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Design of a PLC DC Motor Speed Regulation System Based on Fuzzy Control Algorithm

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In order to ensure the stable operation of PLC (programmable logic controller) DC motor, a PLC DC motor speed control system based on a fuzzy control algorithm is designed. The hardware part of the system is designed by the machine vision hardware selection unit, frequency converter selection unit and controller selection unit. For the software part, by determining the expansion factor of the PLC DC motor speed regulation system, a fuzzy PID automatic controller is constructed based on the fuzzy control algorithm, and then the automatic control of the PLC DC motor speed regulation system is completed by means of fuzzy rules. The experimental results show that the control curve of frequency conversion speed regulation designed in this paper is more consistent with the standard control curve, and the control effect is better.The tracking control error in the initial stage is small, the peak value is −0.15, and the convergence speed is very fast. It has good nonlinear dynamic capability, does not need to input too much robust control voltage, the speed regulation accuracy of PLC DC motor can reach 100%, and the speed regulation effect is the best.

Keywords: Fuzzy control algorithm; machine vision; PID automatic controller; DC motor

1. INTRODUCTION

1.1 Literature Review

In recent years, the control of DC motors has become the focus of motor control. As the main means of speed regulation in modern industry, the DC speed regulation system should adopt a PI controller to control the speed of the DC motor. The traditional PI controller has a simple structure, good stability and high reliability, but it relies too much on the control object model, has poor parameter robustness and is not strong againstanti-load disturbance [1, 2]. At the same time, the traditional PID algorithm is applicable only to linear systems because the PID is constant and the DC motor control is usually a nonlinear system. In order to make the PLC DC motor run stably and meet the requirements of high-performance and high-precision applications, many scholars have conducted extensive research on speed control methods.

An on-line prediction and optimization control method for the sub-synchronous oscillation of wind power grid-connected system based on machine learning interpretable agent model wasproposed by Xiang et al. [3]. Long et al. [4] proposed a model-based adaptive superlocal surface-mounted permanent magnet synchronous motor (SPMSM) continuous control set sliding mode predictive speed control (UL MPSC). Although these two methods realize the control of permanent magnet synchronous motor, they have certain limitations for PLC DC motor. Saed and Mirsali [5] used the radial displacement of the stator to improve the sensor-less speed control of a double-stator brushless DC motor drive. Wu et al. [6] proposed a DC link voltage control strategy for a high-speed, permanent magnet motor drive system powered by a Z-source inverter.

1.2 Research Gap and Motivation

However, the accuracy of the above PLC DC motor speed-regulation methods is still low, resulting in poor speed regulation.As the focus of motor control, the control of DC

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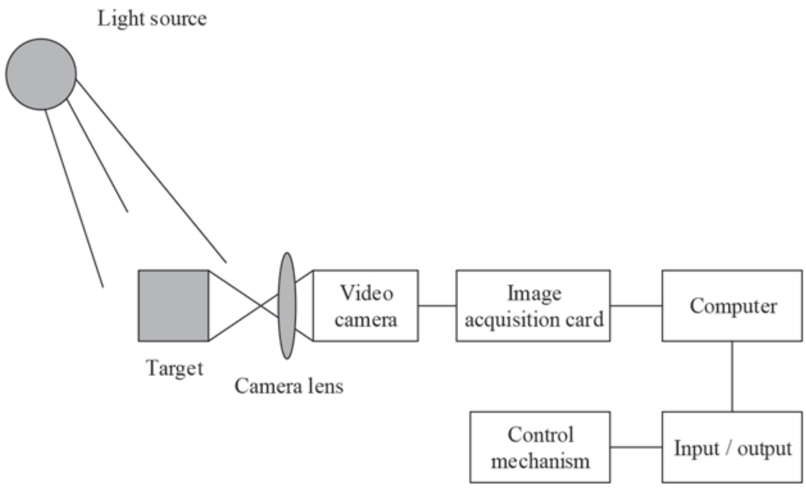

Figure 1 Schematic diagram of machine vision hardware structure.

motor is the main means of speed regulation in modern industry. In order to ensure that the PLC DC motor speed regulation system can meet the requirements of high performance and high precision applications, this paper designs a speed regulation system based on a fuzzy control algorithm derived from both hardware and software. The frequency conversion speed regulation control curve of the system is more consistent with the standard control curve, the control effect is better, the tracking control error in the initial stage is small, and the convergence speed is fast. It has good nonlinear dynamic capability, does not need to input too much robust control voltage, and the speed regulation accuracy of the PLC DC motor can reach 100%, producing the best speed regulation.

1.3 Contribution and Paper Organization

The system not only assists the development and application of a PLC DC motor; it also provides a reference for the research on variable frequency speed regulation, and establishes some foundation for the safe operation of a PLC DC motor. The research framework applied in this paper is described below.

