy logic, providing a more responsive and precise method for temperature regulation. This hybrid approach leverages fuzzy logic to handle the uncertainties and nonlinearities in the control process, adjusting the PID parameters in real-time to optimize performance. As a result, the new system can dynamically respond to changing environmental conditions and occupant needs, maintaining a comfortable indoor climate while minimizing energy consumption.

Keywords: Building temperature control; Control theory; Fuzzy PID algorithm.

1. Introduction

The implementation of effective building temperature control is crucial in both daily life and various production environments. This includes applications in office buildings, apartments, campuses, and production settings such as greenhouses, vehicles, and fermenters [1]. These control objects are inherently complex and subject to variations due to time and climatic changes, influenced by numerous factors. As a result, establishing a precise mathematical model for these systems is challenging, often leading to suboptimal performance, slow response times, or unreasonable control outputs [2].

To address these issues and adjust the indoor ambient temperature according to user needs, it is essential to adopt innovative control systems in building temperature management. One promising approach is the integration of advanced control algorithms such as fuzzy PID (Proportional-Integral-Derivative) control. The fuzzy PID algorithm combines the traditional PID control's precision and robustness with the adaptability and flexibility of fuzzy logic, making it well-suited to handle the uncertainties and nonlinearities inherent in complex environmental systems.

By dynamically adjusting the control parameters in real-time based on the current state of the environment, the fuzzy PID algorithm can provide a more responsive and accurate temperature control solution. This leads to improved comfort for occupants, increased energy efficiency, and greater overall system reliability. The algorithm’s ability to adapt to a wide range of scenarios and conditions ensures that it can be effectively implemented across various building types and usage contexts.

2. Relevant theories

2.1. Definition of Control System and Its Development History

Control theory emerged in the mid-18th century. In the first Industrial Revolution, people began to have a preliminary understanding of control theory, and simple use [3]. The middle of the 20th century is the real development period of control theory, which can be roughly planned into three stages:

Stage I (Classical control Theory).

During the 1940s to 1960s of the 20th centuries, the main research was the control object of a single input and a single output. Some relatively easy linear time-invariant systems are studied, which can handle the simplest control processes [4]. The classical control theory system relies on the mathematical model described by the transfer function and uses the root locus method and the time-frequency domain analysis method as the support, which constitutes the basic framework of the classical control theory. For classical control theory, we are still learning and applying it [5].

Phase II (Modern control Theory).

During the 1960s and 1970s, the main research was nonlinear and time-varying systems, which could be solved by using state space method for multi-input and multi-output control objects [6]. At that time, the mathematical model of the system was expressed by the equation of state of the system and analyzed by the Karman filter and the optimal control, and the modern control theory was gradually formed.

Stage 3 (Intelligent Control Theory).

Since the 1970s of the 20th centuries, since the classical control theory and modern control theory, people have been conducting more in-depth exploration of control methods. Through decades of continuous development, intelligence can be roughly divided into intelligent systems based on expert systems, fuzzy logic control, hierarchical intelligent control and neural network control [7]. At present, intelligent control is being applied in various aspects, and its application degree has become one of the important aspects of a country's modernization and international competitiveness.

2.2. Fuzzy PID algorithm

PID control is a kind of control method widely used in industrial production process, and it is widely used in the field of temperature control at present [8]. PID (control by Proportional unit P (Proportional), Integral unit I (Integral) and Derivative unit D (Derivative) three parts, has the advantages of good stability, simple control algorithm, high reliability.

Fuzzy control, which belongs to the category of nonlinear intelligent control, is based on the theory of fuzzy mathematics and introduces human control experience to control the control object. It is generally used for the control object model that cannot be expressed in strict mathematics and can be well controlled by human knowledge and experience.

When the control system model has been determined, fuzzy rules are used to model the knowledge and experience of staff or experts. Then the optimal tuning PID parameters are obtained by using fuzzy inference method. Because the knowledge and experience of staff or experts are difficult to give accurate and quantitative representation of various semaphore in the control process, fuzzy control theory can effectively solve this situation [9]. Therefore, using fuzzy control theory and method, the conditions and operations of fuzzy control rules are expressed in the form of fuzzy sets, and such information is stored in the knowledge base of microcomputer. In the subsequent control process, the computer can adjust the PID parameters according to the actual needs of the field by fuzzy reasoning, that is, adaptive fuzzy PID control [10].

