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TOPICAL REVIEW

Overview of Sliding Mode Control Technology for Permanent Magnet Synchronous Motor System

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ABSTRACT With the increasingly widespread application of permanent magnet synchronous motors (PMSMs), it is required that PMSMs can still maintain high efficiency and high reliability in complex environments. Due to the nonlinearity of PMSMs and the influence of external disturbances, its precise control is still a challenge. As a modern control scheme, sliding mode control can improve the control PMSM drive system. It has been successfully applied in the control of PMSMs and has become a hot spot in the motor drive system. This paper provides an overview of the current research status of sliding mode control strategies based on PMSMs and introduces the design of sliding mode controllers, as well as the development and application of high-order sliding mode control. The method of suppressing the chattering problem is summarized, and the deficiencies of it are put forward. Finally, the development trend of sliding mode control technology is discussed, and the future development direction of SMC for PMSM is prospected.

INDEX TERMS Sliding mode control (SMC), chattering suppression, high-order sliding mode control, permanent magnet synchronous motor (PMSM), terminal sliding mode control.

I. INTRODUCTION

Due to their simple structure, high power density, and high efficiency, PMSMs find extensive application in high-performance drive systems, such as intelligent robots, new energy vehicles, ships, aerospace, and other fields. It has gradually replaced induction motors in various application fields and has received extensive attention and research [1], [2], [3], [4], [5]. With the development of new energy vehicles, PMSM has gradually become the mainstream motor for automotive drive control due to their advantages such as reliable operation and good speed regulation performance [6], [7], [8], [9], [10], [11], [12]. Due to complex working conditions and requirements, strict requirements are put forward for the control of the motor

Commonly used control techniques in PMSM drive systems include vector control [13], [14], [15], [16], [17], [18] and direct torque control (DTC) [19], [20], [21], [22], [23]. Direct torque control is based on switch control, and there is a large torque fluctuation. Compared with DTC, vector control has lower torque and current ripple. However, the speed loop and current loop in the vector control generally adopt the classic proportional-integral controller. In practical applications, the adjustment performance is poor, and the high-performance control requirements cannot be achieved. With the development of technology and the improvement of motor control performance requirements, scholars have applied modern control theory to it, and have produced methods that can improve the control effect of motor systems, such as internal model control [24], [25], [26], [27], [28], fault-tolerant control [29], [30], [31], [32], [33], [34], [35], [36], model predictive control [37], [38], [39], [40], [41], [42], and sliding mode control [43], [44], [45], [46], [47], etc. These nonlinear control methods improve the control performance of the PMSM drive system from different levels and to varying degrees. Among them, sliding mode variable structure control has strong robustness and high control precision, so it has received extensive attention in the field of motor control.

Sliding mode control (SMC) originated in the 1960s. It is a control method developed from variable structure control. Its core idea is to dynamically drive the system to a low-order sliding mode surface through discontinuous

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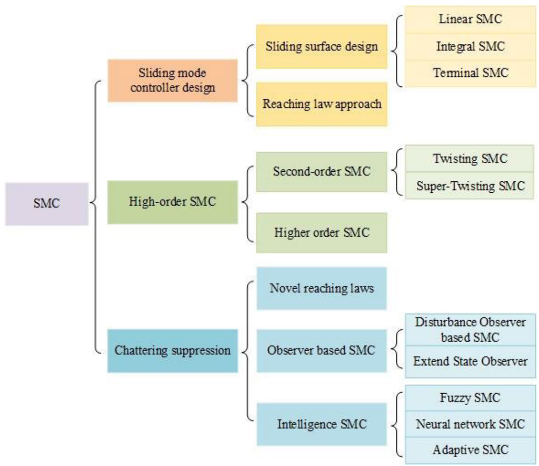


FIGURE 1. **The main research and development direction of SMC.**

switching control. Subsequently, the system moves towards the origin following the sliding mode surface equation [48], [49]. As a robust control method, SMC can ensure commendable tracking performance in the case of system internal parameters and external disturbances, so it has become one of the effective means to improve the control system of PMSMs. It is usually applied to the speed outer loop and sliding mode observer (SMO) in sensorless control systems [50], [51], [52], [53], [54]. In addition, SMC has demonstrated successfully applied in various fields, such as induction motors [55], [56], [57], [58], switched reluctance motors [59], [60], [61], [62], and brushless DC motors [63], [64], [65], etc., under its remarkable features of high precision and ease of use. Improving the control performance of PMSM requires not only optimizing the motor design [66], but also improving the control algorithm [67], [68], [69]. In the speed control, position control, and efficiency control of the PMSM, SMC is directly applied and indirectly applied to the design of the observer.

The proposal of the terminal sliding mode and high-order sliding mode control theory not only improves the performance of the sliding mode controller but also overcomes some shortcomings of the traditional SMC in terms of convergence and relative order, becoming an important part of the sliding mode control theory. The focus of SMC design research is the suppression of chattering, the self-adaptation of uncertain systems, and the improvement of the dynamic performance of closed-loop systems [70], [71], [72], [73], [74]. Aiming at these problems, the existing sliding mode control improvement methods and research directions are shown in Fig. 1.

This paper primarily discusses the application of SMC in the drive control of PMSMs and explains the main issues and related improvement strategies. The main contribution is to summarize the development and application of SMC and high-order sliding mode control, and the suppression method of the chattering problem. Additionally, the paper delves into the exploration of future development and research directions in the field of sliding mode control.

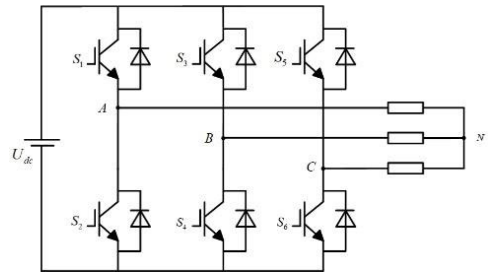


FIGURE 2. **Three-phase PMSM voltage inverter topology.**

The remainder of this paper is structured as follows: Section II presents the principle of sliding mode control in PMSMs. Section III summarizes the design method of the sliding mode controller. Section IV summarizes the development and application of high-order sliding mode control. The fifth part mainly discusses the relevant methods of suppressing chattering in the SMC. Finally, the possible future development direction of sliding mode control is pointed out.

II. PRINCIPLE OF THE SLIDING MODE CONTROL

Since its appearance, SMC has been recognized as a robust method for complex high-order nonlinear dynamic systems operating under various uncertain conditions in control. The main advantage of the SMC is that it does not depend on the model of the system, and it is not sensitive to internal parameter changes and external disturbances [75], [76], [77]. This section mainly introduces the model of PMSM and the basic principle of sliding mode control theory.

A. THE STRUCTURE OF PMSM

Fig. 2 illustrates the topology of the voltage inverter for the three-phase PMSM. The inverter bridge consists of six switch devices, divided into upper and lower sets of three. During the inversion process, the inverter bridge and pulse width modulation technique are employed to turn on and off the switching devices of the three-bridge arms step by step, and the upper and lower bridge arms are turned on in turn to form 8 kinds of switch combinations. This converts the DC power supply into a three-phase AC power supply through the inverter process, which is used to drive the PMSM operation.

The model of the PMSM is generally defined in a synchronous rotating coordinate system, and its stator voltage equation is:

$$\begin{cases} u_d = Ri_d + L_d \dfrac{di_d}{dt} - \omega_e L_q i_q \\ u_q = Ri_q + L_q \dfrac{di_q}{dt} + \omega_e L_d i_d + \omega_e \psi_f \end{cases} \tag{1}$$

where u_d, u_q, i_d, i_q, L_d and L_q are the d-axis and q-axis components of the stator voltage, current, and inductance in the rotor reference frame, respectively. R, ψ_f and ω_e represent stator resistance, flux linkage, and electric angular velocity, respectively [42].

