Research to Improve the Quality of Servo Motor Controller

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***Abstract*— To overcome the disadvantages that traditional controllers bring, in this study, it is proposed to use fractional order controller PI$^{\lambda}$ instead of conventional PI controller, the research also focuses on improving the quality of the controller. the order controller itself by selecting the computational methods, the discretization methods, and the implementation methods that give the best results. The study conducted simulations and experiments and compared the results with conventional PI controllers, in order to demonstrate the effectiveness of the fractional order controller.**

Keywords*— *AC servo system, permanent magnet synchronous motor, vector control, fractional-order controller

I. Introduction

Previously, there was lots of research on controlling servo motors in order to improve the quality of this motor control, and also obtained great results [1–6]. Regarding the structure of the servo motor, the kinematic models of the servo motor have also been introduced in many teaching and research documents [7–11], so the scope of this paper is not presented. In this paper, we only focus on improving the quality of the controller by using the fractional order PI controller instead of the conventional PI controller, in the current loop and the speed loop, through the process of design, select the calculation methods, the discretization method and the implementation methods for the best results, from which it also improves the quality of the designed fractional order controller.

II. Model of Servo Motor Control Loops

Using the vector modulation method for measurement, this method is very mature and has been presented in a lot of research works [8, 12] In this paper, the results obtained previously were used in this paper. vector modulation method to control 3 loop circuits to take a step further to improve and improve the quality of Servo motor controllers by researching and applying fractional order controllers to the process of controlling loops of the system.

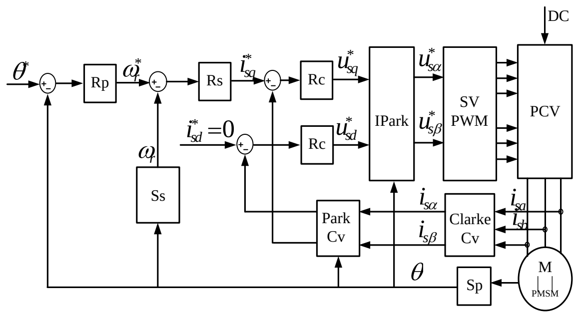

Fig. 1. Vector control of 3-loop servo system

In Fig. 1 shows model of servo motor system with control loops. Where: PVC – power converter, Rp – Regulator position, Rc – Regulator current, Rs – Regulator speed, Sp – Sensor of position, Ss – Sensor of speed, Park Cv – Park converter, Clarke Cv – Clarke converter.

III. Design of a Fractional Order Controller

With any controller, the controller parameter selection calculation plays a very important role. Controller parameters, if calculated correctly, will contribute significantly to improving the quality of system control. There are many methods of calculating controller parameters [12], [13], [15], in this article, we will share the analysis of 2 methods.

A. *Design of a fractional order controller*

With determined parameter tuning of fractional order PI$^{\lambda}$ controller based on frequency domain method, this paper adopts the method of frequency domain analysis and combines the criterion of integrated time and absolute error (ITAE) criterion to tune the parameters of the fractional order PI$^{\lambda}$ controller. The expression of the ITAE criterion is shown in (1).

$$J = \int_0^{\infty} t\left|e(t)\right|dt \quad (1)$$

The tuning process of the fractional order PI$^\lambda$ controller is as follows:

Assuming the general form of the fractional order PI$^\lambda$ controller is (2)

$$C(s)=\frac{U(s)}{E(s)}=K_p(1+\frac{K_i}{s^\lambda}),\lambda\in(0\sim1) \quad (2)$$

For the mathematical model of the permanent magnet AC servo motor [12], considering the inverter output delay and the current sampling filter delay, the controlled object of the current loop can be equivalent to the (3):

$$G_s(s)=\frac{K}{(T_{\Sigma i}s+1)(T_l s+1)}, \quad (3)$$

where $K=k_v k_i/R_s$.

