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A Speed Disturbance Control Method Based on Sliding Mode Control of Permanent Magnet Synchronous Linear Motor

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ABSTRACT Permanent magnet synchronous linear motor (PMSLM) is a linear motion device, which has the characteristics of simple structure, low loss, high precision, repeatability, large stroke, and simple maintenance. Simultaneously, due to its feature of non-linearity, time-varying, strong coupling, and external load uncertainty, a speed disturbance control method base on sliding mode control of PMSLM is proposed in this paper. The method of sliding mode control uses the power function to smooth the processing. It replaces the symbolic function based on the exponential approach method; therefore, the buffeting of the conventional sliding mode can be well suppressed by this method. When considering different disturbances, the simulation proves that the sliding mode control system can overcome the influence of system parameter changes and external disturbances. Therefore, the control of the PMSLM can be achieved. Meanwhile, the simulation results show that the proposed new sliding mode approach rate can better suppress chattering compared with the traditional approach rate. Additionally, the stability of the system and anti-interference is improved.

INDEX TERMS Permanent magnet synchronous linear motor, sliding mode control, speed disturbance.

I. INTRODUCTION

The PMSLM is a direct-drive special motor [1]–[4] that enables contactless transmission. The linear motors have many advantages, such as simple structure, stable, reliable operation, long service life, high sensitivity, strong adaptability, high rated value, fast response, precise positioning, good self-locking ability, and no intermediate links in the entire control system. It is commonly used in the fields of automated production, civil aviation transportation, military, etc. Therefore, its development prospects are very broad. However, since the speed and accuracy of the linear motor operation are directly affected by its controller, it is of major practical significance to study the high-efficiency control strategy to improve the performance of the motor. Reference [5] proposes a new control scheme combining inverse system method and internal model control, which effectively improves the control precision and dynamic performance of high bearingless permanent magnet synchronous motor. In general, for traditional direct thrust control of linear permanent magnet synchronous motors, fluctuations will occur in terms of magnetic flux and thrust. In [6], in order to reduce the ripple of flux and force, a linear thrust control scheme is proposed for linear permanent magnet synchronous motor. In order to achieve better tracking ability and load change regulation, based on Takagi-Sugeno(T–S) fuzzy model, a speed control of a surface-mounted permanent magnet synchronous motor is proposed in [7]. Accurate tracking performance and energy savings can be achieved by minimizing copper losses. In [8], at the unsteady operating point (ie, varying torque and speed), an optimal feedback linearization control is introduced for permanent magnet synchronous motors. Reference [9] describes a composite propulsion system equipped with a high-speed permanent magnet synchronous motor and two in-wheel motors for electric vehicles. At present, the control technologies are widely used in linear motors mainly include: PID control algorithms, neural network control algorithms, robust control algorithms, and adaptive control algorithms.

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A. PID CONTROL ALGORITHM

PID control strategy is still a mature and commonly used in servo system control technology, especially widely used in

PMSLM control. In [10], based on a simple genetic algorithm, a robust PID control scheme with good robust stability is proposed for PMSLM using genetic search methods. More specifically, an adaptive PID speed control scheme for PMSLM drive is presented in [11]. Furthermore, in [12], the authors propose a global asymptotic stability proof for the PID position adjustment of a robotic manipulator driven by a PMSLM. In PID control, the response time and the control accuracy of the control system are determined by K_P, K_I, K_D parameters. But any system exists in the external environment, there are many uncertain factors, such as the system's external load changes, the system's inherent parameter changes, external interference and so on. These changes affect the control accuracy of the control syste. As strong non-linearity and uncertainty exist in the PMSLM, the parameters K_P, K_I, K_D of the PID control are difficult to determine.

At present, most scholars usually combine PID control with other control strategies to form a new composite control with intelligence. For example, the self-correction of PID parameters can be realize by combining PID control with fuzzy control. Thereby, the robustness of the linear motor servo system is enhanced, and a better control effect can be obtained. In [13], the fuzzy adaptive PID control method has the advantages of both adaptive control and fuzzy PID control. Therefore, a novel fuzzy adaptive PID control method is presented for the cordless PMSLM of the elevator. Furthermore, in [14], a three-closed loop control system acting on the mathematical model of a PMSLM is posed. In [15], an evolutionary fuzzy PID controller is developed for the PMSLM.

Since there are fuzzy relationships between the three parameters of the PID controller and the changes of the deviation e_c and the deviation ^{e}, the relationship between them is determined by continuously detecting ^{e} and e_c while the system is running. The fuzzy PID control realizes the self-tuning of the PID parameters by modifying the three parameters of the PID controller online. General nonlinear problems can be solved, due to the ability of self-tuning of the PID parameter. However, the disadvantage of fuzzy PID control lies in the complexity of its rules, and the membership function is sometimes difficult to choose.

B. NEURAL NETWORK CONTROL STATEGY

Neural network is a mathematical model for distributed parallel information processing. It is also a behavioral feature of mimicking animal neural networks. Neural network has broad application prospects in the field of linear servo control. In [16], in order to suppress the mechanical vibration of PMSLM, a neural network compensator has been studied. The linear motor is controlled by a conventional PI speed controller, and a hybrid recurrent neural network is used to suppress the vibration of the flexible mechanism. In [17], a new velocity observation scheme based on artificial neural network inversion method is proposed. This scheme effectively suppresses the stability and accuracy of speed detection for bearingless asynchronous motor systems. Furthermore, in [18], so as to precisely control the position of PMSM servo driver, a hybrid neural network adaptive controller based on local PID is presented. In [19], a novel design method for position control of PMSLM drive is raised, in which the control system adopts a reverse step control scheme. The mathematics and electrodynamics of PMSLM are fully taken into account in the derivation of the control algorithm. In order to achieve fast response and high precision performance, and to ensure the system's robustness to external disturbances and parameter uncertainties, a new type of bearingless permanent magnet synchronous motor decoupling scheme is proposed in [20].