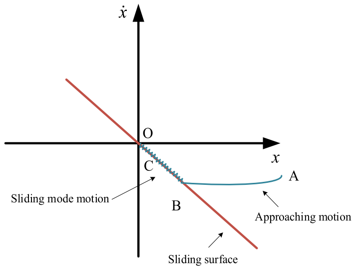


FIGURE 3. **The motion trajectory of the SMC.**

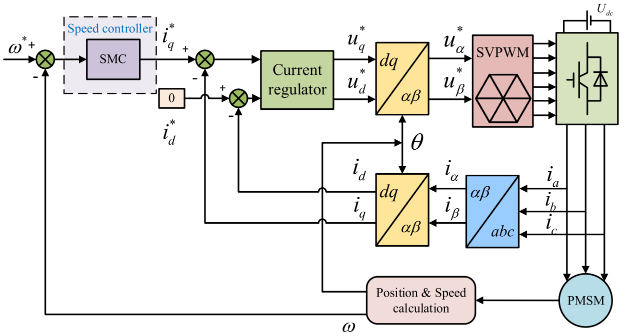


FIGURE 4. **Control structure of the PMSM system with the SMC.**

The equation for electromagnetic torque is:

$$T_e = \frac{3}{2} n_p i_q \left[i_d \left(L_d - L_q \right) + \psi_f \right] \tag{2}$$

where n_p is the number of pole pairs of the PMSM.

The motor motion equation of PMSM is:

$$J \frac{d\omega_m}{dt} = T_e - T_L - B\omega_m \tag{3}$$

$$\omega_e = n_p \omega_m \tag{4}$$

where ω_m is the mechanical angular velocity of the motor, J is the moment of inertia, B is the damping coefficient, and T_L is the load torque.

B. BASIC THEORY OF SLIDING MODE CONTROL

The dynamic characteristics of the system are different under different operating states. To ensure smooth and rapid attainment of a predefined target state for the system, particularly under varying operating conditions, it is necessary to design different controllers and control the system by switching different controllers. It is in this context that SMC is proposed.

Given the nonlinear system:

$$\dot{x} = f(x, u, t) \tag{5}$$

where $x \in R^n$, $u \in R^m$ are the state of the system and the input variables respectively.

Determining the sliding surface:

$$s(t, x) = 0 \tag{6}$$

The sliding surface is a hyperplane that exists in space, and fulfills that as the system state converges to the sliding mode surface, it slides along this surface toward the system's equilibrium point. The state space is divided into two parts $s(t, x) > 0$ and $s(t, x) < 0$ by the sliding surface. Then, according to different states, different control methods will be adopted. The controller is:

$$u_i = \begin{cases} u_i^+(t, x), & s_i(t, x) > 0 \\ u_i^-(t, x), & s_i(t, x) < 0 \end{cases} \quad i = 1, 2, \ldots, m \tag{7}$$

The dynamics of the sliding mode control system can be dissected into two distinct phases: the approach motion and the sliding motion [43], as illustrated in Fig. 3. Initially, the system transitions from any initial position to the sliding surface through the influence of the reaching law. Subsequently, it converges towards the origin while moving along the sliding surface.

The sliding mode surface usually selects a linear convergence equation of lower order than the original system, so that the system state can exponentially converge to the origin along the equation trajectory after reaching the sliding surface. The motion of the state is constrained by this linear equation and is unaffected by the mathematical model of the object. During the approaching motion phase, the system may traverse the sliding mode surface a limited number of times, it does not have the characteristics of sliding mode and robustness at this time. But after reaching the surface, the performance of the system will be determined by the sliding surface and cannot be affected by external disturbances. Then the system state is maintained on the sliding surface through continuous switching control, and then the state converges to the origin along its trajectory. Therefore, thanks to switching control, SMC exhibits robustness against system uncertainties that satisfy the specified matching conditions.

III. DESIGN OF SLIDING MODE CONTROLLER

In the realm of PMSMs, sliding mode control technology finds two primary applications. One is to combine vector control or DTC to realize the regulation and control of motor current, speed and position. The other is the application of observers in PMSMs [78], [79], [80], including motor parameter identification [81], [82], [83], [84], [85], disturbance observation, and motor sensorless control [86], [87], [88], [89]. This section will introduce the design principle of the sliding mode controller and its characteristics, along with summarizing some improved SMCs.

SMC is often used in the speed loop control of PMSM, as shown in Fig. 4, to obtain superior performance and robust speed control. In the speed loop, the SMC employs a designed sliding mode surface and reaching law to direct the motor's actual speed error towards the sliding mode surface, facilitating rapid convergence to zero. Through the feedback function of the SMC, the forced control of the speed error is realized, to realize the accurate tracking and control of the PMSM rotating speed. Fig. 5 represents a sensorless control block diagram of PMSM with SMO, replacing the original

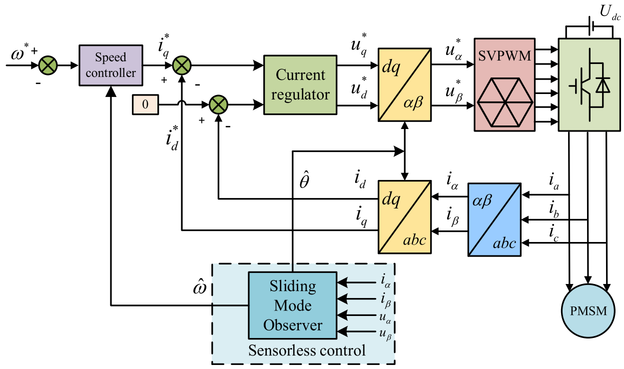


FIGURE 5. Block diagram of SMO-based sensorless control of PMSM.

mechanical sensor with SMO for estimating the position and speed of the rotor.

The design process for sliding mode controller in PMSMs involves the following steps [90]:

Step 1: According to the specific application needs, the sliding mode surface is selected to guide the system state to converge to the desired state or trajectory.

Step 2: Design the reaching law to enable the system to attain the sliding mode surface within a finite duration and establish the sliding mode motion.

A. THE REACHING LAW

There are four traditional sliding mode reaching laws as follows [91]:

1) The constant velocity reaching law:

$$\dot{s} = -\varepsilon \operatorname{sgn}(s), \quad \varepsilon > 0 \tag{8}$$

2) The exponential reaching law:

$$\dot{s} = -\varepsilon \operatorname{sgn}(s) - ks \quad \varepsilon, k > 0 \tag{9}$$

3) The power reaching law:

$$\dot{s} = -q\,|s|^{\alpha} \operatorname{sgn}(s), \quad q > 1, 1 > \alpha > 0 \tag{10}$$

4) The general reaching law:

$$\dot{s} = -\varepsilon s\operatorname{sgn}(s) - f(s), \quad \varepsilon > 0 \tag{11}$$

Table 1 compares the performance of these reaching laws. The reaching law method can satisfy the reaching conditions of the sliding mode motion, and ensure the dynamic characteristics of the reaching motion phase. The reaching law determines the characteristics of the switching controller. According to different control requirements, using different reaching laws can ensure the quality of the system's approaching motion stage and improve performance.

