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Design of single neuron super-twisting sliding mode controller for permanent magnet synchronous servo motor

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Aiming at the control system of permanent magnet synchronous servo motor which is easily affected by external disturbance and parameter uncertainty, a single neuron sliding mode combining single neuron adaptive algorithm and super-twisting sliding mode (STSM) control is proposed. The STSM control is used to overcome the chattering problem in the traditional sliding mode control, and the proportional control and the STSM control are combined to enhance the robustness of the control system. In order to improve the dynamic performance of the system and enhance the anti-disturbance ability of the system, the single neuron adaptive control adopted can adjust the relevant parameters of the designed sliding mode controller online. The simulation and experimental results show that the designed improved sliding mode controller can effectively suppress the chattering of the control system, realize the fast following and no overshoot of the control system, and enhance the robustness of the system.

KEYWORDS

permanent magnet synchronous servo motor, single-neuron adaptive algorithm, super-twisting algorithm, sliding mode control, stability analysis

Introduction

In recent years, permanent magnet synchronous motor (PMSM) has received more and more attention with the continuous research and development of the performance of permanent magnet materials and the progress of power electronics technology (Zhang et al., 2019). It is also more widely used in various aspects of national defense, military industry and daily life owing to its high efficiency, simple and reliable structure, small size and low losses (Du et al., 2016; Wang et al., 2019). The control performance of PMSM drive system is greatly influenced by uncertainties such as load variations and parameter perturbations in actual control. Therefore, suitable controllers need to be designed to reduce the impact of these uncertain external factors on the control system while enhancing the system robustness and improving the system control performance.

Some literatures have proposed various control methods for motor control system, such as sliding mode control (Ali et al., 2019; ZHANG and WANG, 2021), neural network control (Wang and Kang, 2019; Wang et al., 2021), adaptive control (Zhao et al., 2017; Asiain and Garrido, 2021), and fuzzy logic control (Wang and Zhu, 2018; Mesloub et al., 2020), et al. Among them, sliding mode control is widely used in PMSM control system due to its advantages of fast response, insensitivity to parameter changes and perturbations, no need for online system identification, and simple physical implementation (Li et al., 2019; Xia and Zhang, 2019). However, in the actual control system, the sliding mode control cannot achieve the ideal switching and when the system is in the sliding mode surface, it will repeatedly cross

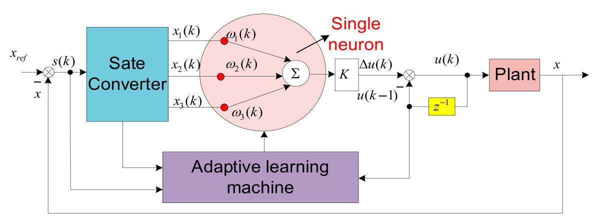

FIGURE 1
Control block diagram of single neuron adaptive sliding mode controller.

the sliding mode surface and so on, resulting in the system chattering and making the control system unstable (Wang et al., 2018). The idea of higher-order sliding mode control algorithm has been proposed to solve this problem. super-twisting sliding mode (STSM) control algorithm is a kind of second-order sliding mode control algorithm, and its control signal is continuous and vibration free, which can suppress the system chattering well. However, since it does not give an estimate of the convergence time and the uncertainty bound of the system is difficult to obtain (Sadeghi et al., 2018; Wan et al., 2018), we need to improve it. In (Zhou et al., 2022), a modified sliding mode self-anti-disturbance control is used to improve the dynamic stability performance of the control system. In (Zhou et al., 2019), the overshoot-free fast following of the control system is achieved using internal mode control. The literature (Abdul Zahra and Abdalla, 2021) combines Super-twisting sliding mode control with fuzzy control to weaken the chattering problem and improve the system robustness.

In this paper, a single-neuron control strategy was combined with super-twisting sliding mode control. In addition to the advantages of strong robustness and fast response of sliding mode control, STSM control can achieve high accuracy and fast following of the reference trajectory as well as suppressing the chattering problem of the control system. The single-neuron algorithm is simple and easy to implement for digital controllers. A single-neuron control strategy is combined with STSM control to reduce system chattering problem, improve system robustness and weaken the effect of uncertainties on the system. The controller can also adjust the parameters of the sliding mode controller online to obtain better control effect. The proposed idea was verified by simulation and experiment, and the results show that the proposed method has good control performance.

