An Improved Hybrid Control Scheme of a Switched Reluctance Motor for Torque Ripple Reduction

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Abstract: In this paper, we present an improved hybrid control scheme based on model predictive torque control using linear active disturbance rejection control (LADRC) for the torque drive system of a 12/14 bearingless switched reluctance motor. The proposed approach can considerably reduce the torque ripple and enhance the anti-disturbance ability. First, a modified piecewise torque sharing function (TSF) is applied to reduce the torque ripple in the commutation interval. Second, model predictive control is introduced to further reduce the torque ripple caused by the hysteresis control. The selection of the optimal weighting factor is avoided, as the current value corresponding to different positions of each phase is determined by the TSF; thus, the cost function can be simplified. Then, a speed controller is designed by an enhanced LADRC for improved tracking performance and anti-disturbance ability, whereby a proportional gain of observation error and a time-varying function are investigated in extended-state observer. Finally, experiments are carried out to verify the effectiveness of the hybrid control scheme by comparison with cosine TSF function and conventional LADRC.

Keywords: switched reluctance motors; torque sharing function; model predictive control; linear active disturbance rejection control

1. Introduction

Switched reluctance motors (SRMs), with a simple structure, low manufacturing cost, and strong robustness, have been extensively studied [1–3]. However, owing to their double salient structure and nonlinear magnetic characteristics, the torque ripple is larger in SRMs than other motors, such as permanent magnet motors and induction motors, especially in the commutation interval. Therefore, a number of approaches regarding torque ripple suppression have been proposed, such as design, optimization, modeling, and control [4–6]. In terms of the control scheme, a basic control strategy and an advanced control algorithm are the two main research directions [7–9].

Popular control strategies in recent years can be classified as torque sharing function (TSF), current profiling, direct instantaneous torque control, direct torque control, and model predictive control (MPC) [10–12]. Among them, TSF allocates the desired torque to each phase; thus, the resultant instantaneous torque can track the desired torque produced by the controller [13,14]. Related improvement studies with respect to functional expression and optimization have been presented. In terms of functional design, for instance, an offline TSF [15], a TSF with a nonlinear modulating factor [16], and a TSF based on dynamic allocation [17] have been proposed to reduce the torque ripple and copper loss. Furthermore, approaches involving compensating current and torque error have been introduced to obtain improved torque performance [18,19]. As another direction on the optimization procedure, related studies on comprehensive performance have also been presented, such as objective functions considering current and the rate of change of current [20–22].

For constraints and multivariable systems, MPC is an alternative method that predicts the future output value according to the current state quantity [23]. The future values,
including current, torque, and flux linkage, can be predicted according to the model. Then, the construction of cost function is established to select the appropriate operation mode. The technique involves online correction and rolling optimization of the model according to feedback information. In [12,24], a virtual space vector modulation and a novel switching table were established to suppress the torque ripple, achieve high efficiency, and reduce the computational burden. In recent works, MPC was combined with other strategies to further improve the performance. For instance, MPC was integrated with DTC to achieve desired performances, such as elimination of negative torque [25]. Similarly, the combination of TSF and MPC can effectively suppress the torque ripple and avoid the frequency conversion caused by hysteresis control [26–28]. Moreover, several control techniques, i.e., adaptive control, deadbeat control, and current profiling, were incorporated with MPC to achieve performances such strong anti-disturbance ability, fixed switching frequency, low torque ripple, and an extended speed range [29,30].

Aside from the multiple control strategy, a variety of control algorithms have been successfully applied to the design of speed controllers for performance improvement. Sliding mode control, adaptive control, active disturbance rejection control (ADRC), and fuzzy control all exhibit considerable potential significance [31–33]. As a common control algorithm, ADRC performs well in speed tracking, adaptability, and anti-disturbance ability [34,35]. In [36], a high-gain nonlinear error decay function based on ADRC was presented to enhance performance during starting operation. Aside from nonlinear ADRC, linear ADRC (LADRC) has been applied in various engineering applications, owing to its fewer tunable parameters. For instance, a class of linear–nonlinear switching ADRC [37] and several advanced LADRCs [38] were designed for strong anti-disturbance ability, the speed of the observer, and position estimation performance, respectively. Other control approaches, i.e., sliding mode control [39] and iterative learning control [40], have also been incorporated into ADRC for performance improvements.