B. THE SLIDING MODE SURFACE

The sliding mode surface design directly affects the convergence characteristics of the system state and is the basis of SMC. Its primary function is to drive the system state toward the origin along its designated trajectory. In this process, the system will not be affected by uncertainties and has invariability. At the beginning of the sliding mode control theory, the form of the sliding mode surface is:

$$s = k_1 x_1 + k_2 x_2 + \cdots + k_n x_n \tag{12}$$

where $k_1, k_2, \cdots k_n$ are the adjustment coefficient, $x_1, x_2, \cdots x_n$ are state variables.

1) LINEAR SLIDING MODE SURFACE

The form of the common linear sliding mode surface is:

$$S(x) = Cx \tag{13}$$

where $C > 0$.

PMSM is a nonlinear system [92], and although the parameter setting of the linear sliding mode control (LSMC) is very simple [75], the control ability is limited in complex nonlinear environments, unable to achieve high-performance control of the system. Considering that the introduction of non-linear terms may lead to better performance [93], so many scholars both domestically and internationally have redirected their research attention toward exploring the realm of nonlinear sliding mode surfaces.

2) NONLINEAR SLIDING MODE SURFACE

Nonlinear sliding mode control is usually more advantageous when dealing with complex nonlinear systems. So far, the nonlinear sliding mode surfaces proposed in the existing literature mainly include integral sliding mode control (ISMC) [94], terminal sliding mode control (TSMC) [95], [96], [97], fast terminal sliding mode control (FTSMC) [98], [99] and nonsingular terminal sliding mode control (NTSMC) [100], [101], [102].

a: INTEGRAL SLIDING MODE CONTROL

Introducing the integral link, can make up for the lack of robustness of the linear sliding mode surface when approaching motion, eliminate the steady-state error, and improve performance, so the integral sliding mode surface is obtained. The ISMC exhibits robustness against internal variations and external disturbances within the system and has been widely used in the control of PMSM.

Its common expression is:

$$s(x) = k_p x + k_i \int_0^t x dt \tag{14}$$

where k_p and k_i are the proportional and integral gain respectively.

In [72], in the speed control of the linear PMSM, the direct integral action is introduced, aimed at eliminating the steady-state error in the speed tracking. Reference [103] designed an integral sliding mode observer to feed forward the observed disturbance to the PMSM model for compensating the lumped disturbance, and verified the proposed method on the FPGA hardware system. Reference [104] used an ISMC to endow the system with immunity to lumped

TABLE 1. Comparison of four common sliding mode reaching laws.

Reaching Law	Advantages	Disadvantages	Applications
The constant velocity reaching law	● Easy adjustment ● Fast response	● Not applicable for non-linear and parameter-varying systems ● Slow convergence	Simple linear system
The exponential reaching law	● Fast convergence speed ● Strong anti-interference ability	● Difficult in parameter adjustment ● Sensitive to system model errors	Fast and accurate tracking control system
The power reaching law	● Flexible parameter selection ● High adaptability	● Difficult in parameter selection ● High requirements on system status	Uncertain parameters and large perturbations
The general reaching law	● Adaptive parameter change ● Broader adaptability	● Complex control strategy design ● Dependent on the system's mathematical model	Nonlinear time-varying system

TABLE 2. Comparison of four kinds of SMC applied in PMSM.

Methods	Complexity	Computation burden	Accuracy	Advantage	Disadvantage
LSMC	Low	Low	Medium	Simple and easy to implement	Slow convergence
ISMC	Medium	Medium	Slightly high	Reduce tracking error	Integral saturation
TSMC	Slightly high	High	High	Fast convergence	Singularity problem
NTSMC	High	High	High	High control precision	Complicated design

disturbances, combined with an improved deadbeat predictive current control method, in the case of disturbances, no external observer is required, and an accurate one-step forecast ahead. Reference [105] defined an integral fuzzy switching surface function, which can effectively attenuate mismatch disturbance, in the corresponding control gain and anti-disturbance gain obtained in the control of PMSM.

b: TERMINAL SLIDING MODE CONTROL

TSMC was first derived from the concept of the terminal attraction factor, which expresses the phenomenon of the physical jump after energy accumulation to a certain extent, and has a finite time convergence characteristic. The terminal factor is introduced into the SMC, which improves the convergence characteristics of the system and can ensure that the system completes the approaching motion and reaches the system zero within a limited time [106].

The common terminal sliding mode surface is:

$$s = x_2 + m x_1^{q/p} \tag{15}$$

where m is a normal number, p, and q are odd numbers and satisfy $p > 0$, $q > 0$, and $p > q$.

The terminal sliding surface is a special sliding surface set when the system is about to reach some steady-state point or target state, which allows the controller to fully control the system during the process of finally letting the system enter the steady state, thus ensuring that the system's finite-time convergence to the desired state, exhibiting high robustness and immunity in the process. Compared with the linear SMC, the TSMC has the advantages of small control switching gain, fast convergence speed, and high stability accuracy. In recent years, the theory of TSMC has attracted the attention of scholars in the field of control and has been extensively and deeply studied [107].

Reference [108] proposed an integral terminal sliding mode surface to solve the mismatch problem of the nonlinear control system. In [109], a global TSMC surface was formulated to facilitate the system's attainment of the sliding mode surface with accelerated convergence speed from its inception until the completion of the process.

Given an initial state $x(0) \neq 0$, the time required for the system state to converge to $x(0) = 0$ is:

$$t_s = \frac{p}{\beta\,(p-q)} \left| x_1\,(0) \right|^{(p-q)/p} \tag{16}$$

Although the terminal sliding mode surface exhibits rapid convergence ability when the system state approaches the origin, the convergence rate of the terminal sliding mode surface is slow when the system state is far from the origin. To overcome this shortcoming, combining the advantages of terminal sliding mode and linear sliding mode, [110] introduced a linear term in equation 15, and constituted the following fast terminal sliding mode surface:

$$s = x_2 + \alpha x_1 + \beta x_1^{q/p} \tag{17}$$

where $\alpha > 0$. The convergence time t_s is:

$$t_s = \frac{p}{\alpha(p-q)} \ln \frac{\alpha x_1(0)^{(p-q)/p} + \beta}{\beta} \tag{18}$$

When the system state is distant from the origin, the linear term plays a dominant role, while when approaches the origin, the terminal term $\beta x_1^{q/p}$ exerts significant influence, and the linear term can be ignored. Therefore, the sliding mode surface exhibits global fast convergence capability.

References [106] and [111] added a sign function to the sliding mode surface. Compared with the tracking response speed of the reference value, it is found that the improved FTSMC has a faster convergence speed and realizes the

TABLE 3. Four common second-order sliding mode algorithms.

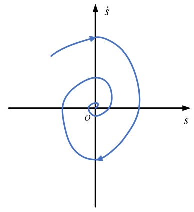
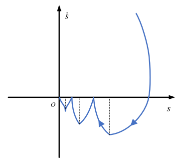
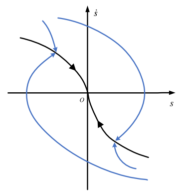
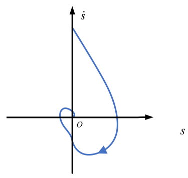
Second-order SMC	Phase trajectory	Controller form
Twisting Control Algorithm		$u = -k_1 \operatorname{sgn}(s) - k_2 \operatorname{sgn}(\dot{s})$ $k_1 > 0, k_2 > 0$
Sub-Optimal Algorithm		$u = -k_1 \operatorname{sgn}(s - s^*/2) + k_2 \operatorname{sgn}(s^*)$ $k_1 > k_2 > 0$
Prescribed Convergence Law Algorithm		$u = -\alpha \operatorname{sgn}(\dot{s} + \lambda \lvert s \rvert^{1/2} \operatorname{sgn}(s))$ $\alpha, \lambda > 0$
Super-Twisting Algorithm (STA)		$\begin{cases} u = -\lambda \lvert s \rvert^{\frac{1}{2}} \operatorname{sgn}(s) + u_1 \\ \dot{u}_1 = -\alpha \operatorname{sgn}(s) \end{cases}$ $\alpha, \lambda > 0$

TABLE 4. Comparison of four second-order sliding mode control performances.

