Active-Disturbance-Rejection-Based Sliding-Mode Current Control for Permanent-Magnet Synchronous Motors

Lizhi Qu, Member, IEEE, Wei Qiao, Fellow, IEEE, and Liyan Qu, Senior Member, IEEE

Abstract—To improve the tracking performance of the current controllers of permanent-magnet synchronous motor (PMSM) drive systems that are subject to internal disturbances, such as parameter variations, a novel active-disturbance-rejection-based sliding-mode current control (ADR-SMCC) scheme for PMSM drives is proposed in this article. First, a fast-response SMCC is designed based on the upper bound of the internal disturbance. Then, an extended state observer (ESO) is designed to estimate the internal disturbance in real time without the need for an accurate mathematical model of the PMSM. The parameters of the ESO can be easily designed based on the desired bandwidth of the ESO. The estimated internal disturbance is then used to update the control law of the SMCC in real time. The resulting ADR-SMCC has improved steady-state and transient current tracking performance and enhanced robustness to internal disturbances. The stability of the closed-loop PMSM drive system with the ADR-SMCC is proven by the Lyapunov theory. The ADR-SMCC is validated by experimental results for a 200-W salient-pole PMSM drive system.

Index Terms—Active disturbance rejection control (ADRC), extended state observer (ESO), permanent-magnet synchronous motor (PMSM), sliding-mode current control (SMCC).

I. INTRODUCTION

PERMANENT-MAGNET synchronous motors (PMSMs) have been widely employed in industrial applications due to their high reliability, high efficiency, and high power density [1], [2]. The PMSM drives usually adopted a double closed-loop control scheme designed by using the field-oriented control (FOC) technique. The inner current control loop, which affects the performance of the drive system directly, needs precise tracking performance. Due to its simplicity, the traditional linear proportional-integral (PI) control method has been widely applied to design the current controllers for PMSM drives [3]. However, parameter variations or mismatches, which are considered as uncertain internal disturbances in this article, are always present in practical PMSM drives. The performance of the traditional linear PI controller will degrade when the disturbances occur.

To improve the performance of the PMSM drive systems with uncertain disturbances, many current control schemes, such as hysteresis control [4], [5], model predictive control (MPC) [6], [7], and sliding-mode control (SMC) [8]–[15], have been developed for PMSM drives. Among these current control schemes, the hysteresis control provides some advantages, such as simple algorithm implementation, fast current response, and strong robustness to disturbances [5], but it also has some drawbacks, such as variable switching frequencies and large current ripples. Based on a discrete-time model of the PMSM, the MPC can forecast and determine future voltage vectors to optimize a certain cost function, such as the robustness to disturbances [7]. However, precise predictions in the MPCs may need high computational costs, which may limit industrial applications of some MPCs. The SMC method has demonstrated superior tracking performance with simple implementation as compared to the hysteresis control and MPC in different applications [8]–[10]. However, since the disturbances usually vary over large ranges, the robustness of the SMC to disturbances was usually achieved by using a large switching gain, which yielded an undesired chattering problem [8]. To overcome this drawback, combining the SMC with a disturbance observer is an attractive proposition. The disturbance observer estimates the internal disturbance of the system in real time. The estimated disturbance is then used timely to adapt the switching gain of the SMC to mitigate the impact of the disturbance variation on the performance of the SMC [11], [12]. Various disturbance observers combined with SMCs have been designed for the speed and/or current controls of PMSM drives [13]–[15]. However, the design of these disturbance observers still relies on an accurate model of the drive system. Moreover, their parameter designs are complex.

Recently, a new method called active disturbance rejection control (ADRC) [16], [17] has attracted considerable attention due to its intrinsic ability of disturbance rejection and the simple design process without the need for an accurate system model. The ADRC has been applied in motor drives [18]–[20]. In [18], a robust control scheme using three first-order ADRCs was presented for the speed control of induction motor drives without the need for rotor flux estimation, which reduced the
computing cost. In [19], an ADRC-based sensorless control scheme for interior PMSM drives was proposed to improve the stiffness of the speed loop by estimating and compensating for the total disturbance of the sensorless drive system. However, the current loop was still designed by using the conventional PI controller. In [20], a hybrid sensorless FOC scheme combining an ADRC-based high-frequency current injection method with another ADRC-based back electromotive force method for the rotor position estimations of PSMSSs in low- and high-speed regions, respectively, was presented. The two ADRC-based rotor position estimation methods were integrated into the same current controllers designed by using the simple proportional control method.