The application of neural networks in linear motors is mainly divided into offline and online modes. The weight and deviation of the neural network can be obtained by offline mode and will not change once acquired. The offline mode has the advantage of fast operation speed. Therefore, it is suitable for occasions with high real-time requirements. Nevertheless, there may still be some errors between the calculation results and the actual target quantity. The online mode has the advantage of high precision of operation, but its limitation is that the time for the execution of the program is too long for practical use. It is generally used in simulation studies. There are still many problems in the study of stability, controllability and observability of the control system based on a neural network, so the design approach for the neural network needs to be improved.

C. ROBUST CONTROL

Robustness refers to the fact that the control system can still maintain certain performance characteristics under certain parameter perturbations. The control theory of H_∞ robust in the control strategy of robustness is gradually improved. The essence of H_∞ control is to make the value range of H_∞ in the transfer function from disturbance to deviation of the system be extremely small or less than a given value, so as to design the controller. This can suppress the disturbance very well. In [21], the velocity control law of surface mount PMSLM with illuminance uncertainty based on multivariate method is proposed. Whereas in [22], in order to resolve the constraint optimization algorithm for the PMSLM speed-control problem, an integrated method for different robust fractional-order PID controllers is raised. The robust control is suitable for the applications where stability and reliability are required. However, the control method is limited by the known dynamic characteristics of the process and the range of uncertainties.

D. ADAPTIVE CONTROL

The main meaning of the adaptive control strategy is to use the equation without the parameters to be estimated as the reference model; it uses the equation containing the parameters to be estimated as an adjustable model. The output of the above two models has the same physical meaning. The error of the output of the two models is used to form an appropriate adjustment rate to adjust the parameters of the adjustable model in real time. Then, the goal, which the output of the control object tracking reference model, can be well implemented. In [23], for a PMSM drive with dead time, an adaptive self-tuning speed control is posed. In [24], due to achieve the high-precision motion control for PMSLM drives, a self-adaptive interval type-2 neural fuzzy network control system is presented. Whereas in [25], a method is mentioned, which can realize the speed control of PMSLM by using two degrees of freedom PI controller based on instant learning method. Nevertheless, for the strategy of adaptive control, it still has the disadvantages of large computation and slow adjustment of control parameters.

Sliding mode control can be employed in nonlinear motion control processes. And, it is insensitive to changes of parameters and perturbation. At the same time, the sliding mode variable structure also has the advantages of simple algorithm, rapid response, and no need for online recognition. Therefore, it is widely used in linear motors. According to the back electromotive force model, the backward electromagnetic pulse equivalent signal can be obtained to establish an observer. In [26], there are adopting a novel sliding mode observer to realize senseless control of Permanent magnet synchronous motor. For a PMSLM, In [27], a combined speed and direct thrust force control scheme in the stator flux reference frame are presented.

In this paper, a new reaching law of sliding mode control is designed. The output speed of the motor is controlled by this method, which improves the control performance of the PMSLM system. By experimental simulation, it proves that the system based on the sliding mode control method is insensitive to system parameter changes and external disturbances. Therefore, the control performance of the linear motor can be well achieved. The rest of the paper is organized as follows: section two presents a description of the mathematical model of a PMSLM. In the third section, a new sliding mode control reaching law is proposed, and the PMSLM is designed based on sliding mode control. In the fourth section, the sliding mode control of PMSLM is tested and analyzed under different disturbance conditions. Simultaneously, the new approach rate and the traditional approach rate are simulated and analyzed. The final section summarizes the paper.

II. MATHEMATICAL MODEL DESCRIPTION OF PMSLM

The basic structure and principle of PMSLM and ac linear servo system are introduced in [28]. The mathematical model of the PMLSM under *dq* coordinate axis can be established, when the fundamental component is only considered. Researchers have proposed the concept of a dynamic model of a linear motor, which consists of flux equation, voltage equation, electromagnetic thrust equation and motion equation. Using coordinate transformation, the voltage and flux equation of PMLSM can be described in synchronous coordinate system as (2.1) show:

$$\begin{cases} u_d = i_d R_s + L_d \dfrac{di_d}{dt} - \omega\psi_q \\ u_q = i_q R_s + L_q \dfrac{di_q}{dt} + \omega\psi_d \end{cases} \tag{2.1}$$

And

$$\psi_d = L_d i_d + \psi_f$$
$$\psi_q = L_q i_q \quad \omega = \frac{\pi v}{\tau}$$

where R_s is the winding resistance of motor, τ is permanent magnet pole pitch, ψ_d, ψ_q are the flux linkage of the d-axis and q-axis, L_d, L_q are the inductance of d-axis and q-axis, ω is the electrical angular velocity of the equivalent rotor $d - q$, ψ_f is the flux linkage of the permanent magnet fundamental wave field magnetic field chain through the stator winding, i_d, i_q, u_d, and u_q are the current and voltage components of the d-axis and q-axis, and v, is the line speed.