3. System design and application details

3.1. Factors to consider

The two-input and three-output thermal model using MATLAB can help to consider various factors in the temperature control system, as shown in Figure 1.

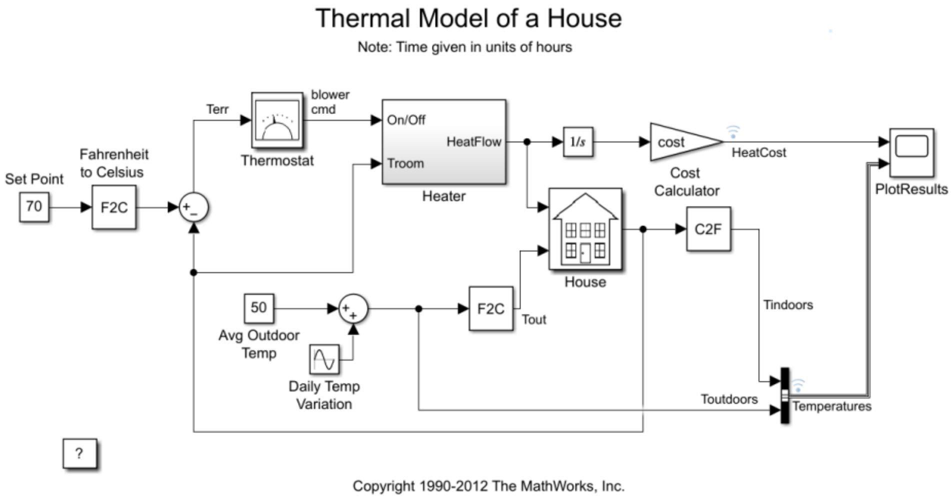

Figure 1. Thermal Model of a house (Photo credit: Original)

A simplified version can be built so that it is convenient to analyze it, as shown in Figure 2.

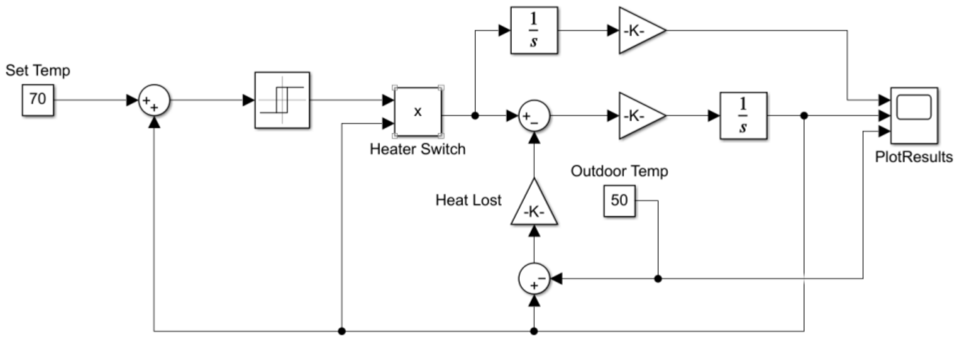

Figure 2. The simplified version (Photo credit: Original)

The model above uses a delay comparator to determine whether a system, such as a building, needs heating. The basis of judgment is whether the difference between the indoor temperature and the set temperature is within the set range. If the user needs heating, the room temperature is fully fed back, and the heat required to be consumed is calculated through the integration process. Next, the heat loss inherent in the house is subtracted, and through an integral process, the achievable indoor temperature after heating is obtained. As you can see, the temperature change is only determined by the integral process. It is a comparator that controls the temperature within a certain range.

Through the above analysis, some output charts can be obtained. The curve in the first graph represents Heat costs. The blue curve in the second graph represents the change in indoor temperature, and the red curve represents the change in outdoor temperature, as shown in Figure 3.

