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Design of a high-dimensional data-driven engineering control method for industrial closed-loop networks

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Abstract In engineering applications, the parameters of traditional PI controllers are often used, but they cannot achieve optimal control. To address this issue, this paper investigates fuzzy controllers and proposes an improved fuzzy control closed-loop system by combining genetic algorithms with traditional fuzzy controllers. An engineering system model is established to compare the performance of the improved fuzzy controller with that of the traditional fuzzy controller, and it is applied to the UFOPDT system for comparison with other algorithms to study the control performance of the closed-loop system. Simulation results indicate that the improved fuzzy controller exhibits faster dynamic response and higher regulation accuracy, achieving effective control of speed and current in a DC speed control system, outperforming traditional control methods and demonstrating greater applicability in engineering design.

Index Terms PID control, genetic algorithm, closed-loop system, fuzzy controller

I. Introduction

A closed-loop system is a control system that maintains system stability by monitoring feedback signals and adjusting them accordingly. Its fundamental principle involves using feedback signals to correct and adjust system output to achieve predetermined objectives. Feedback signals provide information about the system's actual state, enabling the controller to make judgments and decisions based on this information [1]-[3]. The rapid development of industrial production and automation technology has driven the continuous iteration and upgrading of control theory. As a core technology in modern control engineering, closed-loop systems possess self-correcting capabilities similar to those of biological organisms through continuous monitoring, feedback, and adjustment, enabling them to automatically control and maintain system steady-state conditions. Their application scope has long transcended traditional mechanical fields, gradually penetrating into modern technological domains such as smart homes, autonomous driving, medical devices, industrial production, and mechanical equipment [4]-[8]. In industrial production, closed-loop systems can adjust production processes based on quality information monitored by sensors, effectively improving production efficiency, reducing energy consumption, and ensuring product quality [9], [10]. Therefore, designing a scientifically reasonable closed-loop system is crucial for industrial production.

In today's society, with the development of information technology and networks, networks have basically achieved widespread adoption. By using networks as communication channels between controlled objects and controllers, the entire system has evolved into a networked control system [11]. Compared to conventional control systems, networked control systems offer numerous advantages: connecting controlled objects and controllers via networks eliminates the need for extensive wiring infrastructure; digital signal transmission enhances interference resistance, improving security and reliability; and they enable resource sharing and remote monitoring [12]-[15].

These various benefits have led to increasing adoption by factories. However, the introduction of networks has also brought about numerous issues, such as false data attacks, network latency, packet loss, out-of-order packets, and network congestion, which limit communication [16], [17]. In industrial systems, if actuators fail to receive control signals in a timely manner, the controlled objects will lack execution instructions, leading to production failures and accidents. Packet loss, packet reordering, or even more severe issues can result [18]-[20]. Therefore, designing closed-loop systems oriented toward industrial networks to address network latency, packet loss, and packet reordering in networked control systems holds significant importance for industrial production.

This study addresses the issue of difficulty in adjusting fuzzy controller parameters by proposing a method to optimize fuzzy controller parameters using genetic algorithms. This approach enhances the performance of traditional controllers, improves system control accuracy, and designs an improved closed-loop system with fuzzy control. It achieves this by adding an integral term to enhance the system's steady-state accuracy and introducing an auto-adjustment factor to improve response speed. The improved fuzzy control parameter tuning formula is extended to the UFOPDT system. The impact of the additional inertia term in the UFOPDT system on the closed-loop system's control performance is analyzed. Through comparisons with other control methods, the feasibility of the control system is validated via standardized model simulations and robustness tests.

II. Dual closed-loop engineering system based on improved fuzzy control

II. A. Closed-loop speed control system for DC motors

II. A. 1) Mathematical model of DC motors

A DC motor essentially converts electrical energy into mechanical energy. The input voltage generates armature current in the armature circuit, and the armature current produces electromagnetic torque under the influence of the magnetic field. This paper constructs an equivalent model of a separately excited DC motor. Separately excited DC motors are widely used, and their model can also be used for equivalent analysis of permanent magnet synchronous motors.

