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The Control Analysis of Single Capacity Water Tank Liquid Level System Based on PSO Optimized Fuzzy PID

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***Abstract*— *The liquid level automatic control system of a single-capacity water tank is a common industrial process control system, which is widely used in industrial production. Through simulation research, it can effectively ensure the stability of the liquid level of the water tank and meet the requirements of liquid level control in the production process. In this paper, the automatic control system model of a single-volume water tank level is established by MATLAB/Simulink, and its control system is studied and compared. Firstly, the physical modeling of the control system is carried out to obtain its transfer function, which is the basis for subsequent simulation. Then, the influence of Proportional–Integral–Derivative (PID) control parameters on the dynamic characteristic curve of the system is understood, and then the characteristics and application occasions of fuzzy PID control and Particle-Swarm-Optimization (PSO) control are deduced. Finally, the system dynamic characteristic curves of PID control, fuzzy PID control, and PSO control are compared and analyzed. The simulation results show that PID control, fuzzy PID control, and PSO control are suitable for different occasions, and appropriate control strategies can be adopted according to different control system conditions.*

Keywords*— *Simulink simulation, Proportional–Integral–Derivative (PID) control, fuzzy PID control, Particle-Swarm-Optimization (PSO) particle swarm optimization algorithm, automatic control system

I. INTRODUCTION

The liquid level control system of a single-capacity water tank is one of the most widely used automatic control systems in industrial production. It has the characteristics of simple structure, high control accuracy, good stability, fast

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response speed, and wide application range [1], which can effectively ensure the stability of the liquid level of the water tank and meet the requirements of liquid level control in the production process. Its control system usually adopts PID control, which has the characteristics of high stability, good flexibility, and simple implementation [1, 2].

The goal of this paper is to obtain the transfer function of the system by establishing the physical model of the single-volume water tank liquid level system and importing the physical model into MATLAB software for simulation based on MATLAB, PID control, and fuzzy PID control. The dynamic characteristics of the single-volume water tank liquid level automatic control system can be observed and compared, and the results of classical PID control and fuzzy PID control are compared [3] so as to verify the advantages of the fuzzy PID control system in all aspects.

II. RESEARCH METHODOLOGY

2.1 Establish the physical model of the liquid level control system of a single-volume water tank

Firstly, the physical model of the single-volume water tank liquid level automatic control system based on PID control is established, and the dynamic analysis of the model is carried out. The physical model is shown in Figure 1:

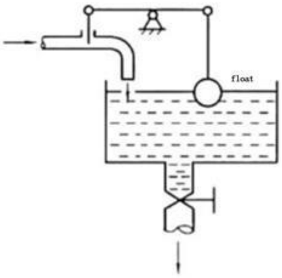

Fig.1 Model of automatic liquid level control system for single capacity water tank

The inlet and outlet flow rates of the water tank are W1 and W2, respectively, and the liquid level height of the water tank is E. The mathematical model of the system can be obtained by calculation. The transfer function of the water tank is formula (1):

$$G(s)=\frac{G(s)}{W_1(s)}=\frac{R_2}{R_2Cs+1}=\frac{K}{Ts+1} \quad (1)$$

According to the inertia link transfer function of the first-order system, $T=R_2C$ is the time coefficient of the control system, and $K=R_2$ is the proportional coefficient of the control system. For the water tank level control, the PID regulator in the mechanical engineering control foundation is applied to the automatic control of the water tank level. In the closed-loop control system, the actual value of the water tank liquid level is returned to the input through negative feedback, and the deviation between the given value and the actual output is compared and calculated. The output value is obtained by the PID algorithm, and the speed of the AC inverter and motor is controlled by digital-to-analog conversion. Finally, the automatic control of the water tank liquid level is realized. The transfer function of the overall control system is shown in Figure 2. The transfer function is formula (2).

$$G_C(s)=\frac{N(s)}{E(s)}=K_p\left(1+\frac{1}{K_i s}+K_d s\right) \quad (2)$$

Where K_P is the proportional coefficient, K_i is the integral coefficient, and K_d is the differential coefficient.