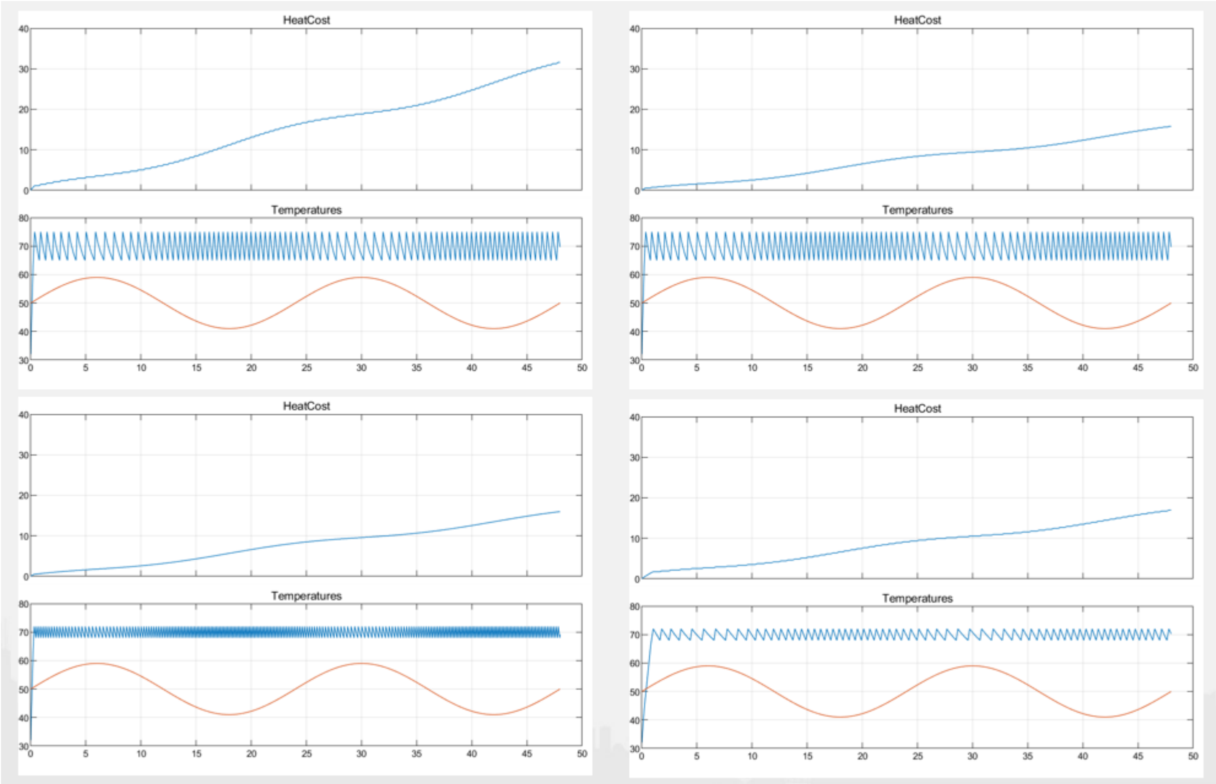

Figure 3. Some output charts (Photo credit: Original)

As you can see, the cost of heat presents a step pattern because the heater does not work when the comparator is turned off. The room temperature fluctuates up and down within a fixed range. In the second chart, the parameters of the thermal cost process are reduced, so there is a significant decrease in it. The threshold of the comparator is then lowered and the temperature changes within a smaller range. Finally, the integral parameters of the temperature control process are reduced so that the temperature changes less frequently.

In the actual project, the energy consumption part needs to be calculated and adjusted according to the actual system, while for the temperature control part, we adjust according to the integrated link and delay comparator given in the system. The advantage of this method is that we only need one integrator and comparator to complete the control, which is equivalent to adding a limit to the control system with the circuit structure. This way, we don't need to spend a lot of time adjusting PID parameters. All we need to do is make sure that the comparator's parameters are appropriate and that it works properly.

3.2. PID parameter comparison and optimization

Next, the theoretical implementation of fuzzy PID algorithm is discussed.

We take the temperature 26 which is most suitable for human body as the basis, taking into account the actual situation, we assume that the error range is [-30, 30], and it is equally divided into six parts: [-30, -20], [-20, -10], [-10, 0], [10, 20], [20, 30]. Then -30, -20, -10, 0, 10, 20, 30 are represented by NB, NM, NS, ZO, PS, PM, PB respectively (N: negative, P: positive, S: small, M: medium, B: large, Z: zero).

After determining the error range, we need to determine the membership function. For simple calculations, we use the triangular membership function, as shown in Figure 4.