Super-twisting sliding mode controller design

Sliding mode controller design

The following first-order non-linear uncertainty system is considered.

$$\begin{cases} \dot{x} = ax + bu + d(t) \\ y = x \end{cases} \tag{1}$$

In Formula. 1, The x, u, $d(t)$ are the state variables, controller and uncertain perturbation terms of the system, respectively, and $d(t)$ satisfies $d(t) = \Delta a{\cdot}x + \Delta b{\cdot}u + g(t)$, where Δa, Δb and $g(t)$ are each uncertain terms and external perturbations of the parameters.

The super-twisting algorithm was applied to design a second-order sliding mode controller to improve the robustness of the control system to load and parameter variations and to reduce the system chattering problem. A sliding surface, s, is defined as follows

$$s = x_{ref} - x \tag{2}$$

Where x_{ref} is the system reference value.

Super-twisting slide controller was used to ensure that the system reaches the slide surface in a finite amount of time, where the equation is as follows

$$u = k_1 |s|^{\frac{1}{2}} \operatorname{sgn}(s) + k_2 \int \operatorname{sgn}(s) dt \tag{3}$$

Where k_1, k_2 are the gains of the sliding mode controller and satisfy $k_1 > 0$, $k_2 > 0$. Where $sgn(s)$ is a symbolic function and satisfies as follows

$$\operatorname{sgn}(s) = \begin{cases} 1, s > 0 \\ -1, s < 0 \end{cases} \tag{4}$$

The derivative of (2) for the slip surface function and substitution of (1) and (3) can be obtained as follows

$$\begin{aligned} \dot{s} &= \dot{x}_{ref} - \dot{x} = \dot{x}_{ref} - (ax + bu + d(t)) \\ &= -bk_1 |s|^{\frac{1}{2}} \operatorname{sgn}(s) - bk_2 \int \operatorname{sgn}(s) dt + \dot{x}_{ref} - ax - d(t) \end{aligned} \tag{5}$$

To facilitate stability analysis, (5) can be further simplified as follows

$$\dot{s} = -k_1' |s|^{\frac{1}{2}} \operatorname{sgn}(s) - k_2' \int \operatorname{sgn}(s) dt + \sigma \tag{6}$$

where, $\sigma = x_{ref} - ax - d(t)$, $k_1' = bk_1$ and $k_2' = bk_2$.

Stability analysis

Drawing on the Lyapunov function method constructed in (Moreno and Osorio, 2008), the stability analysis of the system shown in Formula. 6 is carried out. Define the state variables as follows

$$\zeta = \begin{bmatrix} \zeta_1 \\ \zeta_2 \end{bmatrix} = \begin{bmatrix} |s|^{\frac{1}{2}} \operatorname{sgn}(s) \\ k_2' \int \operatorname{sgn}(s) dt \end{bmatrix} \tag{7}$$

The state variable ξ is derived as follows

$$\begin{aligned} \dot{\zeta} &= \begin{bmatrix} \frac{1}{2} |s|^{-\frac{1}{2}} \left(-k_1' |s|^{\frac{1}{2}} \operatorname{sgn}(s) - k_2' \int \operatorname{sgn}(s) dt + \sigma \right) \\ k_2' \operatorname{sgn}(s) \end{bmatrix} \\ &= -|s|^{-\frac{1}{2}} \begin{bmatrix} \frac{1}{2} (k_1' \zeta_1 + \zeta_2 - \sigma) \\ -k_2' \zeta_1 \end{bmatrix} \end{aligned} \tag{8}$$

The Formula. 8 is further simplified as follows

$$\dot{\zeta} = -|s|^{-\frac{1}{2}} (A\zeta - \phi) \tag{9}$$

Where, $A = \begin{bmatrix} \frac{1}{2} k_1' & \frac{1}{2} \\ -k_2' & 0 \end{bmatrix}$, $\quad \phi = \begin{bmatrix} \frac{1}{2} \sigma \\ 0 \end{bmatrix}$

