Improved Sliding Mode Control of Permanent Magnet Synchronous Linear Motor Based on Model-Assisted Linear Extended State Observer

JIAN LIN, SHULONG ZHANG, LEI ZHOU, YUXIN ZHA, and JITING SUN
Key Laboratory of Advanced Numerical Control Technology of Jiangsu Province, Nanjing Institute of Technology, Nanjing 211167, China
Corresponding author: JIAN LIN (e-mail: zdlxj00777@163.com).
This work was supported by the Major Project of Natural Science Research of Jiangsu Province Colleges and Universities (20KJA460010): Research on Multi-disturbance Compound Suppression of Linear Servo System Based on Prediction and Sliding Mode Control.

ABSTRACT Aiming at the problem that generalized disturbance such as parameter perturbation, load disturbance and unmodeled dynamics will reduce the performance of the mover speed control of the permanent magnet synchronous linear motor (PMSLM), an improved sliding mode control (ISMC) strategy of PMSLM based on model-assisted linear extended state observer (MALESO) is proposed. Firstly, a speed mathematical model of PMSLM considering generalized disturbance is established, then the speed tracking error signal is introduced into the traditional exponential reaching law (TERL) as the system state variable, and the improved exponential reaching law (IERL) based on the system state variable is designed and applied to the integral sliding mode surface to obtain the control variable with generalized disturbance. Secondly, MALESO is designed to estimate the generalized disturbance and its estimated value is feedforward compensated to the output signal of the improved sliding mode speed controller (ISMSC). Finally, the speed control of PMSLM under the generalized disturbance is realized. The simulation results show that the proposed control strategy can significantly optimize the dynamic and static quality, anti-disturbance ability and robustness of the system, and at the same time effectively weaken the chattering phenomenon of sliding mode control.

INDEX TERMS Permanent magnet synchronous linear motor (PMSLM); Model-assisted linear extended state observer (MALESO); Improved exponential reaching law (IERL); Generalized disturbance

I. INTRODUCTION
Permanent magnet synchronous linear motor (PMSLM) has been widely used in precision computerized numerical control machine tools and servo systems due to its unique ‘zero transmission’ mode, which has the advantages of long stroke, large thrust, and high acceleration[1], which also puts forward higher requirements for the system control ability. In recent years, with the development of nonlinear control theory[2]-[3], the sliding mode control (SMC) theory with strong robustness and nonlinear characteristics has been successfully applied in AC servo control systems, but due to the existence of switching characteristics, it is easy to cause chattering in the system, which leads to the reduction of system control accuracy[2].

At present, in order to weaken the chattering phenomenon of SMC and improve the quality of speed loop control, scholars at home and abroad have carried out a lot of research on SMC and achieved certain results. These methods can be roughly divided into two categories. One is to form an adaptive SMC strategy by organically combining with adaptive control on the basis of constructing a new reaching law of SMC[4]-[6]. This kind of control strategy can effectively weaken chattering, suppress some disturbances, and improve the dynamic response speed. However, when suppressing disturbances, these methods often need to assume that the upper and lower bounds of the disturbances are known, which is often difficult to achieve in practical engineering. The other type is based on the construction of SMC with a new reaching law, which is organically
combined with the disturbance observer to form the SMC strategy of disturbance feedforward compensation[7]-[11]. This kind of control strategy uses the disturbance observer to estimate uncertain disturbances such as load disturbance, and feedforward compensates the estimated value to the SMC, which can effectively suppress the chattering and improve the system response speed and robustness. However, these methods do not distinguish the known information of the system objects from the unknown information when establishing the disturbance observer, which leads to a decrease in the estimation accuracy of the disturbance.