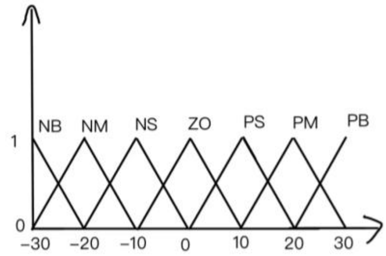

Figure 4. Triangle membership function image (Photo credit: Original)

The range of membership degree is [0, 1], and Figure 5 can be drawn assuming that the error e is 16.7.

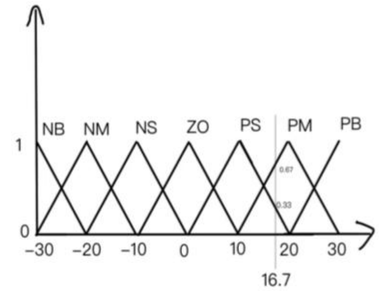

Figure 5. The drawing function image (Photo credit: Original)

As shown in the figure, the probability of PS is 0.33 and the probability of PM is 0.67.

The next step is fuzzy inference, based on the membership of e to de/dt degree. The fuzzy PID reasoning table is shown in Figure. 6, 7 and 8.

△*Kp*		de/dt						
		NB	NM	NS	ZO	PS	PM	PB
e	NB	PB	PB	PM	PM	PS	ZO	ZO
	NM	PB	PB	PM	PS	PS	ZO	NS
	NS	PM	PM	PM	PS	ZO	NS	NS
	ZO	PM	PM	PS	ZO	NS	NM	NM
	PS	PS	PS	ZO	NS	NS	NM	NM
	PM	PS	ZO	NS	NM	NM	NM	NB

Figure 6. ΔKp (Photo credit: Original)

△*Ki*		de/dt						
		NB	NM	NS	ZO	PS	PM	PB
e	NB	NB	NB	NM	NM	NS	ZO	ZO
	NM	NB	NB	NM	NS	NS	ZO	ZO
	NS	NB	NM	NS	NS	ZO	PS	PS
	ZO	NM	NM	NS	ZO	PS	PM	PM
	PS	NM	NS	ZO	PS	PS	PM	PB
	PM	ZO	ZO	PS	PS	PM	PB	PB

Figure 7. ΔKi (Photo credit: Original)

△*Kd*		de/dt						
		NB	NM	NS	ZO	PS	PM	PB
e	NB	PS	NS	NB	NB	NB	NM	PS
	NM	PS	NS	NB	NM	NM	NS	ZO
	NS	ZO	NS	NM	NM	NS	NS	ZO
	ZO	ZO	NS	NS	NS	NS	NS	ZO
	PS	ZO	ZO	ZO	ZO	ZO	ZO	ZO
	PM	PB	NS	PS	PS	PS	PS	PB

Figure 8. ΔKd (Photo credit: Original)

If e = 16.7 and de/dt = 3200 (range [-3600, 3600]), then the membership of fuzzy e is 0.33 (PS) and 0.67 (PM).

The membership degrees of de/dt are 0.67 (NB) and 0.33 (NM), respectively. Finally, e and de/dt membership are calculated in pairwise groups.

$$\begin{aligned}
&\Delta Kp\text{: } 0.33*0.67=0.2211(PS)\\
&0.33*0.33=0.1089(PS)\\
&0.67*0.67=0.4489(PS)\\
&0.67*0.33=0.2211(ZO)\\
&\Delta ki\text{: } 0.33*0.67=0.2211(NM)\\
&0.33*0.33=0.1089(NS)\\
&0.67*0.67=0.4489(ZO)\\
&0.67*0.33=0.2211(ZO)\\
&\Delta Kd\text{: } 0.33*0.67=0.2211(ZO)\\
&0.33*0.33=0.1089(ZO)\\
&0.67*0.67=0.4489(PB)\\
&0.67*0.33=0.2211(NS)
\end{aligned} \tag{1}$$

The above integral gives.

Kp membership is 0.7789 (PS), 0.2211 (ZO).

The membership degree of the Ki is 0.67 (ZO), 0.2211 (NM), 0.1089 (NS).

The membership of Kd is 0.4489 (PB), 0.33 (ZO), 0.2211 (NS).