Assuming that the current in the DC motor is continuous under rated excitation conditions, the armature winding circuit voltage equation of the DC motor can be obtained according to Kirchhoff's first law:

$$U = L_a \frac{di_a}{dt} + R_a i_a + E_a \tag{1}$$

Let the back-EMF coefficient of a DC motor be C_e. This coefficient is related to the motor's structure, the number of turns in the windings, and the magnetic flux of the poles. Then, we have:

$$E_a = C_e \cdot \omega_m \tag{2}$$

Let the torque constant of the DC motor be C_m, the electromagnetic torque under rated excitation conditions be T, the load torque (including the no-load torque of the motor) be T_L, and the load current be i_1. Where the value of C_m is $30 \cdot C_e / \pi$, which is solely dependent on the internal structure of the DC motor, then we have:

$$T = C_m \cdot i_a \tag{3}$$

$$T_L = C_m \cdot i_1 \tag{4}$$

By ignoring viscous friction, elastic torque, and other interference factors during the operation of a DC motor, we can derive the dynamic equation for the motor shaft surrounding the DC motor in motion:

$$T - T_L = J \frac{d\omega_m}{dt} \tag{5}$$

Let the torque time constant of the DC motor be T_m and the electromagnetic time constant of the armature circuit be T_1. These two constants are defined as follows:

$$T_m = \frac{JR_a}{C_e C_m} \tag{6}$$

$$T_1 = \frac{L_a}{R_a} \tag{7}$$

Substituting equations (2) to (4) and equations (6) to (7) into equations (1) and (5) yields:

$$U - E_a = R_a \left(i_a + T_1 \frac{di_a}{dt} \right) \tag{8}$$

$$i_a - i_1 = \frac{T_m}{R_a} \cdot \frac{dE_a}{dt} \tag{9}$$

Under zero initial conditions, applying the Laplace transform to equation (8) yields the transfer function between the armature input voltage and the armature current:

$$\frac{I_a(s)}{U(s) - E_a(s)} = \frac{1/R_a}{T_1 s + 1} \tag{10}$$

Under zero initial conditions, applying the Laplace transform to equation (9) yields the transfer function between the armature current and the counter-electromotive force of the DC motor:

$$\frac{E_a(s)}{I_a(s) - I_l(s)} = \frac{R_a}{T_m s} \tag{11}$$

The transfer function model of a DC motor can be obtained from Equations (10) and (11).

II. A. 2) Dynamic mathematical model of dual closed-loop speed control system

The dual-loop speed control system structure of a DC motor is divided into two feedback control structures: the inner loop and the outer loop. The inner loop refers to the current loop, while the outer loop refers to the speed loop. The controllers for the current loop and speed loop are referred to as the current regulator and speed controller, respectively. The input to the speed controller is the motor's real-time speed, and its output serves as the input to the current loop. The input of the current loop is processed by the current regulator to generate an output control signal, which is used to control the triggering of the thyristors, thereby regulating the motor's speed.

Let the transfer function of the current regulator be $W_{ACR}(s)$, the transfer function of the speed controller be $W_{ASR}(s)$, the transfer function of the power electronic converter receiving the control signal of the control system and directly connected to the DC motor is $W_{UPE}(s)$, the speed feedback coefficient and current feedback coefficient are α and β, respectively, and the given control voltage is U_0, The converted speed regulation gives a given speed value of ω_0, the control quantity of the speed controller is ω_c, the given value of the current input to the current loop is i_0, the control value of the current regulator is i_c, the voltage control quantity output of the current regulator is U_c, and the voltage value of the power converter directly acting on the DC motor is U.

II. A. 3) PI Controller Structure

A PI controller is a simplified form of a PID controller. A PID controller is a proportional, integral, and derivative controller. In actual DC motor dual-closed-loop speed control systems, removing the derivative control yields the best results. However, considering the sampling of digital signals, the system signals are not continuous but discrete. Therefore, the PI controller formula used in this paper is:

$$U_T = K_P \cdot e(t) + K_I \cdot \sum_{j=0}^{t} e(j) \cdot T \tag{12}$$

In the equation: U_T is the controller output; K_P is the proportional control coefficient; K_I is the integral control coefficient; T is the sampling time of the system. Since K_P and K_I are key parameters that determine the control performance of the PI controller, their values need to be selected based on the control performance in practical applications.

II. B.Fuzzy PID control model

II. B. 1) PID control

PID control technology is characterized by its robustness, simplicity of algorithm, wide practical application, and excellent control performance, and has been widely used in the industrial field since its inception. A PID controller consists of three components: the proportional term, the integral term, and the derivative term. By combining these three terms, the system input is dynamically adjusted to achieve effective control of the controlled object [21].

The proportional term calculates the control signal based on the current error, using the proportional gain coefficient K_p multiplied by the error, to respond to the system's instantaneous deviation. This enhances system response speed and reduces system disturbances. The integral term eliminates errors generated during system operation, improving system accuracy. The derivative term enhances system predictability, reduces overshoot, and strengthens control stability and efficiency.