In this paper, an improved hybrid control scheme based on model predictive torque control (MPTC) and LADRC was proposed to achieve satisfactory performance. The MPTC consisting of a modified TSF and MPC was introduced to reduce the torque ripple, whereby hysteresis control was eliminated. On this basis, a speed controller using improved LADRC was introduced to enhance the anti-disturbance ability. The remainder of this paper is organized as follows. In Section 2, the modeling of SRM and modified TSF are described and analyzed. In Section 3, we present the MPTC strategy according to MPC instead of hysteresis control in TSF. Then, in Section 4, improved LADRC is utilized to design a speed controller. Experimental results are presented in Section 5, followed by the conclusion in Section 6.

2. The Modeling of SRM and TSF Control

2.1. Mathematical Modeling

Ignoring cross saturation, the voltage equation of SRM can be expressed as

\[ U_p = R_p i_p + \frac{d}{dt}\left(\frac{\partial \psi_p}{\partial i_p} i_p \theta\right) \]

\[ = R_p i_p + \frac{\partial \psi_p}{\partial i_p} \frac{d\theta}{dt} + \frac{\partial \psi_p}{\partial i_p} \frac{di_p}{dt} \]  

(1)

where \( \theta \) represents the rotor position angle, and \( i_p, \psi_p, U_p, \) and \( R_p \) are phase current, phase flux linkage, phase voltage, and the phase resistance of phase \( p \), respectively. The phase number of the motor is \( N_p = 2 \) and \( p = \{1,2\} \) in this paper.

The mechanical motion equation of the SRM is expressed as

\[ T_e = J \frac{d\omega}{dt} + D \cdot \omega + T_L \]  

(2)

where \( \omega = \frac{d\theta}{dt} \) is the angular speed, and \( T_e, J, D, \) and \( T_L \) are the total torque, rotational inertia, coefficient of friction, and load torque, respectively.
The instantaneous phase torque can be calculated according to the derivation of the magnetic coenergy, which is expressed as

$$T_p = \frac{\partial W_c(\theta, i_p)}{\partial \theta} \bigg|_{i_p=\text{const}}$$  \hspace{1cm} (3)$$

where $T_p$ and $W_c$ are the phase torque of phase $p$ and the magnetic coenergy, respectively. The phase torque based on the torque modeling can be established as [28]

$$T_p = \left[ \frac{L_b - L_c}{2} i_p^2 + Ai_p - \frac{A}{B} \left(1 - e^{-Bi_p}\right) \right] f(\theta)$$  \hspace{1cm} (4)$$

$$\begin{align*}
A &= \psi_m - L_b i_m \\
B &= (L_a - L_b)/\left(\psi_m - L_b i_m\right) \\
f(\theta) &= 2N_r^3 \theta^3/\pi^3 - 3N_r^2 \theta^2/\pi^2 + 1
\end{align*}$$  \hspace{1cm} (5)$$

where $N_r$, $L_a$, $L_b$, and $L_c$ are the number of rotor poles, linear inductance before saturation, saturated inductance, and non-saturated inductance, respectively, and $i_m$ and $\psi_m$ are the maximum current and corresponding flux linkage, respectively. For a more intuitive expression, the magnetization curves can illustrate the related parameters obtained from the finite element model, as shown in Figure 1. Correspondingly, $N_r = 14$, $A = 0.09$, and $B = 0.03$ according to simulation calculation.