This article proposes a novel active-disturbance-rejection-based sliding-model current controller (ADR-SMCC) for FOC-based PMSM drives to improve their disturbance rejection ability as well as steady-state and dynamic current tracking performance. The disturbances considered include PMSM inductance and resistance variations. The ADR-SMCC combines an SMCC with an extended state observer (ESO), which is a core part of the ADRC. The SMCC is designed to achieve fast current tracking performance based on the upper bound of the internal disturbance, which is estimated in real time by the ESO. The design of the ESO does not require an accurate mathematical model of the PMSM. Moreover, the parameters of the ESO can be simply designed based on its desired bandwidth. The control law of the SMCC is then updated in real time by using the upper bound of the disturbance estimated by the ESO in the feedforward path to mitigate the influence of the disturbance on the current tracking performance in both steady-state and transient conditions. Thus, the ADR-SMCC is robust to system disturbances while maintaining fast current tracking performance. The stability of the closed-loop PMSM drive system with the ADR-SMCC is proven by using the Lyapunov theory.

The rest of article is organized as follows. Section II presents the dynamic model of a salient-pole PMSM that considers disturbances and the SMCC design. Section III presents the proposed ESO and ADR-SMCC, the current tracking error dynamic analysis, and the parameter design method for the ESO. Experimental results on a salient-pole PMSM drive system are provided in Section IV to show the superiority of the ADRC-SMCC over the conventional PI current controller (PICC), the SMCC, and the disturbance observer-based SMCC (DO-SMCC). Finally, Section V concludes this article.

II. SMCC DESIGN FOR PMSM DRIVES

A. Dynamic Model of a Salient-Pole PMSM Considering Disturbances

The current model of a salient-pole PMSM in the $d$-$q$ reference frame considering parameter variations is expressed as

$$\begin{align*}
    \dot{i}_{sd} &= \left( v_{sd} - R_{sd}i_{sd} + \omega_{re}L_{d0}i_{sq} \right) / L_{d0} + f_{sd} \\
    \dot{i}_{sq} &= \left( v_{sq} - R_{sq}i_{sq} - \omega_{re}L_{d0}i_{sd} - \psi_{m0}\omega_{re} \right) / L_{q0} + f_{sq}
\end{align*}$$

where $v_{sd}$ and $v_{sq}$ are the $d$- and $q$-axis stator voltages, respectively; $i_{sd}$ and $i_{sq}$ are the $d$- and $q$-axis stator currents, respectively; $\omega_{re}$ is the rotor electrical angular speed; $p = d/dt$ is the time derivative operator; $R_{sd}$ is the nominal stator armature resistance; $L_{d0}$ and $L_{q0}$ are the nominal $d$- and $q$-axis inductances, respectively; $\psi_{m0}$ is the nominal rotor magnet flux linkage; $f_{sd}$ and $f_{sq}$ represent the $d$- and $q$-axis unknown internal disturbances containing the information of parameter variations, respectively, which are defined as follows:

$$\begin{align*}
    f_{sd} &= (-\Delta R_{sd}i_{sd} - \Delta L_{d0}i_{sq} + \omega_{re}\Delta L_{q0}i_{sq}) / L_{d0} \\
    f_{sq} &= (-\Delta R_{sq}i_{sq} - \omega_{re}\Delta L_{d0}i_{sd} - \Delta L_{q0}i_{sq} - \Delta \psi_{m0}\omega_{re} / L_{q0})
\end{align*}$$

where $\Delta R_{sd} = R_{sd} - R_{sd0}$; $\Delta L_{d0} = L_{d0} - L_{d00}$; $\Delta L_{q0} = L_{q0} - L_{q00}$; $\Delta \psi_{m0} = \psi_{m0} - \psi_{m00}$; $R_{sd}$, $R_{sq}$, $L_{d0}$, $L_{q0}$, and $\psi_{m0}$ denote the actual parameter values. In addition, assume that $|\Delta R_{sd}| < a$, $|\Delta L_{d0}| < b$, $|\Delta L_{q0}| < c$, and $|\Delta \psi_{m0}| < d$, where $a$, $b$, $c$, and $d$ are the corresponding upper bounds of the parameter variations.