In order to make orthogonal for the stator current vector and the permanent magnet magnetic field in space, a control strategy is cited, where the current component $i_d = 0$ is adapted under the d-axis for the current inner ring. In this paper, when only the basic wave component is considered, the conditions for orthogonal can be satisfied. Therefore, the updated voltage equation can be further defined as (2.2).

$$u_q = R_s i_q + L_q \frac{di_q}{dt} + \frac{\pi}{\tau}\psi_f v \tag{2.2}$$

According to the operating principle of the linear motor, the mechanical motion equation of PMLSM can be expressed as (2.3).

$$F_e = M\frac{dv}{dt} + B_v v + F_l = K_f i_q \tag{2.3}$$

where M is primary quality, B_v is the viscous friction coefficient, F_l is the load disturbance. When the Lagrangian transformation is performed on the equations (2.2) and (2.3), the following equation can be obtained:

$$F_e = MsV + B_v V + F_l = K_f I_q \tag{2.4}$$
$$U_q = R_s I_q + L_q s I_q + \frac{\pi}{\tau}\psi_f v \tag{2.5}$$
$$K = \frac{\pi\psi_f}{\tau}, \quad K_f = \frac{3}{2}K$$

When $F_l = 0$,by using the method of structural diagram equivalent transformation, the transfer function of the system can be defined as (2.6).

$$\begin{aligned} \phi(s) = \frac{V}{U_q} &= \frac{\frac{1}{(L_q s+R_s)(Ms+B_v)}K_f}{1+\frac{1}{(L_q s+R_s)(Ms+B_v)}K_f} \\ &= \frac{K_f\tau}{K_f\pi\psi_f + (L_q s + R_s)(Ms+B_v)\tau} \\ &= \frac{K_f\tau}{L_q M\tau s^2 + (L_q B_v\tau + MR_s\tau)s + R_s B_v\tau + K_f\pi\psi_f} \end{aligned} \tag{2.6}$$

If $U_q = 0$, the transfer function can be got that described as follows:

$$\phi_d(s) = \frac{V}{F_l} = \frac{-\left(L_q s + R_s\right)\tau}{K_f \psi_f \pi + \left(L_q s + R_s\right)\left(Ms + B_v\right)\tau}$$
$$= \frac{-\tau L_q s - R_s \tau}{L_q M \tau s^2 + \left(L_q B_v \tau + R_s M \tau\right) s + R_s B_v \tau + K_f \psi_f \pi} \tag{2.7}$$

The state space model can be obtained as shownin (2.8) when considering the disturbance.

$$\begin{cases} \dot{x} = Ax + Bu_q + F_i(t) \\ y = Cx \end{cases} \tag{2.8}$$

And

$$A = \begin{bmatrix} 0 & 1 \\ -\dfrac{R_s B_v \tau + K_f \pi \psi_f}{L_q M \tau} & -\dfrac{L_q B_v + M R_s}{L_q M} \end{bmatrix},$$
$$B = \begin{bmatrix} 0 \\ \dfrac{K_f}{L_q M} \end{bmatrix}, C = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

where the state variable is $x = \begin{bmatrix} v & \dot{v} \end{bmatrix}^T$, the output is $y = v$. The $F_i(t)$ is amount of disturbance.

III. SLIDING MODE CONTROL OF PMSLM

A. THE CONSTRUCTION OF SLIDING MODE CONTROL

In the process of dynamic control, Since the structure of the controller is not constant, and its control law is not continuous. it always changes with its state. Thereby, it slides toward the equilibrium point along the preset switching surface, and finally gradually stabilizes to the equilibrium point.

Since sliding mode variable structure control has the characteristics of high frequency switching. The structure of the system can make a purposeful change in the dynamic process. The system motion state is not susceptible to uncertainties, parameter changes, mathematical model uncertainty, and external disturbances. Sliding mode control also has the advantage of fast response. In this paper, a sliding mode control method is designed. The dynamic tracking response performance of the PMSLM can be guaranteed. Meanwhile, the effects of system parameter changes and external disturbances are overcome.

In this sliding mode control variable structure, the sliding surface is designed according to the system state error and its derivative (the design of the sliding mode is independent of the parameters of the controlled object and the external disturbance), and the state of the PMSLM system is always sliding along the sliding surface by switching back and forth between the control quantities.

The design of sliding mode is mainly composed of the sliding surface and the control rate.

In this paper, the traditional sliding surface $s = CE$ is adopted, Where C is the parameter of sliding mode. Defined the $C = \begin{bmatrix} J & 1 \end{bmatrix}$, where J is the normal number. E is the state variable, and $E = \begin{bmatrix} e & \dot{e} \end{bmatrix}^T$, where $e, \dot{e}$ are their velocity error and velocity error derivatives respectively, ie $e = v_s - v$, $\dot{e} = \dot{v}_s - \dot{v}$, where v_s is the given input and v is the output response speed. The switching function selected in this paper is as follows:

$$s = \begin{bmatrix} J & 1 \end{bmatrix} \begin{bmatrix} e \\ \dot{e} \end{bmatrix} = Je + \dot{e} \tag{3.1}$$

$s = 0$ defined as switching boundary, and the motion for the boundary is discontinuous. In order to ensure the stable operation of the system on the sliding surface, the (3.2) needs to be satisfied.

$$\begin{cases} \lim\limits_{s \to 0^+} s < 0 \\ \lim\limits_{s \to 0^-} s > 0 \end{cases} \quad \text{or } S \cdot \dot{S} < 0 \tag{3.2}$$

Equation (3.2) guarantees that no matter which end of the sliding mode surface the approaching motion is located. it will approach the sliding mode surface, so as to improve the steady-state error.