Method	Response time	Convergence time	Computation burden	Calculation error	Parameter adjustment
Twisting Control Algorithm	Medium	Short	High	Medium	Complex
Sub-Optimal Algorithm	Short	Medium	Low	High	Simple
Prescribed Convergence Law Algorithm	Long	Short	Medium	Low	Medium
Super-Twisting Algorithm	Short	Very short	High	Very low	Slight complex

steady-state operation of the system. Reference [112], the FTSMC strategy of equivalent control was employed for tracking the PMSM d-q axis current, to obtain the appropriate voltage value and improve the dynamic performance of the motor current. Unlike other FTSMC, it guarantees faster convergence of the system while keeping chattering small.

The derivative of formula (15) is obtained:

$$\dot{s} = \dot{x}_2 + m\frac{q}{p}x_1^{q/p-1} \tag{19}$$

Since $p > q$, $q/p\text{-}1 < 0$. Then when $x_1 = 0$, there will be a singularity problem in the derivative of the sliding variable. To solve the problem of TSMC, the method of NTSMC is proposed [113].

c: NONSINGULAR TERMINAL SLIDING MODE CONTROL

In the speed control system of the PMSM servo system, by introducing the nonsingular terminal factor, the following nonsingular terminal sliding mode surface is proposed:

$$s = x_1 + \frac{1}{\beta}x_2^{p/q} \tag{20}$$

The value of the power term of the sliding mode surface is greater than 1, and there will be no negative value when deriving, thus avoiding the singularity problem.

Table 2 compares the application effects of four kinds of SMC in PMSMs. Combining the benefits of the NTSMC with fast convergence, a new single-loop non-cascade controller for PMSMs is designed, which effectively simplifies the controller structure [114]. In [115], a novel speed loop terminal sliding mode controller was constructed according to the NTSMC, enabling the motor speed to quickly reach the reference value, thereby achieving swifter convergence speed and enhanced tracking precision. Reference [116] adopted an NTSMC to design the velocity controller. Additionally, to make up for the lack of NTSMC, [117] introduced a global nonsingular fixed-time TSMC, so that the control system has global fast convergence. Compared with TSMC, the NTSMC retains the finite time convergence of the TSMC, and directly avoids the control of the singular region from the aspect of sliding mode design.

IV. HIGHER ORDER SLIDING MODE CONTROL

When using the traditional sliding mode theory for controller design, the sliding mode surface is required to be first-order, the control input must explicitly appear in the first-order derivative of the sliding variable. This requirement strictly limits the selection and design of the sliding mode surface, which becomes a problem in the development of the SMC. High-order sliding mode control (HOSMC) is an extension of the traditional SMC. It avoids the relative order limitation problem in the first-order SMC and weakens the chattering while retaining the benefits of the traditional SMC, to improve the performance. It enables the sliding mode controller to track the system state more accurately and suppresses the effects of chattering and uncertainty by introducing higher-order terms in the sliding surface design. The HOSMC method is discussed in this section to solve the problems of chattering and relative order limitation in the traditional SMC without affecting the robustness of the system.

A. THE DEFINITION OF HIGH-ORDER SLIDING MODE

Levant A. first proposed the concept of HOSMC, but the algorithm is still flawed in theory, and the estimation of the sliding mode has not been solved, so the theory did not attract attention at that time. Later, at the 3rd symposium on variable structure control and Lyapunov technology, the HOSMC theory introduced by Fridman and Levant aroused the great interest of researchers. Since then, the HOSMC has attracted widespread attention in the international control community.

The main idea of the HOSMC is to apply the chattering discontinuous switching control to the r-order differential of the sliding mode variable. The definition of high-order sliding mode is given below:

Consider a discontinuous differential equation:

$$\dot{x} = f(x), s = s(x) \tag{21}$$

Satisfies the solution in the ''average'' sense proposed by Filippov, and s is a smooth output function. If the following conditions are met [118]:

(1) The full-order derivative $\dot{s}, \cdots, s^{(r-1)}$ is a continuous function of the state variable x;

(2) The set is non-empty and contains the Filippov trajectory, then the motion on set (2) is called the r-order sliding mode.

The sliding mode surface for HOSMC can be defined as:

$$s(t) = s^m(t) \tag{22}$$

where m represents the order of the sliding mode surface, and $s^m(t)$ is the sliding mode surface function.

B. SECOND-ORDER SLIDING MODE CONTROL

The main idea of the second-order SMC is not only to let $s = 0$, but also to let $\dot{s} = 0$. In the second-order SMC, the control input appears explicitly in the second derivative $\ddot{s}$ of the sliding surface, and the control law takes the form of a switching law based on s and $\dot{s}$ or their sign functions, ensuring the system's stability on the sliding surface $s = \dot{s} = 0$ within a finite time. In the HOSMC, the second-order SMC has become the most widely employed, because of the advantages of its simple controller structure and little information required and is implemented in many motor types, such as PMSM [119], [120], [121], [122], induction motor [123], [124], [125], [126], [127], DC motor [128], [129], switched reluctance motor [130], [131], [132], [133], etc.

As the simplest HOSMC, the second-order SMC has been gradually improved in theoretical research. Table 3 introduces several commonly used second-order SMC. The twisting algorithm was first proposed, its system trajectory revolves around the origin and converges to the origin after numerous circles within a limited time. The suboptimal algorithm evolved from the classic time optimal control algorithm, and its characteristic is that the convergence area can be set in advance. The Prescribed Convergence Law algorithm essentially uses the idea of traditional sliding mode, which is very similar to TSMC. The Super-Twisting algorithm (STA) only needs the information of the sliding mode surface can make s and its derivative reach zero at the same time, which is the only continuous and suitable method for the first-order sliding mode surface in the second-order SMC [134], [135].

Reference [136] focused on the study of the theory and application characteristics of the second-order SMC. Moreover, it presents a method for demonstrating the stability of the controller. Table 4 compares the performance of several second-order sliding mode algorithms. The four algorithms each have their own emphasis. The twisting algorithm and Super-Twisting algorithm are outstanding in improving dynamic performance and robustness, but their design and implementation are complicated. The Sub-Optimal sliding mode algorithm simplifies the design and is more suitable for resource-constrained environments, but sacrifices some control performance. The Prescribed Convergence Law algorithm improves the smoothness of control by reducing buffeting, but it may affect the convergence speed in some cases. The STA enables the control system to realize finite-time convergence without the necessity for information concerning the derivatives of sliding variables and can stabilize the state of a one-dimensional system and its first derivatives. With its outstanding advantages, STA is the most widely used second-order SMC.

Super-twisting sliding mode (STSM) control was compared with conventional SMC in [137], and pointed out that reducing chattering is one of the challenges in the design of STSM control. An improved STA is proposed in [134] for systems encompassing multiple dimensions, but for some system states, it cannot converge in a finite time. On this basis, [138] proposed a homogeneous continuous STA applied to multi-dimensional systems, which ensures that all states can converge in a finite time. Reference [139] designed an STA-based SMO to suppress torque fluctuations, converge faster and enhance power.