In view of the existence of generalized perturbation in the above-mentioned literatures, especially the perturbation of parameters, which leads of the insignificant effect of chattering suppression and the low accuracy of disturbance estimation, this article takes the vector control system of surface-mounted PMSLM with \( i_s = 0 \) as the research object, establishes a speed mathematical model of PMSLM considering generalized disturbance and proposes an improved exponential reaching law (IERL) of piecewise function based on the system state variable in the speed loop, and demonstrates and analyzes its stability, weakening buffeting and optimizing the dynamic quality of the system and other performances; At the same time, IERL is applied to the integral sliding mode surface which can suppress high-frequency noise interference to obtain the control variable with generalized disturbance. In order to further optimize the anti-disturbance ability of SMC to generalized disturbances, based on the traditional linear extended state observer (TLESO), a model-assisted linear extended state observer (MALESO) is designed to improve the estimation accuracy of generalized disturbances and its estimated value is compensated to the improved sliding mode control (ISMC) as a feedforward signal, at the same time, its convergence, estimation error characteristics, frequency band characteristics and filtering performance are demonstrated and analyzed, and the bandwidth \( \omega_0 \) selection principle of MALESO is given. Finally, ISMC strategy of PMSLM based on MALESO is proposed. The effectiveness of the control strategy is verified by MATLAB/Simulink simulation.

II. MATHEMATICAL MODEL OF PMSLM

In order to facilitate analysis and modeling, assuming that the stator winding is a three-phase symmetrical winding, at the same time, the saturation effect of the magnetic circuit and the eddy current and hysteresis losses in the motor are ignored, the mathematical model of the voltage equation of the surface-mounted PMSLM in the \( dq \) coordinate system is expressed as follows[1]:

\[
\begin{align*}
\dot{u}_d &= R_i i_d + L_d \frac{d i_d}{dt} - \frac{\pi}{\tau} v L_{\phi q} i_q \\
\dot{u}_q &= R_i i_q + L_q \frac{d i_q}{dt} + \frac{\pi}{\tau} v L_q i_d + \psi_i \frac{\pi}{\tau}
\end{align*}
\]

where \( u_d \) and \( u_q \) represent the \( dq \)-axis voltage of the primary winding, respectively; \( R_i \) represents the armature resistance; \( i_d \) and \( i_q \) represent the \( dq \)-axis armature current; \( L_d \) and \( L_q \) represent the \( dq \)-axis inductance, respectively; \( \tau \) represents the pole distance; \( v \) represents the linear speed of the air-gap magnetic field; \( \psi_i \) represents the secondary permanent magnet flux linkage.

For the surface-mounted PMSLM, there is \( L_d = L_q \), then the electromagnetic thrust equation and the motion balance equation are written as follows, respectively:

\[
F_e = \frac{3p_m \pi}{2} \tau \psi_I i_q
\]

\[
M \frac{dv}{dt} = F_e - F_L - B_m v
\]

where \( F_e \) represents the electromagnetic thrust; \( p_m \) represents the number of pole pairs; \( M \) represents the mass of the moving part; \( F_L \) represents the load thrust; \( B_m \) represents the viscous friction coefficient.

Substituting (2) into (3) and simplifying it into a mathematical model about speed, thus it can obtain that

\[
\frac{dv}{dt} = -\frac{B_m}{M} v - \frac{1}{M} F_L + \frac{3p_m \pi \psi_I}{2M \tau} i_q
\]

Considering the internal parameters of the motor will be perturbed with the operation of the motor, at this time, (4) can be further expressed as follows[12]:

\[
\frac{dv}{dt} = \frac{-B_{m0} + \Delta B_m}{M} v - \frac{1}{M} F_L + \frac{3p_m \pi (\psi_{0f} + \Delta \psi_I)}{2M \tau} i_q
\]

\[
= -a_q v + f + \frac{b_0 i_q}{\omega_0} = \frac{-\Delta B_m}{M} v - \frac{1}{M} F_L + \frac{3p_m \pi \Delta \psi_I}{2M \tau} i_q
\]

where \( B_{m0} \) and \( \psi_{0f} \) represent the nominal values on the motor nameplate; \( \Delta B_m \) and \( \Delta \psi_I \) represent the perturbation of the internal parameters of the motor; \( a_q = \frac{B_{m0}}{M} \) and \( b_0 = \frac{3p_m \pi \psi_{0f}}{2M \tau} \) are known the motor information; \( f' = -a_q v + f \) is the sum of the known object information and the unknown total disturbance, which is defined as a generalized disturbance.