Step 1: The system is designed to comprise: a machine vision hardware selection unit, a frequency converter selection unit and a controller selection unit.

Step 2: System software design: the control parameters are adjusted to determine the expansion factor of the text system through fuzzy control, two outputs are set as fuzzy subsets through fuzzy control, and then they are input into the text system.According to the setting result, the text system is controlled by frequency conversion using fuzzy PID automatic control. Finally, the fuzzy control rules of PLC DC motor governor are established, the output of fuzzy PID automatic controller is obtained, and the automatic control of text system is completed.

Step 3: Experiments are conducted and the results are analyzed.

Step 4: The paper is concluded and recommendations are made.

2. MATERIALS AND METHODS

2.1 System Hardware Design

To improve the frequency and speed control performance of a text system, machine vision is used for the design. The hardware design consists of a machine vision hardware selection unit, a frequency converter selection unit and a controller selection unit.

2.1.1 Machine Vision Hardware Selection Unit

Machine vision refers to the perception and acquisition of target and environmental information by means of the camera, and the collected information is in the form of an image which cannot be processed by the computer. Also, image processing equipment is needed to convert the image todigital form, so as to obtain the relevant information about the DC motor and speed regulation structure, and provide support for frequency and speed control [7]. The hardware structure of machine vision is shown in Figure 1.

As shown in Figure 1, the camera is one of the most critical components of the machine vision's sub-system. Because the DC motor requires variable frequency speed regulation, the fh-5050/2050 series ultra-high-speed camera is selected as the machine vision image acquisition device, the specification is CCD, and the pixels can reach 20.4 million. Machine vision can combine multiple ultra-high-speed cameras to obtain information about the DC motor and the speed regulation structure, integrate them accordingly, and generate an image that shows the speed regulation information and provides more powerful support for the realization of PLC DC motor speed regulation.

2.1.2 Selection Unit of Frequency Converter

The frequency converter is a type of electric energy control device that converts and controls the frequency through power

Table 1 Code range of frequency converter function group.

Function code	Name	Function code	Name
Pr0-9	Basic function	Pr110-116	Third function
Pr10-37	Operation function	Pr117-124	Communication function
Pr41-43	Output terminal function	Pr128-134	PID regulation function
Pr42-50	Second function	Pr135-139	Frequency conversion and power frequency
Pr52-56	Display function	Pr140-143	Switching function
Pr57-58	Restart function	Pr144	Backlash function
Pr59	Additional functions	Pr150-153	Display function
Pr60-79	Operation selection function	Pr180-195	Current detection
Pr80-96	Motor parameter selection function	Pr200-230	Terminal arrangement function
Pr100-109	V/F adjustment function	Pr231-239	Program running

Table 2 Communication parameters of frequency converter.

Communication parameters	Function code	Value setting
Operation mode	Pr79	1
Base frequency	Pr3	50Hz
Upper limit frequency	Pr1	50Hz
Communication rate	Pr118	19200bit/s
Base frequency voltage	Pr19	50Hz
Communication verification interval	Pr122	9999
Waiting time setting	Pr123	20
Parameter writing mechanism	Pr77	2
Stop bit length	Pr119	11

semiconductor devices. Given the requirements of a PLC DC motor, fr-540 equipment is selected as the frequency converter of the design system. Many parameters are involved in the operation of the frequency converter, and each parameter has a certain value range [8]. If the parameters are not set properly, the frequency converter is likely to fail and, if this is serious, it will be scrapped directly.

The code range of the frequency converter function group is shown in Table 1.

In the frequency converter, input the function code pr0-9 to output the basic function, input pr10-37 to output the operation function, input pr41-43 to output the terminal function, input pr57-58 to output the restart function, and so on. The frequency converter is connected with other hardware units of the design system through RS-485 bus. Due to different hardware structures and interfaces, it is necessary to properly adjust and set the communication parameters of the frequency converter, to ensure the effective connection and communication of multiple hardware of the design system [9]. In addition, communication parameters are an indispensable step in the initialization of the frequency converter. The specific settings are shown in Table 2.

Adjust the parameters of the frequency converter according to the data shown in Table 1 and Table 2 so as to meet the speed regulation requirements of the PLC DC motor.

2.1.3 Controller Selection Unit

The controller is the key hardware component of the design system [10], which undertakes the functions of machine vision image processing, logic operation, timing, control and so on. According to the variable frequency speed regulation requirements of DC motor, FX2N series PLC is selected as the controller for the design system. The structure is shown in Figure 2.

The controller is responsible for controlling the frequency converter through the RS-485 bus to achieve the transmission target of materials. The specific allocation of I/O points is shown in Table 3.