Reference [140] adopted the STSM control technology to design the speed controller, which enables the motor speed to quickly and accurately track the given reference speed, which enhances the system's robustness and reduces the chattering effects. In [141], the super-twisting controller was improved by adding an adaptive control law, which automatically adjusts the gains of the controller, which has been implemented in the control of PMSMs [142], [143]. In fact, chattering magnitude is highly dependent on sampling frequency, and sampling delay, Nyquist sampling theorem, [141] did not take into account the limitations of discrete systems implementing adaptive super-twisting mode control (STSM). Furthermore, there is a limitation that chattering cannot be further attenuated by increasing the STA gain, and [142], [143] did not consider this aspect. To solve this problem, [142] combined PI control and STSM control, and proposed an adaptive super-twisting controller that can suppress dead-zone distortion and reduce current distortion. Reference [144] proposed a variable gain STA sliding mode observer, which adjusts the observer gain online according to the rotor speed, effectively suppressing the chattering phenomenon caused by digitization and parameter uncertainty. Reference [145] used the integrator in the STA to smooth the discontinuous signal and attenuate the chattering phenomenon while ensuring higher tracking accuracy. Combined with generalized proportional integral observer feed-forward compensation to form a composite controller, it avoids unsatisfactory dynamic performance caused by excessive switching gain.

C. ARBITRARY ORDER SLIDING MODE CONTROL ALGORITHM

Several commonly used second-order SMC algorithms are introduced above, which overcome the defects of traditional sliding mode and have been applied in practical engineering. However, the challenge in the application of the second-order SMC is the determination of control law parameters and they are related to the bounds of the system uncertainty. The convergence conditions given above are all-sufficient and have a certain degree of conservatism; at the same time, the second-order SMC algorithm is generally applied to systems with relative order $r \leq 2$.

According to the definition of the HOSMC, the system state can reach the sliding mode surface $s = 0$ in a limited time and has an r-order sliding mode:

$$s = \dot{s} = \cdots = s^{(r-1)} = 0 \tag{23}$$

$$s^{(r)} = f(t, x) + g(t, x)\, u \tag{24}$$

where $f(t, x) = s^{(r)}|_{u=0}$ and $g(t, x) = \frac{ds^r}{du} \neq 0$ is an unknown smooth function.

Reference [146] proposed an arbitrary-order sliding mode controller for the first time and proved its finite-time convergence using geometric methods. This controller effectively addresses the challenge of achieving finite-time stability and precise disturbance compensation for arbitrary relative degree outputs. Its main problem is that only one gain parameter can be adjusted, and the convergence speed is not chosen arbitrarily. In the arbitrary order SMC scheme proposed in [147], based on the initial and final value information of the input state variable, a higher-order controller is devised, so that the system trajectory can only reach any small neighborhood of the origin within a certain period. Reference [148] proposed a new controller based entirely on the Lyapunov method to ensure that the HOSMC can be accurately established within a limited time and eliminate the above shortcomings. Reference [149] proposed a fully adaptive arbitrary HOSMC for the first time in terms of a continuous distribution of motor input current, developed a third-order controller, and gave proof of stability. Extending the continuous STA to the output dimension, [150] proposed a continuous high-order sliding mode algorithm, which accurately compensates disturbances with discontinuous integral terms, generates continuous homogeneous control signals, and achieves a limited time convergence to $n + 1$ level sliding mode.

Reference [151] provided a general method for the design and parameter tuning of the HOSMC. For single-input single-output nonlinear systems, a new class of high-order sliding mode (HOSM) controllers with discontinuous integral terms was proposed in [152], and an adaptive gain is introduced to reduce chattering. The closed-loop system based on this method is robust in the whole response process. Reference [153] proposed a new HOSM controller with a discontinuous integral term and accurately compensated for finite-time disturbances using a continuous control signal. Reference [154] extended terminal SMC by designing a polynomial homogeneous HOSMC without a recursive process. These HOSMC algorithms mentioned above require that the uncertainty bounds are known. How to design HOSMC when the uncertainty bound is unknown remains an unresolved issue. To solve the problem, the controller must satisfy two basic conditions: the uncertainty bound is known and the overestimation of the gain is avoided. Adaptive HOSMC have been proposed in [149], [155], and [156], and in [149], the adaptation of the control gain largely relies on the sliding variable. During the establishment of the sliding mode, the gain of the controller keeps increasing, so the gain of the controller may be overestimated and stabilize at unnecessarily high values. In [155] and [156], the difficulty of gain overestimation is overcome by reducing the gain reaching the sliding surface. A new adaptive HOSMC method was proposed in [157], which can also be a suitable scheme for conventional SMC.

V. RESEARCH ON THE CHATTERING PROBLEM OF SLIDING MODE CONTROL

The system under the SMC frequently switches between different control logics during operation, and the control device inevitably has inertia and delay. The inherent discontinuous switching characteristics of the SMC, coupled with time delay and space delay, will cause the actual sliding mode motion to not occur accurately on the ideal sliding mode surface. Due to the inertia of the system, when the trajectory of the system reaches the switching surface, it will cross the switching surface at a certain speed. The crossing phenomenon of this motion trajectory is superimposed with the ideal sliding mode, causing the system to vibrate along the ideal sliding mode surface. This phenomenon is usually called "quasi-sliding mode". The natural chattering is superimposed on the ideal sliding mode surface, which makes the system exhibit the chattering phenomenon, which may lead to problems such as performance degradation of the controller, damage to system stability, and damage to mechanical equipment. Therefore, the research on the chattering problem in the SMC becomes very important. This chapter will focus on the research status and progress of the chattering problem in the SMC.

Many factors cause chattering, including the unreasonable selection of controller parameters, inaccurate models, measurement noise, and external disturbances may all cause chattering, and even cause system instability in severe cases. Chattering can only be weakened, and cannot be eliminated. Table 5 summarizes some of the main methods for suppressing chattering.

A. THE FILTERING METHOD

From the research and practice of the SMC, it is found that the output of the sliding mode controller may cause chattering, especially when the system has uncertainty and nonlinearity. Filters are an effective way to remove chatter from signals. Place a filter at the output of the controller to filter the output signal, which can smooth the output signal of the controller and reduce the amplitude and frequency of chattering. The smoothed output can be used to drive actuators or further control operations. Excessive filtering may result in slower system response or reduce the robustness of the controller, and it is necessary to balance the balance between chattering suppression and control performance.

To reduce the chattering of discrete SMC, [158] designed a new type of SMC controller with a filter on the output terminal to smooth the output signal of the controller. Reference [159] designed a sliding mode controller with a filter, which has better robustness compared with a feedback linearization controller. The traditional SMO uses a low-pass filter (LPF) to extract the back electromotive force (EMF), and there will be a phase lag problem. Thanks to the advantages of the adaptive filter without phase shift and amplitude attenuation, the frequency adaptive filter is used in [160] to solve the phase shift problem and suppress chattering. Reference [161] used the back-EMF method to improve the LPF, and proposed an adaptive filter based on back-EMF. The error measured by back-EMF was used to change the cut-off frequency of the LPF in real time and achieved a good control effect. An LPF with the cutoff frequency varying with speed

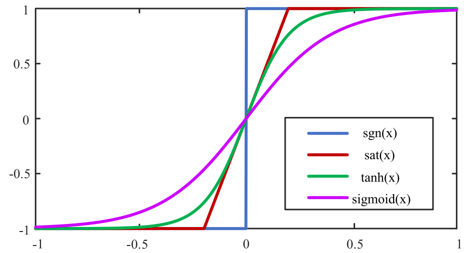


FIGURE 6. Comparison of different switching functions.