Sliding mode motion consists of two processes: one is the approaching motion, and the other is the sliding mode motion. Approaching motion refers to a motion in which the system close to the surface of the switch from any initial state, and then reaches the surface of the switch. In general, it is the process of $s \to 0$. According to the principle of sliding mode variable structure, the moving point comes from any position in the state space, can reach the surface of switching within a limited time. And there is no restriction on the specific trajectory of the approaching movement. Therefore, in this paper, the method of approaching rate is adopted to improve the dynamic quality of motion.

For the design of the approach law, the traditional approaching rate can be expressed as (3.3).

$$\dot{s} = -\varepsilon \cdot \text{sgn}(s) - ks \; \varepsilon > 0, \quad k > 0 \tag{3.3}$$

where, s is the sliding surface, and ks is the exponential approach. It can guarantee that the system state can approach the sliding mode at a large speed when s is large. $-\varepsilon \cdot \text{sgn}(s)$ is the constant velocity approach. When s is close to 0, the approaching speed is ε instead of 0, which ensures the system will reach the sliding surface in a limited time.

The disadvantage is existed on traditional approach rate, which switching belt is strip-shaped. The traditional approach rate can't approach the origin when the system moves to the origin in the switching band. A chattering near the origin will be generated. It will excite the high- frequency components which are not considered in the modeling of the system. It causes the burden on the controller to be increased.

To solve the above problems, a new approach rate based on the traditional approach rate is proposed. It uses the power function $T(s, \alpha)$ instead of the symbol function sgn(s) for smoothing, and the power function $T(s, \alpha)$ is defined as follows:

$$T(s, \alpha) = |s|^\alpha \,\text{sgn}(s) \tag{3.4}$$

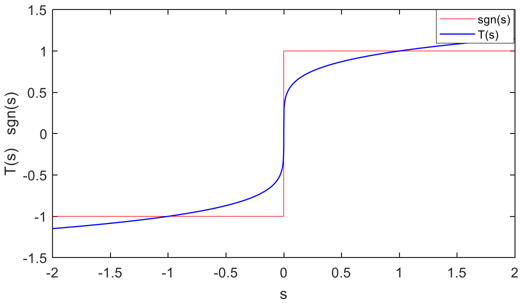

FIGURE 1. T(s) and sgn(s) switching functions.

where $0 < \alpha < 1$,when the power function act as a switching function, the motion process of the system approaches the origin on the sliding surface will be smoother. For the parameter s, it will be adjusted in real time. It can be seen from Figure 1 that the system chattering will be suppressed when adopted power function, which improved the disadvantage of the traditional approach rate. The motion trajectory of power function $T(s, \alpha)$ and sgn(s) are shown in Figure 1.

Simultaneously, the exponential term $-k \cdot s$ of the traditional approach rate is replaced by $-k \cdot s^3$, which increases the rapid response of the system.

Therefore, according to formula (3.4), the final improved sliding mode approach law can be obtained as:

$$\dot{s} = -\varepsilon |s|^{\alpha} \operatorname{sgn}(s) - ks^3 \tag{3.5}$$

B. CONTROL DESIGN OF PMSLM BASED ON SLIDING MODE

For the design of the sliding mode controlled PMSLM, the (2.2) and (2.3) can be used to derive the following relationship between input u_q and output v:

$$\begin{aligned} u_q &= R_s \cdot \left(\frac{M}{K_f} \cdot \dot{v} + \frac{B_v}{K_f} \cdot v\right) + L_q \cdot \left(\frac{M}{K_f} \cdot \ddot{v} + \frac{B_v}{K_f} \cdot \dot{v}\right) \\ &\quad + \frac{\pi}{\tau} \cdot \psi_f \cdot v \\ u_q &= \frac{L_q \cdot M}{K_f} \cdot \ddot{v} + \left(\frac{R_s \cdot M}{K_f} + \frac{L_q \cdot B_v}{K_f}\right) \cdot \dot{v} \\ &\quad + \left(\frac{R_s \cdot B_v}{K_f} + \frac{\pi \cdot \psi_f}{\tau}\right) \cdot v \end{aligned} \tag{3.6}$$

Inferred

$$\begin{aligned} \ddot{v} &= -\left(\frac{R_s}{L_q} + \frac{B_v}{M}\right) \cdot \dot{v} - \left(\frac{R_s \cdot B_v}{L_q \cdot M} + \frac{K_f \cdot \pi \cdot \psi_f}{L_q \cdot M \cdot \tau}\right) \cdot v \\ &\quad + \frac{K_f}{L_q \cdot M} \cdot u_q \end{aligned} \tag{3.7}$$

Since the output speed of the PMSLM is v, the given input speed is v_s. Then the speed error is $e = v_s - v$, and $\dot{e} = \dot{v}_s - \dot{v} = -\dot{v}$. This paper use e and $\dot{e}$ as the state variables, and $u = u_q$ as the control amount of the controller outputs, namely:

$$\begin{cases} e = v_s - v \\ \dot{e} = \dot{v}_s - \dot{v} = -\dot{v} \end{cases}$$

Then

$$\begin{aligned} \ddot{e} = \ddot{v}_s - \ddot{v} &= \left(\frac{R_s}{L_q} + \frac{B_v}{M}\right) \cdot \dot{v} + \left(\frac{R_s \cdot B_v}{L_q \cdot M} + \frac{K_f \cdot \pi \cdot \psi_f}{L_q \cdot M \cdot \tau}\right) \\ &\quad \cdot v - \frac{K_f}{L_q \cdot M} \cdot u \\ &= \left(\frac{R_s}{L_q} + \frac{B_v}{M}\right) \cdot \dot{v} - \left(\frac{R_s \cdot B_v}{L_q \cdot M} + \frac{K_f \cdot \pi \cdot \psi_f}{L_q \cdot M \cdot \tau}\right) \cdot (v_s - v) \\ &\quad - \frac{K_f}{L_q \cdot M} \cdot u + \left(\frac{R_s \cdot B_v}{L_q \cdot M} + \frac{K_f \cdot \pi \cdot \psi_f}{L_q \cdot M \cdot \tau}\right) \cdot v_s \end{aligned} \tag{3.8}$$