The PID control transfer function is calculated as follows:

$$G_c(s) = K_p\left(1 + \frac{k_d}{s} + K_d S\right) = K_p \frac{K_i s^2 + K_d S + 1}{s} \tag{13}$$

According to the transfer function calculation, the PID control equation is given by equation (14):

$$m(t) = K_p e(t) + K_p K_i \int_0^t e(t)dt + K_p K_d \frac{de(t)}{dt} \tag{14}$$

In the equation, K_p is the proportional coefficient, K_i is the integral coefficient, and K_d is the derivative coefficient.

Traditional PID controller parameters are difficult to tune and have poor interference resistance, making it difficult to meet the control requirements of intelligent sheep sheds. They are typically used in conjunction with fuzzy control algorithms to improve the response speed and stability of the system control. The PID algorithm is simple, adaptable, robust, and stable, making it easy for operators to use and providing excellent control performance, making it suitable for harsh environments. However, some systems exhibit time-varying and nonlinear characteristics, with a large number of influencing factors, making it difficult to accurately establish a system model, and thus rendering the PID control algorithm inapplicable.

II. B. 2) Fuzzy control

Fuzzy control algorithms are a type of control method based on fuzzy logic, designed to address complex and ambiguous control problems. Fuzzy control technology holds significant application potential, providing a powerful tool for resolving ambiguous issues in everyday life, and represents a major breakthrough in the field of control technology [22]. This control algorithm does not require the establishment of a complete and precise mathematical control model. Instead, it primarily involves formalizing the practical experience accumulated by staff over the long term, establishing appropriate fuzzy control rule tables, performing fuzzy inference operations, and then applying the results of the inference operations to the execution control devices after defuzzification, thereby achieving fuzzy control of the controlled object. Fuzzy control features rapid response and strong interference resistance, making it suitable for intelligent control of nonlinear and time-delayed systems. The fuzzy controller is the core of the fuzzy control system, primarily composed of four components: fuzzification, knowledge base, fuzzy inference, and defuzzification.

II. B. 3) Fuzzy PID control

Fuzzy PID controllers [23] are classified into one-dimensional, two-dimensional, and multi-dimensional types. The measured precise error value e is used as the input variable, which undergoes fuzzy processing and other operations to obtain the output variable U. Since there is only one input and output variable in this process, it is referred to as a one-dimensional fuzzy PID controller. However, since control is based solely on the error, this results in unstable dynamic performance and is typically used for first-order controlled systems. The two-dimensional fuzzy PID controller adds a deviation change ec to the input variable of the one-dimensional fuzzy PID controller, thereby achieving different PID parameter values required by e and ec at different times. For fuzzy systems, if there are multiple input and output variables, it is referred to as a multi-dimensional fuzzy PID control system. Due to its multi-variable characteristics and the complexity of fuzzy controller design, it is rarely adopted. Due to its high precision, strong stability, and excellent control performance, the two-dimensional fuzzy PID controller is now widely applied.

The fuzzy PID control algorithm combines PID control algorithms with fuzzy control algorithms to address control systems with nonlinear and fuzzy characteristics. By fuzzifying input and output variables, a set of fuzzy rules is constructed to determine the control output. The advantage of the fuzzy PID control algorithm lies in its ability to combine the advantages of both PID control algorithms and fuzzy control algorithms, enabling it to flexibly address complex and fuzzy control problems. It can select the most appropriate control strategy based on specific application requirements. The principle diagram of fuzzy PID control is shown in Figure 1.

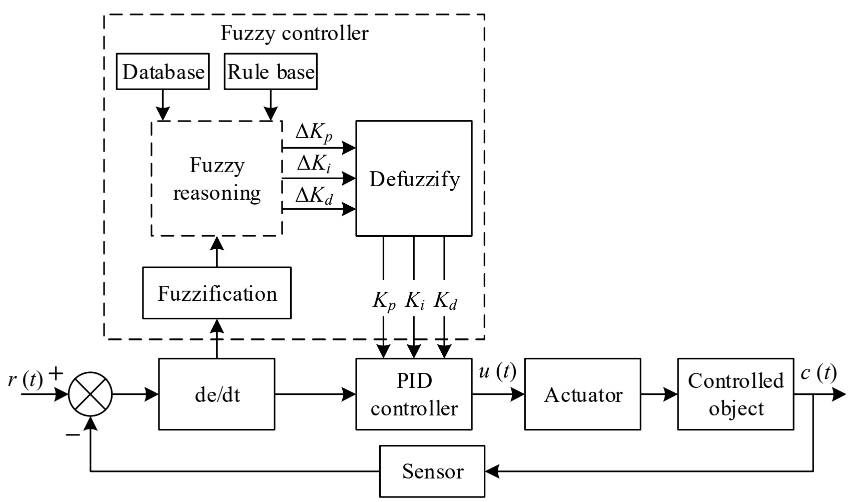


Figure 1: Fuzzy PID control schematic diagram

III. Engineering design and parameter optimization of improved fuzzy controllers

III. A. Improvements to Fuzzy Controllers

III. A. 1) Design of adjustment factors

Through analysis of the fuzzy control rule table, the fuzzy rule table can be parsed as follows:

$$U = -\left\langle \frac{E+EC}{2} \right\rangle \tag{15}$$

In the equation, E represents the error, and EC represents the change in error. However, in equation (15), the fuzzy rules apply the same weighting to both E and EC. However, in different stages of a step response, different variables need to be adjusted. For example, at the beginning of control, the error is large and the error change is small, so we need to increase the control of the error; in the middle of control, the error becomes smaller but the error change is larger, so we need to increase the control of the error change. By introducing an adjustment factor α, we can obtain fuzzy rules with an adjustment factor:

$$U = -\langle \alpha E + (1-\alpha)EC \rangle \alpha \in (0,1) \tag{16}$$

By adjusting the value of α, the control system can be made to respond differently to errors and changes in errors at different times. For example, when the error is large, the primary task of the controller is to eliminate the error, so a larger value of α is chosen to increase the weighting of E; when the error is small, the primary task of the controller is to stabilize the system, so a smaller value of α is chosen to increase the weighting of EC and eliminate overshoot.

However, once the adjustment factor α is determined, it cannot be changed and cannot vary with changes in E and EC. If α can be expressed as a function containing E and EC, the value of α can be adjusted as needed. Let α be:

$$\alpha = \frac{1}{1+e^{-(|E|-|EC|)}}; E \in (-6,6), EC \in (-6,6) \tag{17}$$

Equation (17) is a function of α with respect to E and EC. Let $x = |E| - |EC|$, then $x \in (-6,6)$.

III. A. 2) Fuzzy controller with integral term

Fuzzy control is essentially a nonlinear controller. Under zero initial conditions, the output of a traditional fuzzy controller is:

$$u(t) = k_u \cdot f\left[k_e e(t), k_{ec}\frac{de(t)}{dt}\right] \tag{18}$$

In equation (18), k_e, k_{ec} are quantization factors, and k_u is a proportional factor.

The output of a traditional PD controller is:

$$u(t) = k_p e(t) + k_d \frac{de(t)}{dt} \tag{19}$$

In Equation (18), k_p is the proportional coefficient, and k_d is the derivative coefficient. By comparing Equations (18) and (19), it is not difficult to see that they share similarities. The controller's output $u(t)$ is a function of the error $e(t)$ and the error change rate $e_c(t)$. Therefore, traditional fuzzy controllers can be approximated as PD controllers.

The output of an integral controller is proportional to the integral of the error over time. In simple terms, the integral term represents the accumulation of error over a long period of time. The longer the time, the larger the error, and the larger the error accumulated by the integral term, resulting in a larger output from the integral term. When the error reaches zero, the output of the integral term also becomes zero, thereby eliminating the residual error.

III. A. 3) Improving the structure of fuzzy controllers

Figure 2 shows the structure of the improved fuzzy controller. By adding an integrator and an adjustment factor, the error E and error change EC are used as inputs to the adjustment factor. The value of the adjustment factor α is calculated and output to the fuzzy controller. The adjustment factor determines the process of the control system based on the values of the error and error change, and adjusts the weighting of the error and error change. Adding an integrator helps the control system eliminate steady-state error. The integrator accumulates the error and adds it to the output of the fuzzy controller's control quantity, which together act on the controlled object.

III. B. Parameter optimization of improved fuzzy controller

III. B. 1) Optimized and Improved Fuzzy Controller Parameters

Based on the basic structure of the improved fuzzy controller, the output of the improved fuzzy controller can be obtained as follows:

$$u(t) = k_u f\left[k_e e(t), \alpha k_{ec}\frac{de(t)}{dt}\right] + k_i \int e(t)dt \tag{20}$$

Due to the insufficient adaptability of the improved fuzzy controller, it is necessary to automatically adjust the fuzzy controller parameters to improve its adaptability. From equation (20), it can be seen that the output of the fuzzy controller is affected by many parameters, such as the quantization factors k_e and k_{ec}, the proportional factor k_u, and the integral coefficient k_i, and these parameters are crucial to the dynamic performance and steady-state performance of the control system.