The PLC DC motor operates in three stages: input refresh, program execution and output refresh [11]. (1) Input refresh stage: the PLC works in scanning mode. The input circuit monitors the input status at all times and temporarily stores it in the input image register. (2) Program execution stage: the PLC performs serial scanning processing on the program in sequence, obtains the required data from the input image register and the output image register for operation and processing, and then writes the program execution result into the output image area where the execution result is registered for storage. (3) Output refresh stage: after all user programs are executed, the PLC sends the output result of operation to the output image register, as shown in Figure 3.

The process described above completes the selection and design of the hardware of the design system, but the variable frequency speed regulation of PLC DC motor is not achieved. Therefore, the software module is developed and designed accordingly.

2.2 System Software Design

2.2.1 Determine the System Expansion Factor

The system expansion factor refers to the additional functional parameters of the system. When determining the expansion

Table 3 Allocation of controller I/O points.

I/O points	Definition	I/O points	Definition
X0	DC motor start	Y0	Material electric
X1	Material full	Y1	Motor forward rotation
X2	Switch SQ1	Y2	Motor running at low speed
X3	Switch SQ2	Y3	Motor running at high speed
X4	Origin	Y4	Motor reverse

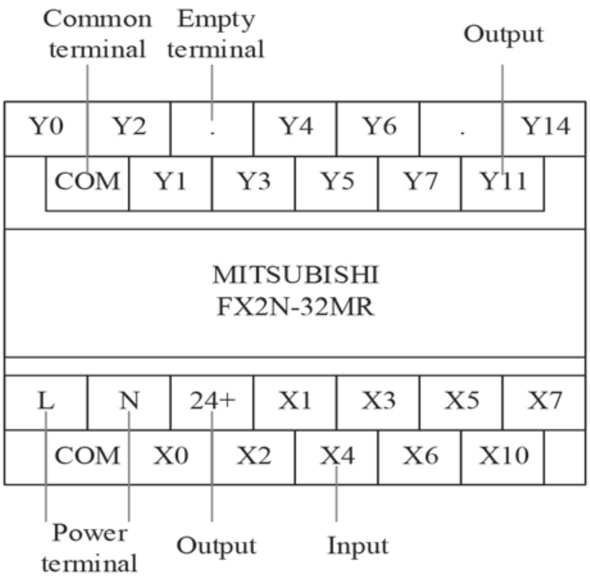

Figure 2 Structure diagram of controller.

factor of a text system, fuzzy control needs to be applied. Fuzzy control ensures the control accuracy of the expansion factor according to the invariable principle of fuzzy rules. As PLC DC motor loading speed increases, the error of expansion factor gradually increases. In order to reduce the continuous expansion of error, an interpolator needs to be used to increase interpolation points. To change the fuzzy control rules, the determination of the expansion factor will affect the frequency conversion control accuracy of text system, so the careful selection of the expansion factor is essential.

The text system is nonlinear operation characterized by a broad range of regulation speeds,large inertia and frequent changes of PLC DC motor speed. Moreover, the text system is a fuzzy system. To guarantee that the frequency conversion speed regulation function of the system is effective, the fuzzy adaptive control method is selected. This method not only improves the frequency conversion speed regulation ability of the system, but also effectively determines the expansion factor of the text system [12].

Before determining the expansion factor, the control parameters need to be adjusted by fuzzy control. The control parameters of a text system are shown in Figure 4.

As shown in Figure 4, the control parameters of a text system include the power frequency difference, frequency conversion difference and the difference change of the PLC DC motor. These control parameters need to take the change rate of the power frequency difference and the frequency conversion difference as the correction parameters of the expansion factor and input them. The parameters are adjusted by the fuzzy matrix table and fuzzy rules. After the adjustment, the expansion factor of the text system is determined. Firstly, the exponential expansion factor is selected:

$$\alpha = 1 - \lambda k^2 (\lambda \in (0, 1), k > 0) \quad (1)$$

where α represents the exponential expansion factor; λ is the common frequency difference; k represents the change rate of frequency conversion difference; When inputting the power frequency difference λ and the frequency conversion difference change rate k, it is necessary to use fuzzy control for telescopic transformation. The power frequency difference λ is transformed into $\lambda_i(x_i)$, the frequency conversion difference change rate is transformed into $k_i(x_i)$, and i represents the transformation coefficient; x represents the input variable; The transformed $k_i(x_i)$ and $\lambda_i(x_i)$ [13] are then initialized and output.