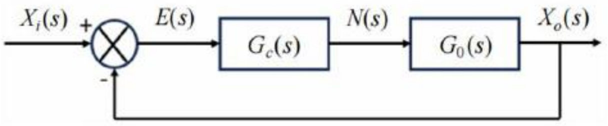

Fig.2 Transfer function block diagram of PID automatic liquid level control for a single-volume water tank

2.2 Classic PID control principle

In a general control system, the most common control mode is classical PID control. PID control can effectively adjust the system deviation through the synergy of proportional (P), integral (I) and differential (d) and has the characteristics of strong adaptability and flexible adjustment [1, 2]. The classic PID control system is shown in Figure 3.

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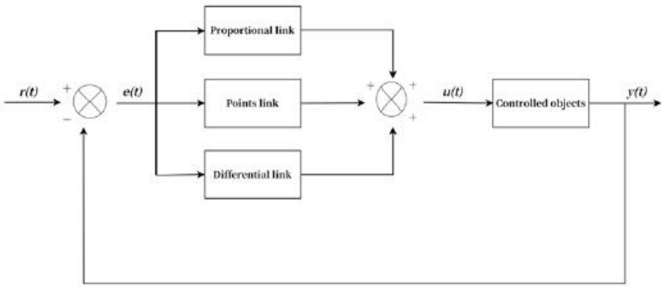

Fig.3 The PID system structure

The expression of a classical PID controller usually has two forms: time domain and frequency domain. The expressions of the time domain and frequency domain are formula (3) and formula (4), respectively:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)\,dt + K_d \frac{de(t)}{dt} \quad (3)$$

$$G(s) = K_p + \frac{K_i}{s} + K_d s \quad (4)$$

In Figure 3, the proportional link (P), integral link (I), and differential link (d) correspond to the proportional coefficient K_P, integral coefficient K_i and differential coefficient K_d in the expression, respectively. The proportional coefficient determines the response strength of the controller to the current deviation. The larger the proportional coefficient, the faster the controller responds to the deviation. The integral coefficient determines the response strength of the controller to the accumulated deviation. The larger the integral coefficient, the stronger the ability of the controller to eliminate the steady-state error. The differential coefficient determines the response strength of the controller to the deviation change rate.

The larger the differential coefficient, the stronger the predictive ability of the controller to the deviation change. In PID control, when the system order is high and the open-loop transfer function is unknown, it is necessary to optimize and analyze the gain margin, phase margin, and dynamic response performance. In the face of complex systems or special control requirements, it is necessary to consider the frequency domain analysis. Since the selected automatic control system for the liquid level of a single-capacity water tank is relatively simple and stable, and the open-loop transfer function is known, it is not necessary to consider the frequency domain analysis.

2.3 Fuzzy PID control principle

Fuzzy PID controller is a control strategy that combines fuzzy logic with traditional PID control. It uses fuzzy logic and certain fuzzy rules to optimize PID parameters in real time so as to overcome the disadvantage that traditional PID parameters cannot adjust PID parameters in real time [6][7]. It is mainly used to deal with nonlinear, time-varying, and uncertain systems [4, 5]. The fuzzy PID controller has the advantages of adaptive characteristics, which can automatically adjust the control parameters according to the dynamic changes of the system, achieve rapid response, reduce the rise time and overshoot of the system, and reduce the complexity and time-consuming of parameter setting, making it an effective tool to deal with complex control problems. The structure of the fuzzy PID control system is shown in Figure 4:

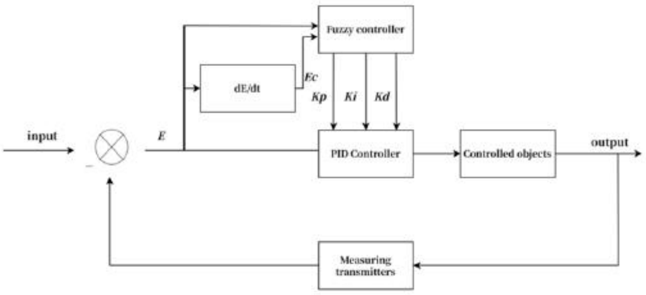

Fig.4 Structure diagram of fuzzy PID control system

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In Figure 4, the fuzzy controller is mainly composed of three modules: fuzzification, fuzzy reasoning, and clarity (Figure 5).