Through analysis of the improved fuzzy controller, it is found that after adding the integral term, the output of the fuzzy controller can be described as:

$$u(t) = k_u f\left[k_e e(t), k_{ec} ec(t)\right] + k_i \int_0^t e(t)dt \tag{21}$$

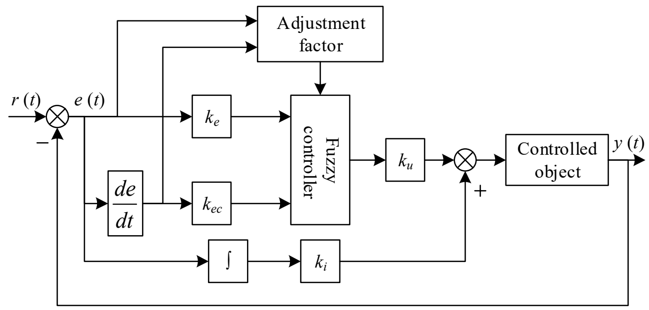


Figure 2: Improved fuzzy control system structure

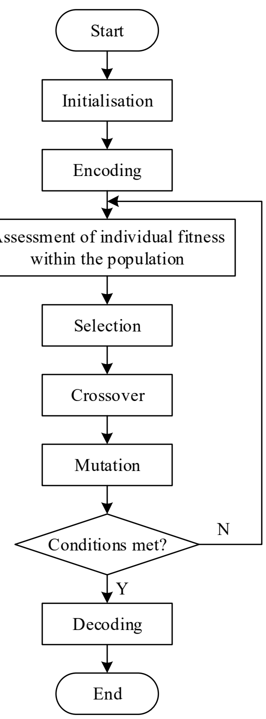


Figure 3: Genetic algorithm flowchart

As can be seen from Equation (21), the output of the fuzzy controller is determined by k_e, k_{ec}, k_u, and k_i. Therefore, selecting appropriate coefficients plays a crucial role in the response of the control system.

The parameters of the improved fuzzy controller have a significant impact on its control performance. Genetic algorithms mimic the evolutionary laws of biological organisms, continuously generating new individuals through replication, crossover, and mutation. Based on the objective fitness function, the population is optimized as the number of evolutionary generations increases. Genetic algorithms have advantages such as global optimization and fast convergence speed. However, optimizing the fuzzy rules and membership functions of a fuzzy controller using genetic algorithms is relatively complex, resulting in a large number of variables and longer encoding lengths, which increases computational complexity. Optimizing the quantization factor, proportional factor, and integral coefficient of a fuzzy controller using genetic algorithms is a method to enhance the adaptive performance of the fuzzy controller.

III. B. 2) Program Design of Genetic Algorithms

The flowchart of the genetic algorithm program is shown in Figure 3.

IV. System modeling and simulation analysis

IV. A. System Modeling

To simplify the model, this paper uses a permanent magnet DC motor for simulation, with the following basic parameters: rated voltage Ud = 250 V, rated current Id = 12 A, maximum allowable current Imax = 25 A, and rated speed n = 2500 r/min. The simulation model is shown in Figure 4. In the figure, the speed loop ASR is composed of a fuzzy controller, the current loop ACR is composed of a conventional PI regulator, and the PWM module is a pulse generator under bipolar control mode, which adjusts the duty cycle based on the magnitude of the control voltage uc to achieve speed regulation.

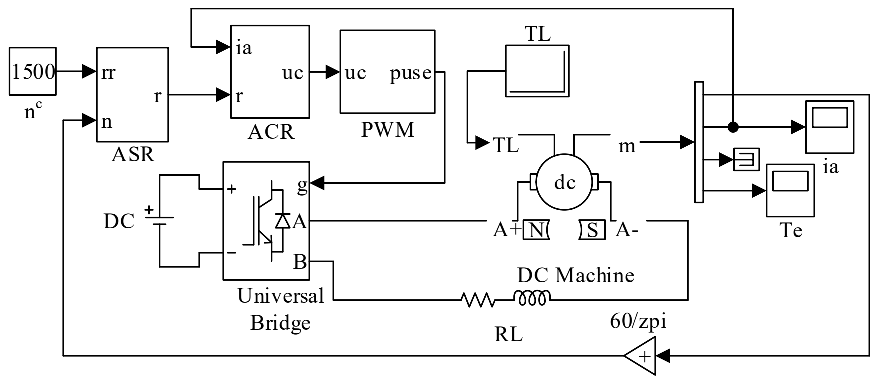


Figure 4: Fuzzy control dual ring speed regulation system

When the given speed is 1500 r/min, the load torque increases from 1 Nm to 2 Nm over 3 seconds. At this point, the waveforms of speed, current, and electromagnetic torque are shown in Figures 5 and 6. From the simulation waveforms, it can be observed that compared to the traditional dual-closed-loop control system, the overshoot of the rotational speed waveform is significantly reduced, and the transition time is shorter when using the improved fuzzy control system. When the load changes, the rotational speed remains virtually unchanged, and the current and electromagnetic torque respond more quickly.