The two outputs are set into fuzzy subsets through fuzzy control, and then input into the text system. Since the starting speed value of the PLC DC motor is less than the variable frequency speed regulation value at the beginning of startup, the set fuzzy subsets are applied to the initial stage of the PLC DC motor in the form of difference transformation, and the adaptive controller is used to control the initial stage of the PLC DC motor [14, 15]. After control, the expansion factor of the text system is $\alpha_j(x_j)(j = 1, 2, 3, \ldots, n)$. Where, j represents the control coefficient of the expansion factor. Through the determined expansion factor, the maximum and minimum synthesis method is used for fuzzy operation. The expansion membership degree obtained after fuzzy operation is $u_j(\alpha)$. The center of gravity

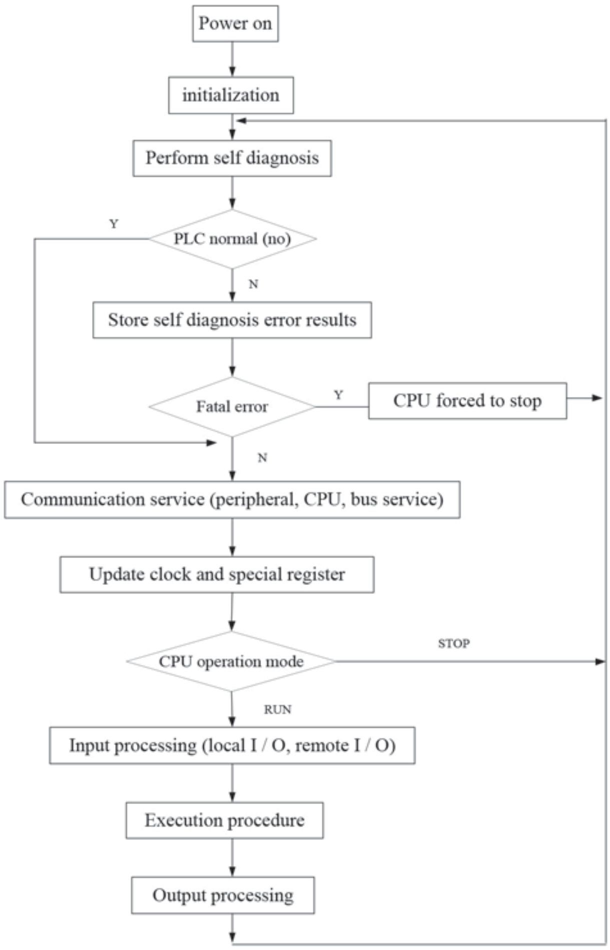

Figure 3 Specific work flow chart of PLC DC motor.

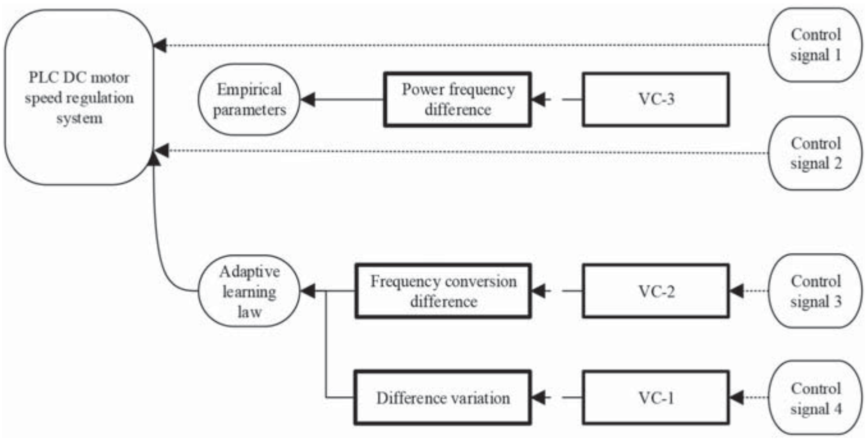

Figure 4 Control parameters of text system.

method is adopted to defuzzify the expansion membership degree, and the defuzzified parameters are output in the text system. Through the expansion factor determined above, the frequency conversion control of text system can be improved.

2.2.2 Frequency Conversion Control of Text System

After setting of the expansion coefficient and various control parameters determined above, frequency conversion control is performed on the text system according to the setting results. Although the traditional PI controller has a simple structure, good stability and high reliability, it relies too much on the control object model, has poor parameter robustness, and has weak resistance to load disturbance. Therefore, the text system based on the fuzzy control algorithm combines fuzzy control method with PID control method to achieve fuzzy PID automatic control. The fuzzy PID controller can improve the anti-interference ability and adaptive control ability of the system, and make up for the shortcomings of the traditional PID controller in terms of anti-interference ability and adaptive control ability. The structure of the fuzzy PID controller is shown in Figure 5.

(1) The speed control deviation e and the speed control deviation change rate e_c are taken as the membership function inputs of the fuzzy PID automatic controller, and the output is set at u.

(2) Scale factor and quantization factor

$e = [-e_{\max}, e_{\max}]$ are used to describe the corresponding basic domain of speed regulation control deviation e; $e_c = [-\Delta e_{\max}, \Delta e_{\max}]$ is used to describe the basic domain corresponding to the deviation change rate e_c of speed regulation control; $u = [-u_{\max}, u_{\max}]$ is adopted to describe the basic domain of PLC DC motor speed control quantity u.