![Figure 1. Magnetization curves.](image)

**2.2. Torque Sharing Function**

The most prominent feature of SRM is the commutation operation. During commutation, the switch of the former phase ($p$) is off, and the output torque decreases. The latter phase ($p + 1$) is conductive, and the output torque increases. The goal of the TSF design is to make the increased torque exactly offset the decreased torque; thus, the total output torque can remain constant. A TSF control strategy combining hysteresis control is employed to allocate the given torque to each phase based on the distribution function. Then, the synthetic instantaneous torque can track the given torque output by the speed controller [13–16,19]. The control block of the TSF strategy is shown in Figure 2.
Figure 2. The TSF control block strategy.

The curve shape and expression of distribution function determine the inhibition effect of torque ripple and the waveform of phase current. The four conventional TSFs are linear, exponential, cubic, and cosine. The sum of each phase TSFs at any time must be constant at 1, so the following equation is satisfied.

\[
\begin{align*}
    \sum_{p=1}^{N_p} f_p(\theta) &= 1, \quad 0 \leq f_p(\theta) \leq 1 \\
    T_p^* &= T^* f_p(\theta)
\end{align*}
\]  

(6)

where \( T_p^* \) and \( f_p \) are the reference phase torque and distribution function of phase \( p \), respectively.

However, owing to the slow current response, the torque distribution function cannot be tracked well during commutation, resulting in a relatively large torque ripple. The inductance of the latter phase \((p+1)\) has a low rate of change, resulting in low phase torque. In addition, the former phase \( (p) \) cannot be rapidly attenuated to the given torque, owing to the presence of continuing current. The TSF cannot be tracked well in actual operation, causing a high-torque ripple. Therefore, a modified piecewise TSF is proposed to reduce the torque ripple in the commutation interval. Figure 3 shows the typical waveform of cosine and the proposed TSFs, where \( \theta_{on}, \theta_{off}, \) and \( \theta_{ov} \) are the turn-on angle, turn-off angle, and overlap angle, respectively. The reference torque is increased to compensate for the low phase torque of the latter phase \((p+1)\) compared with cosine TSF. The proposed TSF reduces the given torque to accelerate the decay of the former phase \( (p) \). The proposed TSF is expressed as

\[
f_p^*(\theta) = \begin{cases} 
    0, & 0 \leq \theta \leq \theta_{on} \\
    (\theta - \theta_{on})/\theta_{ov}, & \theta_{on} \leq \theta \leq \theta_{on} + 0.5\theta_{ov} \\
    1 - 2(\theta_{on} + \theta_{ov} - \theta)^2/\theta_{ov}^2, & \theta_{on} + 0.5\theta_{ov} \leq \theta \leq \theta_{on} + \theta_{ov} \\
    1, & \theta_{on} + \theta_{ov} \leq \theta \leq \theta_{off} \\
    1 - (\theta - \theta_{off})/\theta_{ov}, & \theta_{off} \leq \theta \leq \theta_{off} + 0.5\theta_{ov} \\
    2(\theta_{off} + \theta_{ov} - \theta)^2/\theta_{ov}^2, & \theta_{off} + 0.5\theta_{ov} \leq \theta \leq \theta_{off} + \theta_{ov} \\
    0, & \theta_{off} + \theta_{ov} \leq \theta \leq \tau
\end{cases}
\]

(7)

where \( \tau \) is the rotor pole pitch.
Figure 3. The cosine and proposed TSF.

3. Model Predictive Torque Control

Figure 4 shows the control diagram of the MPTC scheme, whereby the hysteresis control is replaced by MPC to further reduce the torque ripple. First, the current and position at the next sampling moment \((k + 1)\) are predicted by current and position at the current moment \((k)\) according to the discrete model. Then, the phase torque at the sampling moment \((k + 1)\) can be achieved by the torque modeling method. Lastly, the cost function is established based on a comparison between the predicted and the reference values, thereby selecting the optimal voltage vector and corresponding switching state.