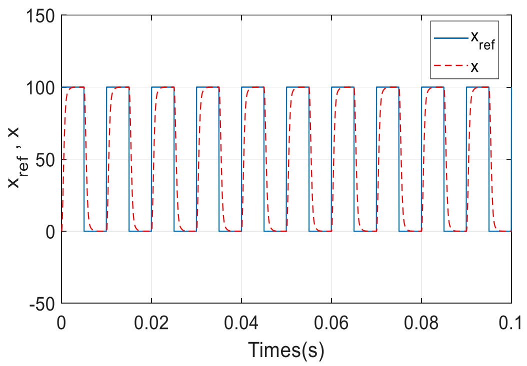

FIGURE 2
Change curve of reference value and actual value.

For the stability analysis of the control system, the Lyapunov function is defined as follows

$$V = \zeta^T P \zeta \tag{10}$$

where P is a real symmetric positive definite matrix and P is designed as follows.

$$P = \begin{bmatrix} \frac{1}{2}k_1'^2 + 2k_2' & \frac{1}{2}k_1' \\ \frac{1}{2}k_1' & 1 \end{bmatrix}$$

In order to analyze the system stability, the derivative of Formula. 9 is obtained as follows.

$$\begin{aligned} \dot{V} &= \dot{\zeta}^T P\zeta + \zeta^T P\dot{\zeta} \\ &= -|s|^{-\frac{1}{2}}\zeta^T\left(A^T P + PA\right)\zeta + |s|^{-\frac{1}{2}}\phi^T P\zeta + |s|^{-\frac{1}{2}}\zeta^T P\phi \end{aligned} \tag{11}$$

Assume that ϕ is bounded and satisfies $|\phi| \le \lambda|\zeta_1|$, $\lambda > 0$. Then Formula 11 can be expressed as follows.

$$\begin{aligned} \dot{V} \le &-|s|^{-\frac{1}{2}}\zeta^T\left(A^T P + PA\right)\zeta + |s|^{-\frac{1}{2}}\zeta^T\begin{bmatrix} \lambda & 0 \\ 0 & 0 \end{bmatrix}P\zeta \\ &+ |s|^{-\frac{1}{2}}\zeta^T P\begin{bmatrix} \lambda & 0 \\ 0 & 0 \end{bmatrix}\zeta = -|s|^{-\frac{1}{2}}\zeta^T Q\zeta \end{aligned} \tag{12}$$

Where,

$$\begin{aligned} Q &= A^T P + PA - \begin{bmatrix} \lambda & 0 \\ 0 & 0 \end{bmatrix}P - P\begin{bmatrix} \lambda & 0 \\ 0 & 0 \end{bmatrix} \\ &= \frac{k_1'}{2}\begin{bmatrix} k_1'^2 + 2k_2' - 2\lambda\left(k_1' + \frac{4k_2'}{k_1'}\right) & k_1' - \lambda \\ k_1' - \lambda & 1 \end{bmatrix} \end{aligned}$$

According to Lyapunov stability theorem, if the control system is stable, then (12) should satisfy $\dot{v} \le 0$ Consequently, Q must be a real symmetric positive definite matrix, when the principal sub formula of each order of Q is greater than 0

$$\begin{cases} k_1'^2 + 2k_2' - 2\lambda\left(k_1' + \frac{4k_2'}{k_1'}\right) - \left(k_1' - \lambda\right)^2 > 0 \\ k_1' > 0 \end{cases} \tag{13}$$

The simplified (13) is as follows:

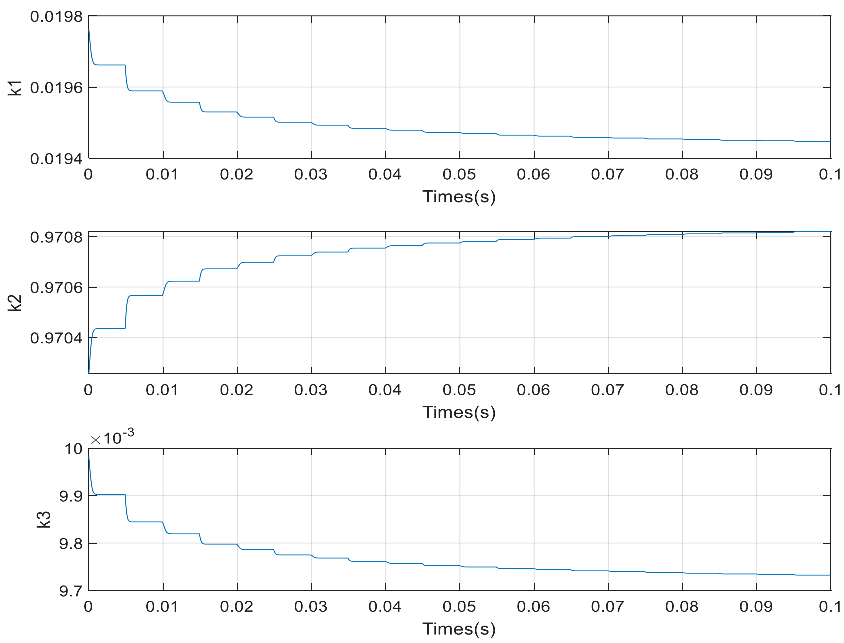

FIGURE 3
The curve of controller parameters k_1,k_2,k_3.

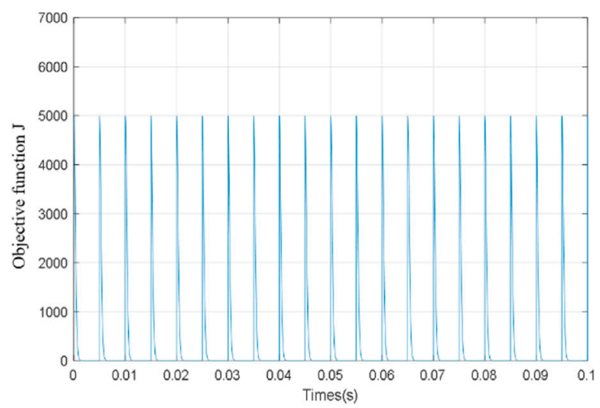

FIGURE 4
The curve of cost function *J*.

$$\begin{cases} k_2' > \dfrac{k_1'\lambda^2}{2(k_1' - 4\lambda)} \\ k_1' > 4\lambda \end{cases} \tag{14}$$

Therefore, under the conditions shown in (14), Q is a real symmetric positive definite matrix. There exists $\dot{V} \le -|s|^{-\frac{1}{2}}\zeta^T Q\zeta < 0$, which satisfies Lyapunov stability theorem.

Single-neuron sliding mode controller design

Improved sliding mode controller design

The proportional control is combined with the super-twisting sliding mode control to further improve the convergence characteristics and dynamic performance of the Super-twisting sliding mode controller. The improved sliding mode controller is as follows

$$u = k_1|s|^{\frac{1}{2}}\mathrm{sgn}(s) + k_2\int \mathrm{sgn}(s)dt + k_3 s \tag{15}$$

In (15), k_3 is the proportional control gain and satisfies $k_3 > 0$.

Comparing (15) and (3), it can be found that the improved sliding mode controller adds a proportional sliding mode term, and a better control effect can be obtained by designing a reasonable gain of k_3. Although the controller (15) ensures that the system is in a steady state as long as it meets the design requirements of (13) and $k_3 > 0$, however, the specific values of the controller gains k_1, k_2 and k_3 to meet the design requirements cannot be calculated. This posed some difficulties in designing optimal controller parameters k_1, k_2 and k_3.

Thus, in this paper, we designed an adaptive single-neuron sliding mode controller that can adjust the gain of the sliding mode controller online. The control strategy combines the advantages of both the single neuron control strategy with good adaptive capability and simple algorithm with STSM control theory. The detailed design method of the control algorithm is as follows.

Single-neuron sliding mode controller design

Since the single neuron controller uses digital control, the improved sliding mode controller (15) is discretized using the forward difference method to obtain the incremental controller as follows.

$$\begin{aligned} \Delta u(k) &= u(k) - u(k-1) \\ &= k_1\left(|s(k)|^{\frac{1}{2}}\mathrm{sgn}(s(k)) - |s(k-1)|^{\frac{1}{2}}\mathrm{sgn}(s(k-1)\right) \\ &\quad + k_2\mathrm{sgn}(s(k)) + k_3(s(k) - s(k-1)) \end{aligned} \tag{16}$$

The structure of the single neuron adaptive sliding mode controller is shown in Figure l.

