

A Current Measurement Offset Error Elimination Method Based on Signal Injection for Interior Permanent Magnet Synchronous Motor Drives

Jinshan ZHAO, Huimin WANG, Sibao WAN, Runchan LIU, and Huanqing ZOU

Abstract—Accurate information of the measured phase current is of high importance for interior permanent magnet synchronous motor (IPMSM) drives. However, under the long-term effects of electrical and thermal stress, the current sensors may suffer from the current measurement offset errors (CMOE), which causes obvious speed fluctuations and torque ripples. To address this, a current measurement offset error elimination (CMOEE) method based on the signal injection is proposed in this paper, which enables to maintain the performance of the IPMSM drives. In the proposed CMOEE method, the effects of the CMOEs on the performance of the IPMSM drives are analyzed. On the basis of this, the details of the proposed CMOEE method are provided. Then, considering that the response of the injected signal is extracted by the band-stop filter, obvious amplitude attenuation and phase deviation are introduced into the proposed CMOEE method. With this, the performance of the proposed CMOEE method may be degraded. Accordingly, a simple yet effective compensation method is adopted. Consequently, the amplitude attenuation and phase deviation are effectively compensated, ensuring the performance of the proposed CMOEE method. Finally, experimental tests are carried out to verify the effectiveness of the proposed CMOEE method under different cases.

Index Terms—Amplitude attenuation and phase deviation

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compensation, band-stop filter, current measurement offset error elimination, interior permanent magnet synchronous motor (IPMSM) drives, signal injection.

I. INTRODUCTION

THE interior permanent magnet synchronous motor (IPMSM) drive system that conforms to the concept of green and low-carbon development has become a key development direction of urban rail transit systems [1]–[4]. In IPMSM drive systems, current sensors are used to measure phase current information to achieve high-performance control. However, due to the long-term effects of continuous operation under high-power conditions and non-stationary conditions such as sudden starts and stops, and variable loads, the current sensor frequently undergoes strong electrical and thermal stress, resulting in offset errors in the measured current, which in turn causes adverse speed fluctuations and torque pulsations in the IPMSM, reducing system control performance [5]–[7].

In order to ensure the performance of the IPMSM drive system, it is crucial to adopt a high-performance CMOEE method. Common CMOEE methods can be roughly divided into offline suppression methods [8]–[9] and online suppression methods [10]–[26]. The offline suppression method eliminates CMOEs by calibrating the current sensor when the motor drive system is not running, ensuring that its output at zero point is zero. In [8], an offline suppression method based on least squares estimation is proposed, this method analyzes the impact of current measurement errors on the d -axis and q -axis current components, and uses the least squares estimation method to achieve effective estimation and compensation of current measurement errors. The offline suppression method has the advantages of simple principle and easy implementation, but this method cannot cope with dynamically changing offset errors, and this method requires a large number of calibration experiments and has high testing costs. In addition, after long-term use of the current sensor, changes in hardware characteristics will cause the offset error to re-accumulate, resulting in a significant decrease in the performance of the offline suppression method.

The online suppression method is a method that uses control or modulation strategies to achieve CMOEE under the normal operating status of the motor drive system. Common online suppression methods can be divided into hardware design methods [10]–[13] and software control methods [14]–[26].

Among them, the hardware design method eliminates the CMOEs by adjusting the motor drive system structure. In [10], by changing the wiring of the current sensor and using a high-performance current sampling method to self-correct the current measurement value, the CMOEs can be effectively suppressed without affecting the operation of the IPMSM. Additionally, in [11], a similar suppression method is adopted, and a fixed-point sampling strategy is proposed to reduce the current sampling error and ensuring CMOEE performance under different working conditions. This hardware design approach effectively suppresses CMOEs while providing enhanced resistance to interference, but this method requires changing the structure of the motor drive system, which is highly intrusive. Moreover, this method is not adaptable enough, that is, when this method is applied to motor drive systems with different parameters, the hardware circuit needs to be redesigned [14].