B. SMCC Design for the PMSM

Define the $q$-axis stator current error $e_{q}$ as follows:

$$e_{q} = i_{sq} - i_{sqr}$$

where $i_{sqr}$ is the $q$-axis stator current reference. The objective of the SMCC is to control $e_{q}$ to be zero.

To design the SMCC, the following sliding surface function [15] is chosen due to its simple structure and precise current tracking performance:

$$\sigma_{q} = e_{q} + c_{q} \int e_{q}$$

where $c_{q}$ is a positive number that determines the decay rate of the $q$-axis stator current error.

Then, a suitable control law is derived such that $\sigma_{q}$ satisfies the following sliding mode condition:

$$\sigma_{q} \dot{\sigma}_{q} < 0.$$  \hspace{1cm} (5)

If (5) is satisfied, $\sigma_{q}$ will approach zero in finite time. To satisfy (5), the control law of the SMCC can be designed as follows to generate the $q$-axis stator voltage reference $v_{sq}$:

$$\begin{align*}
    v_{sq} &= L_{q0}[p_{sq}i_{sq} + R_{sq}i_{sq} / L_{q0} + \omega_{re}L_{d0}i_{sq} / L_{q0} + c_{q} \dot{e}_{q} + \eta_{q} sgn(\sigma_{q})]
\end{align*}$$

where $sgn$ is the sign function and $\eta_{q}$ is the $q$-axis switching gain, which guarantees the stability, induces a sliding motion on the sliding surface in finite time, and is defined as follows:

$$\eta_{q} > \frac{1}{L_{q0}} (a |i_{sq}| + b |\omega_{re}| |i_{sd}| + c |p_{sq}| + d |\omega_{re}|).$$  \hspace{1cm} (7)

Then, the sliding mode condition (5) can be proven to be satisfied as follows:

$$\begin{align*}
    \sigma_{q} \dot{\sigma}_{q} &= \sigma_{q}(p_{sq}i_{sq} - p_{sq}i_{sq} + c_{q} \dot{e}_{q}) \\
    &= \sigma_{q}(p_{sq}i_{sq} - v_{sq}/L_{q0} + R_{sq}i_{sq}/L_{q0} + \omega_{re}L_{d0}i_{sq}/L_{q0} + c_{q} \dot{e}_{q}) \\
    &= \sigma_{q}(v_{sq} - L_{q0}i_{sq} - \omega_{re}L_{d0}i_{sq} - \psi_{m0}\omega_{re} / L_{q0})
\end{align*}$$
\[ + \Delta L_q p_i_{sq} / L_{q0} + \Delta \psi_m \omega_{re} / L_{q0} + c_q e_q \]
\[ = - \eta_q | \sigma_q | + (| \Delta R_s | i_{sq} + \omega_{re} \Delta L_d i_{sd} + \Delta L_q p_i_{sq} + \Delta \psi_m \omega_{re} \sigma_q / L_{q0} \]
\[ \leq - \eta_q | \sigma_q | + (| \Delta R_s | | i_{sq} | + | \Delta L_d | | \omega_{re} | | i_{sd} | + | \Delta L_q | | p_i_{sq} | + | \Delta \psi_m | | \omega_{re} | \sigma_q / L_{q0} \]
\[ \leq - \eta_q | \sigma_q | + (a | i_{sq} | + b | \omega_{re} | | i_{sd} | + c | p_i_{sq} | + d | \omega_{re} | \sigma_q / L_{q0} \]
\[ = - \eta_q + (a | i_{sq} | + b | \omega_{re} | | i_{sd} | + c | p_i_{sq} | + d | \omega_{re} | \sigma_q / L_{q0} \] \[ < 0. \] \[ (8) \]

Thus, the closed-loop q-axis current control system is asymptotically stable [21].