It can be seen from Figure 1 that the controller mainly consists of state converter, single neuron and adaptive learning machine,

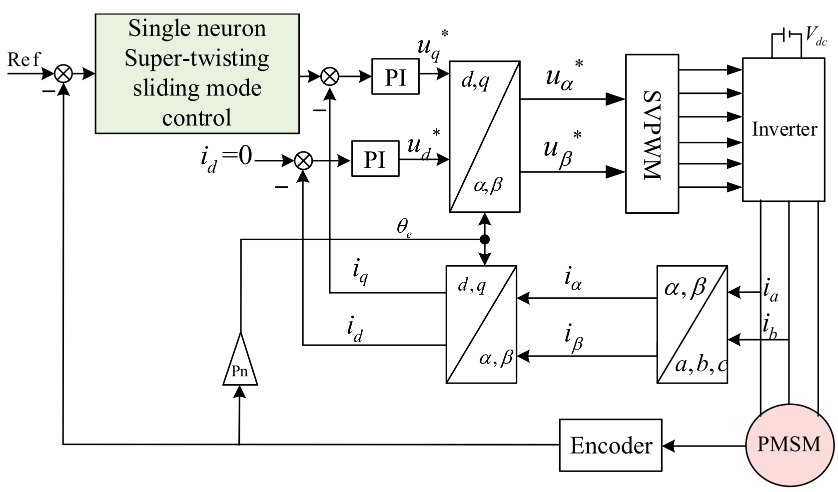

FIGURE 5
Control block diagram for single neuron super-twisting sliding mode control for PMSM system.

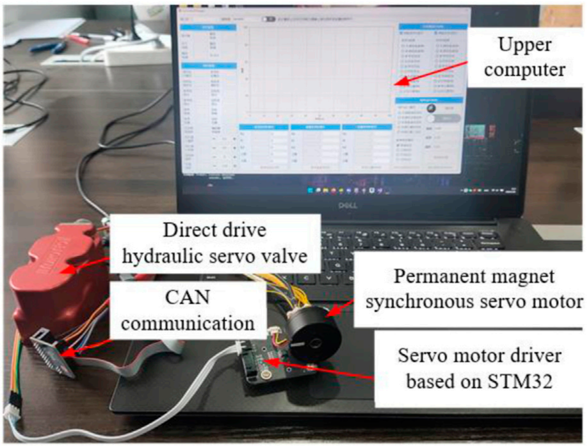

FIGURE 6
Experimental platform of servo motor control.

TABLE 1 Parameters of PMSM.

Parameter and unit	Value
Number of poles pairs	2
Inductance Ld = Lq	1.378 mH
Permanent magnet flux linkage ψ_f	0.0221Wb
Stator phase resistance R	2.15Ω
Moment of inertia	0.175×10^{-4} J/kg.m^2
Viscosity coefficient B/	0.044×10^{-5} N.m.s/rad

and the working principle of each part will be discussed in the following paper.

Define the output $x(k)$ of the state converter as follows

$$\begin{aligned} x_1(k) &= |s(k)|^{\frac{1}{2}}\mathrm{sgn}(s(k)) - |s(k-1)|^{\frac{1}{2}}\mathrm{sgn}(s(k-1)) \\ x_2(k) &= \mathrm{sgn}(k) \\ x_3(k) &= s(k) - s(k-1) \end{aligned} \quad (17)$$

In (17), $s(k)$ is a sliding mode surface function and is the input of a single neuron.

Based on these inputs, the single neuron can calculate the incremental controller. Thus, (16) can be rewritten as follows:

$$\Delta u(k) = K\omega_1(k)x_1(k) + K\omega_2(k)x_2(k) + K\omega_3(k)x_3(k) \quad (18)$$

where K is the gain coefficient of the neuron and satisfies $K > 0$; ω_i (i = 1,2,3) is the weighting coefficient of x_i.