III. IMPROVED SLIDING MODE SPEED CONTROLLER

A. Design of IERL

In order to improve the quality of the arrival phase, IERL is proposed based on the traditional exponential reaching law (TERL), i.e., \( \dot{s} = k \text{sgn}(s) - q s \), which can be shown as

\[
\dot{s} = -f(x_i) \text{sgn}(s) - q |x_i|^\epsilon \ s
\]

where \( f(x_i) = \begin{cases} k_{x_i} & |x_i| > \delta \\ k_{|x_i|^\epsilon} & |x_i| < \delta \end{cases} \) is a piecewise function with \( \epsilon > 0 \), \( k_{x_i} > 0 \), \( k_{|x_i|^\epsilon} > 0 \) is the coefficient of the reach term of the piecewise function; \( q > 0 \) is the exponential reach term coefficient; \( x_i \) is the system state variable; \( s \) is a sliding mode surface function; \( p \geq 0 \); \( \delta > 0 \); \( 0 < \epsilon < 1 \).
It can be seen from (6) that when \(|x_1|\) is far away from the sliding mode surface, i.e., \(|x_1|>\delta\), the reaching speed is composed of two parts of variable speed reaching law \(-\frac{k}{\varepsilon} \text{sgn}(s)\) and variable exponential reaching law \(-q|x_1|^s\), during the reaching process, its speed changes from fast to slow, which shortens the reaching time and slows down the speed of the moving point when it reaches the switching surface, which optimizes the quality of the arrival phase; When \(|x_1|\) is close to the sliding mode surface, i.e., \(|x_1|<\delta\), the reaching speed is determined by the variable speed term \(-\frac{k}{|x_1|+1} \text{sgn}(s)\). Under the action of the sliding mode control law, \(|x_1|\) enters the sliding mode surface and moves towards the origin. This process makes \(-\frac{k}{|x_1|+1} \text{sgn}(s) - q|x_1|^s\) gradually tend to 0, and finally stabilizes at the origin, thereby weakening the sliding mode chattering. It can be seen that IERL designed by introducing \(|x_1|\) into TERL improves the dynamic quality of the sliding mode motion.

B. Stability and performance analysis of IERL

In order to verify the stability of IERL proposed in this article, the Lyapunov function can be constructed as follows

\[ V = \frac{1}{2} s^2 \]  \tag{7}

Substituting (6) into (7) after derivation, we can get

\[ \dot{V} = s \left[ -f(x_1) \text{sgn}(s) - q|x_1|^s \right] = -|s| f(x_1) - q|x_1|^s s^2 \leq 0 \]  \tag{8}

According to the Lyapunov stability judgment, IERL proposed in this article is asymptotically stable.

Then, in order to verify that the performance of IERL is better than TERL, the following typical system is adopted as an example for analysis and research[13]-[14].

\[ \dot{x} = Ax + Bu \]  \tag{9}

The sliding mode surface function \(s\) of the system is defined as follows:

\[ s = Cx \]  \tag{10}

Taking the derivative of (10), we can get

\[ \dot{s} = CX = \frac{ds}{dt} \]  \tag{11}

Substituting (9) into (11) and simplifying it, the sliding mode controller output expression is given by

\[ u = (CB)^{-1} (-CAx + \frac{ds}{dt}) \]  \tag{12}

where \(x=[x_1, x_2]^T\) is the system state variable; \(ds/dt\) represents reaching law and the simulation parameters are set as follows:

\[ A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ -4200 \end{bmatrix}, \quad C = \begin{bmatrix} 15 & 0 \\ 1 & 1 \end{bmatrix}, \quad x(0) = \begin{bmatrix} 10 \\ 10 \end{bmatrix}, \quad k=5, \quad q=10, \quad p=2, \quad \delta=0.01, \quad \varepsilon=0.1. \]

The TERL and the IERL are simulated in MATLAB, and the results are shown in Fig. 1.