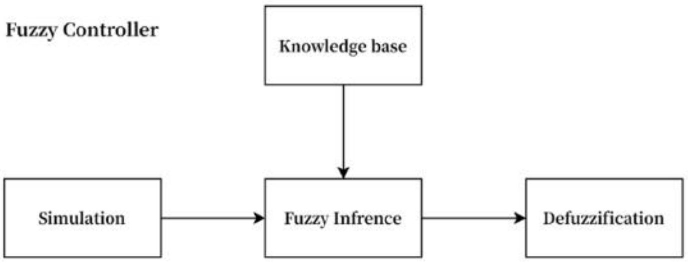

Fig.5 Structure of fuzzy rule base

In the fuzzy PID control system, error E and error change rate EC are the two inputs of the fuzzy PID controller, and K_P、 K_i、 and K_d are the three outputs of the controller [5].

Set the definition domain and display range of E and EC to [-2, 2], and its fuzzy subset is E = ES = {negative large, negative small, zero, positive small, positive large} = {Nb, N, ZE, P, PB}. Input and select the gauss2mf waveform membership function, output and select the trimf waveform membership function, and establish fuzzy rules according to fuzzy rule Table 1.

Table 1 Table of fuzzy rules

e(t)\ △e(t)	NB	N	ZE	P	PB
NB	$K_p = B$ $K_i = MB$ $K_d = S$	$K_p = B$ $K_i = MB$ $K_d = MS$	$K_p = MB$ $K_i = MS$ $K_d = MS$	$K_p = MS$ $K_i = MS$ $K_d = S$	$K_p = S$ $K_i = MB$ $K_d = B$
N	$K_p = B$ $K_i = MB$ $K_d = MS$	$K_p = MB$ $K_i = MS$ $K_d = MS$	$K_p = MS$ $K_i = MS$ $K_d = MS$	$K_p = S$ $K_i = MB$ $K_d = MS$	$K_p = S$ $K_i = MB$ $K_d = B$
ZE	$K_p = MB$ $K_i = MS$ $K_d = MS$	$K_p = MS$ $K_i = MS$ $K_d = MS$	$K_p = S$ $K_i = MB$ $K_d = MS$	$K_p = MS$ $K_i = MS$ $K_d = MS$	$K_p = MB$ $K_i = MB$ $K_d = B$
P	$K_p = S$ $K_i = MB$ $K_d = MB$	$K_p = S$ $K_i = MB$ $K_d = MS$	$K_p = MS$ $K_i = MS$ $K_d = MS$	$K_p = MB$ $K_i = MS$ $K_d = MS$	$K_p = B$ $K_i = MB$ $K_d = S$
PB	$K_p = S$ $K_i = MB$ $K_d = B$	$K_p = S$ $K_i = MB$ $K_d = MS$	$K_p = MS$ $K_i = MS$ $K_d = MS$	$K_p = MB$ $K_i = MS$ $K_d = MS$	$K_p = B$ $K_i = MB$ $K_d = S$

2.4 Basic control principle of PSO algorithm

Particle-swarm-optimization (PSO) is an optimization algorithm based on swarm intelligence. The inspiration of this algorithm comes from the research on the foraging behavior of birds, and the optimal solution is found by simulating the cooperation and information sharing among individuals in the group [6, 8].

PSO simulates birds in a flock of birds by designing a massless particle. The particle has only two attributes: speed and position. Speed represents the velocity of movement, and position represents the direction of movement. Each particle searches for the optimal solution separately in the search space

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and records it as the current individual extremum and shares the individual extremum with other particles in the whole particle swarm to find the optimal individual extremum as the current global optimal solution of the whole particle swarm. All particles in the particle swarm adjust their speed and position according to the individual extremum they find and the current global optimal solution shared by the whole particle swarm so as to approach the global optimal solution. The update formulas for speed and position are (5) and (6):

$$v_i^{(t+1)} = v_i^{(t)} + c_1 + r_1\left(pbest_i - x_i^{(t)}\right) + c_2 r_2\left(gbest - x_i^{(t)}\right) \quad (5)$$

$$x_i^{(t+1)} = x_i^{(t)} + v_i^{(t+1)} \quad (6)$$

Where pbest represents the individual optimal position of particles and gbest represents the global optimal position of particles.