$E = \{-n_a, -n_a + 1, \cdots - 1, 0, 1, \cdots, n_a - 1, n_a\}$, $EC = \{-n_b, -n_b + 1, \cdots - 1, 0, 1, \cdots, n_b - 1, n_b\}$ and $U = \{-n_c, -n_c + 1, \cdots - 1, 0, 1, \cdots, n_c - 1, n_c\}$ are used to describe the fuzzy universe corresponding to the speed control deviation E, speed control deviation change rate EC and speed control quantity E, in which a, b and c represent the speed control deviation change rate of PLC DC motor.

Let K_a represent the quantization factor corresponding to the speed regulation deviation of PLC DC motor, calculated with Formula (2):

$$K_a = \frac{n_a}{e_{\max}} \tag{2}$$

The quantization factor K_a corresponding to the deviation change rate can be calculated with Formula (3):

$$K_b = \frac{n_a}{\Delta e_{\max}} \tag{3}$$

Let K_c represent the scale factor corresponding to the control quantity, and its expression is shown as Formula (4):

$$K_c = \frac{n_c}{u_{\max}} \tag{4}$$

The size of the scale factor and the quantization factor largely affects the control process of the text system. There is an interactive relationship between scale factor and quantization factor in the speed regulation control of the PLC DC motor. The control requirements of the PLC DC motor speed regulation can be met through different values, although it will be a challenge to ensure the control effect only through a group of factors. Therefore, when building a fuzzy PID automatic controller, it is necessary to adjust the size of the proportional factor and the quantitative factor.

(3) Blur clarity

The basic domain is the actual change range of output variables and input variables of the fuzzy PID automatic controller used for speed regulation control [16–18].

The values existing in the universe cannot be directly recognized by the fuzzy PID automatic controller. It is necessary to discretize the actual universe and transform it into a fuzzy universe:

$$\begin{cases} E = \{NB,\ NM,\ NS,\ ZO,\ PS,\ PM,\ PB\} \\ EC = \{NB,\ NM,\ NS,\ ZO,\ PS,\ PM,\ PB\} \\ U = \{NB,\ NM,\ NS,\ ZO,\ PS,\ PM,\ PB\} \end{cases} \tag{5}$$

where PB is positive, NB is negative, PM is positive, NM is negative, PS is positive, NS is negative and ZO is Fatal Frame [19–21].

(4) According to the experience and control theory of PLC DC motor speed regulation control, the fuzzy control rules of PLC DC motor speed regulation are established, as shown in Table 4.

AB AC ad Ao ob OC od in Table 4 represents fuzzy language variables. This table shows the expansion of errors caused by PLC DC motor speed regulation, and forecasts various changes of errors. The value must be strictly controlled. If the value is too large, the speed regulation will be advanced and the regulation time will increase, resulting in poor speed regulation accuracy of the PLC DC motor.

(5) The output of fuzzy PID automatic controller is obtained to complete the automatic control of the text system.

3. EXPERIMENT

3.1 Experimental Preparation

To verify the feasibility of the fuzzy control algorithm based text system, an experiment was designed and conducted. The experimental object is a SINAMICS S120 PLC DC motor. The specific parameters of the PLC DC motor are shown in Table 5.

To guarantee the smooth progress of the experiment, some preparations need to be made beforehand, including the debugging of PLC controller. Because of the complex working mode of the PLC controller, it needs to be debugged separately to ensure that the variable frequency speed regulation function of DC motor is achieved. The debugging program for the PLC controller is shown in Figure 6.

Figure 6 shows the steps involved in debugging the PLC controller. Following the debugging, the speed regulation experiment for the PLC DC motor is carried out. The enhanced sensor-less speed regulation method based on mechanical bias of double-stator brushless DC motor driver proposed in [5] is selected for comparison, and the system described in [3] is taken as the traditional system. Through the following experiments, the performance and applicability of the designed system is verified.

3.2 Experimental Test and Result Discussion

3.2.1 Response Curve of Variable Frequency Speed Regulation of DC Motor

The response curve of variable frequency speed regulation of DC motor is obtained through an experiment, as shown in Figure 7.

Compared with the comparison system and the conventional system, the response curve of variable frequency speed regulation of DC motor obtained by the application of the design system is smoother, has less overshoot, has better dynamic performance and can obtain better control effect. The comparison system and the traditional system fluctuate greatly, the overshoot is too large, and the dynamic performance is poor as is the control effect.