The d-axis control voltage \( v_{sdr} \) can be derived in a similar way. Consider the current model (1) and define the q-axis stator current tracking error \( e_q = i_{sdr} - i_{sd} \) and the d-axis sliding surface function as \( \sigma_d = c_q + c_q \int e_d \), where \( i_{sdr} \) is the d-axis stator current reference; \( c_q \) is a positive number that determines the decay rate of the d-axis stator current error. Then, \( v_{sdr} \) can be obtained as follows to satisfy the sliding mode condition \( \sigma_d \sigma'_d < 0 \):
\[ v_{sdr} = L_{d0} [p_i_{sd} + R_s i_{sd} / L_{d0} - \omega_{re} L_{q0} i_{sq} / L_{d0} + c_d e_d + \eta_d \text{sgn}(\sigma_d)] \] \[ (9) \]

where \( \eta_d \) is the d-axis sliding gain, which guarantees the stability, induces a sliding motion on the sliding surface in finite time, and is defined as follows:
\[ \eta_d > \frac{1}{L_{d0}} (a | i_{sd} | + b | p_i_{sd} | + c | \omega_{re} | | i_{sq} |) . \] \[ (10) \]

III. PROPOSED ADR-SMCC FOR PMSM DRIVES

The SMCC has a certain degree of robustness to the internal disturbance, i.e., parameter variations. To minimize the effect of the chattering problem, a small switching gain is desired for the SMCC. However, to ensure that the SMCC is robust to large disturbances, a large switching gain is desired, which, however, will lead to the undesired chattering problem. An attractive proposition to solve this dilemma is to make the control law of the SMCC adaptive to the disturbance, which is estimated online by a disturbance observer.

A. Proposed ADR-SMCC for the PMSM

An ESO is designed as follows to online estimate the q-axis internal disturbance \( f_{dq} \) that contains the information of the unknown q-axis parameter variations:

\[
\begin{aligned}
  e_q &= \dot{i}_{sq} - i_{sq} \\
p_i_{sq} &= v_{sq} / L_{q0} - R_s \cdot i_{sq} / L_{q0} - \omega_{re} \cdot L_{d0} \cdot i_{sd} / L_{q0} - \psi_m \omega_{re} / L_{q0} + \dot{\beta}_{01} e_q \\
p f_{dq} &= -\beta_{02} e_q
\end{aligned}
\] \[ (11) \]

where \( i_{sq} \) is the estimated q-axis stator current; \( \dot{f}_{dq} \) represents the estimated q-axis internal disturbance; \( \beta_{01} \) and \( \beta_{02} \) are the gains of the ESO.

By taking into account the estimated internal disturbance, a new q-axis control law of the SMCC is designed as follows to generate the new q-axis stator voltage reference \( v_{sqr} \):
\[ v_{sqr} = L_{q0} [p_i_{sq} + R_s i_{sq} / L_{q0} + \omega_{re} L_{d0} i_{sd} / L_{q0} + \psi_m \omega_{re} / L_{q0} + c_q e_q + \eta'_q \text{sgn}(\sigma_q) + \dot{f}_{dq}] \] \[ (12) \]

where \( \eta'_q \) is a positive constant, which is much smaller than the original switching gain \( \eta_q \) expressed by (7) to avoid the large chattering problem; \( m_q \) is the compensation gain designed as \( m_q = \sigma_q / \dot{f}_{dq} > 0 \).