![FIGURE 1. Performance comparison curves of two exponential reaching laws. (a) Phase trajectories of sliding mode motion. (b) System state convergence process. (c) The time required for reaching process. (d) Output from the controller.](image)

It can be seen from Fig. 1 that, compared with TERL, IERL has a faster reaching speed in the reaching phase and a shorter reaching process time. In the sliding phase, the speed of near the sliding mode surface is smaller, the system state convergence speed is faster and the output signal of the sliding mode controller tends to zero more smoothly, which shows that IERL can effectively weaken the sliding mode chattering and optimize the dynamic quality of the system.

C. Design of improved sliding mode speed controller

Using the rotor field oriented control with \(i_d=0\), (1) and (5) can be simplified into the following mathematical models

\[ \begin{aligned}
\frac{di_q}{dt} &= \frac{R}{L_{qy}} i_d - \frac{\pi \psi i}{L_q} v + \frac{1}{L_{qy}} \\
\frac{dv}{dt} &= f + b_i q
\end{aligned} \]  \tag{13}

In order to reduce the high-frequency noise interference caused by the differential process[13], the speed tracking error signal and the integral signal of the speed tracking error are used as the input of the improved sliding mode speed controller (ISMSC) in this article, and the state variables of the system are defined as follows:

\[ \begin{aligned}
\dot{x}_1 &= v_{ref} - v \\
\dot{x}_2 &= \int x_1 dt
\end{aligned} \]  \tag{14}

Where \(v_{ref}\) represents the reference linear speed value of the air gap magnetic field.

Substituting (13) into (14) after derivation, it can be known that

\[ \begin{aligned}
\dot{x}_1 &= -v = -f - b_i q \\
\dot{x}_2 &= x_1
\end{aligned} \]  \tag{15}

By introducing the integral variable of the state variable, the sliding mode surface function can be expressed as follows[7]:

\[ \begin{aligned}
\dot{x}_1 &= -v = -f - b_i q \\
\dot{x}_2 &= x_1
\end{aligned} \]  \tag{15}
\[
\dot{s} = x_i + c \int x_i \, dt
\]  
(16)

where \( s \) represents the integral sliding mode surface; \( c > 0 \) is the parameter to be designed.

Substituting (15) into (16) after derivation, we can get

\[
\dot{s} = -\dot{v} + cx_i
\]  
(17)

In the actual system, the internal parameters of the motor will be perturbed with the operation of the motor, and the sudden change of the load disturbance will seriously affect the control performance of the system. Therefore, it is necessary to consider the influence of internal disturbance and external disturbance on the system. Substituting (6) and (15) into (17) can obtain

\[
-f(x_i) \text{sgn}(s) - q |x_i|^p s = -f - b_d di + cx_i
\]  
(18)

Thus, the output signal of ISMC can be given by

\[
i_y = \frac{1}{b_d} \left[ f(x_i) \text{sgn}(s) + q |x_i|^p s - f + cx_i \right]
\]  
(19)

It can be seen from (19) that \( q \)-axis current reference value contains the generalized disturbance \( f \), so it is necessary to estimate the generalized disturbance \( f \) first, and feed forward the estimated value to the output signal of ISMC.

### IV. MODEL-ASSISTED LINEAR EXTENDED STATE OBSERVER

#### A. Design of MALESO

It can be seen from the foregoing that the generalized disturbance \( f \) exists in the sliding mode control system and seriously affects the control accuracy of the system, so it is necessary to provide timely and effective compensation. Thus, this article designs a MALESO to estimate the generalized disturbance \( f \) online.

According to (5), the generalized disturbance \( f \) can be expanded into a system state variable, and the state variables are selected: \( x_1 = \dot{v} \), \( x_2 = f \), then (5) can be transformed into a continuous expanded state space equation as follows:[12]:

\[
\begin{align*}
\dot{x} &= Ax + Bu + Ef
\end{align*}
\]  
(20)

where \( A = \begin{bmatrix} 0 & 1 \\ 0 & -a_0 \end{bmatrix} \), \( B = \begin{bmatrix} b_d \\ -a_d b_d \end{bmatrix} \), \( E = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \), \( C = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \).

Compared with TLESO, it can be seen from (20) that the state matrix \( A \) and input matrix \( B \) of MALESO contain more motor information, which can improve the estimation accuracy of the disturbance.