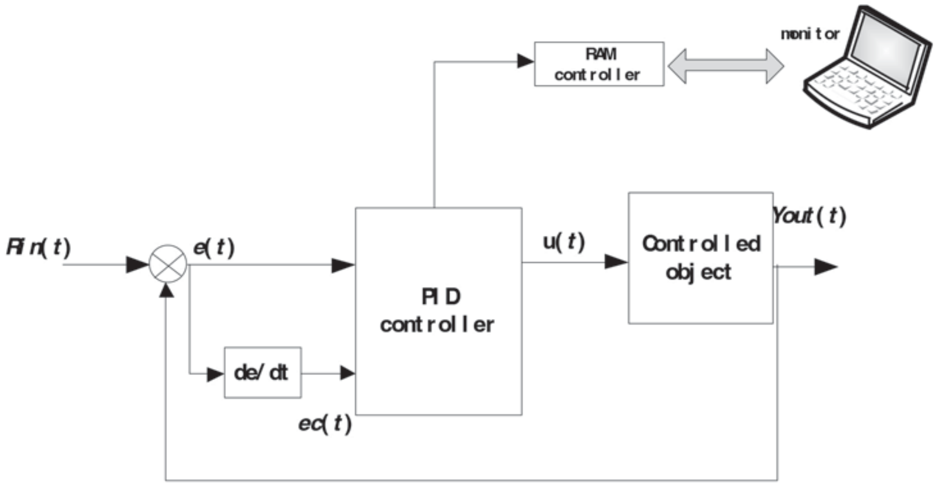

Figure 5 Composition of fuzzy PID controller.

Table 4 Fuzzy control rules.

	AB	AC	AD	AO	OB	OC	OD
AB	AC	AC	AD	AO	OB	OD	OC
AC	AC	AC	AD	AO	OB	OD	OC
AD	AD	AD	AO	AO	OB	OD	OC
AO	AO	AO	AO	AO	OB	OD	OC
OB	OB	OB	OB	OB	OB	OB	OB
OC	OD	OD	OD	OD	OB	OD	OC
OD	OC	OC	OC	OC	OB	OC	OC

Table 5 Specifications parameter setting.

Project	parameter
Rated current	60(A)
Shell protection grade	IP55
Plate thickness	Cabinet 1.5, door panel 2.0 mm
Short circuit making current	1000(KA)
Overall dimension	2000*800*600 (mm)
Shell material	Cold rolled steel plate plastic spraying
Screw hole spacing	117.2

3.2.2 Frequency Conversion Speed Regulation Control Curve of DC Motor

The frequency conversion speed regulation control curve of DC motor is obtained through an experiment, as shown in Figure 8.

Compared with the comparison system and the traditional system, the frequency conversion speed regulation control curve of the design system is more in line with the standard control curve. The comparison system and the traditional system deviate significantly from the standard control curve after 10s, indicating the better control effect of the proposed system. Because the proposed system is affected by external factors and has errors in terms of frequency conversion and speed regulation control of the PLC DC motor, there is a certain error between the proposed system's control curve and the standard control curve, although this does not affect the control result.

3.2.3 Fixed Angle Speed Regulation Control

The tracking angle of the PLC DC motor's constant angle speed regulation control was analyzed, and the expected command angle is shown in Figure 9.

According to Figure 9, the angle of the PLC DC motor is 40 degrees. When the speed of the PLC DC motor reaches 40 degrees, the speed regulation angle remains stable. After starting from 20 s, the speed of the PLC DC motor is stabilized at 40 degrees. At the same time, the system proposed in this paper and the comparison system are used for experimental comparison. The experimental results of the tracking control error are shown in Figure 10.

It can be seen from Figure 10 that there is a tracking control error in the initial stage of the proposed system, and the peak value of the control error is $-0.15°$, although it converges quickly. The tracking control error of the comparison system is large and fluctuates greatly up and down. The maximum error in the positive direction reaches $0.1°$,