Equation (3.9) can be derived by bringing $\dot{e} = \dot{v}_s - \dot{v} = -\dot{v}$ and $e = v_s - v$ into equation(3.8).

$$\begin{aligned} \ddot{e} &= -\left(\frac{R_s}{L_q} + \frac{B_v}{M}\right) \cdot \dot{e} - \left(\frac{R_s \cdot B_v}{L_q \cdot M} + \frac{K_f \cdot \pi \cdot \psi_f}{L_q \cdot M \cdot \tau}\right) \cdot e \\ &\quad - \frac{K_f}{L_q \cdot M} \cdot u + \left(\frac{R_s \cdot B_v}{L_q \cdot M} + \frac{K_f \cdot \pi \cdot \psi_f}{L_q \cdot M \cdot \tau}\right) \cdot v_s \end{aligned} \tag{3.9}$$

Then the equation of state for sliding mode control are defined as follows:

$$\begin{aligned} \begin{bmatrix} \dot{e} \\ \ddot{e} \end{bmatrix} &= \begin{bmatrix} 0 & 1 \\ -\left(\frac{R_s \cdot B_v}{L_q \cdot M} + \frac{K_f \cdot \pi \cdot \psi_f}{L_q \cdot M \cdot \tau}\right) & -\left(\frac{R_s}{L_q} + \frac{B_v}{M}\right) \end{bmatrix} \begin{bmatrix} e \\ \dot{e} \end{bmatrix} \\ &\quad + \begin{bmatrix} 0 \\ -\frac{K_f}{L_q \cdot M} \end{bmatrix} u + \begin{bmatrix} 0 \\ \left(\frac{R_s \cdot B_v}{L_q \cdot M} + \frac{K_f \cdot \pi \cdot \psi_f}{L_q \cdot M \cdot \tau}\right) \end{bmatrix} \cdot v_s \end{aligned} \tag{3.10}$$

Traditional sliding surface is adopted in this paper as bellow:

$$s = \begin{bmatrix} J & 1 \end{bmatrix} \begin{bmatrix} e \\ \dot{e} \end{bmatrix} = Je + \dot{e} \tag{3.11}$$

The sliding surface parameters $J > 0$.

To find the partial derivative of (3.11), it combine the (3.10) with the (3.11) to get.

$$\begin{aligned} \dot{s} &= J\dot{e} + \ddot{e} \\ &= J\dot{e} - \left(\frac{R_s}{L_q} + \frac{B_v}{M}\right) \cdot \dot{e} - \left(\frac{R_s \cdot B_v}{L_q \cdot M} + \frac{K_f \cdot \pi \cdot \psi_f}{L_q \cdot M \cdot \tau}\right) \cdot e \\ &\quad - \frac{K_f}{L_q \cdot M} \cdot u + \left(\frac{R_s \cdot B_v}{L_q \cdot M} + \frac{K_f \cdot \pi \cdot \psi_f}{L_q \cdot M \cdot \tau}\right) \cdot v_s \end{aligned} \tag{3.12}$$

The improved reaching rate used in this paper is $\dot{s} = -\varepsilon |s|^{\alpha} \operatorname{sgn}(s) - ks^3$, substituting it into (3.12) to obtain the control rate:

$$\begin{aligned} u &= \left[\frac{L_q \cdot M}{K_f} \cdot J - \left(\frac{R_s \cdot M}{K_f} + \frac{B_v \cdot L_q}{K_f}\right)\right] \cdot \dot{e} \\ &\quad - \left(\frac{R_s \cdot B_v}{K_f} + \frac{\pi \cdot \psi_f}{\tau}\right) \cdot e + \left(\frac{R_s \cdot B_v}{K_f} + \frac{\pi \cdot \psi_f}{\tau}\right) \cdot v_s \\ &\quad + \frac{L_q \cdot M}{K_f} \cdot \varepsilon \cdot |s|^{\alpha} \cdot \operatorname{sgn}(s) + \frac{L_q \cdot M}{K_f} \cdot k \cdot s^3 \end{aligned} \tag{3.13}$$

C. STABILITY ANALYSIS OF SLIDING MODE CONTROL

According to the Lyapunov stability theorem, the motion trajectory of the system state variable will reach the sliding surface within a finite time. That is, the system is stable, as long as the (3.14) is satisfied. Next, the Lyapunov function is defined to analyze whether the system is stable.

$$V = s \cdot \dot{s} < 0 \tag{3.14}$$

Theorem 1: For the sliding mode variable structure control system, the switching function is shown in (3.11), and its control rate is as shown in the above (3.13).

If $\dot{V} = s \cdot \dot{s} = -\varepsilon \cdot |s|^{\alpha} \cdot s \cdot \operatorname{sgn}(s) - k \cdot s^4 \leq 0$, the control system is asymptotically stable.