The LSEO obtained from (20) is called the MALESO, and its expression is expressed as follows:

\[
\begin{align*}
\dot{z} &= (A - LC) z + BL u_e
\end{align*}
\]  
(21)

where \( z = [z_1, z_2]^T \) is the state vector of the observer, representing the tracking signal for \( x \), i.e., \( z_1 = x_1 \), \( z_2 = x_2 \). \( u_e = [u y]^T \) is the combined input, \( y_e \) is the output, and \( L \) is the observer gain matrix to be designed.

After parameterization, the pole of observer characteristic equation can be placed at the same position \((-\omega_0, \omega_0)\) is the observer bandwidth), which makes the design of LSEO simple,[15] that is as follows

\[
\lambda(s) = \left| sI - (A - LC) \right| = (s + \omega_0)^2
\]  
(22)

The gain matrix of available observer can be expressed as:

\[
L = \begin{bmatrix} l_1 \\ l_2 \end{bmatrix}
\]  
(23)

where

\[
\begin{align*}
l_1 &= 2a_0 - a_0 \\
l_2 &= a_0^2 - 2a_0 a_d + a_d^2
\end{align*}
\]

In order to make MALESO run on MATLAB, the related algorithms need to be discretized. In this article, the forward difference method is used to discretize (21), thus, the system (21) can be rewritten as follows:

\[
\begin{align*}
\dot{e}_1(k) &= z_1(k) - y(k) \\
z_1(k+1) &= z_1(k) - l_1 e_1(k) + b_0 u \\
z_2(k+1) &= z_2(k) - l_2 e_2(k) + b_0 u
\end{align*}
\]  
(24)

where \( T_s \) represents the sampling period; \( l_1 \) and \( l_2 \) represent the discrete estimator error feedback gain matrix to be designed.

Similar to the aforementioned continuous MALESO design, the discrete estimator can also be parameterized so that its characteristic equation satisfies the following expression

\[
\lambda(z) = \left| (zI - \Phi) \right| = (z - \beta)^2
\]  
(25)

where \( \Phi = \begin{bmatrix} 1 - T_s l_1 & -T_s l_2 \\ -T_s l_1 & 1 - T_s a_0 \end{bmatrix} \); \( \beta \) is pole of discrete MALESO.

The gain matrix of the discrete estimator can be obtained as follows:

\[
\begin{align*}
l_1 &= \frac{2 - 2\beta - T_s a_0}{T_s} \\
l_2 &= \frac{\beta^2 + 2(T_s a_0 - 1)\beta + (1 - T_s a_0)^2}{T_s^2}
\end{align*}
\]  
(26)

The relationship between the discrete estimator pole and the continuous observer pole is[16]

\[
\beta = e^{-\alpha T_s}
\]  
(27)

According to (24), the structural block diagram of MALESO can be constructed, as shown in Fig. 2.

![FIGURE 2. Block diagram of MALESO](image-url)
B. Analysis of Convergence and Estimation Error of MALESO

According to (21) and (23), the transfer functions of \( z_1 \) and \( z_2 \) can be obtained, which are respectively as follows

\[
\begin{align*}
\z_1(s) &= \frac{b_0 s^3 + (2a_0 - a_1) s + a_0^2}{s^2 + a_0 s + a_0^2} y \\
\z_2(s) &= \frac{-a_0 b_0 s + b_0 a_0^2}{s^2 + a_0 s + a_0^2} u + \frac{(a_0 - a_1)^2 s}{s^2 + a_0 s + a_0^2} \eta
\end{align*}
\]

Let the tracking error \( e_1 = z_1 - y \), we can get

\[
e_1 = \frac{b_0 s^3 + (2a_0 - a_1) s + a_0^2}{s^2 + a_0 s + a_0^2} y
\]

(30)

Let tracking error \( e_2 = z_2 - y \), according to (13), there is \( f = x_2 = y - b_0 u \), then \( e_2 \) is expressed as

\[
e_2 = \frac{b_0 s^3 + (2a_0 - a_1) s + a_0^2}{s^2 + a_0 s + a_0^2} y
\]

