Design and Simulation of Double Closed-loop DC Motor Speed Regulation System with Fuzzy PID Controller

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Abstract. This paper introduced the principle of one dual closed-loop DC motor speed control system with fuzzy PID controller. The algorithm could reduce the setting time and the over-shoot of the step response of the speed-current loop control system, with comparison of the traditional PID after simulation.

Introduction

The traditional PID was too difficult to adjust some controlled system with nonlinear, time-varying, and uncertainties, even arrived at the less satisfactory performance results, such as direct-current motor. In this paper, one double-loop PID controlled was presented to improve the performance of the object, by fuzzy adjuster. The method could coordinate all various parameters to achieve adaptability and flexibility. At the last parts, several sets of simulation were made to demonstrate its advantages with traditional PID controllers by simple loop and dual structures.

Dual Closed-loop DC Motor Speed Control Principle

In order to eliminate the influence of the load’s disturbance in steady state, we usually add the speed’s feedback regulator basis on the open-loop control system and add the current cut-off negative feedback basis on the speed’s feedback to limit the impact of the pivot current. The dynamic structure of double closed-loop DC speed control system is shown in figure 1.

Figure 1. The structure of double closed-loop DC speed control system.

where, $W_{ASR}(S)$ is the transfer function of speed regulator, $W_{ACR}(S)$ the transfer function of current regulator, α the feedback coefficient of speed and β the feedback coefficient of electric current.
Speed Regulator Principle

Feedback is a process which can inhibit or even eliminate the impact of the disturbance on the entire system effectively. The system is controlled by a deviation which is generated by the comparison between the measured value and the given value. In order to digitize the signal of speed, we generally use the encoder connected with the DC motor which rotates to drive the encoder.

In order to achieve the floating speed regulation, there must be an integration loop ahead of the load disturbance point, which can make the system maintain the constant speed with floating. Because there is already an integration loop behind the load disturbance point, the open-loop transfer function of the speed loop should have a total of two integrations loop and should be designed as a typical type II system. The saturation nonlinear of the speed regulator system will greatly reduce the over-shoot, therefore, the PI regulator is usually adopted in fact. The transfer function is:

\[ W_{LSS}(s) = \frac{K_n (r \cdot nS + 1)}{r \cdot nS} \]  

where, \( K_n \) is the proportional coefficient of the speed regulator, \( r \cdot n \) the speed regulator lead time constant of the speed regulator. The speed regulation system open-loop transfer function is:

\[ W_n(s) = \frac{K_n \alpha R (r \cdot nS + 1)}{r \cdot \beta C \cdot T_0 s^2 (T \Xi nS + 1)} \]  

The open-loop gain is:

\[ K_n = \frac{K_n \alpha R}{r \cdot \beta C \cdot T_0} \]  

Taking into account equation (3), (2) becomes:

\[ W_n(s) = \frac{K_n (r \cdot nS + 1)}{s^2 (T \Xi nS + 1)} \]  

\( \tau = hT \)

Refer to equation (5), the following equation can be deduced:

\[ \tau = hT \Xi n \]

\[ K = \frac{h + 1}{2h^2T^2} \]

From (7), the following equation can be deduced:

\[ K_n = \frac{h + 1}{2h^2T^2 \Xi n} \]

Taking into account equations (6), (8), and (2) becomes:

\[ K_n = \frac{(h + 1) \beta C \cdot T_0}{2h \alpha R T \Xi n} \]

Under normal circumstances, the general choice \( h=5 \).
Current Regulator Principle

When the motor starts, stops or is in the blocked state, the current is larger than the allowable current, so we introduce the current cut-off negative feedback. We connect a small resistor $R_s$ in series with the motor armature circuit, making the comparison with the resulting current $I_d$ and the critical cut-off current $I_{der}$, when $I_d$ is greater than $I_{der}$, the $I_d$ is added to the amplifier input, when the $I_d$ is smaller than $I_{der}$, we should use the microcontroller to cut off the current feedback [1].

The main role of current regulator is to follow, it should use type I system and PI regulation, the transfer function is:

$$W_{oc}(S) = \frac{K_i \left( \tau \cdot iS + 1 \right)}{\tau \cdot iS},$$  \hspace{1cm} (10)

where, $K_i$ is the proportional coefficient of the current regulator, $\tau$ the forward time constant of the current regulator, and the open-loop transfer function of the current loop is:

$$W_{op}(S) = \frac{K_i \left( \tau \cdot iS + 1 \right)}{\tau \cdot iS} \frac{\beta \cdot K_i / R}{(T \cdot iS + 1) (T \cdot iS + 1)}.$$  \hspace{1cm} (11)