If the bandwidth of the ESO is high enough as compared with the time variation of the internal disturbance, the variation of \( f_{dq} \) is nearly zero during each short sampling period, such as 100–200 µs commonly used for FOC-based PMSM drives, that is, \( f_{dq} = 0 [15] \). Define the internal disturbance observation error \( \Delta f_{dq} = f_{dq} - \dot{f}_{dq} \). Then
\[ \Delta f_{dq} = \dot{f}_{dq} - \dot{f}_{dq} = -\dot{f}_{dq} . \] \[ (13) \]

Define the following Lyapunov function:
\[ V = \frac{1}{2} \sigma_q^2 + \frac{1}{2} m_q \Delta f_{dq}^2 . \] \[ (14) \]

Then, the derivative of \( V \) can be derived as follows:
\[ \dot{V} = \eta_q \sigma_q + m_q \Delta f_{dq} \Delta f_{dq} \]
\[ = \eta_q (p_i_{sq} + R_s i_{sq} / L_{q0} + \omega_{re} L_{d0} i_{sd} / L_{q0} + \psi_m \omega_{re} / L_{q0} + f_{dq} + c_q e_q) + m_q \Delta f_{dq} \Delta f_{dq} \]
\[ = \eta_q f_{dq} - f_{dq} - \eta'_q \text{sgn}(\sigma_d) + m_q \Delta f_{dq} \Delta f_{dq} \]
\[ \leq - \eta'_q | \sigma_q | + (f_{dq} - \dot{f}_{dq}) \sigma_q + m_q (f_{dq} - f_{dq}) \dot{f}_{dq} \]
\[ = - \eta'_q | \sigma_q | < 0 . \] \[ (15) \]

Thus, the asymptotical stability of the closed-loop q-axis current control is proved. Finally, the q-axis control law of the proposed ADR-SMCC is obtained by combining (11) and (12).

The d-axis control law of the ADR-SMCC can be derived in a similar way as follows:
\[ v_{sdr} = L_{d0} [p_i_{sd} + R_s i_{sd} / L_{d0} - L_q \omega_{re} i_{sq} / L_{d0} + c_d e_d + \eta'_d \text{sgn}(\sigma_d) + \dot{f}_{dq}] \] \[ (16) \]

where \( \eta'_d \) is a positive constant, which is much smaller than the original switching gain \( \eta_d \) expressed by (10) to avoid the large chattering problem; \( \dot{f}_{dq} \) represents the estimated d-axis internal disturbance that contains the information of the unknown d-axis parameter variations.

Fig. 1 depicts the block diagram of the plant controlled by the ADR-SMCC scheme, where \( x \) stands for \( d \) and \( q \), respectively. Fig. 2 depicts the block diagram of the entire FOC scheme for a PMSM drive that uses the proposed ADR-SMCC for the current tracking control, where the PMSM, inverter, space-vector...
pulselength modulation (SVPWM), and coordinate transformation blocks form the plant in Fig. 1. The PMSM is fed by a pulselength modulated inverter. The entire control system adopts the commonly used double-loop structure. A PI controller is used for the outer speed loop, which generates the reference \(i_{sqr}\) for the torque producing current \(i_{sq}\). The reference of the field current \(i_{sd}\) is set to be 0 A. The proposed ADR-SMCC is used for the inner current loop, which generates the desired voltage vector for the pulselength modulation (PWM) control of the PMSM inverter. An incremental encoder is used to measure the PMSM rotor position \(\theta_{r}\) for the coordinate transformation. The rotor speed \(\omega_{rc}\) is obtained by differentiating the rotor position \(\theta_{r}\).

**B. Stability Analysis and Parameter Design for the ESO**

Let \(e_{mq} = [i_{sq} - i_{sq}, f_{dq} - f_{dq}]^T\) be the tracking error of the \(q\)-axis ESO. According to the \(q\)-axis current model in (1) and (11), the error state equation can be derived as

\[
\dot{e}_{mq} = A_{mq}e_{mq}
\]

where \(A_{mq} = \begin{bmatrix} -\beta_{01} & 1 \\ \beta_{02} & 0 \end{bmatrix}\). Equation (17) shows that the eigenvalues of \(A_{mq}\) determine the behavior of the ESO. If and only if \(\beta_{02} > 0\), the error dynamics (17) is asymptotically stable.