Compared with the hardware design method, the software control method has the advantages of high adaptability, low intrusion, and fast response, so it is very popular in motor drive systems. Common software control methods mainly include harmonic filtering method [14]–[20] and observer method [21]–[26]. Typically, CMOEs will cause specific harmonics (such as the 1st harmonic) to appear in the direct and quadrature components of the current. In this regard, the harmonic filtering method eliminates specific harmonics by designing filters to achieve effective filtering of CMOEs. In [15], a CMOEE method based on an improved complex coefficient filter is proposed. This method uses a motor model to replace the complex coefficient filter, and effectively suppresses the adverse effects of external disturbances by correcting the gain error coefficient, thereby improving the CMOEE performance. Subsequently, in [17], a band-pass filter is used to extract periodic ripples caused by current measurement errors, and a low-pass filter is used to dynamically decouple different types of current measurement errors, thereby improving the suppression effect of measurement errors. It is known that modulation strategies can also change the harmonic distribution of motor drive systems. Based on this, an CMOEE method based on random pulse width modulation is proposed, which achieves self-correction of CMOEs through dynamic double sampling of current complementary non-zero vectors in [18]. Additionally, in [19], effective suppression of CMOEs using a hybrid modulation strategy. This method switches continuous pulse width modulation to discontinuous pulse width modulation under different working conditions to achieve accurate compensation of CMOEs. Although the harmonic filtering method can provide good CMOEE performance, this method usually reduces the system dynamic performance and increases the system computational burden. In addition, the use of discontinuous modulation or random pulse width strategies will inevitably affect the current quality and reduce the motor operating performance.

The observer method designs an observer based on the mathematical model of the motor to estimate and compensate for the CMOEs, thereby eliminating the adverse effects of the CMOEs. Common observers include PI observers [21], extended state observers [22]–[23], sliding mode observers [24]–

[25], Kalman filters [26], etc. In [21], a PI observer is constructed based on the voltage model to estimate the CMOEs. These estimated CMOEs are then subtracted from the measured current, achieving effective compensation. Subsequently, a CMOEE method based on an adaptive extended state observer is studied in [22]. This observer exhibits second-order low-pass filter characteristics, thereby enhancing robustness against external disturbances and mitigating the associated degradation in CMOEE performance. In [23], a quasi-fractional resonant controller is introduced into the extended state observer to enhance the estimation accuracy of the CMOEs, thereby ensuring the CMOEE performance. Additionally, design a fast terminal sliding mode observer to estimate and compensate for CMOEs. In this observer, the sliding mode surface and sliding mode control structure are carefully designed to ensure the CMOEE performance while avoiding the adverse effects of chattering in [25]. In [26], a novel method to suppress CMOEs is proposed. It replaces the extended state observer with an ultra-local prediction model based on a Kalman filter and applies this model to a model-free predictive controller. This approach aims to overcome the system performance degradation caused by CMOEs. The observer method avoids the adverse influence on the motor drive system, but this method is easily affected by the change of motor parameters, and the CMOEE performance is difficult to be guaranteed.

In summary, this paper studies a CMOEE method based on signal injection. This method does not change the structure of the IPMSM drive system and is less intrusive. Moreover, this method does not require the participation of motor parameters and can avoid the adverse effects of changes in motor parameters. Section I begins by analyzing the impact of CMOEs on the performance of the IPMSM drive system. On this basis, Section II introduces the studied CMOEE method in detail and conducts performance analysis. The analysis results show that in the method studied, using a band-pass filter to extract the injected signal response will bring about amplitude attenuation and phase deviation, which will affect the suppression performance of the CMOEs. Subsequently, Section III presents a simple yet effective compensation method to address amplitude attenuation and phase deviation. This compensation is designed to ensure the reliable performance of the studied method. Then, in Section IV, a small-power IPMSM drive system experimental platform is built to experimentally verify the performance of the studied method under different working conditions. Finally, in Section V, the full text is summarized and conclusions are drawn.

II. ANALYSIS OF THE INFLUENCE OF CMOEs

In order to facilitate a clear presentation of the proposed CMOEE method, this chapter first analyzes the impact of CMOEs on the performance of the IPMSM drive system.

In a typical IPMSM drive system, two current sensors are often used to collect phase-A and phase-B current information to achieve high-performance control. Taking phase-A current as an example, the impact of CMOEs on the performance of

the IPMSM drive system is analyzed. When the phase-A current sensor has a CMOEs, it can be expressed as:

$$i_{\text{sam}} = i_{\text{sa}} + I_{\text{dc}} = I_{\text{m}} \sin(\omega t) + I_{\text{dc}} \quad (1)$$

where i_{sam} , i_{sa} , I_{dc} , I_{m} , and ω are the measured phase-A current (the phase-A current containing the CMOEs), the actual phase-A current (the phase-A current free of CMOEs), the CMOEs, the amplitude of the actual phase-A current, and the frequency, respectively.