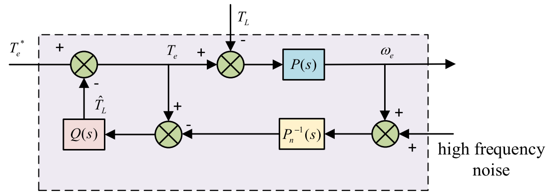


FIGURE 7. Structure of load disturbance observer.

was designed by adding fuzzy control theory [162]. To reduce the current measurement error and suppress chattering, [163] used a high-pass filter controlled by fuzzy logic to realize the automatic adjustment of the switching function coefficients to reduce the system chatter resulting from the continuous boundary layer.

The occurrence of chattering degrades the performance of the motor drive in terms of torque ripple, current harmonics, and noise. In the speed controller of PMSM, [164] added an extended Kalman filter algorithm based on the SMC to estimate speed, position, and unknown load torque. The speed observer based on the Kalman filter algorithm can observe the motor speed online, which effectively reduces the pulsation of the motor speed in the high-frequency range. Reference [104] used an LPF to smooth the signal, and introduced an improved STSMC combination method, which significantly suppressed the chattering due to the signum function. An inevitable DC bias will manifest in the system due to measurement errors in the current sensor and uncertainties in the parameters. Reference [165] replaced the traditional LPF with a band-pass filter, and only the signal in a specific frequency range is reserved to decrease the chattering of the SMO, and effectively suppress the DC bias and high-frequency noise.

There are certain limitations in the filter method to suppress chattering, and the introduction of the filter will cause signal delay, which may impact the response speed and stability of the system. Especially for the filtering of high-frequency chattering components, the delay effect may cause system instability or adversely affect the fast dynamic response of the system. Moreover, the suppression effect of the filter will be affected by the filter design parameters. Choosing inappropriate filter parameters may cause chattering to still exist. Therefore, careful filter design and parameter adjustment are required to achieve the best chattering suppression effect.

TABLE 5. Main methods to alleviate the chattering problem of SMC.

Methods	Operation principles	Related references	Performances
Filtering method	• smooth control signal • Filter out high frequency components	[160]	Sliding mode gain is reduced to half that of traditional SMO, and current chattering is reduced.
Reaching law method	• Use nonlinear control law to achieve smooth convergence near the sliding mode surface to suppress chattering	[167-171]	Improve response speed and reduce torque ripple.
Observer method	• Estimating the state of the system generates control inputs to reduce chattering near the sliding mode surface	[74] [182-187]	Reduced effects of chattering on speed tracking and interference estimation
Intelligent SMC method	• Approximately compensate for disturbances and uncertainties with smooth functions close to arbitrary precision	[193] [194]	The torque ripple suppression effect is better and the error fluctuation is small.
HOSMC method	• Introducing high-order derivatives and high-order control laws to more accurately control the dynamic performance of the system	[139-142] [145] [152]	Compensate speed controller to reduce torque ripple and chattering.

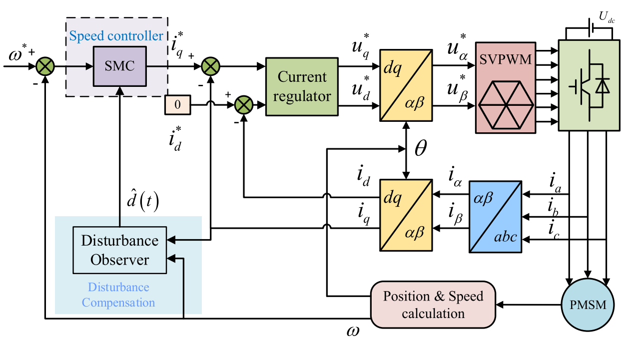


FIGURE 8. Control block diagram of PMSM speed regulating system based on SMC+DOB.

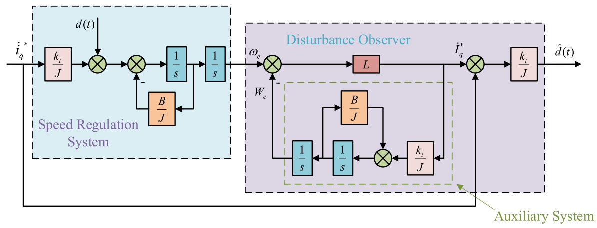


FIGURE 9. From [73] Schematic diagram of DOB.

B. THE REACHING LAW METHOD

The reaching law is mainly used to eliminate the chattering caused by the failure to reach the ideal sliding mode surface. In the section on sliding mode controller design, four common-reaching laws were mentioned. In SMC, the larger the parameter selection of the reaching law, the faster the system state will approach the sliding mode surface, but at the same time, the chattering will be stronger. On the contrary, the smaller the parameter selection, the weaker the chattering caused, but the slower the approach speed. For this reason, in the speed control of PMSM, [44], [166] proposed novel reaching laws to solve this contradiction. Reference [167] improved the constant speed reaching law and introduces a nonlinear function to reduce the chattering arising from the high switching gain of the traditional reaching law. In [168], the system state variable is introduced based on the exponential approach law, that is the absolute value of the velocity error, which speeds up the approach velocity. When reaching the sliding mode surface, the trajectory tends to be stable, thereby suppressing the chattering phenomenon. This approach promotes stability of the trajectory when reaching the sliding mode surface, effectively suppressing the chattering.

The four common approach laws all contain sign functions, which cause chattering due to its discreteness and fast-switching characteristics. Many references use continuous switching functions instead of sign functions to weaken chattering. Fig. 6 compares four continuous switching functions. The hyperbolic tangent function gradually decreases as the sliding mode variable approaches, which makes the variable approach the expected value smoothly, thereby reducing the amplitude of overshoot chattering. Reference [169] used it to replace the sign function. Compared with the sign function, the hyperbolic function has a smoother characteristic as the approach function in the sliding mode reaching law and has a saturation characteristic in a certain range, which constrains the rate of variation of sliding mode variables. This prevents the rapid onset of chattering and improves system stability. References [117] and [170] replaced the sign function with a saturated function and added a power term to the exponential reaching law. Compared with the discrete nature of the sign function, it can make the control signal change more smoothly and help reduce the system's chattering amplitude, improving control stability and performance.

Reference [171] proposed a new switching reaching law for discrete-time system SMC. In a nonlinear system with multiple inputs and outputs, the nonlinear reaching law is designed with an exponential function, which can adapt to system changes. Fast convergence and good robustness of the control system are guaranteed without increasing the critical signal amplitude. However, the complexity of controller design poses challenges to its application in dynamic systems. Reference [172] added the power function of the state variable, and a hybrid reaching law is proposed, which

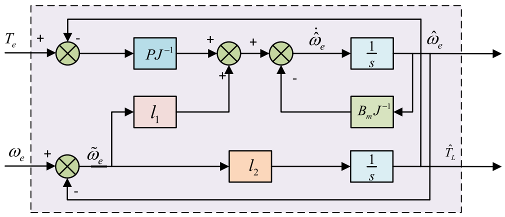


FIGURE 10. Structure of closed-loop load state observer.