According to the phase voltage Equation (1), which is executed for each phase at any time,

\[
\frac{di_p}{dt} = \frac{1}{\partial \psi_p / \partial \theta} (U_p - R_p i_p - \frac{\partial \psi_p}{\partial \theta} \omega)
\]  

Discretizing (8), the phase current and position at the sampling moment \((k + 1)\) can be predicted by [28]

\[
\begin{align*}
\theta_{k+1} &= \theta_k + \omega_k T_s \\
i_{p,k+1} &= i_{p,k} + \frac{T_s}{\partial \psi_p / \partial \theta} (U_p - R_p i_p - \frac{\partial \psi_p}{\partial \theta} \omega_k)
\end{align*}
\]  

where \(T_s\) is the sampling time; \(\psi_{p,k}, \theta_k, \omega_k,\) and \(i_{p,k}\) are the phase flux linkage, rotor position, angular speed, and phase current, respectively, at the current moment \((k)\)

Next, the phase torque at the sampling moment \((k + 1)\) can be calculated as

\[
T_{p,k+1} = \left[ \frac{L_b - L_c}{2} i_{p,k+1}^2 + Ai_{p,k+1} - \frac{A}{B} (1 - e^{-B \omega_{k+1}}) \right] f(\theta_{k+1})
\]  

The phase voltages differ depending on the switching state, resulting varying generated torques. A typical asymmetric half-bridge converter is utilized in this study, so three switching states of power converter can be analyzed, as shown in Figure 5.
Figure 5. The three switching states. (a) State “1”, (b) state “0”, and (c) state “−1”.

As shown, states “1”, “0”, and “−1” indicate that both the switches are on, only one of the switches is off, and both switches are off, respectively. Accordingly, the phase voltage $U_p$ is defined as

$$
U_p = \begin{cases} 
U_b - 2U_T, & 1 \\
-U_T - U_D, & 0 \\
-U_b - 2U_D, & -1
\end{cases}
$$

(11)

where $U_b$, $U_T$, and $U_D$ are the bus voltage, voltage drop in the power switch, and voltage drop in the diode, respectively.

In order to better track the desired torque, it is necessary to define the selection criteria of the optimal control quantity and evaluate a series of predicted values using the cost function. Considering torque ripple and copper loss, the cost function can be expressed as [41]

$$
J = \sum_{p=1}^{N_p} (q_1 (T_{p,k+1} - T_{p,*})^2 + q_2 i_{p,k+1}^2)
$$

(12)

where $q_1$ and $q_2$ are the weight coefficients of torque and current, respectively.

As for MPTC, the desired torque corresponding to different positions of each phase is determined by the torque distribution function; the current value of the determined position of each phase is also determined. Therefore, consideration of the current in the objective function is not necessary. The cost function can be simplified, and only the torque term is retained. There is almost no difference between the instantaneous torque at time $k + 1$ and $k$ because the sampling time is sufficiently short, so the cost function ($J$) is expressed as

$$
J = \sum_{p=1}^{N_p} (T_{p,k+1} - T_{p,*})^2
$$

(13)

The optimal switching state can be obtained by the minimum value of the cost function for the next sampling period.

4. Speed Controller Based on Modified LADRC

The input of the speed controller is the given speed and feedback speed, and the output is the given torque. LADRC was chosen for lower complexity in terms of model and parameter tuning, which consists of a linear tracking differentiator, a linear extended-state observer, and a linear state-error feedback. The speed loop controller is designed as a first-order LADRC based on the first-order system mathematical model. As the key component, the linear extended-state observer is used to observe and compensate for model uncertainties and external disturbances, with good adaptability and robustness.
Based on (2), the state equation of the controlled object is as follows:

\[
\dot{\omega} = \frac{d\omega}{dt} = \frac{T^* - D \cdot \omega - T_L}{J}
\]  

(14)

Then, (14) can be rewritten as \[42\]

\[
\dot{\omega} = bT^* + f_t
\]  

(15)

\[
f_t = \frac{-D \cdot \omega - T_L}{J}
\]  

(16)

where \(f_t\) is the total disturbance, and \(bT^*\) is the control quantity.