The PSO particle swarm optimization algorithm has been widely used in the application fields of function optimization, neural network training, engineering system control, and other genetic algorithms. In PID control, the particle swarm optimization algorithm is mainly used to optimize the parameters of the PID controller (proportional gain K_P, integral gain K_i and differential gain K_d) to improve the performance of the control system.

The process of PSO optimizing PID parameters can be divided into the following steps:

(1) Initialize

Randomly initialize the position and velocity of the particle swarm. The position of each particle represents a set of PID parameters (K_P、K_i、K_d), and the speed represents the change of parameters. Define the upper and lower limits of particles, such as K_P、K_i、K_d value range.

(2) Calculate fitness

The position of each particle (PID parameter) is substituted into the control system to run the simulation model (such as the Simulink model). Calculate the performance indicators of the system, such as ITAE (integral of the product of time and absolute value of error) and IAE (integral of the absolute value of error), and take this value as the fitness value of particles.

(3) Update particle position and velocity

According to the velocity and position update formula of PSO, the velocity and position of each particle are updated, and the individual optimal position (pbest) and global optimal position (gbest) of particles are updated.

(4) Iterative optimization

Repeat the above steps until the termination conditions are met (such as the maximum number of iterations or the fitness value is small enough)

The global optimal position is output as the optimal PID parameter. In this way, PSO plays an important role in PID control, and provides an efficient and reliable solution for parameter optimization of complex control systems.

III. ANALYSIS AND RESULTS

3.1 Establish the PID control simulation model

In order to observe the influence of the PID controller and fuzzy PID controller on the control system, the PID controller model is established first. The liquid level of the water tank is selected as the control object, and the PID controller is used to realize the automatic control of the liquid level of the water tank. In order to intuitively show this process, a simulation model of PID automatic liquid level control for a water tank is built based on the MATLAB/Simulink platform (Figure 6). In this model, the set input value is the desired liquid level (i.e., the set value), and the output result reflects the water inflow of the tank. Through this model and dynamic simulation process, we can intuitively observe the working principle of the PID controller and the influence of parameter adjustment on system performance.

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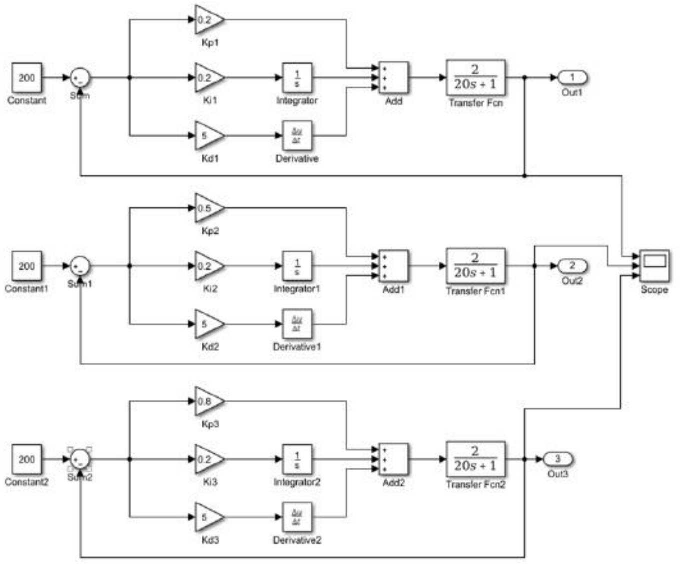

Fig.6 Simulation model of PID automatic liquid level control of a water tank based on MATLAB/Simulink.

3.2 Influence of parameters in PID controller on dynamic characteristics of water tank system

3.2.1 Effect of proportional parameter Kp on dynamic characteristics of water tank system

In the simulation process, the set value of the water tank liquid level is 200, and K_P is set to 0.2, 0.5, and 0.8, respectively. Observe the simulation dynamic characteristic curve of the model under different scale parameters. As shown in Figure 7.