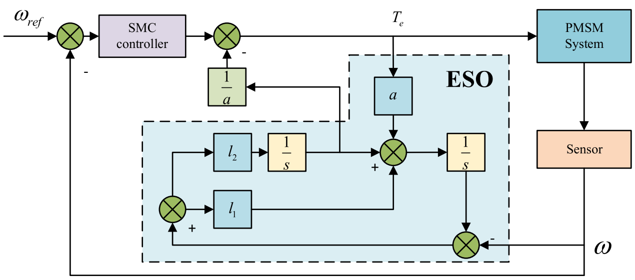


FIGURE 11. Block diagram of the SMC+ESO controller.

combines the terminal arrival part and the exponential plus proportional arrival part to achieve global rapid convergence and achieve the effect of suppressing chattering.

By improving the approach law, the chattering phenomenon can be effectively alleviated, but through this method, as the state approaches the sliding surface, the robustness of the controller decreases, and the arrival time increases. For this reason, some scholars have designed the sliding surface accordingly. Therefore, in order to reduce the chattering of the system, it is necessary to reasonably design the reaching law and sliding mode surface.

C. THE OBSERVER METHOD

In theory, when the switching gain of the SMC is larger than the upper bound of the lumped disturbance, the disturbance can be completely suppressed. But in fact, this is impossible to achieve, so the switching gain is usually set higher, but a high switching gain will bring larger chattering. In the PMSM control system, the disturbance cannot be measured directly, so it is necessary to introduce the feedforward compensation part based on the conventional feedback control. The method of disturbance compensation does not require the switching gain to be higher than the upper limit of the aggregate disturbance, as long as it is greater than the boundary of the disturbance compensation error so that chattering can be weakened while ensuring the anti-disturbance performance of the controller. In the SMC strategy of the PMSM, the compensation part needs to be estimated and then fed to the controller. The observer method is commonly used. Reduce sources of chattering by using observers to eliminate disturbances and uncertainties.

1) THE DISTURBANCE OBSERVER

The fundamental principle of the disturbance observer (DOB) is to estimate the external disturbance and model parameter changes to the system in real-time by observing and estimating the input and output of the system. The DOB compares these estimated disturbance signals with the control input of the system and introduces equivalent disturbance signals into the controller so that the system can better resist external disturbances [173]. The load torque T_L is used as the external disturbance, the electromagnetic torque T_e is used as the system input, and the electrical angular velocity ω_e is used as the system output. The structure of the load DOB is shown in Fig. 7. T_e' is the torque control input, $\hat{T}_L$ is the observed value of load disturbance, and $Q(s)$ is the filter used to suppress high-frequency noise.

The DOB is often used for compensation control, and its control block diagram is shown in Fig. 8. [74] adopted DOB to estimate the disturbance, using the spectrum analysis method, analyzing the input state and the estimated disturbance to reduce the chattering in the SMC input. In robust control of current, [174] used the coupling variable of the stator current as the disturbance estimate, and adopted a compound control strategy combining discrete sliding mode and DOB. On the basis of [174] and [175] added a discrete backward step control algorithm to DOB, and used a discrete sliding mode current controller to combine with the disturbance compensation algorithm. Through experiments, it is proved that adding the disturbance observed by DOB to the sliding mode current control law cannot only reduce the cross-coupling effect in the current loop, but also effectively suppress the buffeting of the discrete sliding mode and enhance the robustness. Reference [176] combined adaptive techniques and DOB to estimate high bandwidth.

Reference [177] designed DOB with nonlinear functions, which can effectively estimate lumped disturbances such as uncertain parameters and unmodeled dynamics. Based on the nonlinear DOB, [178] combined the second-order sliding mode control law to improve the tracking accuracy of the system. Reference [179] used DOB to estimate load torque and back-EMF. Reference [180] introduced a new type of DOB, combined with STSM technology, constituted a compound controller with feed-forward compensation items and state feedback control, which significantly improved the performance of the PMSM speed control system. The compound sliding mode disturbance observer proposed in [39] was used for the current predictive control of PMSM.

Reference [73] proposed DOB as shown in Fig. 9. It only needs to adjust the DOB of one parameter, and adopts the auxiliary system based on the PMSM mathematical model, which not only reduces the burden of parameter adjustment but also accurately estimates the interference. Compared with traditional SMC, chattering is reduced under the premise of ensuring robustness.

2) THE EXTENDED STATE OBSERVER

When the state observer is applied to PMSM, considering the electrical angle ω_e and the load torque T_L as the state estimation variables, T_e is used as the system input, and ω_e is defined as the system output. The structure of the closed-loop load state observer is shown in Fig. 10. There are uncertainties and disturbances in the real system, and these disturbances need to be estimated and compensated more accurately. The state observer can only estimate the state variables but cannot estimate the disturbance. The disturbance item can be estimated as an "extended state", so the extended state observer (ESO) becomes a more appropriate choice [181].

The control block diagram of the conventional SMC+DOB is shown in Fig. 11. The actual speed and control signal can be estimated by using ESO. In [182], the FTSMC brings fast convergence while causing inevitable chattering and steady-state changes. The ESO is used to estimate the disturbance of feedforward compensation by taking the load torque as the state variable. Reference [183] designed an ESO-based compensator to solve the problem that sliding mode control requires large switching gains to handle disturbances. Reference [93] proposed a new type of nonlinear fractional sliding mode surface, combined with ESO, to achieve feedback compensation to the disturbance. Considering the chattering resulting from the change of the internal parameters of the motor, [184] designed an ESO that can update the SMC control law in real-time, and adjust the control law by using the disturbance estimated on the feedforward path to ensure the stability of the current tracking. To improve the observation accuracy of traditional ESO, [85] combined with the STA algorithm, a new ESO was designed to make the estimated errors converge in a finite time and improve the accuracy.

However, despite the incorporation of ESO, chattering persists in the designed control system. Reference [111] developed an ESO based on the FTSMC method, which fed back the estimated disturbance to the q-axis current for compensation, improving system performance and effectively reducing chattering. In [185], predictive function control is introduced together with ESO to optimize the control performance of PMSM. In [186], model reference adaptive control using ESO for disturbance estimation is used for speed regulation of PMSM. Reference [187] adopted two state observers, one is used to observe the internal parameter changes of PMSM and adjust the parameters of the sliding surface in real time to improve the speed response, and the other is used for the compensation of the current loop predictive control.

D. INTELLIGENT CONTROL METHOD

With the rapid development of intelligent algorithms, without changing the stability and dynamic performance of the closed-loop system, the combination of SMC and intelligent control methods [188], such as adaptive control [189], [190], fuzzy control, neural network [191], etc., can be used in it effectively reduces chattering while improving controller performance.

To suppress chattering caused by switch control in SMC, fuzzy control theory is introduced in many literatures. Reference [192] uses fuzzy control instead of a discontinuous sliding mode controller, and [105] designs integral fuzzy switching surface functions with the fuzzy algorithm. Reference [193] introduced fuzzy control theory and combined it with the advantages of adaptive control to suppress the uncertainty of system parameters, effectively reducing the influence of switching control and suppressing the chattering. [194] designed a fuzzy sliding mode speed controller, which can observe the change of load torque, effectively restrain the chattering under the change of model parameters and load torque, and ensure the robustness of speed control of PMSM.

The neural network algorithm has the characteristics of fault tolerance, parallelism, learning, etc. Reference [195] aiming at the speed regulation problem of PMSM, proposed an adaptive sliding mode control based on a fuzzy neural network. Reference [196] combined with the fuzzy neural network algorithm, an STSM controller is designed. Reference [197] adopts the dynamic neural network to design the speed controller, which can not only give full play to the insensitivity of the SMC to parameter changes and disturbances but also has the ability of fuzzy neural self-regulation. To optimize the online learning time of the neural network, based on the traditional feed-forward neural network, [198] proposed the fuzzy SMC based on the recurrent neural network to achieve precise speed tracking and chattering suppression of PMSM.