(31)

Taking into account the typicality of the analysis, \( y \) and \( u \) both take the step signal \( y(2) = K/s \) and \( u(2) = K/s \) with an amplitude of \( K[17] \), then the steady-state error expressions can be obtained as follows

\[
\begin{align*}
e_{1s} &= \lim_{s \to 0} e_1 = 0 \\
e_{2s} &= \lim_{s \to 0} e_2 = 0
\end{align*}
\]

(32)

It can be seen from (32) that MALESO has good convergence and estimation ability, and can realize the undifferentiated estimation of system state variables and generalized disturbances.

C. Analysis of the Frequency Band Characteristics and Filtering Performance of MALESO

Considering the influence of the noise \( \delta_0 \) of observation variable \( y \) and the disturbance \( \delta_0 \) of the input end of control variable \( u \) on the second-order MALESO[17]-[19], the transfer function of the observation noise \( \delta_0 \) can be obtained according to (28) as follows

\[
\frac{z_1(s)}{\delta_0(s)} = \frac{b_0 s^3 + (2a_0 - a_1) s + a_0^2}{s^2 + 2a_0 s + a_0^2}
\]

(33)

Taking \( \omega_0 = 100 \), 200, and 300, the frequency domain characteristic curves can be obtained as shown in Fig. 3. It can be seen that with the increase of \( \omega_0 \), the system response speed is accelerated, but at the same time, the high frequency band gain increases, and the noise amplification effect is more obvious.

D. Design of ISMSC of PMSLM Based on MALESO

In order to improve the control accuracy of the sliding mode control system, when the generalized disturbance \( f \) cannot be measured, MALESO is designed and combined with a sliding mode speed loop controller. In this control method, the generalized disturbance \( f \) estimated value is used as the feedforward compensation item of ISMSC, thus, the output signal of ISMSC can be re-expressed as follows

\[
\frac{z_1(s)}{\delta_0(s)} = \frac{b_0 s^3 + (2a_0 - a_1) s + a_0^2}{s^2 + 2a_0 s + a_0^2}
\]
where \( z_2 \) is MALESO estimate.

It can be seen from (35) that ISMSC designed in this article can achieve online estimation and compensation for generalized disturbances, which can effectively weaken the chattering, improve the control accuracy and robustness of the sliding mode system, and enhance the anti-disturbance ability of the system. The block diagram of the system control structure of the improved control strategy proposed in this article is shown in Fig. 5.

**FIGURE 5. Block diagram of ISMSC of PMSLM based on MALESO**

In order to verify the stability of the control system proposed in this article, substituting (17) and (18) into (7) after derivation, we can get

\[
\dot{V} = s(\dot{v} + c x) = s(-f - b_i q + cx_i) = -\left| s \right| f(x_i) - q|x_i|^\beta s^2 \leq 0
\]  

(36)

According to the Lyapunov stability judgment, the whole closed-loop control system is asymptotically stable.

**V. SYSTEM SIMULATION VERIFICATION**

The effectiveness of the control strategy proposed in this article is verified by MATLAB/Simulink simulation. The vector control scheme with \( i_q = 0 \) is adopted. The three control strategies for TSMC[20], SMC based on LSEO and the control strategy proposed in this article, i.e., ISMC based on MALESO, are simulated and compared, and the parameters of the PMSLM are shown in Table 1.

**TABLE I**

| Parameter and unit | Value |
|--------------------|-------|
| the number of pole pairs \( p_n \) | 2 |
| pole distance \( \alpha \) mm | 60.96 |
| armature resistance \( R/\Omega \) | 2.875 |
| Inductance \( L=L/\text{nH} \) | 8.5 |
| the secondary permanent magnet flux linkage \( \psi_p/\text{Wb} \) | 0.16 |
| the mass of the moving part \( M/\text{kg} \) | 0.66 |
| viscous friction coefficient \( B_{nf}/\text{N·m·s} \) | 0.2 |