According to the design principle of the linear extended-state observer, (16) can be expressed as

\[
\begin{aligned}
\hat{\omega} &= \hat{f}_t + bT^* + \beta_1(\omega - \hat{\omega}) \\
\hat{f}_t &= \beta_2(\omega - \hat{\omega})
\end{aligned}
\]  

(17)

where \(\omega\), \(\hat{\omega}\), and \(\hat{f}_t\) are the feedback value of speed, the estimated value of speed, and the estimated value of disturbance, respectively, and \(\beta_1\) and \(\beta_2\) are tunable gain parameters.

To improve the observation speed of the linear extended-state observer in response to disturbance, a proportional gain of the observation speed error derivative can be added in the disturbance observation channel. Therefore, (17) can be further expressed as

\[
\begin{aligned}
\hat{\omega} &= \hat{f}_t + bT^* + \beta_1(\omega - \hat{\omega}) \\
\hat{f}_t &= \beta_2(\omega - \hat{\omega}) + \beta_3(\omega - \hat{\omega})
\end{aligned}
\]  

(18)

where \(\beta_3\) is the tunable gain parameter.

The control law adopts the form of a linear combination for fast response and easy implementation. The linear state-error feedback is mainly applied to offset the disturbance, and \(bT^* = u_0 - \hat{f}_t\) is selected, where \(u_0\) is the linear state-error feedback. The controlled object can be equivalent to a pure integral link, and (13) can be derived as

\[
\dot{\omega} = u_0 - \hat{f}_t + f_t \approx u_0
\]  

(19)

Next, the proportional linear control law can be used to achieve tracking of the given error. Therefore, the linear state-error feedback can be expressed as

\[
u_0 = k_p(\omega^* - \hat{\omega})
\]  

(20)

where \(\omega^*\) is the reference speed, and \(k_p\) is the proportional gain.

A structural diagram of LADRC is shown in Figure 6.

\begin{center}
\includegraphics[width=0.5\textwidth]{structure.png}
\end{center}

**Figure 6.** Structural diagram of LADRC.
Based on the introduction of the bandwidth concept [43], the value of tunable parameters in LADRC can be expressed as

\[
\begin{align*}
\beta_1 &= \beta_3 = 2\omega_0 \\
\beta_2 &= \omega_0^2 \\
k_p &= \omega_{cv} = (0.1 \sim 0.2)\omega_0
\end{align*}
\]

(21)

where \(\omega_0\) and \(\omega_{cv}\) are the bandwidth of the linear extended-state observer and the speed loop, respectively.

However, for constant bandwidth gain, stronger anti-disturbance ability is associated with a more prominent overshoot phenomenon. It is difficult to ensure no overshoot and strong anti-interference performance simultaneously. Low gain parameters can ensure no overshoot and the controllability of the system, whereas anti-interference ability and speed tracking effect are reduced. Conversely, high gain parameter behaves well in terms of anti-disturbance ability and tracking performance, whereas overshoot under varied conditions will be obvious. Thus, a linear extended-state observer with variable gain is designed to improve the anti-interference ability and reduce the overshoot simultaneously, which solves the contradiction resulting from fixed gain parameters. The bandwidth of the linear extended-state observer \(\omega_0\) can be described as

\[
\omega_0 = \frac{c_1}{1+e^{-c_2t}}
\]

(22)