The combination of SMC and adaptive control can effectively deal with system parameter changes and uncertainties by using the robustness of SMC and the parameter adjustment ability of adaptive control. However, the design of the adaptive law requires a certain understanding of the system model, and involves online parameter estimation, which increases the complexity of the algorithm, but improves the adaptability and accuracy of the control system. Fuzzy logic brings an imprecise rule-based decision mechanism to SMC, which is suitable for systems that are difficult to establish accurate models. However, the design of fuzzy rules and the determination of membership function increase the flexibility of design, but also increase the complexity of the control strategy, especially in the construction and optimization of processing rule base. The introduction of neural network enables the control strategy to learn and adapt to complex nonlinear relations, and improves the intelligence and adaptability of SMC. However, the training and optimization process of neural network often requires a lot of computing resources, and the parameter selection and network architecture design have a great impact on the final performance, which makes the complexity of the whole control system significantly increased.

VI. FUTURE DIRECTIONS

By reviewing and summarizing existing literature, the utilization of the SMC in PMSMs has garnered significant attention and thorough investigation. Nowadays, the requirements of industrial control for PMSM are gradually increasing. To adapt to new demands and improve the efficiency and quality of industrial production, in addition to optimizing the design of the motor structure [199], [200], the control algorithm also needs to continuously develop and innovate. This section suggests some future directions for the SMC.

A. PARAMETER ADJUSTMENT OF SMC

The performance and stability of the sliding mode controller are highly dependent on the selection of parameters. In most cases, the parameters of SMC are selected based on experience and experimental results. This method is fast and easy, but it cannot guarantee optimal control excellence and stability. Some principles should be followed when selecting parameters. While suppressing chattering, the arrival time and convergence speed should also be considered [172]. A higher gain can improve the response speed, but may cause chattering and instability of the controller; a lower gain can enhance the stability of the system, but the response speed is slower. The selection of parameters requires a trade-off between response speed and stability.

Many literatures have adopted adaptive algorithms to adjust the parameters of the controller, and have achieved certain results, but there are still some improvements to be made [201], [202]. The variable gain controller can be designed to adjust the controller parameters according to the state inside the sliding mode algorithm [144]. In addition, optimization algorithms, such as genetic algorithm [203], particle swarm algorithm, etc., can be employed to realize the rapid tuning and optimization of SMC parameters. In terms of data-driven, big data analysis technology is used to extract features from massive system operation data, and data-driven parameter optimization is carried out to improve the precision and efficiency of control strategies. This includes using machine learning algorithms to predict system behavior and adjust control parameters in real time.

B. SUPPRESSION OF CHATTERING PROBLEM

Chattering in the SMC cannot be eliminated, only suppressed. Section V reviews and summarizes the existing methods for reducing the chattering problem in the SMC. These methods can suppress the chattering phenomenon to a certain extent and improve the stability and smoothness of the system. For example, the reaching law can completely suppress chattering in theory, but the design and debugging of the reaching law are more complicated [74]. The HOSMC makes the sliding mode surface smoother by introducing higher-order functions, thereby reducing the amplitude and frequency of chattering. Neural network control and fuzzy control have the potential to suppress chattering. Through the learning and approximation ability of the neural network, the output of the sliding mode controller can be corrected and optimized [204]. By introducing self-adaptability, learning ability and optimization strategy, intelligent control algorithms can control the dynamic behavior of the system more accurately, effectively alleviate the buffeting problem, and improve the stability and robustness of the control system. Future research may focus on developing more efficient intelligent control methods to improve the performance and adaptability of chattering suppression.

C. APPLICATIONS OF THE HOSMC

The HOSMC has stronger control performance and wider application potential. In terms of theory, the theory of the HOSMC will continue to deepen, and further explore the methods of convergence analysis, robustness analysis, and performance optimization of the HOSMC [205]. Computational realization and hardware support of the HOSMC is an important development direction. Future developments will involve efficient computational methods, real-time guarantees, and hardware optimization to enable the widespread application of the HOSMC in practical systems.

The HOSMC has high control accuracy and robustness and can realize high-precision position control of PMSMs, such as robot control and precise positioning. In the future, the HOSMC can be applied to more precise position control and trajectory tracking to meet the needs of different application fields for position control. In addition, the HOSMC may be combined with other emerging technologies, such as deep learning, reinforcement learning, etc., to tackle more complex control problems.

D. COMBINATION OF SMC AND OTHER CONTROL METHODS

Sliding mode control will be more integrated with other methods to expand the application and further improve the adaptability and performance of the SMC. In [206], [207], [208], [209], [210], and [211], the combination of the SMC and adaptive algorithm can be adjusted according to the actual changes of the system and has a certain fault tolerance. The proposed adaptive algorithm in [87] can reduce the error of position estimation in a wide speed range. Reference [184] combined with Active Disturbance Rejection Control, which does not require an accurate system model, it achieves fast-tracking performance on the current. The development of finite time sliding mode control can ensure that a stable state is achieved in a finite time and reduce adverse effects in the control process [212]. Reference [213] used SMO to estimate the current and disturbance in the current predictive control, which reduces the computational burden and improves the robustness. Moreover, the forward-looking and rolling optimization characteristics of the model predictive control can be utilized to consider the future state during the control process and make adjustments in advance to reduce the buffeting caused by instantaneous perturbations.

The observer enables real-time estimation of the system's internal disturbance and utilizes the estimated disturbance to timely adjust the switching gain of the SMC, thereby mitigating the influence of disturbance variations on the performance of the SMC. In the case of parameter mismatch, [83] combined with sliding mode control, the load torque observer is designed, and two identification methods of moment of inertia are proposed, the moment of inertia is identified

TABLE 6. Development of composite sliding mode control.

Methods	Features of application
Observer + SMC	Anti-disturbance Chattering reduction
Adaptive control + SMC	Parameter identification
MPC+ SMC	Current tracking Motor parameter mismatch
ADRC + SMC	Velocity tracking problem
Sensorless control +SMC	High cost of mechanical sensors
Fuzzy Neural Network + SMC	Real-time adjustment Chattering reduction Complex calculations

online and fed back to the controller in real time, so as to improve the observation accuracy of the load observer. The observer method will also be a focus of the development of the SMC in the future. In addition, the SMC is combined with fuzzy control [214], [215], [216], model predictive control (MPC) [217], [218], [219], Active Disturbance Rejection Control (ADRC) [220], [221], [222], [223], neural network control [224], [225], [226], etc. Table 6 summarizes the combination of SMC and other advanced control methods.

VII. CONCLUSION

This paper reviews the research and development of SMC methods for PMSMs. The development of SMC is introduced, as well as the application in PMSMs, and the existing control schemes are summarized and analyzed. The theoretical development of high-order SMC is relatively mature, but its application to PMSMs is not much, and there is still room for development in this area. How to suppress the chattering problem of SMC is the most important thing to consider. Most of the methods to weaken chattering will reduce the robustness of the system. Therefore, how to suppress the negative impact of chattering without affecting the system performance is the core problem that the SMC theory needs to solve. Furthermore, how to better combine SMC with other advanced control algorithms is also worthy of further study.

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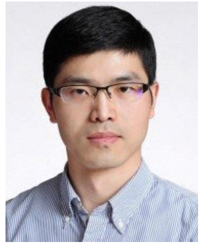

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