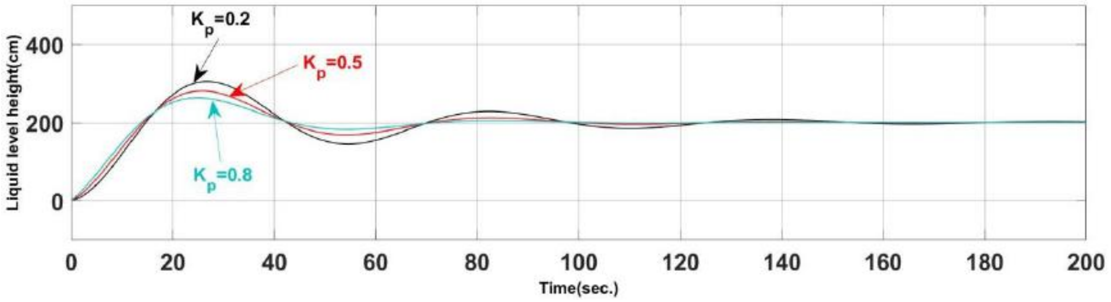

Fig.7 Effect of different proportional parameters Kp on dynamic characteristics of water tank system

It can be observed from Figure 7 that no matter what value K_P is taken, the liquid level will tend to be stable after a certain fluctuation. It should be noted that with the increase of K_P value, the maximum overshoot of the system shows a decreasing trend, and the response time required to reach the steady state is correspondingly shortened, and the response speed is accelerated. This observation shows that properly increasing the proportional coefficient can help to improve the performance of the controller.

3.2.2 Influence of integral parameter Ki and differential parameter Kd on dynamic characteristics of water tank system

In PID control, the integral link and differential link are indispensable parts of the PID controller. In the simulation model of the single-capacity water tank level PID control system, the integral parameter K_i and differential parameter K_d are also adjusted differently to observe the influence of the integral parameter K_i and differential parameter K_d on the dynamic characteristics of the system. The effects of

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integral parameter K_i and differential parameter K_d on the dynamic characteristics of the system are shown in Figure 8 and Figure 9, respectively.

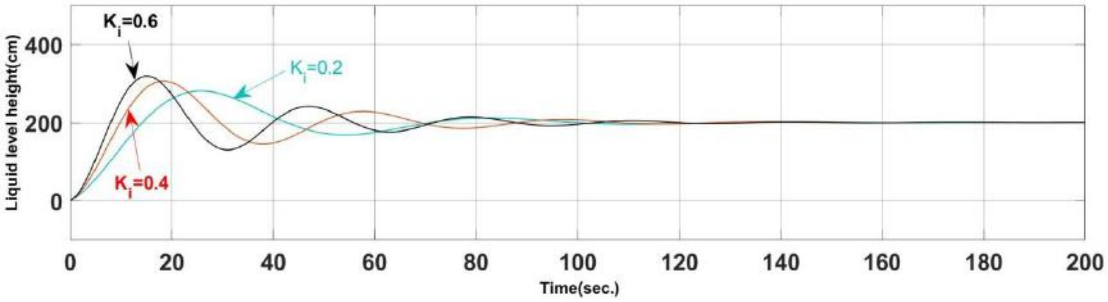

Fig.8 Effect of different integration parameters Ki on dynamic characteristics of a water tank system

It can be observed from figure 8 that with the increase of the integral coefficient K_i (K_i =0.2, 0.4, and 0.6), the response speed of the system to reach the steady state becomes slower, the overshoot phenomenon of the system increases, and the stability decreases. The increase of the integration coefficient leads to the system needing more time to accumulate errors and makes the phase lag of the system, which makes the system more prone to oscillation and makes the system unstable.

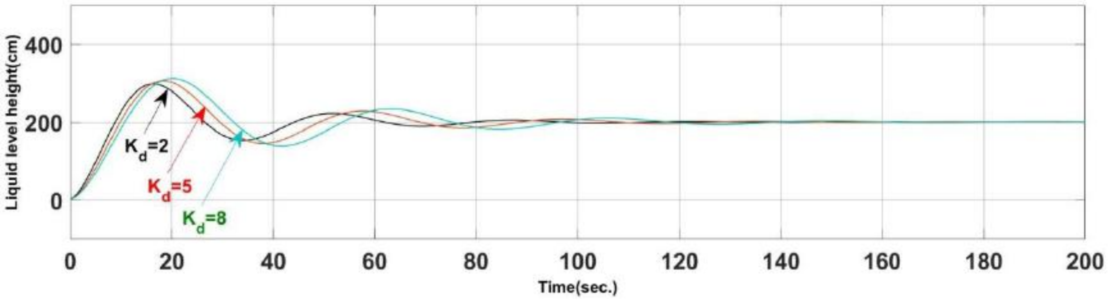

Fig.9 Effect of different differential parameters Kd on dynamic characteristics of water tank

It can be observed from Figure 9 that as the differential parameter K_d increases (K_d is 2, 5, and 8), the stability of the system gradually deteriorates, the maximum overshoot increases, and the adjustment time required to reach the steady state also increases accordingly.