Proof: Define the Lyapunov function $V = \frac{1}{2}s^2$,then

$$\begin{aligned}
\dot{V} &= s \cdot \dot{s} = s \cdot \left[J\dot{e} - \left(\frac{R_s}{L_q} + \frac{B_v}{M}\right) \cdot \dot{e} \right.\\
&\quad - \left(\frac{R_s \cdot B_v}{L_q \cdot M} + \frac{K_f \cdot \pi \cdot \psi_f}{L_q \cdot M \cdot \tau}\right) \cdot e \\
&\quad \left. - \frac{K_f}{L_q \cdot M} \cdot u + \left(\frac{R_s \cdot B_v}{L_q \cdot M} + \frac{K_f \cdot \pi \cdot \psi_f}{L_q \cdot M \cdot \tau}\right) \cdot v_s \right] \\
&= s \cdot \left[-\frac{K_f}{L_q \cdot M} \cdot \left(\left[\frac{L_q \cdot M}{K_f} \cdot J - \left(\frac{R_s \cdot M}{K_f} + \frac{B_v \cdot L_q}{K_f} \right) \right] \right.\right. \\
&\quad \cdot \dot{e} - \left(\frac{R_s \cdot B_v}{K_f} + \frac{\pi \cdot \psi_f}{\tau}\right) \cdot e + \left(\frac{R_s \cdot B_v}{K_f} + \frac{\pi \cdot \psi_f}{\tau}\right) \cdot v_s \\
&\quad \left. + \frac{L_q \cdot M}{K_f} \cdot \varepsilon \cdot |s|^{\alpha} \cdot \operatorname{sgn}(s) + \frac{L_q \cdot M}{K_f} \cdot k \cdot s^3 \right) \\
&\quad + J\dot{e} - \left(\frac{R_s}{L_q} + \frac{B_v}{M}\right) \cdot \dot{e} - \left(\frac{R_s \cdot B_v}{L_q \cdot M} + \frac{K_f \cdot \pi \cdot \psi_f}{L_q \cdot M \cdot \tau}\right) \cdot e \\
&\quad \left. + \left(\frac{R_s \cdot B_v}{L_q \cdot M} + \frac{K_f \cdot \pi \cdot \psi_f}{L_q \cdot M \cdot \tau}\right) \cdot v_s \right] \\
&= s \cdot \left[J\dot{e} - \left(\frac{R_s}{L_q} + \frac{B_v}{M}\right) \cdot \dot{e} - \left(\left[J - \left(\frac{R_s}{L_q} + \frac{B_v}{M}\right) \right] \cdot \dot{e} \right.\right. \\
&\quad \left.\left. + \varepsilon \cdot |s|^{\alpha} \cdot \operatorname{sgn}(s) + k \cdot s^3 \right) \right] \\
&= s \cdot \left[-\varepsilon \cdot |s|^{\alpha} \cdot \operatorname{sgn}(s) - k \cdot s^3 \right] \\
&= -\varepsilon \cdot |s|^{\alpha} \cdot s \cdot \operatorname{sgn}(s) - k \cdot s^4
\end{aligned}$$

where $k > 0, 0 < \alpha < 1, \varepsilon > 0$, we can get $\dot{V} \leq 0$. Therefore, the PMSLM system controlled by sliding mode is stable.

IV. SYSTEM SPECFICATION

According to (2.2), (2.3) and (3.13), we can get the block diagram of the PMSLM based on sliding mode control as follows:

The figure is divided into two parts, namely the sliding mode control rate (left) and the controlled object (right). It can be seen from Figure 2, the block diagram of the controlled PMSLM is equivalent to the block diagram from u to v, Where u is input voltage of the PMSLM. The velocity v is output, and $J, \alpha, \varepsilon, k$ are defined as the parameters of sliding mode control, respectively. The given speed v_s is taken as input for the whole system. The errors of given speed and the actual

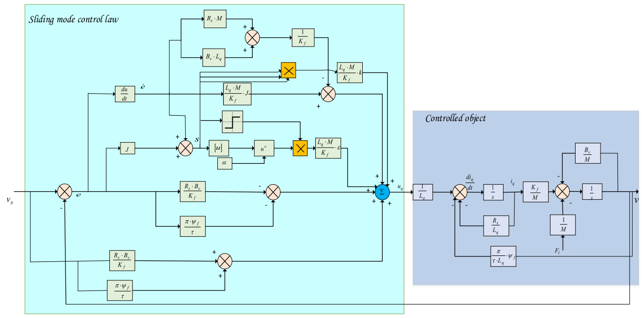

FIGURE 2. Block diagram of sliding mode control of PMSLM.

output and its derivative are set as the sliding surface. A new approach rate is introduced. Then, the required control rate can be obtained. The sliding mode control rate u is used as an input to realize the sliding control of PMSLM. For the entire system of sliding mode, the design of the sliding mode and sliding mode control rate are mainly.

V. SIMULATION ANALYSIS

Based on the above design of the sliding mode control rate of the PMSLM, the output control rate is applied to the mathematical model of the PMSLM, and the sliding mode control system of the PMSLM is built.

The simulation parameters of the PMSLM system are as follows:

$$R_s = 1.23\Omega, L_d = L_q = 3.452mH, \psi_f = 0.55Wb$$
$$M = 10.6kg, B_v = 2N/S, \tau = 3cm$$

In the case of considering the disturbance, simulation parameters are brought into (2.8). The (4.1) of state of the PMSLM can be obtained.

$$\begin{cases} \dot{x} = Ax + Bu_q + F_i(t) \\ y = Cx \end{cases} \tag{4.1}$$

where

$$A = \begin{bmatrix} 0 & 1 \\ -0.08 & -0.54 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 0.02 \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

The $F_i(t)$ is amount of disturbance.