From (16) and (17), we have

$$\begin{cases} k_1 = K\omega_1(k) \\ k_2 = K\omega_2(k) \\ k_3 = K\omega_3(k) \end{cases} \quad (19)$$

Define the objective function of the system as $J = s(k)^2/2$ and the adaptive learning algorithm by the gradient law, we make J converge to zero quickly by adjusting the weights $\omega_i(k)$ along the negative direction of the sliding mode surface of the system makes J converge to zero quickly.

$$\begin{aligned} \omega_i(k) &= \omega_i(k-1) + \Delta\omega_i(k) \\ &= \omega_i(k-1) - \eta_i s(k)\frac{\partial s(k)}{\partial \omega_i(k)} \end{aligned} \quad (20)$$

Where η_i is the learning coefficient.

The learning rule for single neuron weights used the modified Hebb learning rule, and the algorithm was obtained after normalization as follows:

$$\Delta u(k) = K\sum_{i=1}^{3}\omega_i{}'(k)x_i(k) \quad (21)$$

$$u(k) = u(k-1) + \Delta u(k) = u(k-1) + K\sum_{i=1}^{3}\omega_i{}'(k)x_i(k) \quad (22)$$

$$\omega_i{}'(k) = \omega_i(k)\Big/\sum_{i=1}^{3}\omega_i(k) \quad (23)$$

$$\begin{aligned} \omega_1(k) &= \omega_1(k-1) + \eta_1 s(k)u(k-1)(2s(k) - s(k-1)) \\ \omega_2(k) &= \omega_2(k-1) + \eta_2 s(k)u(k-1)(2s(k) - s(k-1)) \\ \omega_3(k) &= \omega_3(k-1) + \eta_3 s(k)u(k-1)(2s(k) - s(k-1)) \end{aligned} \quad (24)$$

Where η_1, η_2, η_3 is the corresponding learning rate respectively.

Simulation verification

To verify the correctness and feasibility of the single-neuron STSM controller proposed in the paper, simulation modeling was performed using Matlab/Simulink simulation software, where the controlled object was a first-order linear system with a transfer function of $G(s) = 1000/(s + 1000)$. In the simulation, the reference value was set to a square wave signal with an amplitude of 100 and a frequency of 100 Hz. The gain coefficient of the neuron was $K = 10$ and the initial value of the gain of the controller was $k_1 = 0.2$, $k_2 = 10$, $k_3 = 0.1$.

The simulation results are shown in Figures 2, 3.

From the simulation results shown in Figure 2, it can be seen that with the single neuron adaptive sliding mode controller, the system output can quickly track the reference value and can achieve overshoot-free operation. The variation curves of controller parameters k_1, k_2 and k_3 are given in Figure 3, and it is obvious from the figure that the single neuron designed in the paper was able to adjust the parameters of the super-twisting sliding mode controller online without manual adjustment, which reduced the workload of parameter adjustment. Figure 4 shows the variation curve of the objective function J. From the figure, it can be seen that the objective function J is 0 at steady state.

Experimental verification of servo motor control system

In order to verify the correctness and feasibility of the proposed single neuron super-twisting sliding mode control method, a single neuron super-twisting sliding mode controller for a permanent magnet synchronous servo motor as shown in Figure 5. The control algorithm used a dual closed-loop control strategy of position loop and current loop, where the position loop used the sliding mode control with online adjustment of controller parameters designed in the paper, and the current loop used PI control. In addition, the experimental platform used STM32F405 chip as the