Finally, you need to de-blur and calculate the specific value of ΔPID for each membership degree.

$$\begin{aligned}
&E(Kp)=0.7789*10+0.2211*0=7.789\\
&E(Ki)=0.67*0+0.2211*(-20)+0.1089*(-10)=-5.511\\
&E(Kd)=0.33*0+0.4489*30+0.2211*(-10)=11.256
\end{aligned} \tag{2}$$

The ΔPID value obtained by the above calculation cannot be directly used as the system adjustment, and the specific range of Kp, Ki and Kd need to be mapped to the interval as the adjustment value.

Guess the temperature and heat transfer in the house.

For example, in a resident's house, it is impossible to guarantee that the temperature everywhere is the same value. For example, when you take a shower, the temperature of the bathroom is higher than that of the general-purpose room. When the bedroom is air-conditioned in summer, the temperature of the living room will be higher than that of the bedroom.

To make the indoor temperature regulation system does not always receive a large temperature difference input, we can use a variety of methods to balance the indoor temperature, such as:

The use of new materials (such as: the paper of Professor Ma Mingyi of China University of Petroleum pointed out the seasonal operation characteristics and adaptability of natural ventilation translucent photovoltaic double-layer leather curtain wall). This can reduce the slope of the error, reduce the number of adjustments to the system, and achieve a more environmentally friendly and energy-saving way of working.

Set up multiple feedback channels for adjustment. The error of each feedback channel is calculated through the setting values of several different rooms, and more accurate temperature control is achieved under the control and adjustment of the specified parameters, to avoid the excessive rise or fall of de/dt faults caused by large temperature changes in a room, resulting in unnecessary indoor heating or heat dissipation.

Use heat transfer devices. Install heat conduction devices in places with large temperature differences (such as bedrooms, bathrooms, entryways, etc.) to disperse excess heat to other Spaces or fill other Spaces with heat.

3.3. Input data selection

When the input data is selected, the traditional PID first controls the temperature value. Let the transfer function of the system be $\frac{1}{0.02s+1}$, and set the PID parameters as follows: $K_p = 0.2, K_i = 0.2, K_d = 0.5$, the results obtained are shown in Figure 9.

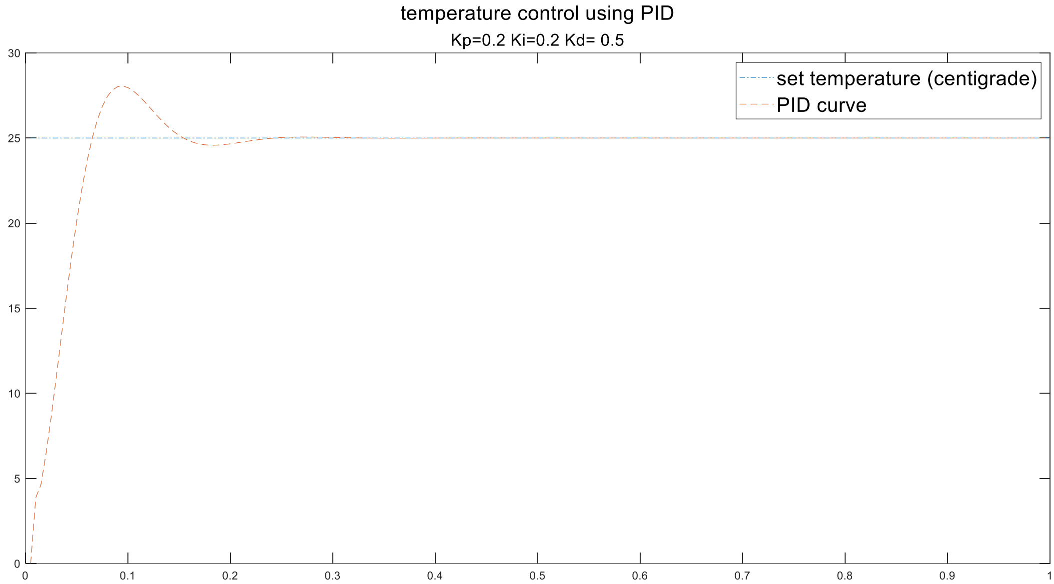

Figure 9. Temperature control using PID (Photo credit: Original)

As can be seen from the figure, the control effect of the three parameters selected is not good, mainly reflected in the excessive overshoot. Therefore, in view of the influence of different PID parameters on the control system, the control effect can be compared by changing different parameter values. The results are shown in Figure 10, and the PID parameters used are labeled in each diagram.