The open-loop transfer function of the system is shown by (4)

$$G_k(s)=C(s)G_s(s) \quad (4)$$

Assuming that the expected phase margin φ_m index of the system is known, taking the current loop as an example, the corresponding parameters of the system need to meet the following two criteria [13], we have (5), (6).

$$Arg[G_k(j\omega_c)]=Arg[C(j\omega_c)G_s(j\omega_c)]=-\pi+\varphi_m \quad (5)$$

$$|C_k(j\omega_c)|=|C(j\omega_c)G_s(j\omega_c)|=1 \quad (6)$$

According to formula (2), the frequency characteristics of the fractional order PI$^\lambda$ controller can be obtained as (7) and (8)

$$|C(j\omega)|=K_p\sqrt{[1+\frac{K_i}{\omega^\lambda}\cos(\frac{\pi\lambda}{2})]^2+[\frac{K_i}{\omega^\lambda}\sin(\frac{\pi\lambda}{2})]^2} \quad (7)$$

$$Arg[C(j\omega)]=-\arctan\frac{\frac{K_i}{\omega^\lambda}\sin(\frac{\pi\lambda}{2})}{1+\frac{K_i}{\omega^\lambda}\cos(\frac{\pi\lambda}{2})} \quad (8)$$

According to (3), the frequency characteristics of an object combined with the current loop controller can be shown as (9) and (10)

$$|G_s(j\omega)|=\frac{K\sqrt{(1-\omega^2T_{\Sigma i}T_l)^2+\omega^2(T_{\Sigma i}+T_l)^2}}{(1+\omega^2T_{\Sigma i}^2)(1+\omega^2T_l^2)} \quad (9)$$

$$Arg[G_s(j\omega)]=-\arctan(\omega T_{\Sigma i})-\arctan(\omega T_l) \quad (10)$$

Substituting (7) ~ (10) into (5) and (6), we get (11) and (12)

$$-\arctan\frac{\frac{K_i}{\omega_c^\lambda}\sin(\frac{\pi\lambda}{2})}{1+\frac{K_i}{\omega_c^\lambda}\cos(\frac{\pi\lambda}{2})}-\arctan(\omega_c T_{\Sigma i})-\arctan(\omega_c T_l) =-\pi+\varphi_m \quad (11)$$

$$K_pK\sqrt{[1+\frac{K_i}{\omega_c^\lambda}\cos(\frac{\pi\lambda}{2})]^2+[\frac{K_i}{\omega_c^\lambda}\sin(\frac{\pi\lambda}{2})]^2} * \frac{\sqrt{(1-\omega_c^2T_{\Sigma i}T_l)^2+\omega_c^2(T_{\Sigma i}+T_l)^2}}{(1+\omega_c^2T_{\Sigma i}^2)(1+\omega_c^2T_l^2)}=1 \quad (12)$$

According to the above design steps, there are 2 independent equations, which are formulas (11) and (12), and there are 4 variables（K_p, K_i, λ, ω_c）, in the equations, which are not enough to directly solve the controller parameters. Therefore, this paper introduces the ITAE criterion, and the control system designed according to this criterion has less oscillation in transient response and has good selectivity to parameters.

The bandwidth of the current loop is much larger than the bandwidth of the speed loop [12], so when designing the speed loop, the current loop can be equivalent to a first-order inertial link. However, since the control object of the permanent magnet AC servo motor contains an integral link, the traditional PI controller will reduce the phase margin of the speed control system and limit the cut-off frequency of the speed loop, thus affecting the dynamic response performance of the entire servo control system. The order of the fractional-order integration link is adjustable, and when the value is between 0 and 1, its phase margin is higher than that of the integer-order integration link, so this system also uses the fractional-order PI$^\lambda$ The controller replaces the integer-order PI controller in the speed loop to improve the response speed of the speed and reduce the overshoot of the speed, thereby improving the dynamic response performance of the entire servo control system.