3.3 Fuzzy PID control of simulation model of water tank control system

As a classical control strategy, the PID controller is widely used in various industrial process controls because of its simplicity, universality, stability, economy, and other characteristics, but it has some limitations in dealing with nonlinear, time-varying, and other systems. The automatic liquid level control system of a single-capacity water tank is generally PID control, but more uncontrollable factors need to be considered when dealing with some special occasions, so it is necessary to consider fuzzy PID control for the control system [3, 4, 9]. In order to compare with PID control, the fuzzy PID control simulation model of the single-capacity water tank liquid level control system is established through the MATLAB/Simulink platform, as shown in Figure 10. Through the model and dynamic simulation process, the influence of the fuzzy PID controller on system performance can be observed intuitively.

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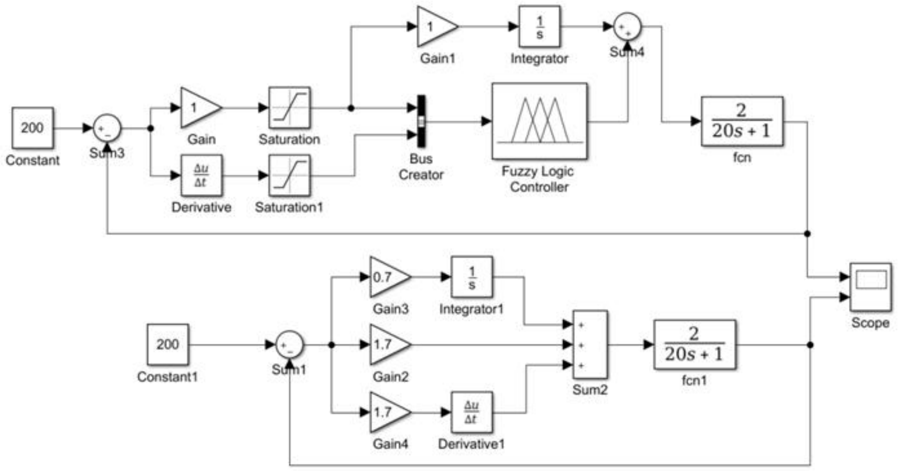

Fig.10 Simulation model of fuzzy PID automatic liquid level control of a water tank based on MATLAB/Simulink.

The system dynamic characteristics of fuzzy PID control and PID control are compared, as shown in Figure 11.

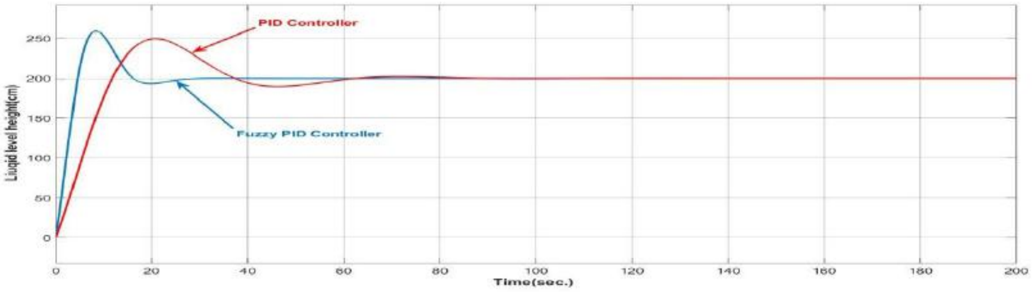

Fig.11 influence of PID control and fuzzy PID control on system dynamic characteristics

It can be observed from Figure 11 that the fuzzy PID control rises rapidly at the initial stage of control and then drops rapidly after reaching the peak value and tends to be stable. The PID control rises smoothly without obvious overshoot and finally tends to be stable. Through observation, it can be concluded that the fuzzy PID controller has a faster response speed and reaches the steady state [7], but there will be a large overshoot; the PID controller provides a smoother response and smaller overshoot, but it takes longer to reach the steady state.