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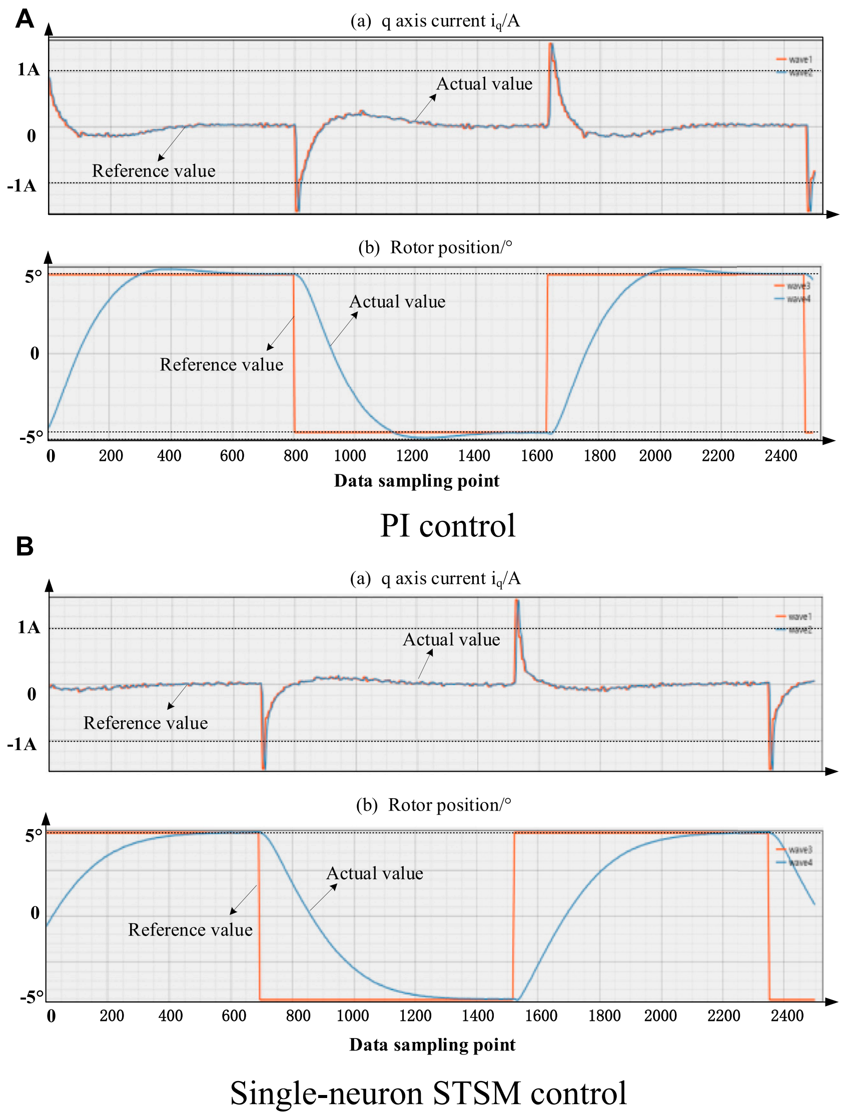

FIGURE 7
Experimental results when the reference value is square wave signal. **(A)** PI control; **(B)** Single-neuron STSM control.

controller, and uploaded the experimental data and state variables of servo motor control to the specific experimental platform through CAN bus as shown in Figure 6. This experimental platform was mainly used for the independent development and application research of direct-drive hydraulic servo valve.

In addition, the parameters of the PMSM are shown in Table 1, and the position loop PI controller parameters are $k_{pp} = 45.5$, $k_{ip} = 15$, the current loop PI controller parameters are $k_{pc} = 145$, $k_{ic} = 6450$. For the proposed single neuron super-twisting sliding mode controller, the gain coefficient of the neuron was $K = 150$ and the initial value of the gain of the controller was $k_1 = 6$, $k_2 = 35$, $k_3 = 2.5$.

The superiority of the proposed control strategy was verified by comparing the analysis with the PI controller for the position loop, and the operating conditions of the servo motor under the two algorithms were identical, and the experimental data were obtained by the host computer. In addition, square wave and sine wave signals were used as command signals to further illustrate the feasibility of the proposed control algorithm, where the amplitude and frequency of the square wave signal are set to 5° and 15Hz, and the amplitude and frequency of the sine wave signal were set to 5° and 20 Hz, respectively. The experimental results are shown in Figures 7, 8.

It can be found that under the action of PI control, the actual position of the servo motor can track the reference value with an overshoot of about 4% by comparing and analysing the experimental results under the two control strategies given in Figure 8. On the contrary, the servo motor can operate without overshoot with relatively short regulation time under the action of the sliding mode controller proposed in this paper.