The parameters of the ESO can be simply designed according to the desired bandwidth of the ESO [22]. Specifically, in this work, the parameters of the ESO are designed such that the matrix \(A_{mq}\) has a double eigenvalue \(\lambda\) that is equal to the bandwidth of the ESO. Thus, the following equation should be satisfied:

\[
|\lambda E - A_{mq}| = \lambda^2 + \beta_{01}\lambda + \beta_{02} = (\lambda + \omega_0)^2
\]

where \(\omega_0\) is viewed as the bandwidth of the ESO, which should be large enough to ensure that the dynamics of the ESO is sufficiently fast to track the variation of the internal disturbance. Once \(\omega_0\) is chosen, the ESO parameters can be determined according to (18) to be \(\beta_{01} = 2\omega_0\) and \(\beta_{02} = \omega_0^2\).

The stability can be analyzed and the parameters can be designed for the \(d\)-axis ESO in the same way.

**IV. EXPERIMENTAL RESULTS**

**A. Experiment Setup**

Experimental studies are carried out for a 200-W FOC-based salient-pole PMSM drive system to evaluate the proposed ADR-SMCC in comparison with the conventional PICC, the SMCC, and the DO-SMCC [15]. The block diagram and hardware setup of the experiment system that is shown in Figs. 3 and 4, respectively. The parameters of the PMSM and experiment system are listed
in Table I. The control algorithms are implemented in a dSPACE 1104 real-time control system.

In the experimental studies, the same PI controller with a bandwidth of 285 Hz is used for the speed loops of the FOC systems with the four different current control schemes. The bandwidth of the conventional PICC is chosen as 2000 Hz according to [23] and [24]. The bandwidth of the ESO is designed as 2000 Hz as a tradeoff between current tracking performance and immunity to noise. The SMCC parameter $\epsilon_q$ that determines the decay rate of the stator current error is usually between 0 and 1 and is chosen to be 0.1 to achieve fast current tracking performance in this article. The SMCC parameters $\eta_q$ and $\eta_{\delta q}$ are chosen to be 2 according to (7) and 0.01 according to the definition after (12), respectively. The compensation gain $m_2$, which only needs to be larger than zero, is chosen to be 0.5 as a tradeoff between steady-state and transient performance. The corresponding parameter settings of the $d$-axis current controllers of the ADR-SMCC are the same as those of the $q$-axis current controllers of the ADR-SMCC.
Fig. 7. Experimental results at 1500 r/min with a $d$-axis current reference step change. (a) PICC. (b) SMCC. (c) DO-SMCC. (d) Proposed ADR-SMCC.

Fig. 8. Comparison of transient responses of the four $d$-axis current controllers.

B. Sudden Current Changes at Constant Speed Without PMSM Parameter Mismatch

In this test, the speed reference is kept constant at 1500 r/min. The $q$-axis current reference is step changed from 0 to 5 A.

Fig. 9. Mismatch of the $d$- and $q$-axis inductances used by the four current controllers.

Fig. 5 compares the reference and actual $q$-axis currents and the $q$-axis current tracking errors of the PMSM with the PICC, the SMCC, the DO-SMCC, and the proposed ADR-SMCC during the test. Fig. 6 compares the detailed transient responses of the
Fig. 10. Experimental results at 1500 r/min with the inductance mismatch. (a) PICC. (b) SMCC. (c) DO-SMCC. (d) Proposed ADR-SMCC.

Table III

<table>
<thead>
<tr>
<th>Performance metrics</th>
<th>ADR-SMCC</th>
<th>DO-SMCC</th>
<th>SMCC</th>
<th>PICC</th>
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</thead>
<tbody>
<tr>
<td>Amplitude of $d$-axis current tracking error $e_d$ (A) (before/after inductance mismatch)</td>
<td>0.12/0.12</td>
<td>0.52/0.61</td>
<td>0.70/0.82</td>
<td>0.85/1.15</td>
</tr>
<tr>
<td>Amplitude of $q$-axis current tracking error $e_q$ (A) (before/after inductance mismatch)</td>
<td>0.12/0.12</td>
<td>0.58/0.67</td>
<td>0.73/0.91</td>
<td>0.96/1.28</td>
</tr>
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Fig. 11. Mismatch of the stator resistance used by the four current controllers.