PID controller can achieve faster response speed and reach steady state faster by adjusting parameters. When debugging PID parameters, it is necessary to adjust the proportional link (P), integral link (I) and differential link (d) in turn, and reduce the proportional parameters when the system curve vibrates. In case of floating and large fluctuation, the proportional parameter needs to be increased. When the system curve deviates from the target value, the integral parameter needs to be reduced. When the fluctuation period of the system curve is long, the integral parameter needs to be increased. If the oscillation frequency of the system curve is fast, the differential parameter needs to be reduced. When the fluctuation difference of the system curve is large and the fluctuation is slow, the differential parameter needs to be increased. According to the above pithy formula, the PID controller parameters are debugged to match the PID control with the fuzzy PID control, so that the set expected liquid level and water inflow are stable. The commissioning results are shown in Figure 12.

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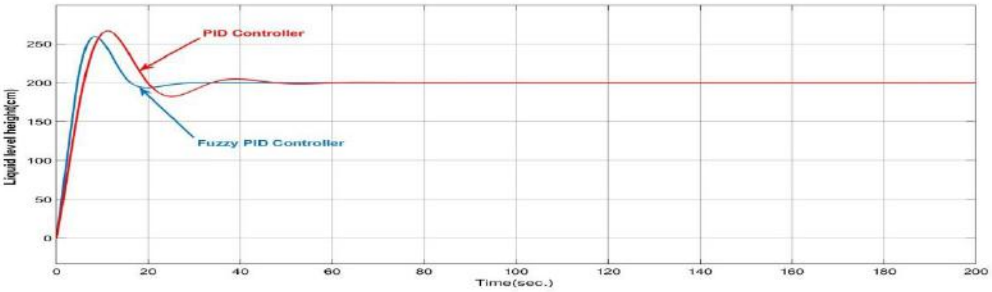

Fig.12 PID control and fuzzy PID control fitting

It can be observed from Figure 12 that even if the PID parameters are debugged to match the fuzzy PID control as much as possible, they cannot be completely matched. Therefore, considering the economic benefits, the control system that selects fuzzy PID control as the automatic control system of the liquid level of a single-capacity water tank will be better than PID control.

3.4 PID control based on PSO algorithm

The PSO algorithm is widely used in engineering system control, which is reflected in the fact that the PSO algorithm can be applied to nonlinear, time-varying, and other complex control systems, and the PID parameters optimized by PSO can significantly improve the stability and response speed of the system and can adapt to complex systems [6,9,10]. At the same time, it can be combined with MATLAB /Simulink and other tools to make the method of PSO optimizing PID parameters more simple and easy. In order to reflect the optimization and debugging of the parameters of the PID controller by the PSO optimization algorithm, the PSO-PID control simulation model of the liquid level control system of the single-capacity water tank is established on the MATLAB/Simulink platform, as shown in Figure 13. Through the model and dynamic simulation process, the results of the optimization of the parameters of the PID controller by the PSO-PID controller can be observed.

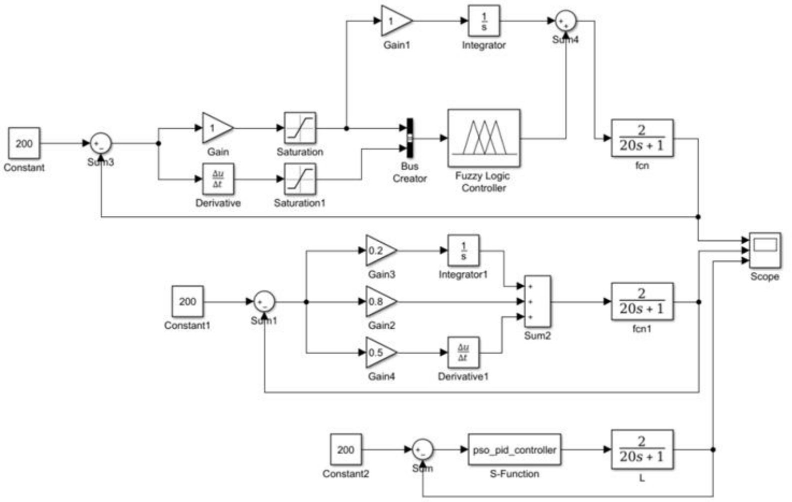

Fig.13 Simulation model of automatic liquid level control of a water tank using PSO-PID based on MATLAB/Simulink