In order to verify the start-up performance and disturbance compensation performance of the control strategy proposed in this article, the motor adopts the no-load start-up mode, and the linear speed of the mover is given as 2 m/s; the load disturbance of 100 N is suddenly added at 0.15 s; the load disturbance is suddenly reduced to 50 N at 0.25 s. Moreover, the TSMC parameters of both current loops are the same as: \( k_p=L_i/1100 \), \( k_i=R_i/1100 \). The TSMC parameter of the speed loop is set as: \( c=150 \), \( k=200 \), \( q=300 \), \( T_c=1 \times 10^{-5} \). The SMC based on LSEO parameters are: \( c=95 \), \( k=0.5 \), \( q=1100 \), \( \beta=0.8 \), \( T_c=1 \times 10^{-5} \). The ISMC based on MALESO parameters are: \( c=990 \), \( k=0.05 \), \( q=175 \), \( \beta=0.8 \), \( T_c=1 \times 10^{-5} \).

Fig. 6 shows the comparison curves between the observed value of the generalized disturbance and the actual disturbance without considering the parameter perturbation and considering the parameter perturbation and \( \Delta B_m=B_m0 \) and \( \Delta \psi_p=\psi_p0 \), respectively. It can be seen from the Fig. 6 that when the load disturbance is abrupt and the parameters are perturbed, MALESO can estimate the generalized disturbance faster and more accurately except for the motor start-up phase, and then compensate the ISMC in a timely and effective manner.

**FIGURE 6. Comparison curves of observed value and actual value of generalized disturbance. (a) \( \Delta B_m=0 \) and \( \Delta \psi_p=0 \). (b) \( \Delta B_m=B_m0 \) and \( \Delta \psi_p=\psi_p0 \)**
speed at start-up without obvious overshoot. Combined with (5), it can explain why the MALESO is inaccurate in estimating the generalized disturbance in the motor start-up stage.

When the load disturbance is abrupt and the parameter is perturbed, the control performance of the SMC based on LESO and the ISMC based on MALESO is better than that of the TSMC. It can be seen from the partial enlarged image that the MALESO can quickly and accurately estimate the generalized disturbance, and compensate the ISMSC in a timely and effectively manner. Therefore, the speed response of the control strategy proposed in this article can quickly restore the steady state of when the load disturbance is abrupt and the parameters are perturbed, and effectively reduce the speed fluctuation and overshoot.

When the load disturbance is abrupt and the parameter is perturbed, the SMC based on LESO and the control strategy proposed in this article are better than the TSMC. It can be seen from the partial enlarged diagram that the electromagnetic thrust response of the control strategy proposed in this article has a faster response speed and smaller overshoot when the load disturbance is abrupt and the parameter is perturbed, and has a strong anti-disturbance capability and robustness.

**FIGURE 8.** Comparison curves of electromagnetic thrust response of three control strategies under load disturbance. (a) $\Delta B_m=0$ and $\Delta \psi=0$. (b) $\Delta B_m=B_m0$ and $\Delta \psi=\psi_0$

Fig. 9 and Fig. 10 are the $dq$-axis current response curves of the two control strategies of the SMC based on LESO and the control strategy proposed in this article without considering the parameter perturbation and considering the parameter perturbation and $\Delta B_m=B_m0$ and $\Delta \psi=\psi_0$, respectively. It can be seen from the figure that, compared with the SMC based on LESO, the overshoot time of the $dq$-axis current response of the control strategy proposed in this article is significantly shortened at start-up, and the $dq$-axis current response is basically not affected by the load disturbance and parameter perturbation, which can quickly track the change of the load torque.
VI. CONCLUSION

Aiming at the influence of generalized disturbance on the mover speed control performance of PMSLM, this article proposes ISMC strategy of PMSLM based on MALESO, in which the sliding mode controller is designed by IERL, and the generalized disturbance observer is designed by MALESO. The contributions of the article are as follows: (1) The IERL designed by introducing the speed tracking error signal as a state variable into TERL effectively optimizes the dynamic quality of the sliding mode motion, weakens the chattering phenomenon of SMC, and improves the system control precision; (2) The MALESO designed by adding some known motor information to TLESO can improve the estimation accuracy of the generalized disturbance without reducing LESO bandwidth, especially when the motor parameters are perturbed; (3) The observed generalized disturbance feedforward is compensated to ISMC to form ISMSC, which further improves the rapidity, stability, anti-disturbance ability and robustness of the system and can effectively suppress the chattering phenomenon of SMC. Simulations verify the feasibility and effectiveness of the control strategy proposed in this article.