The controlled object of the speed loop can be equivalent to (13).

$$G_s(s)=\frac{K'}{s(T's+1)}, \quad (13)$$

Its frequency characteristics can be expressed as:

$$|G_s(s)|=\frac{K'}{\omega\sqrt{(\omega T')^2+1}} \quad (14)$$

$$Arg[G_s(j\omega)]=-\frac{\pi}{2}-\arctan(\omega T') \quad (15)$$

B. Parameter of integer order PI controller based on Frequency Domain Method

In order to make the designed fractional-order PI$^\lambda$ controller comparable to the integer-order PI controller, this section adopts the same parameter tuning criterion as the fractional-order PI$^\lambda$ controller, and re-tunes the parameters of the integer-order PI controller under the same conditions. when λ=1 in the fractional-order PI$^\lambda$ controller, it can be equivalent to an integer-order PI controller. Therefore, the above-mentioned method based on the frequency domain can still be used to tune the parameters of the integer-order PI controller. Among them, under the integer-order PI controller, λ=1 in formulas (11) and (12) can be directly set, and the amplitude and phase angle of the current loop can be obtained to satisfy the following expressions:

$$-\arctan\frac{K_i}{\omega_c}-\arctan(\omega_c T_{\Sigma i})-\arctan(\omega_c T_l)=-\pi+\varphi_m \quad (16)$$

$$K_pK\sqrt{1+\frac{K_i^2}{\omega_c^2}}\cdot\frac{\sqrt{(1-\omega_c^2T_{\Sigma i}T_l)^2+\omega_c^2(T_{\Sigma i}+T_l)^2}}{(1+\omega_c^2T_{\Sigma i}^2)(1+\omega_c^2T_l^2)}=1. \quad (17)$$

Since the integer-order PI controller has only two adjustable parameters K_p and K_i, we only need to limit the search range of the cut-off frequency ω_{ci}, combined with the

ITAE criterion, the parameters of the integer-order PI controller can be obtained. Since the integer-order search is only related to the cut-off frequency ω_{ci} , it is a one-dimensional search, while the parameter tuning of the fractional-order PI^{λ} controller is a two-dimensional search, which also shows that the fractional-order PI^{λ} controller has better flexibility.

C. Realization of Fractional Order PI^{λ} Controller

Calculated parameters of the fractional order controller need to be discretized to realize it in the digital system. There are two main methods of fractional discretization: direct discretization and indirect discretization. Each method has its own advantages but more convenient is the indirect discretization method with approximation in the s domain, the classical control theory can be used to analyze and optimize the approximate model. Therefore, using the indirect discretization approach with the Oustaloup approximation for the realization of fractional order controllers in digital control is optimal.

IV. EXPERIMENT

A. Experimental models

The model shown in Fig. 1 includes a three-phase grid voltage 380 VAC supply to the AC servo motor through the converter, controlled by the control board. The PC relates to the control board through the DSP emulator, which is used to display the value of the system variables in real-time and obtain the real-time system operation curve when the control system runs in the state of CCS software debug during the experiment. The AC servo motor used in this system is Sanyo P series, model PI0B18200BXS00 with parameters got from the catalogue. The physical model of the AC servo control system experiment platform is shown in Fig. 2.

Fig. 2. Physical model of AC servo control system experiment platform

B. Calculation of parameters

The calculated parameters of the fractional order controller play an important role in the design of the fractional controller, it largely determines the working quality of the system. After calculating, the authors have realized this controller in simulation and experiment to obtain the following experimental results.

1) Calculation of parameters for fractional order controller

Based on parameters of system in part A, we calculate parameters of controllers. Parameters of the fractional order controller for the current loop are calculated according to the analysis of the typical type I system of the current loop, with the cut-off frequency is about 10500rad/s, the range of the cut-off frequency can be selected from 8000 to 12000 rad/s, with the value of step is 100rad/s. At the same time, the value λ changes from 0.1 to 0.9 with step 0.1. Parameters of the controller can be obtained by combining formulas (11) and (12), and then according to the ITAE rule, select the time multiplied by the absolute error integral J as the minimum value corresponding to the parameters of the final tuned fractional order PI^{λ} controller parameters. The surface diagram of ITAE changing with cut-off frequency ωc and integration order λ is shown in Fig. 3.