DO-SMCC and ADR-SMCC after the sudden $q$-axis current change are much shorter than those of the SMCC and the PICC; the amplitudes of the $q$-axis current tracking error of the two observer-based SMCC schemes are much smaller than those of

four different $q$-axis current controllers. Table II compares the settling time $t_s$, rising time $t_r$, and amplitudes of current tracking error $e_{dq}$ using the four $q$-axis current controllers after the current reference step change. The test results show that the settling time and rising time of the two observer-based SMCC schemes
the SMCC and the PICC due to the significant mitigation of the chattering problem. Moreover, with the help of the ESO to properly estimate and compensate for the internal disturbance in (2) in both the steady-state and transient conditions, shown in Fig. 5(d), the transient current tracking performance of the proposed ADR-SMCC is better than that of the DO-SMCC.

Similarly, the $d$-axis current reference is also step changed from 0 to 5 A. Fig. 7 compares the reference and actual $d$-axis currents and the $d$-axis current tracking errors of the PMSM with the PICC, the SMCC, the DO-SMCC, and the proposed ADR-SMCC during the test. Fig. 8 compares the detailed transient responses of the four different $d$-axis current controllers. Table I also compares the settling time $t_s$, rising time $t_r$, and amplitudes of current tracking errors $e_{sd}$ using the four $d$-axis current controllers after the current reference step change. The test results show that the settling time and rising time of the two observer-based SMCC schemes DO-SMCC and ADR-SMCC after the sudden $d$-axis current change are much shorter than those of the SMCC and the PICC; the amplitudes of the $d$-axis current tracking error of the two observer-based SMCC schemes
are much smaller than those of the SMCC and the PICC due to the significant mitigation of the chattering problem. Moreover, with the help of the ESO to properly estimate and compensate for the internal disturbance in (2) in both the steady-state and transient conditions, shown in Fig. 7(d), the transient current tracking performance of the proposed ADR-SMCC is better than that of the DO-SMCC.

C. Constant Current at Constant Speed With PMSM Parameter Mismatch

In this test, the speed, $d$-axis, and $q$-axis current references are kept constant at 1500 $r/min$, 5 A, and 5 A, respectively. Assume that the $d$-axis inductance $L_d$ and $q$-axis inductance $L_q$ used by the four current controllers are mismeasured to be 200% of $L_{d_0}$ and $L_{q_0}$ from 0.1 s onward, respectively, as shown in Fig. 9. Fig. 10 and Table III compare the current tracking performance of the PMSM using the PICC, the SMCC, the DO-SMCC, and the proposed ADR-SMCC during the test. The results clearly show that the magnitude of the $d$-axis current tracking error $e_{sd}$ using the proposed ADR-SMCC is much smaller than those using the DO-SMCC, the SMCC, and the PICC. Moreover, with the help of the ESO for estimating and compensating the $d$-axis internal disturbance in (2) in the ADR-SMCC, shown in Fig. 10(d), the current tracking performance is not affected by the inductance mismatch at all. However, when using the DO-SMCC, the SMCC, or the PICC, the magnitude of the $d$-axis current tracking error increases significantly when the stator resistance mismatch occurs. Thus, the ADR-SMCC exhibits a remarkably improved robustness to the disturbance (resistance mismatch) compared to the PICC, the SMCC, and the DO-SMCC. Similar results are obtained for the $q$-axis current controllers, as shown in Fig. 12 and Table IV.

V. CONCLUSION

An ADR-SMCC was proposed for PMSM drive systems to achieve fast dynamic response, precise current tracking performance, and strong robustness to internal disturbances of the system, such as parameter variations or mismatches. First, a fast-response SMCC was designed based on the upper bound of the internal disturbance. Then, an ESO was proposed to online estimate the internal disturbance of the PMSM drive system. Finally, the control law of the SMCC was adapted by compensating the estimated internal disturbance with the stability proven by the Lyapunov theory, leading to an ADR-SMCC with an improved disturbance rejection ability over the SMCC and the DO-SMCC. The experimental results showed that the PMSM drive system using the proposed ADR-based SMCC has a better disturbance rejection capability, smaller current tracking error, and improved dynamic response than that using the conventional PICC, the SMCC, and the DO-SMCC.

REFERENCES


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