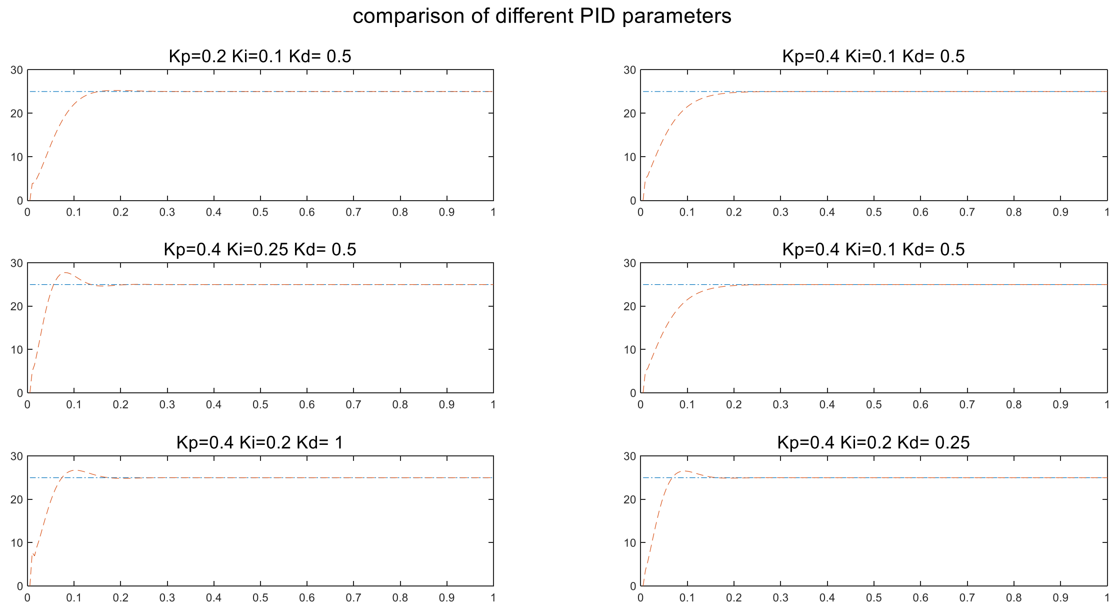

Figure 10. Comparison of different PID parameters (Photo credit: Original)

For the above two figures, the parameter K_p is mainly changed. Its change has little impact on the control effect in this system. For the two pictures in the middle, the value of K_i is mainly changed. In this system, its change will lead to the transformation of the overshoot, which will have a greater impact. For the two pictures below, the main changes are: the value of K_d, and its change has little impact on the control effect of the system. In short, changes in the K_i value have the greatest impact on the system, so subsequent optimization is mainly focused on the integration link.

The optimization link uses the integral separation PID control method. Use two conditions to control the integration link. Under these two conditions, the integral element will be disabled, which are when output of PID larger than target temperature value and if output has not reached the specified value or output of PID smaller than 0, and if output exceeds the specified value, the integral element will be disabled. The optimized control results are shown in Figure 11. Under these two conditions, the overshoot is smaller, and the rising time is shorter, which proves this is an effective method to optimize the PID control system.