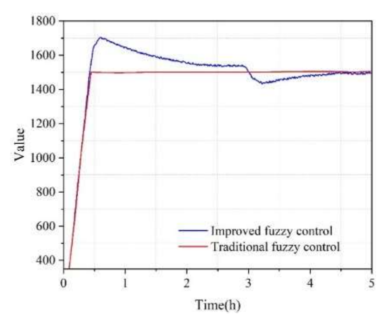


Figure 5: Speed curve of the load when the speed is given

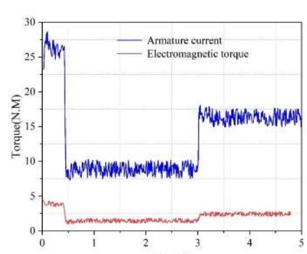
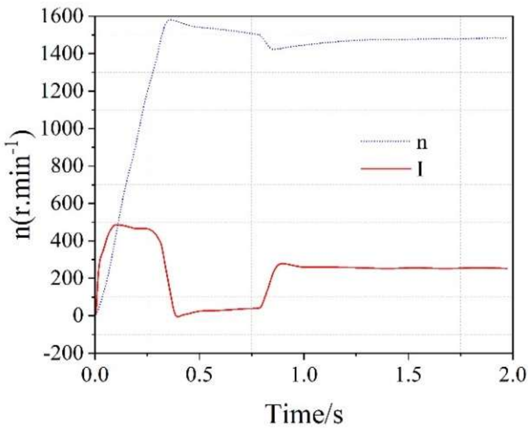


Figure 6: Current and electromagnetic torque curves under load variation at given speed

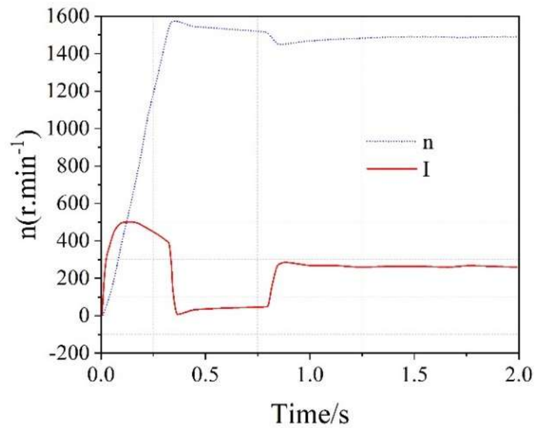
IV. B. Simulation Results

In the improved fuzzy closed-loop DC motor regulator system, the motor parameters are as follows: rated voltage U_N = 210 V, excitation voltage U_f = 210 V, rated current I_N =130A, rated speed n_N =1400 r/min, R_a =0.25Ω, GD^2 =20.5 kg·m². Excitation current I_f = 1.2A, smoothing reactor L_d = 22mH, rectifier internal resistance R_{rec} = 0.2Ω.

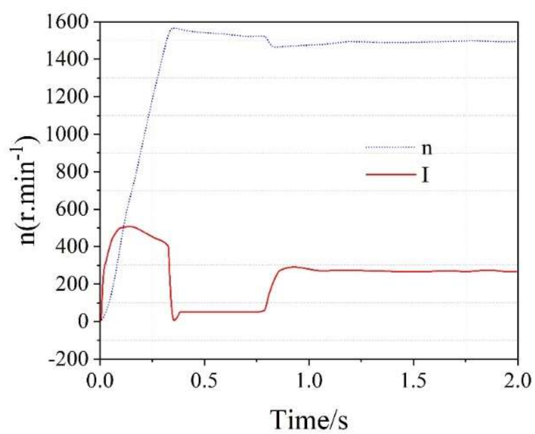
Supply voltage $U = \frac{U_N + R_{rec} I_N}{2.29 \cos \alpha_{\min}} \approx$ 120V, load applied at 0.8s, interference test conducted, simulation results shown in Figure 7. From the simulation results, it can be seen that the rise time t_r = 0.28 s, peak time t_p = 0.35 s, settling time t_s = 0.62 s, and overshoot $\delta\%$ = 6.5% for the traditional engineering PI dual-loop control system. The rise time t_r = 0.28 s, peak time t_p = 0.37 s, settling time t_s = 0.60 s, and overshoot $\delta\%$ =5.5%; The improved fuzzy closed-loop PID control system has a rise time of t_r =0.27s, peak time, and can ensure that the impact current on the grid side does not exceed I_n when the motor switches to mains frequency.