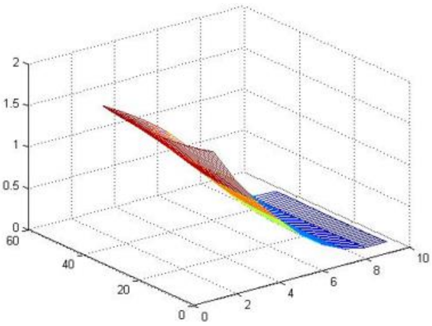

Fig. 3. Current loop step response ITAE variation surface with cut-off frequency ωc and integration order λ

Through the above search method, it can be solved that the fractional-order PI^{λ} controller of the current loop can obtain the minimum ITAE value in its step response when the selected cut-off frequency is 11200 rad/s and the integration order is 0.8, then the obtained current loop fractional order PI^{λ} controller transfer function is shown in (18).

$$G_{ci}(s) = 1.536(1+\frac{129.494}{s^{0.8}}) \tag{18}$$

When designing the speed loop, since the bandwidth of the current loop is much larger than the bandwidth of the speed loop [12], the current loop can be equivalent to a first-order inertial link, therefore the system with the speed loop equivalent to (19).

$$G_s(s) = \frac{K'}{s(T's+1)} \tag{19}$$

Its frequency characteristics can be expressed as:

$$|G_s(s)| = \frac{K'}{\omega\sqrt{(\omega T')^2+1}} \tag{20}$$

$$Arg[G_s(j\omega)] = -\frac{\pi}{2} - \arctan(\omega T') \tag{21}$$

Similar to the design method of the current loop PI^{λ} controller, its cut-off frequency is about 2370 rad/s. Based on this, assuming that the phase margin of the speed loop is 45°, the search range of the selectable cut-off frequency is 1000~4000rad/s. Similarly, set the search step size to 100rad/s, and the value varies from 0.1 to 0.9, and the step size is 0.1. The transfer function of the fractional order PI^{λ} controller of the speed loop is expressed by (22).

$$G_{cn}(s) = 43.238(1+\frac{184.853}{s^{0.7}}) \tag{22}$$

2) Calculation of parameters for Integer Order PI controller

To design fractional-order PI^{λ} controller comparable to the integer-order PI controller, this section adopts the same parameter tuning criterion as the fractional-order PI^{λ} controller, and re-tunes the parameters of the integer-order PI controller under the same conditions. when λ=1 in the fractional-order PI^{λ} controller, it can be equivalent to an integer-order PI controller. Therefore, the above-mentioned method based on the frequency domain can still be used to tune the parameters of the integer-order PI controller. Among them, under the integer-order PI controller, λ=1 in formulas (11) and (12) can be directly set, and the amplitude and phase angle of the current loop can be obtained to satisfy the following expressions:

$$-\arctan\frac{K_i}{\omega_c}-\arctan(\omega_c T_{\Sigma i})-\arctan(\omega_c T_l)=-\pi+\varphi_m \quad (23)$$

$$K_p K\sqrt{1+\frac{K_i^2}{\omega_c^2}}\cdot\frac{\sqrt{(1-\omega_c^2 T_{\Sigma i}T_l)^2+\omega_c^2(T_{\Sigma i}+T_l)^2}}{(1+\omega_c^2 T_{\Sigma i}^2)(1+\omega_c^2 T_l^2)}=1 \quad (24)$$

The integer-order PI controller has only two adjustable parameters K_p and K_i, we only need to limit the search range of the cut-off frequency ω_{ci}, combined with the ITAE criterion, the parameters of the integer-order PI controller can be obtained. Since the integer-order search is only related to the cut-off frequency ω_{ci}, it is a one-dimensional search, while the parameter tuning of the fractional-order PI^{λ} controller is a two-dimensional search, which also shows that the fractional-order PI^{λ} controller has better flexibility.

Similarly, consistent with the parameter tuning of the fractional order PI^{λ} controller, assuming that the current loop phase margin φ_{mi} is 60°, the search range of the cut-off frequency can be selected as 8000~12000rad/s, and the search step is set as 100rad/s. The graph of ITAE changing with the cut-off frequency ω_c can be obtained as shown in Fig. 4.