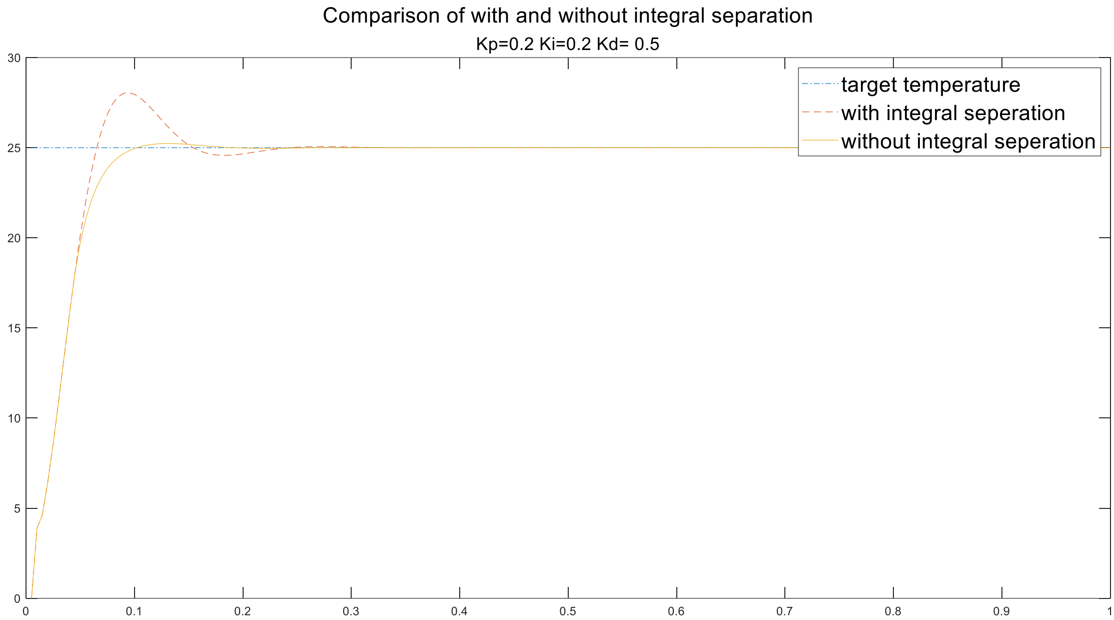

Figure 11. The optimized control result (Photo credit: Original)

Generally, the indoor temperature control system can use PID control, but different parameters will lead to different control results, it is difficult to achieve good control effect by adjusting the parameters. In the process of optimization, the integral separation method is used to obtain better control effect than the method without optimization.

3.4. Comparative advantage

Strong adaptability: the fuzzy PID control algorithm can adapt to a variety of complex nonlinear systems such as building temperature control, and can automatically adjust the control parameters according to the changes of the system to achieve better control effects, so it has better comfort than the traditional building temperature control system.

Good robustness: Because the fuzzy PID control algorithm can deal with the uncertainty and interference of the system, it can still maintain good control performance in the face of system parameter changes and external interference, so it has better stability compared with the traditional building temperature control system, and will not produce a huge temperature difference in temperature regulation.

High control accuracy: The fuzzy PID control algorithm can automatically adjust the control parameters according to the actual state and target requirements of the system to achieve accurate control of the system, so the application in temperature control can adapt to some production environments with high temperature accuracy requirements, such as laboratories.

Easy to implement: Compared with other complex control algorithms, fuzzy PID control algorithm is relatively simple to implement, and the calculation amount is small, which is more suitable for real-time control systems, so it is a building temperature control system that is easier to establish mathematical models.

4. Challenges

Difficulty in parameter adjustment: The performance of fuzzy PID control algorithm largely depends on the choice of control parameters, and the adjustment of parameters requires a certain amount of experience and professional knowledge, which may be difficult for beginners, which needs to provide users with more reasonable parameter choices when designing the system, so that the temperature control system can be applied to more scenarios and meet more requirements.

High computational complexity: Although the calculation amount of fuzzy PID control algorithm is small compared with other complex control algorithms, it still requires large computational resources in some complex systems, which requires simplifying related operations or making necessary calculations in advance when developing and designing related temperature control software fire system, thereby reducing the computing power requirements of the client.

Sensitive to the selection of fuzzy sets: the selection of fuzzy sets in the fuzzy PID control algorithm has a great impact on the control effect, and if it is improperly selected, the control effect may be reduced or unstable, so the appropriate fuzzy set should be selected in advance when the fuzzy PID control algorithm is applied to the building temperature control system to prevent application problems.

5. Conclusion

The fuzzy PID control algorithm, rooted in fuzzy logic, holds significant promise for control systems. Despite certain drawbacks, such as challenging parameter tuning and high computational complexity, its strong adaptability, robust performance, and high control accuracy make it highly effective in numerous applications. These attributes enable it to outperform traditional control methods in dynamic and uncertain environments. Consequently, fuzzy PID control can be a valuable choice for optimizing existing temperature control systems, addressing their limitations while enhancing overall performance. By leveraging its advanced capabilities, a new building temperature control system can be designed to meet diverse residential and industrial needs. This innovative approach ensures precise and efficient temperature management, adapting to various conditions and user requirements, thereby improving comfort and energy efficiency across multiple life and production scenarios.

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