(a) Adjust the PI regulation system



(b) Fuzzy PID regulation inner ring system



(c) Improve the fuzzy closed-loop PID control system

Figure 7: Comparison of simulation results

IV. C. UFOPDT System Simulation Verification

Taking three typical delay times as examples (short delay system τ =0.3s, medium delay system τ =0.7s, and long delay system τ =1.2), the PID parameters and performance metrics of the method proposed in this paper compared with four existing tuning methods are shown in Table 1.

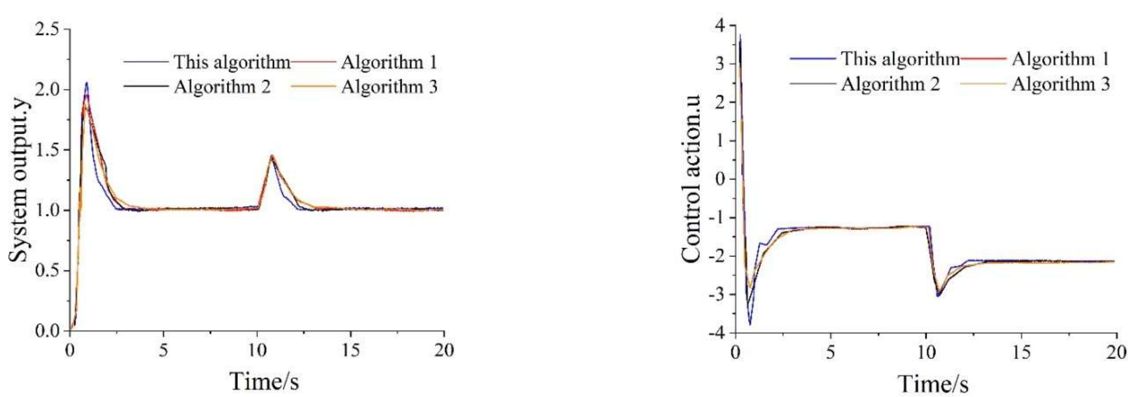
From the table, it can be seen that in the small-delay τ =0.3s and medium-delay τ =0.7s controlled objects, the robustness-priority tuning rule of the method proposed in this paper achieves similar or even better robustness than other methods, while also achieving better load disturbance suppression performance and improved control performance. For the controlled object with a large delay τ = 1.2s, the robustness and disturbance rejection performance obtained by the robustness-priority tuning rule of the proposed algorithm are superior to those of Algorithms 2 and 3. Although the robustness of Algorithm 4 is better than that of the proposed method, its disturbance rejection performance is significantly worse, and the response convergence speed is slow. The proposed method places greater emphasis on balancing these two performance metrics.

It can be seen that as the delay time τ of the controlled object increases, the aforementioned advantages become more pronounced, which also demonstrates the advantages of the proposed method in large-delay unstable time-delay systems, with a broader range of applications. For systems with smaller model uncertainties, if a parameter tuning rule that balances robustness and disturbance rejection capability is adopted, the advantage in disturbance rejection capability becomes more evident when compared with other methods.

Table 1: Results of controller parameerformance indicators of the UFPDT system

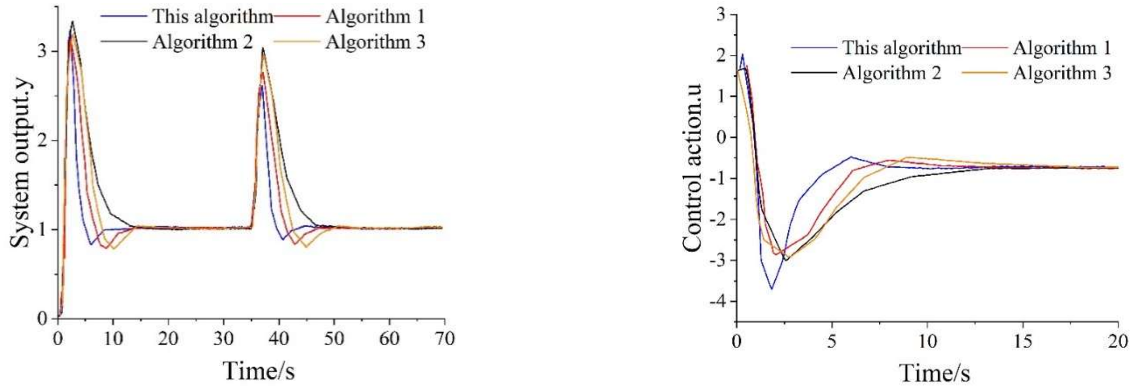
Controlled process	Set the rules	λ	K_p	K_i	K_d	M_s	ITAE
τ =0.3	This algorithm	-	3.8754	2.9342	0.4957	3.2863	0.3755
	Algorithm 1	-	3.2949	2.1564	0.4085	2.6137	0.5584
	Algorithm 2	0.482	3.2584	2.3073	0.4922	2.5917	0.6122
	Algorithm 3	-	3.3471	1.8755	0.4411	2.6392	0.6359
τ =0.7	This algorithm	-	1.7433	0.3984	0.5528	4.5983	8.7965
	Algorithm 1	-	1.5527	0.2463	0.5185	3.4762	18.731
	Algorithm 2	1.8	1.4982	0.1338	0.3927	3.4985	37.129
	Algorithm 3	-	1.4579	0.1728	0.4833	3.5853	32.093
τ =1.2	This algorithm	-	1.2564	0.0743	0.7125	12.39	148.55
	Algorithm 1	-	1.1175	0.0328	0.6929	9.7753	228.79
	Algorithm 2	4	1.1825	0.0218	0.6914	11.258	355.14
	Algorithm 3	-	0.0177	0.0263	0.0028	27.137	394.17
	Algorithm 4	5.875	1.1564	0.0109	0.6921	8.5528	1054.72