Compare the system dynamic characteristic curve output of the PID controller, fuzzy PID control, and PID control participated in by the PSO algorithm, as shown in Figure 14:

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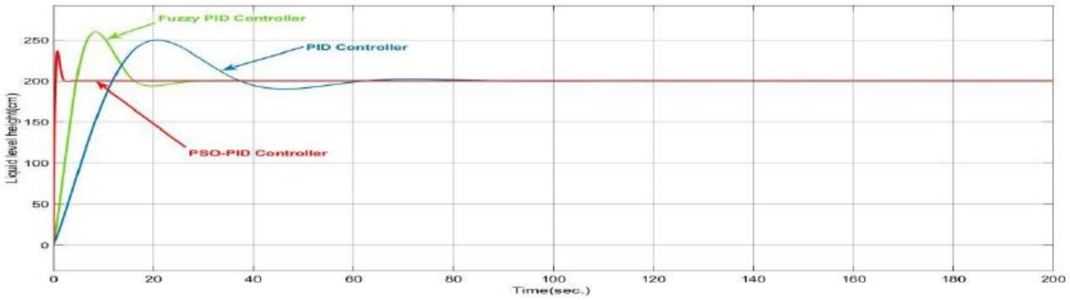

Fig.14 Influence of PSO control, PID control, and fuzzy PID control on dynamic characteristic curve

From the analysis of Figure 14, it can be seen that the fuzzy PID control responds very quickly in the initial stage, reaching a higher value almost immediately.

It reaches the peak at about 10 time units, significantly exceeding the target value, showing a large overshoot. After reaching the peak value, the curve of fuzzy control began to decline, but there was a certain oscillation until it tended to be stable after about 30 time units. This shows that the fuzzy control has a large fluctuation before reaching the stable state. Finally, the response value of fuzzy control is stable around the target value of 200 but may be slightly lower than the target value.

The initial response of PID control is also faster but slower than that of fuzzy control. It reaches the peak at about 15 time units, and the overshoot is small, showing good control performance. After reaching the peak value, the PID control curve gradually decreased and tended to be stable, with small oscillation. The response value of PID control finally stabilized around the target value of 200, showing good control accuracy.

The initial response of PSO control is relatively slow but very stable. There is almost no overshoot, and the curve is smoothly close to the target value. The curve of PSO control has almost no oscillation in the whole process, showing high stability. The response value finally stabilized at the target value of 200, showing the best control accuracy and stability.

In general, from the comparison of response speed, fuzzy control has the fastest response speed, but it is accompanied by large overshoot and oscillation; PID control takes the second place, while PSO control has the slowest response speed. From the comparison of overshoot, the overshoot of fuzzy control is the largest, followed by PID control, and there is almost no overshoot of PSO control. From the stability comparison, the stability of PSO control is the best, and there is almost no oscillation; PID control takes the second place, while fuzzy control has the worst stability and large oscillation. From the comparison of final control accuracy, the final control accuracy of PSO control is the highest, followed by PID control, and the final control accuracy of fuzzy control may be slightly lower than the target value.

IV. CONCLUSION

As a common industrial process control system, the automatic control system of a single-volume water tank liquid level is widely used in industrial production. The general automatic control system of a single-volume water tank liquid level adopts PID control, which can not only achieve stable control but also meet economic benefits. In this paper, the influence of the parameters of each link of the PID controller on the dynamic characteristics of the system is analyzed by taking the single-capacity water tank level control system as an example. At the same time, PID control, fuzzy PID, and PSO optimization control are studied and compared. The results show that if the system requires a high response speed but can tolerate a certain degree of overshoot and oscillation, fuzzy control can be considered. If the system needs better balance, response speed, and stability, PID control is a better

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choice. If the system requires very high stability and final accuracy, PSO control is the best choice, although its response speed may be slow.

In general, the automatic control system of water tank level needs both response speed and stability, and PID control can be used. When a higher response speed is needed, fuzzy PID control is a better choice. If it is necessary to further pursue higher control accuracy and better stability, PSO control is the optimal choice.

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