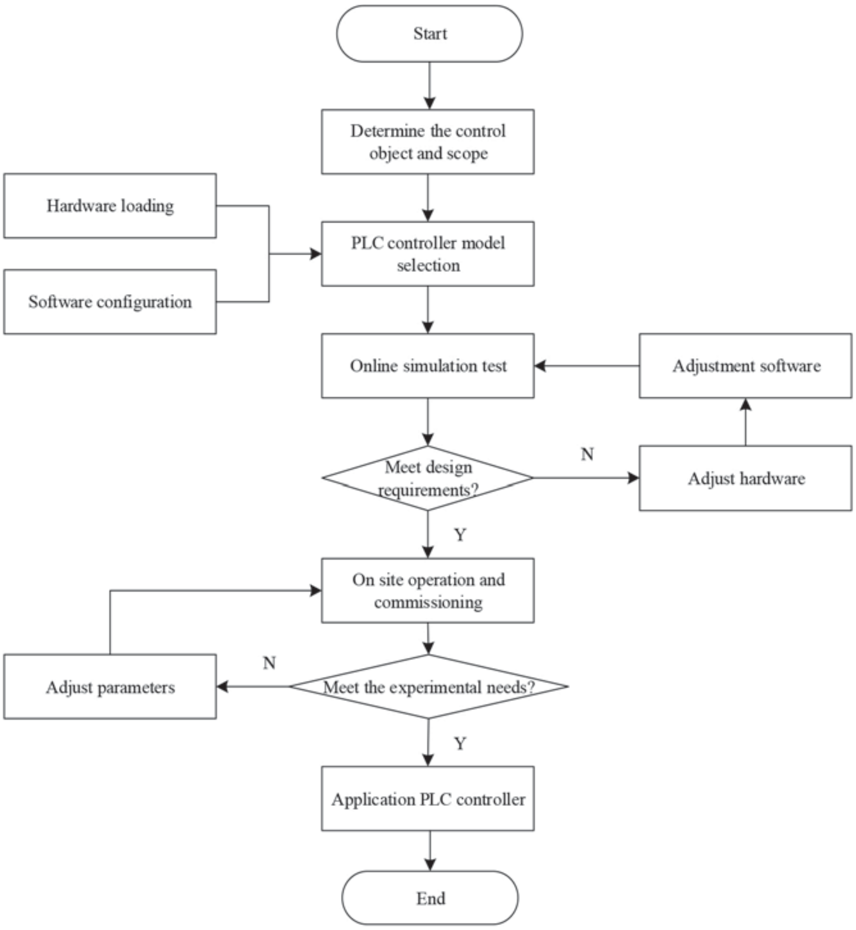

Figure 6 Commissioning program diagram of PLC controller.

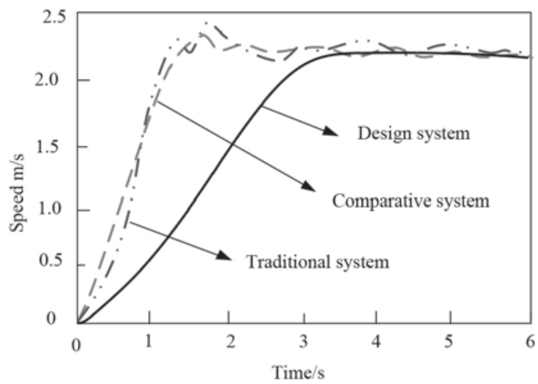

Figure 7 Schematic diagram of response curve of variable frequency speed regulation of DC motor.

and that in the negative direction reaches $-0.2°$. The first convergence occurs when the control time is 0.8 s, and the second fluctuation occurs when the control time is 3 s. The second convergence does not begin until 3.3 s. The traditional system fluctuates greatly up and down. The maximum error in the positive direction reaches $0.1°$, and the maximum error in the negative direction exceeds $-0.2°$. It converges gradually after 20 s. It can be seen that the system designed in this paper can achieve good convergence quickly, which is of positive significance for the selection of adaptive parameters.

The experimental results of constant angle speed regulation control input voltage are shown in Figure 11.

According to the input voltage test results of constant angle speed regulation control in Figure 10, there is no large gap between the compensation control input and the total control input of the proposed system. The method has good nonlinear dynamic ability and does not need to input too much robust control voltage. Although affected by impulse voltage, there is interference, and the internal control input voltage increases rapidly; however,it tends to stabilize within a short time. The traditional control method produces great fluctuation after being affected by impulse voltage, and the fluctuation time is more than 5 s. Therefore, the proposed system has stronger control performance and robust feedback control

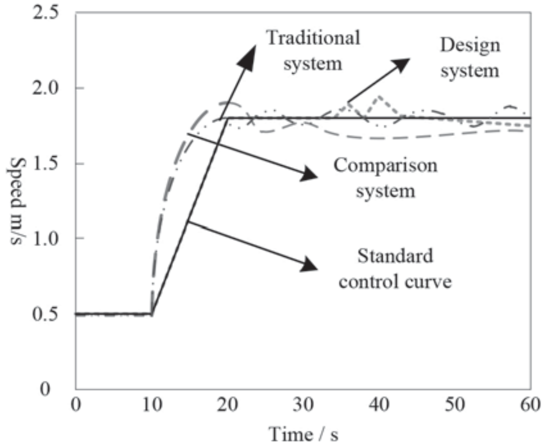

Figure 8 Schematic diagram of variable frequency speed regulation control curve of DC motor.

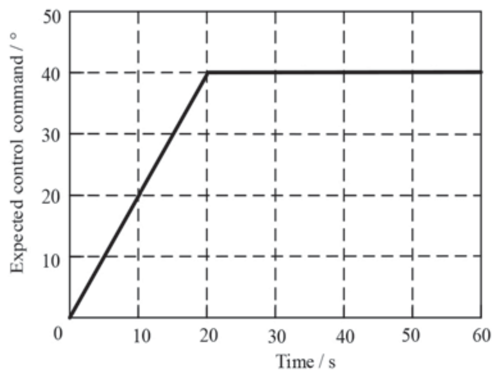

Figure 9 Desired command angle.