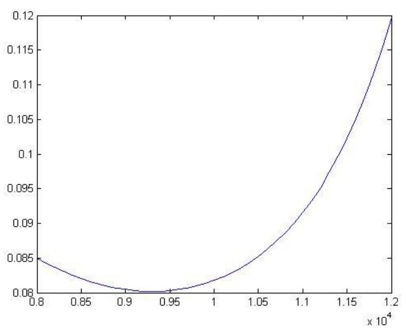

Fig. 4. Current loop step response ITAE variation curve with selected cut-off frequency ωc

In Fig. 4, through the above search method, the current loop fractional-order PI controller can be solved when the selected cut-off frequency is 9300rad/s, and its step response obtains the minimum ITAE value. At this time, the corresponding Kp=1.317, Ki=1325.675, then the obtained current loop fractional order PI controller transfer function is:

$$G_{ci}(s)=1.317(1+\frac{1325.675}{s}) \quad (25)$$

Similarly, for the integer-order PI controller of the speed loop, this tuning method is also used for tuning, and the controlled object of the speed loop still uses formula (3-19). Also assume that the speed loop phase margin A is 45°, and the search range of the selected cut-off frequency is 1000~4000rad/s. According to the above current loop design method, the value of the speed loop cutoff frequency B can be obtained as 2100rad/s, and the speed The transfer function of the ring integer order PI controller is:

$$G_{cn}(s)=39.685(1+\frac{1508.436}{s}) \quad (26)$$

C. Experiment results

In this system, the data of the software is processed in the form of per unit value. Among them, the current is standardized by the rated current of 9.5A, that is, the current value of 1 in the system means that the actual current is 9.5A; and the speed is standardized by the rated speed of 2000r/min, that is, the speed value of 1 in the system means that the actual speed is 2000r /min. Considering the overload capacity of the motor, this system takes twice the overload capacity, that is, the limit value of the output of the speed controller is ±2.0; and considering that the maximum speed of the servo motor is 2000r/min, the limit value of the output of the position controller is set The amplitude is ±1.0.

1) No-load start-up experiment

With the speed setting value is 0.8, that is, 1600r/min, the motor starts without load. From speed response curves, characteristics are compared following Table 1.

TABLE I. COMPARISON OF SPEED DYNAMIC PERFORMANCE INDICATORS UNDER TWO DIFFERENT CONTROLLERS

Controller	Rise Time	Overshoot	Adjustment time
PI	0.504s	4.8%	0.987s
PI^{λ}	0.483s	2.8%	0.760s

2) Experiment with load

Carried out loading experiments on the servo motor respectively, and compared and analyzed the experimental results under the action of the integer-order PI controller and the fractional-order PI^{λ} controller. During the load experiment, this system adopts the coaxial drag platform of the AC servo motor and DC motor. Among them, the power of the DC motor is 2kW, the rated speed is 1450r/min, and the Eurotherm 590 DC speed controller is used to control the torque output of the DC motor.

First, set the DC speed controller to work in the torque output mode, and the servo motor starts to run stably without load. After a certain period of time, start the DC speed controller to make the DC motor output a reverse constant torque, which is added to the rotor shaft of the servo motor. Above, realize the loading and running experiment of the servo motor. The experimental results of the system under the action of integer-order PI controller and fractional-order PI^{λ} controller are received, and from speed response curves, characteristics are compared following Table 2.

TABLE II. DYNAMIC PERFORMANCE INDICATORS OF SYSTEM SPEED UNDER DIFFERENT CONTROLLERS

Controller	RPM drop	Adjustment time
PI	24r/min	0.162s
PI^{λ}	16r/min	0.155s

It can be seen from Table 2 that during the loading process, the speed of the servo motor remains basically unchanged, and under the action of the fractional-order PI^{λ}

controller, the speed drop is relatively small, and the adjustment time is relatively short. Therefore, it is shown that the system has better anti-disturbance ability when the load increases, and the anti-disturbance ability of the fractional-order PI^{λ} controller is stronger than that of the integer-order PI controller.

V. CONCLUSION

Through the experiment with the AC servo system under the action of the integer-order PI controller and fractional-order PI^{λ} controller, the effectiveness of the controllers was compared experimentally. Experimental results show that the fractional-order PI^{λ} controller is used instead of the traditional integer-order PI controller to improve the dynamic response performance and anti-disturbance performance of the current loop and speed loop of the system is improved, thereby improving the overall control performance of the servo system.

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