Since $T_i >> T \Sigma$, select $T_i = T_i$, use the adjuster zero to eliminate the large time constant pole in the control object, so:

$$W_{op}(S) = \frac{K_i \beta \cdot K_s / R}{\tau \cdot iS (T \cdot iS + 1)} = \frac{K_i}{s (T \cdot iS + 1)}.$$  \hspace{1cm} (12)

In equation (12),

$$K_i = \frac{K_i \beta \cdot K_s / R}{T_i R}.$$  \hspace{1cm} (13)

Under normal circumstances, $\xi = 0.707$, $K_i T \Sigma = 0.5$. Then,

$$K_i = \frac{T_i R}{2K_s \beta T \Sigma i} = \frac{R}{2K_s \beta} \left( \frac{T_i}{T \Sigma i} \right).$$  \hspace{1cm} (14)

Fuzzy Controller

Fuzzy Controller Principle

There are many vague concepts in human thinking, some concepts without connotation and extension can only be described by fuzzy sets, which are expressed as $A$, others have a clear connotation and denotation, they are called the general set or the classic set. The function called the fuzzy characteristic function is the membership functions, it is recorded as $\mu_A(x)$ [2]. The size of the membership function reflects the degree of membership of the element to the fuzzy set $A$.

Fuzzy control system consists of fuzzy controller, input interface, output interface, actuator, polishing device and the controlled object. The core of fuzzy control system is the fuzzy controller. The fuzzy controller mainly includes fuzzy input interface, knowledge base, inference engine and output clearness interface[2]. Input interface converts the input into a fuzzy vector, and uses it for fuzzy control. The knowledge base
consists of a database and a rule base, the database stores the membership values of the fuzzy sets of all the output variables, the rule base is used to store the fuzzy control rules. In order to get the fuzzy control quantity, inference engine is based on the amount of fuzzy input and knowledge base to complete the fuzzy inference to solve the fuzzy equation. The output clearness interface is to clarify the amount of output blur obtained by the fuzzy decision and converts it to a precise amount.

**Fuzzy Controller Design**

In fuzzy control, the general choice of ‘large, medium and small’ to describe the fuzzy controller input and output value, plus positive, negative and zero state, there are seven words: \{negative big, negative middle, negative small, zero, positive small, positive middle, positive big\}. Its abbreviations are: \{NB, NM, NS, O, PS, PM, PB\}. Due to the discourse domain of input and output is \([-6,6]\), we can divide the discourse domain into n files to get the input and output membership function[2]. The fuzzy subset membership function is shown in figure 2.

![Figure 2. Fuzzy subset membership function](image)

For a DC motor speed control system, not only to consider the error given value and the actual value, but also to consider the change rate error, so the system should meet when the simultaneous input A and B, then output C. The corresponding statement is ‘if A and B then C’, through this sentence to design fuzzy controller rules in table 1[3].

| Input | Output |
|-------|--------|
| NB    | NB     |
| NM    | NM     |
| NS    | NS     |
| O     | O      |
| PS    | PS     |
| PM    | PM     |
| PB    | PB     |

Then the fuzzy controller was added into the dual closed-loop DC motor speed control system. We can see the dynamic structure of dual closed-loop DC speed control system based on fuzzy controller in figure 3.
Simulation Design and Results Data Analysis

According to the relevant information, the DC motor parameters are as follows: rated voltage is 220V, rated current is 136A, rated speed 1460r/s, $C_e=0.132\text{V min/r}$, allow overload multiple $\lambda=1.5$, thyristor amplification factor: $K_s=40$, armature circuit total resistance: $R=0.5\Omega$, time constant: $T_1=0.03s$, $T_m=0.18s$, current feedback coefficient $\beta=0.05\text{V/A}$, speed feedback coefficient $\alpha=0.007\text{V min/r}$, no static speed requirements[1]. we can use MATLAB to simulate, the models and the waveform is as figure 4, figure 5 and figure 6.

![Figure 4. Simulation mode of dual-loop DC motor speed control system](image)

![Figure 5. Simulation model of dual closed-loop DC motor based on fuzzy controller](image)

![Figure 6. Step response of one DC motor system](image)
From the waveform of the traditional PID controller and the fuzzy PID controller, we can infer that the fuzzy PID control could reduce the setting time and the over-shoot of the step response and it can make the system reach the stability faster. Therefore, we can conclude that the fuzzy PID controller can improve the dynamic and stability of the speed control system. As a whole, the fuzzy PID controllers have better suitability. It has more obvious advantages than the traditional PID controller.

**Conclusion**

In this paper, the fuzzy algorithm was combined with double closed-loop DC motor speed control system. After simulation, the result of the fuzzy PID controller was compared with the result of the traditional PID controller. The results show that the fuzzy controller has good stability, dynamic and robustness. It also has good adaptability and flexibility to parameters. The fuzzy controllers have many advantages. Therefore, it has been mainly applied in aerospace, advanced electronic equipment, medical equipment, chemical and other advanced technology.

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