where \(t\) is the run time, \(\omega_0\) is a time-varying function, \(c_1\) and \(c_2\) are tunable parameters, \(c_1 > 0\), and \(c_2 > 0\). According to (21), the adjustable gain parameters, \(\beta_1, \beta_2, \beta_3,\) and \(k_p\), are associated with \(\omega_0\). Obviously, \(\omega_0 = c_1/2\) when \(t = 0\) s and \(\omega_0\) approaches \(c_1\) when \(t\) increases gradually. The lower and upper values of \(\omega_0\) are \(c_1/2\) and \(c_1\), respectively. The value of \(\omega_0\) is equal to \(c_1/2\) when the run time \(t = 0\) s, which is smaller than \(c_1\) and beneficial to overshoot suppression and stability. Then, the value of \(\omega_0\) increases gradually with increased time. After the system reaches a steady state, \(\omega_0\) is relatively large, thereby enhancing the performance in fields of anti-interference ability and tracking accuracy. The value almost reaches the maximum value of \(c_1\) when the system runs stably for a long time, which guarantees controllability. Compared with a fixed value of \(\omega_0\) in conventional LADRC, the value of \(\omega_0\) in the proposed design varies with run time during the operation of the motor. The shape of change function is determined by the values of \(c_1\) and \(c_2\), which depend on the given condition of the used motor, such as given reference speed and load torque. The dichotomy method is applied in this study for parameter debugging, such as \(c_1\) and \(c_2\), finally selecting the parameters that improve dynamic performance both in terms of speed and torque. In general, values are determined by trial by experience and experiment. \(\omega_0\) varies with run time during the operating period. In general, the modified linear extended-state observer with proportional gain and time-varying function achieves superiority in terms of fast response, anti-disturbance ability, overshoot suppression, and tracking performance.

5. Experimental Result

The effectiveness of the proposed hybrid control scheme was evaluated through detailed experiments. In this study, a decoupled 12/14 bearingless SRM was chosen as the research object, which was studied in our recent project. The prototype including the stator and the rotor is shown in Figure 7, and additional details regarding the two-phase motor can be found in [44]. The torque drive control of this motor is suitable for SRMs, as the torque is independent of the suspension system. Figure 8 shows the experiment platform consisting of a prototype, a magnetic powder brake, the torque and speed sensors, controller, power supply, power converter, and oscilloscope. A prototype, a magnetic powder brake, and the torque and speed sensors are connected by two couplings. The position signal detected by the Hall sensor is input to the controller, and the controller outputs the switching signal based on the compiled control system. To verify the superiority of the hybrid control scheme (method 3),
MPTC with cosine TSF using conventional LADRC (method 1) and MPTC with modified TSF using conventional LADRC (method 2) are selected for experimental comparison.

**Figure 7.** The prototype.

**Figure 8.** The experimental platform.

Figures 9–11 show the experimental results including speed and total output torque with three MPTC schemes under different operation conditions. The speed ($\omega$) and total output torque are detected by a torque and speed sensor. The value of the output torque is basically equal to the sum of the predicted phase torques ($T_{p,k+1}$). For the fairness of the comparison of the three methods, the same control requirements are applied for each operational condition. Figure 9 shows the speed and torque results when reference speed and load torque are set as 1000 r/min and 0.4 Nm, respectively, considering that the TSF is more suitable for low- and medium-speed ranges. The startup time of method 3 is 0.11 s, whereas that of method 1 and 2 require 0.2 s and 0.18 s, respectively. The proposed scheme has a shorter dynamic response time without overshoot in the initial stage. The torque ripple ranges (the difference between the maximum and minimum torque values) of three methods are 0.47 Nm, 0.38 Nm, and 0.31 Nm, respectively. The torque ripple range of method 3 is reduced by 34% and 18% compared with method 1 and 2, respectively. The proposed method behaves well in terms of dynamic response, speed tracking, and torque ripple reduction.
Figure 9. Speed and torque under 1000 r/min and 0.4 Nm. (a) Method 1, (b) method 2, and (c) method 3.

Figure 10. Speed and torque under speed change. (a) Method 1, (b) method 2, and (c) method 3.
Figure 10 illustrates the speed and torque results when the speed changes from 800 to 1000 rpm with a constant load torque (0.4 Nm). All three methods can reach the steady state after the speed change, and the startup time of three methods are 0.19 s, 0.18 s, and 0.14 s, respectively. Similar to the condition described above, method 3 exhibits the fastest acceleration during the startup stage. The response time of the proposed method requires 0.13 s, and methods 2 and 3 require 0.2 s and 0.17 s, respectively, when the speed change occurs at 0.25 s. The torque ripple range does not change significantly under variable speed. Moreover, the same conclusion can be obtained as that described above. Method 3 behaves well in terms of torque ripple reduction.