Bring the parameters to get the sliding mode control rate as (4.2) show:

$$\begin{aligned} u = 61.75 \cdot \dot{e} - 3.43 \cdot e + 3.43v_s \\ + 42.375\varepsilon \cdot |s|^{\alpha} \cdot \operatorname{sgn}(s) + 42.375k \cdot s \end{aligned} \tag{4.2}$$

The parameters of PMSLM system have been given above, and the parameters of sliding mode system are set as $J = 2 \cdot \varepsilon = 8 \cdot \alpha = 0.2 \cdot k = 5$, and the given speed is set as $v_s = 2m/s$. In this paper, the disturbances in four different cases are given, and the influence of the disturbance on the output speed of the PMSLM is analyzed. Simultaneously, two methods of traditional approach rate and new approach rate are simulated, compared and analyzed.

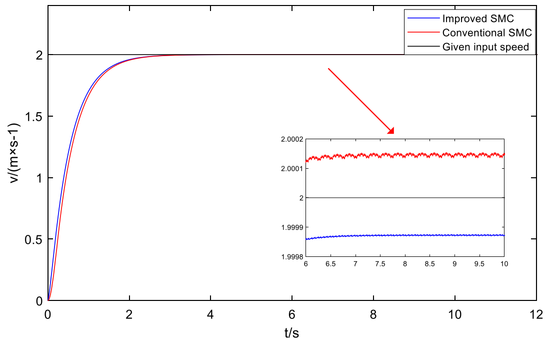

FIGURE 3. Input and output curve.

A. WHEN ADDING DISTURBANCE $F_1(t)$

$$F_1(t) = 0$$

Figure 3 shows the speed response curve of input and output. In this paper, the input speed is given as $v_s = 2m/s$. The output response curve is derived from two methods, namely traditional approach rate control and new approach rate control. The response curve of error of speed for two methods can be seen from Figure 4. As can be seen from Figures 3 and 4, the velocity response curve approaches 2m/s for a certain period of time and stabilizes at 2m/s. Since the value of error of speed tracking is small, it proved that accurate tracking can be achieved for the system of sliding mode control, Furthermore, the good stability can also be obtained. Additionally, the chattering can be better suppressed for the control of the new sliding mode approach rate than the traditional sliding mode approaching rate. This conclusion can be derived from the curve fluctuations in Figure 3.

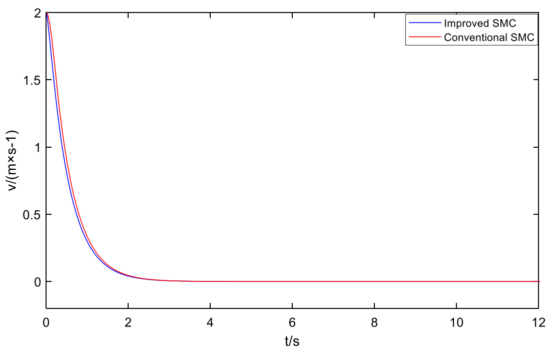

FIGURE 4. Speed error curve.

B. WHEN THE DISTURBANCES $F_2(t)$ ARE ADDED TO THE PMSLM SYSTEM

$$F_2(t) = \begin{cases} 0 & t < 6 \\ 50 \cdot e^{4-t} \cdot \cos(\pi \cdot t) & 6 \le t < 10 \\ 50(1 - e^{4-t}) + \sin(\pi \cdot t) & 10 \le t < 15 \\ 0 & 15 \le t \end{cases}$$

The disturbances are added to the system at 6-15s. One disturbance is added at 6-10s and another disturbance is added at 10-15s. As shown in Figures 5 and 6, the curve of output speed and velocity error produce fluctuations at the moment of adding disturbances, but it tends to be stable immediately. And the curve of output velocity converges to a given speed; the curve of speed error converges to zero. It's proves that the system of sliding mode is not affected by disturbances, and the precision tracking can be achieved.

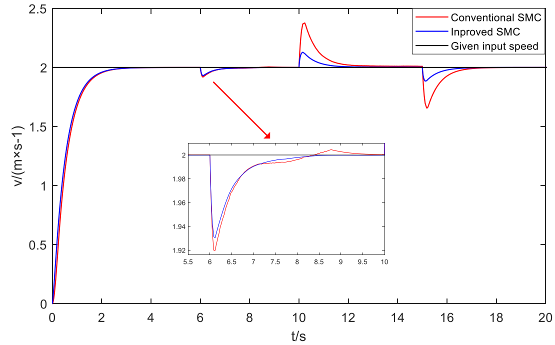

FIGURE 5. Input and output curve.

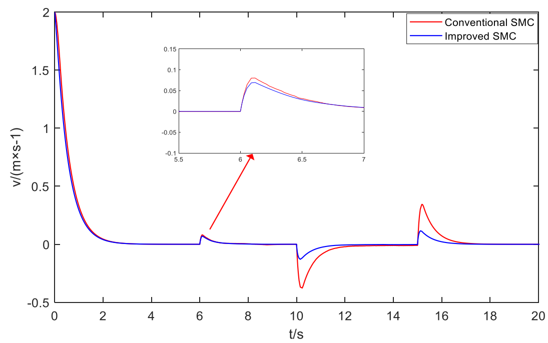

FIGURE 6. Speed error curve.

C. WHEN THE DISTURBANCES $F_3(t)$ ARE ADDED TO THE OUTSIDE OF THE PMSLM SYSTEM

$$F_3(t) = \begin{cases} 0 & t < 6 \\ 0.6\cos(2 \cdot \pi \cdot t) & 6 \le t < 15 \\ 0 & 15 \le t \end{cases}$$

When a disturbance is added to the output of the system, the response state is analyzed. As shown in Figure 7, the jitter is exhibited in system at 6-15s and fluctuates around a large range of 1.416-2.595m/s. It can be concluded that the system is greatly affected, when adding disturbances at the output. As can be seen from Figure 8, the velocity error converges to 0 at 2.7 s. There is no effect for the error of speed when adding disturbances.