Subsequently, according to the coordinate transformation, it can be expressed as:

$$\begin{bmatrix} i_{\text{sdm}} \\ i_{\text{sqm}} \end{bmatrix} = \begin{bmatrix} \cos(\theta_r) & \sin(\theta_r) \\ -\sin(\theta_r) & \cos(\theta_r) \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{1}{\sqrt{3}} & \frac{2}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} i_{\text{sam}} \\ i_{\text{sb}} \end{bmatrix} \quad (2)$$

where i_{sdm} , i_{sqm} , θ_r , and i_{sb} are the d -axis and q -axis current components considering the influence of CMOEs, the rotor position, and the actual phase-B current (the phase-B current free of CMOEs), respectively.

Substituting (1) into (2) entails:

$$\begin{cases} i_{\text{sdm}} = i_{\text{sd}} + \Delta i_{\text{sd}} \\ i_{\text{sqm}} = i_{\text{sq}} + \Delta i_{\text{sq}} \end{cases} \quad (3)$$

where i_{sd} , i_{sq} , Δi_{sd} , and Δi_{sq} are the actual d -axis and q -axis current components (the d -axis and q -axis current components free of CMOEs) and the current pulsations caused by the CMOEs, respectively, and it holds that:

$$\begin{cases} \Delta i_{\text{sd}} = \frac{2\sqrt{3}}{3} I_{\text{dc}} \sin(\theta_r + \frac{\pi}{3}) \\ \Delta i_{\text{sq}} = \frac{2\sqrt{3}}{3} I_{\text{dc}} \cos(\theta_r + \frac{\pi}{3}) \end{cases} \quad (4)$$

According to (3), the motor torque considering the influence of CMOEs is calculated as follows.

$$T_{\text{em}} = \frac{3}{2} n_p [\psi_f i_{\text{sqm}} + i_{\text{sdm}} i_{\text{sqm}} (L_d - L_q)] = T_e + \Delta T_e \quad (5)$$

where T_{em} , n_p , ψ_f , L_d , L_q , and ΔT_e are the motor torque considering the influence of CMOEs, the number of pole pairs, the permanent magnet flux linkage, the d -axis inductance, the q -axis inductance, and the torque pulsation caused by the CMOEs, respectively, and it holds that:

$$\Delta T_e = \frac{3}{2} n_p [\psi_f \Delta i_{\text{sq}} + (\Delta i_{\text{sd}} i_{\text{sq}} + \Delta i_{\text{sq}} i_{\text{sd}} + \Delta i_{\text{sq}} \Delta i_{\text{sd}} (L_d - L_q))] \quad (6)$$

In addition, the motion equation of the IPMSM can be expressed as:

$$T_{\text{em}} - T_L = \frac{J}{n_p} \frac{d\omega_{\text{em}}}{dt} \quad (7)$$

where T_L , J , and ω_{em} are the load torque, the moment of inertia,

and the motor speed considering the influence of CMOEs, respectively.

With (5), (6) and (7), the speed fluctuation caused by the CMOEs can be obtained as:

$$\Delta\omega = \omega_{\text{em}} - \omega_e = \int \frac{\Delta T_e n_p}{J} dt \quad (8)$$

where $\Delta\omega$ is the speed fluctuation caused by CMOEs.

In summary, it can be concluded that the CMOEs introduces significant pulsations in the d -axis and q -axis current components, which in turn causes torque pulsation and speed fluctuation in the IPMSM, thereby degrading the performance of the IPMSM drive system.

III. CMOEE METHOD BASED ON SIGNAL INJECTION

In order to reduce the adverse impact of CMOEs on the performance of the IPMSM drive system, this chapter studies a CMOEE method based on signal injection to ensure the performance of the IPMSM drive system.

A. Design Ideas of CMOEE Method

As illustrated, the phase current signal i_{sam} containing the bias error is first multiplied by two high-frequency signals i_{ha} and i_{hb} with an injection frequency of ω_h and a phase difference of 90° , yielding intermediate variables X and Y that contain three frequency components: $\omega + \omega_h$, $\omega - \omega_h$, and ω . Subsequently, these two intermediate variables are processed through band-stop filters to eliminate the harmonic component at frequency ω_h , resulting in M and K . Finally, M and K are subjected to a second operation with the injected high-frequency signals and then summed, thereby extracting the current information free from bias errors.