Similarly, it can be found that under the action of PI control, the actual position of the servo motor is limited by the bandwidth of the PI controller, and there is a large static difference when tracking the sine wave signal, and the q-axis current fluctuates more by comparing and analysing the experimental results under the two control strategies given in Figure 8. On the contrary, the sliding mode control strategy proposed in this paper can track the sinusoidal signal better, and the

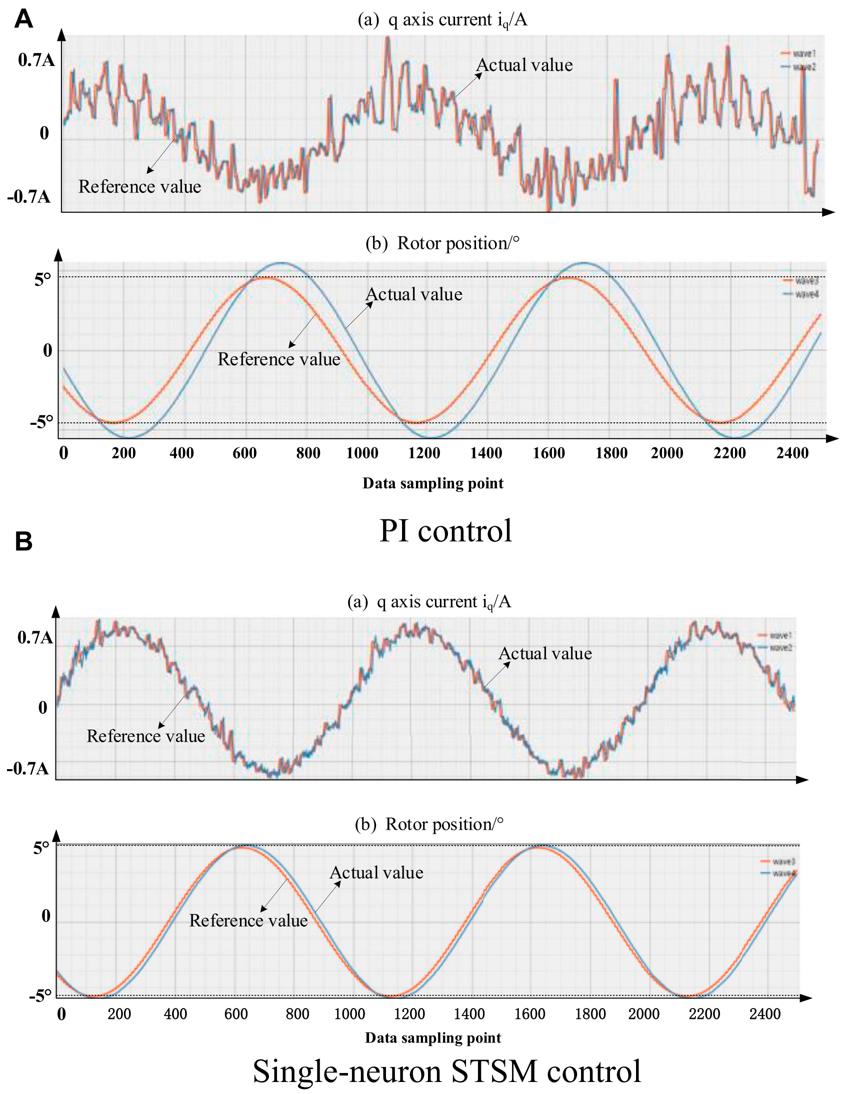

FIGURE 8
Experimental results when the reference value sine wave signal. **(A)** PI control; **(B)** Single-neuron STSM control.

static difference was relatively small, and the q-axis current fluctuation is smaller.

Conclusion

In this paper, a single neuron super-twisting sliding-mode controller was designed based on the control method combining proportional control and super-twisting sliding mode control, using the ability of the single neuron adaptive control algorithm to adjust the controller parameters online. The sliding mode controller designed under this control strategy can realize online adjustment of the controller parameters and had the advantages of simple algorithm, strong robustness, and good chattering suppression effect. The simulation and experimental results demonstrated that the single neuron adaptive control can adjust the parameters of the super-twisting sliding mode controller online and had better dynamic performance and anti-disturbance capability when applied to the servo control system of permanent magnet synchronous motor.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

The main work of this paper was completed by LY and PW conducted some theoretical derivation, YL was responsible for writing the paper, and HC and AX were responsible for experimental verification.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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