REFERENCES

[1] L. C. Jiao, Z. P. Cheng. operating characteristics and control of permanent magnet linear synchronous motor[M]. Beijing: Science press, 2014: 3-23+119.
[2] W. B. Gao. Variable structure control theory[M]. Beijing: China Science and Technology Press, 1990: 28-30.
[3] J. Q. Han. Active disturbance rejection control technique-the technique for estimating and compensating the uncertainties[M]. Beijing: National Defense Industry Press, 2008.
[4] X. M. Zhao, C. Liu, G. X Zhu. Adaptive nonlinear sliding mode control for permanent magnet linear synchronous motor[J]. Electric Machines and Control, 2020, 24(07): 39-47.
D. X. Fu, X. M. Zhao. Adaptive nonsingular fast terminal sliding mode control for permanent magnet linear synchronous motor[J]. Transactions of China Electrotechnical Society, 2020, 35(04): 717-723.

D. X. Fu, X. M. Zhao. Adaptive backstepping global fast terminal sliding mode control for permanent magnet linear synchronous motor[J]. Transactions of China Electrotechnical Society, 2020, 35(08): 1634-1641.

F. Zhao, W. Luo, F. Y. Gao, et al. An improved sliding mode control for PMSM considering sliding mode chattering and disturbance compensation[J]. Journal of Xi’an JiaoTong University, 2020, 54(06): 28-35.

K. Zhang, K. Y. Cao, G. L. Kong. Sliding mode robust control for permanent magnet synchronous motor multiple disturbance[J]. Chinese Journal of Electron Devices, 2020, 43(06): 1346-1351.

P. F. Jin, Y. Xie, J. Wang, et al. Sliding mode control of permanent magnet synchronous motor based on load torque observer[J]. Small & Special Electrical Machines, 2018, 46(08): 62-64+69.

S. Yuan, J. X. Chen, Y. Zhou. Design of improved integral sliding mode structure based on extended state observer[J]. Transducer and Microsystem Technologies, 2021, 40(06): 107-109.

M. Wang. Research on novel non-singular terminal sliding mode speed control of permanent magnet synchronous motor introducing load disturbance compensation[D]. Xi’an University of technology, 2021.

J. Q. Han. Auto-disturbances-rejection controller and it’s applications[J]. Control and Decision, 1998, 13(1): 19-23.

X. G. Zhang, K. Zhao, L. Sun, et al. Sliding mode control of permanent magnet synchronous motor based on a novel exponential reaching law[J]. Proceedings of the CSEE, 2011,31(15): 47-52.

X. D. Guo, D. Bai, S. W. Zhou, et al. A PMSM sliding mode control system based on a novel exponential reaching law[J]. Control Engineering of China, 2018, 25(10): 1865-1870.

Z. Q. Gao. Scaling and bandwidth-parameterization based on controller tuning[C]. Proceedings of the American Control Conference. Denver Colorado, USA: IEEE,2003: 4989-4996.

B. Zhu. Getting started with active disturbance rejection control[M]. Beijing: Beihang University press, 2017: 37-47.

D. Yuan, X. J. Ma, Q. H. Zeng, et al. Research on frequency-band characteristics and parameters configuration of linear active disturbance rejection control of second-order systems[J]. Control Theory & Applications, 2013,30(12):1630-1640.

H. J. Mao, W. Li, D. N. Jiang, et al. State estimation and performance analysis based on linear extended state observer for permanent magnet synchronous motor[J]. Transactions of China Electrotechnical Society, 2019, 34(10): 2155-2165.

B. Sun, H. X. Wang, T. Su, et al. Nonlinear active disturbance rejection controller design and tuning for permanent magnet synchronous motor speed control system[J]. Proceedings of the CSEE, 2020, 40(20):6715-6726.