Figures 8-10 show the closed-loop output responses and controller output signals of small, medium, and large delay controlled systems after applying different PID controller parameter tuning methods. It can be clearly seen from the figures that the method proposed in this paper is more accurate than other algorithms.



(a) Output response (b) Controller signal

Figure 8: Output response and controller signal of the UFOPDT system with delay time τ =0.3



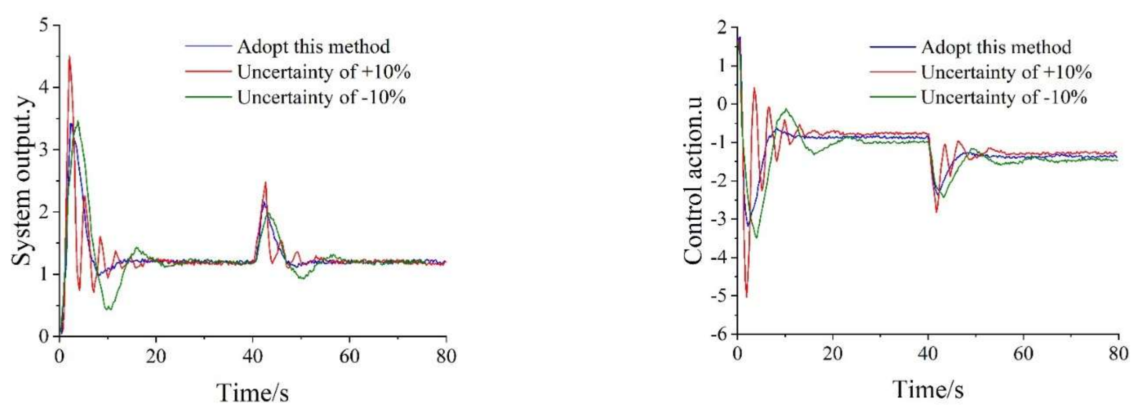
(a) Output response (b) Controller signal

Figure 9: Output response and controller signal of the UFOPDT system with delay time τ =0.7

(a) Output response (b) Controller signal

Figure 10: Output response and controller signal of the UFOPDT system with delay time τ =1.2

To analyze the robustness of the closed-loop control system, we assume that the model parameters of the UFOPDT system with medium delay (τ = 0.7 s) have an uncertainty of ±10%, i.e., the static gain k and delay time τ vary within ±10%, and the time constant T varies within ±10%. Two extreme models representing the upper and lower limits of parameter variations were selected for simulation, as shown in Figure 11. As can be seen from the figure, the closed-loop control system is sufficiently robust to ensure stable operation even under parameter perturbations.



(a) Output response (b) Controller signal

Figure 11: The closed-loop system output response and controller signal

V. Conclusion

After tuning the PI parameters of a dual-loop speed control system for DC motors in industrial networks, an improved fuzzy controller was designed to address the shortcomings of conventional fuzzy controllers. This improved controller incorporates self-adjusting factors and integral terms, significantly enhancing the control performance of the fuzzy controller. Through simulation experiments, the improved fuzzy controller was compared with the conventional fuzzy controller, revealing that the improved fuzzy control system exhibits faster response speeds, higher regulation accuracy, and improved steady-state performance. Further simulations were conducted on a standardized UFOPDT system and a specific controlled object model to validate the feasibility of the proposed method. It was found that the system remains stable even in controlled objects with large time delays, and the standardized time delay has a broader applicability range than existing controller parameter tuning methods.

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