Figure 11 shows the output speed and torque results of three control methods when load torque changes from 0.4 Nm to 0.6 Nm under 1000 r/min. The speed responses of method 1 and 2 are 0.17 s and 0.16 s, respectively, to return the reference speed, which are much slower than that of method 3 (0.13 s). The speed overshoots of the three methods are 98 r/min, 80 r/min, and 45 r/min, respectively, when load torque change occurs at 0.25 s. Moreover, the torque ripple ranges of the three methods are 0.5 Nm, 0.42 Nm, and 0.36 Nm, respectively, under 0.6 Nm. The output torque is positively correlated with the load torque. The proposed method is superior in terms anti-disturbance ability and torque ripple reduction. As for MPTC, the torque performance is controlled by the angles. The proposed method influences the torque ripple, dynamic response, and anti-disturbance ability. Figure 12 shows the phase current waveforms of the three control methods under 0.4 Nm and 0.6 Nm when the reference speed is set as 1000 r/min. The current waveforms and amplitudes of different schemes are similar. The peak current under 0.4 Nm is approximately 6 A, which is smaller than that under 0.6 Nm (8 A). Moreover, the current ripple of method 3 is lower than that of the other methods, which is positively correlated with torque ripple.
The intuitive comparison results of the three methods under different working conditions are listed in Table 1. The critical performance information including startup time, response time, speed overshoot, and torque ripple range demonstrates the effectiveness of the proposed method. The above results reveal that the proposed method can provide much better control performance, including speed tracking, dynamic response, torque ripple reduction, anti-disturbance ability, and robustness, compared to the two other schemes.

Table 1. Experimental results of the three methods.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Parameters</th>
<th>PI</th>
<th>SMC</th>
<th>TSMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant load torque</td>
<td>Startup time</td>
<td>0.2 s</td>
<td>0.18 s</td>
<td>0.11 s</td>
</tr>
<tr>
<td></td>
<td>Torque ripple range</td>
<td>0.47 Nm</td>
<td>0.38 Nm</td>
<td>0.31 Nm</td>
</tr>
<tr>
<td>Speed change</td>
<td>Startup time</td>
<td>0.19 s</td>
<td>0.18 s</td>
<td>0.14 s</td>
</tr>
<tr>
<td></td>
<td>Response time</td>
<td>0.2 s</td>
<td>0.17 s</td>
<td>0.13 s</td>
</tr>
<tr>
<td>Load torque disturbance</td>
<td>Response time</td>
<td>0.17 s</td>
<td>0.16 s</td>
<td>0.13 s</td>
</tr>
<tr>
<td></td>
<td>Speed overshoot</td>
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<td>80 r/min</td>
<td>45 r/min</td>
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<tr>
<td></td>
<td>Torque ripple range</td>
<td>0.5 Nm</td>
<td>0.42 Nm</td>
<td>0.36 Nm</td>
</tr>
</tbody>
</table>

6. Conclusions

In this paper, an advanced hybrid control scheme using a speed controller based on modified LADRC was proposed, which combines improved TSF and MPC. In the study, the MPTC with enhanced piecewise TSF was employed to reduce the torque ripple, whereby hysteresis control was replaced by torque prediction. Torque was chosen as the only control objective to define the cost function, thereby avoiding the selection of weight coefficients and reducing computation. Furthermore, an improved LADRC was designed to obtain improved anti-disturbance ability and speed tracking. A proportional gain of observation error in the linear extended-state observer was added to accelerate the observation speed of disturbance, such as load torque variation. Furthermore, to solve the
contradiction resulting from fixed gain parameters, a linear extended-state observer with variable gain was investigated to simultaneously improve the anti-interference ability and reduce the overshoot. The effectiveness of the proposed hybrid control scheme was verified by comparative experimental results. Compared with the other two methods, the proposed control scheme achieves the best control performances in terms of torque ripple reduction, speed tracking, dynamic response, robustness, and anti-disturbance ability.

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