D. WHEN ADDING BOTH INTERNAL AND EXTERNAL DISTURBANCES TO THE SYSTEM

$$F_4(t) = F_2(t) + F_3(t)$$

When adding both internal and external disturbances $F_4(t)$ to the system at the same time, as shown in Figure 9, the speed response curve has a fluctuation range of 1.38-2.6m/s. It is not

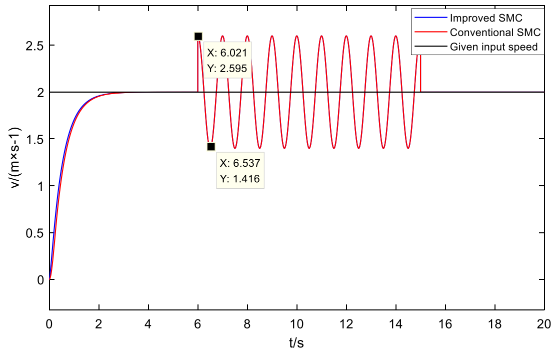

FIGURE 7. Input and output curve.

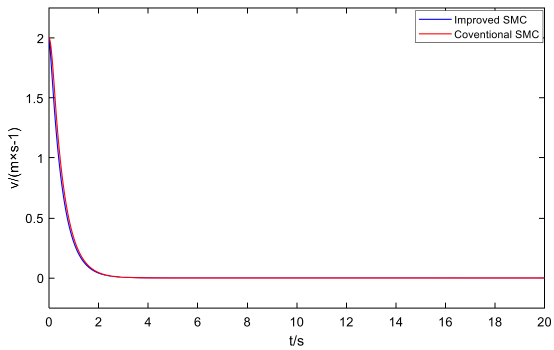

FIGURE 8. Speed error curve.

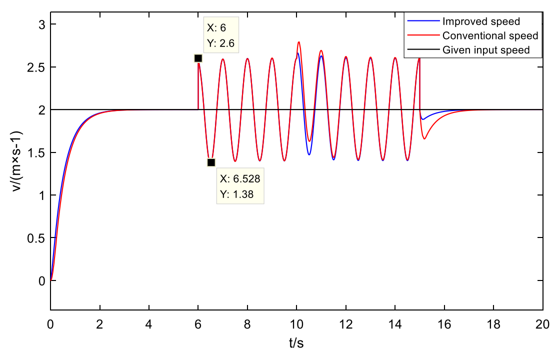

FIGURE 9. Input and output curve.

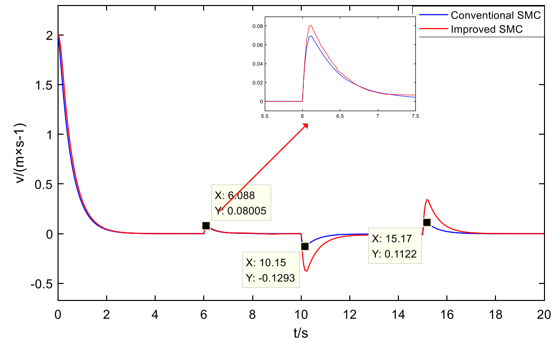

FIGURE 10. Speed error curve.

much different from the curve fluctuation shown in Figure 7. It proves that the curve oscillation mainly comes from the influence of external disturbances on the system. However, disturbances within the system have little effect on it. For the speed error response curves are shown in Figure 10, referred to the curve of new approach rate, its fluctuation range is from -0.11m/s to 0.11m/s in time of 10-25s. When it is in this case, it's proved that the disturbance has little effect on the speed error response of the PMSLM. Also, through Figure 9 and 10, it can be concluded that the new approach rate has better anti-interference performance than the traditional approach rate.

Disturbances in four different situations are added to the system. When there is no disturbance, it can be seen from the curve of system output response and the speed error response that the sliding mode control can realize the accurate tracking of the system speed; when the disturbance is in addition to the inside of the system, the system errors and speed responses are almost unaffected by disturbance; when a small disturbance is added to the outside of the system, the speed response curve has a large fluctuation; when the two disturbances are superimposed on the system, the output response curve is affected mainly by the external disturbance of the system. Since the curve fluctuations of the error response are very small, it proves that the system is not subject to internal disturbances. Meanwhile, The results show the sliding mode control has the advantages of strong adaptability to external disturbances and good robustness. And in this paper, by comparing the traditional approach rate with the new approach rate, it can be concluded that the chattering can be better suppressed for new approach rate than traditional approach rate. Simultaneously, it has better anti-interference. However, it can be seen from the simulation that the response speed needs to be improved.

VI. CONCLUSION

In this paper, a new sliding mode variable structure method is applied to the PMSLM system, which realizes the high-performance speed control of the motor. In order to overcome the shortcomings of the traditional approach rate approach, a new power approach rate is designed. The new power approach rate uses the power function to smooth the processing. It replaces the symbolic function based on the exponential approach method. The buffeting of the conventional sliding mode can be well suppressed by this approach rate. At the same time, the exponential term of the approach rate is added into the cubic term to achieve rapid response. Finally, the simulation proves that the system has good anti-interference, robustness and tracking performance for external disturbances and system parameter changes. In addition, the system can be stabilized in a short time. Meanwhile, sliding mode control has the characteristics of simple control and easy implementation. It proves that the performance of PMSLM can be improved by using the sliding mode control method.

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