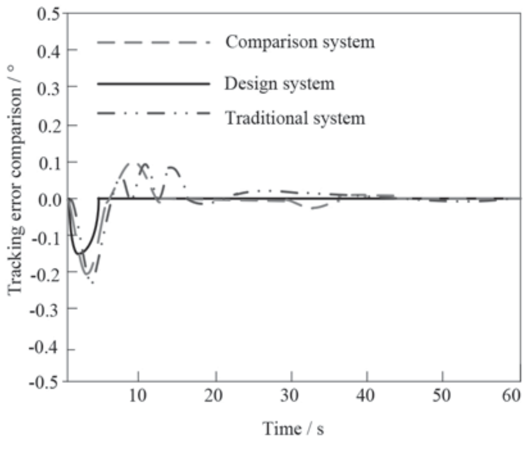

Figure 10 Experimental results of tracking control error.

ability, which can effectively prevent external interference. Although the gap between the comparison system and the compensation control input is not large, the overshoot is very large. Although it enters the steady state, there are still many oscillations, and the control input capacity cannot meet the requirements.

In order to further verify the effectiveness of the proposed system, the systems proposed in [3] and [5] are used to compare and analyze the speed regulation accuracy of the PLC DC motor. The comparison results are shown in Figure 12.

The accuracy of PLC DC motor speed regulation in the proposed system can reach 100%, while the accuracy of the PLC DC motor speed regulation in [3] is only 88%, and the accuracy of PLC DC motor speed regulation in [5] is only 70%. The accuracy of the PLC DC motor speed regulation in the proposed system is the highest, and the speed regulation effect is the best.

4. RESULTS AND DISCUSSION

To sum up, the fuzzy control algorithm-based text system is a nonlinear model, and can effectively solve the problem of random control instability and mismatch caused by nonlinear

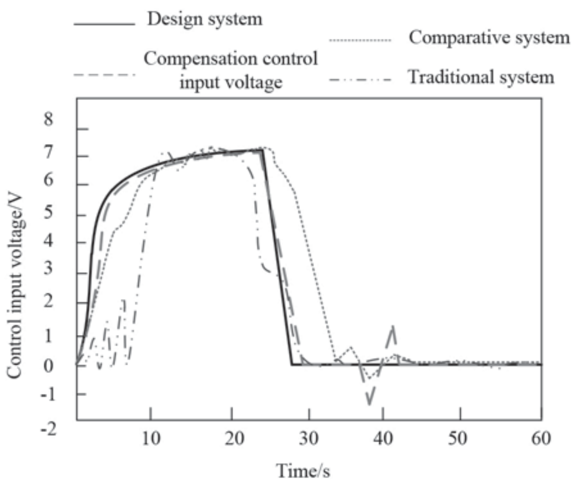

Figure 11 Experimental results of input voltage of constant angle speed regulation control.

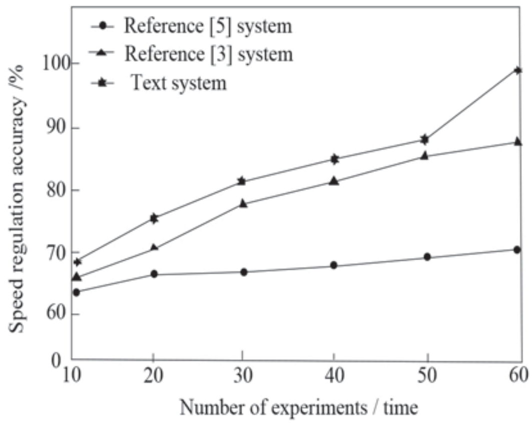

Figure 12 Comparison results of PLC DC motor speed regulation accuracy of three systems.

characteristics. The method proposed in this paper has better reference value for text systems and is more suitable for practical application.The system has good nonlinear dynamic ability and does not need to input too much robust control voltage. The accuracy of the PLC DC motor speed regulation in this system can reach 100%, so as to obtain a better effect of frequency conversion speed regulation, which not only assists the development and application of the PLC DC motor, but also provides a valuable reference for the research on frequency conversion speed regulation. During the research process, due to the high internal computational complexity of the designed algorithm, the speed control of the PLC DC motor requires longer time. In order to shorten the response time of the system, in the next research, this paper improves the algorithm to improve the efficiency of PLC DC motor speed regulation.

5. CONCLUSION

In this study, a fuzzy control algorithm-based text system is proposed. The hardware part applies machine vision technology and selects the corresponding machine vision equipment. The software part designs a fuzzy PID automatic controller based on fuzzy control algorithm to achieve the control of the PLC DC motor. Finally, the feasibility of the system is verified by experiments. Although there is a tracking control error in the initial stage of the design system, and the peak value of the control error is -0.15, the convergence speed is fast.

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