If the injected signal is a pure string signal with an amplitude of 1, there are:

$$\begin{cases} i_{\text{ha}} = \cos(\omega_h t) \\ i_{\text{hb}} = \sin(\omega_h t) \end{cases} \quad (9)$$

where i_{ha} , i_{hb} , and ω_h are the injected high-frequency signal and the frequency of the injected signal, respectively.

Subsequently, it can be expressed as

$$\begin{aligned} X &= i_{\text{sam}} i_{\text{ha}} = [I_{\text{m}} \sin(\omega t) + I_{\text{dc}}] \cos(\omega_h t) \\ &= \frac{1}{2} I_{\text{m}} [\sin(\omega + \omega_h)t + \sin(\omega - \omega_h)t] + I_{\text{dc}} \cos(\omega_h t) \end{aligned} \quad (10)$$

$$\begin{aligned} Y &= i_{\text{sam}} i_{\text{hb}} = [I_{\text{m}} \sin(\omega t) + I_{\text{dc}}] \sin(\omega_h t) \\ &= \frac{1}{2} I_{\text{m}} [\cos(\omega - \omega_h)t - \cos(\omega + \omega_h)t] + I_{\text{dc}} \sin(\omega_h t) \end{aligned} \quad (11)$$

where X and Y are intermediate variables, and both X and Y contain three frequency components, namely the components at frequency $(\omega + \omega_h)$, frequency $(\omega - \omega_h)$, and frequency ω_h .

After processing X and Y with a band-stop filter to remove the component at frequency ω_h , it can be expressed as:

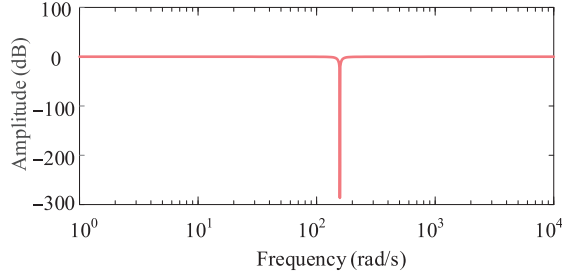


Fig. 4. Bode diagram of the second-order generalized integrator-based band-stop filter

According to (23), after applying the band-stop filter based on the SOGI, the amplitude of the component at frequency ω_h is zero, which indicates that the SOGI-based band-stop filter can effectively eliminate the component at frequency ω_h .

Subsequently, based on (19), the Bode plot of the band-stop filter based on the SOGI is plotted as shown in Fig. 4. It can be observed from Fig. 4 that under the action of the band-stop filter, the amplitude of the component at frequency ω_h is significantly reduced, thereby ensuring the performance of CMOEE.

IV. PERFORMANCE ANALYSIS AND SPECIFIC IMPLEMENTATION CMOEE METHOD

A. Analysis of the Influence of Band-Stop Filter on CMOEE Method

As shown in Fig. 1, X and Y contain three frequency components: the component at frequency $(\omega + \omega_h)$, the component at frequency $(\omega - \omega_h)$, and the component at frequency ω_h . After processing through the band-stop filter, the component at ω_h is effectively suppressed. However, the filter also introduces significant amplitude attenuation and phase deviation to the other two components, namely $(\omega + \omega_h)$ and $(\omega - \omega_h)$. These distortions directly impair the accuracy of subsequent signal processing and, more specifically, degrade the performance of the CMOEE method studied in this work. Therefore, this section provides a detailed analysis of the influence mechanism and extent of the band-stop filter on the proposed method.

After considering the influence of the band-stop filter and combining (12), (13), and (20), the amplitudes of the $(\omega + \omega_h)$ and the $(\omega - \omega_h)$ are calculated as:

$$H[j(\omega_h + \omega)] = \frac{|\omega_h^2 - (\omega_h + \omega)^2|}{\sqrt{[\omega_h^2 - (\omega_h + \omega)^2]^2 + [\Gamma\omega_h(\omega_h + \omega)]^2}} \quad (24)$$

$$H[j(\omega_h - \omega)] = \frac{|\omega_h^2 - (\omega_h - \omega)^2|}{\sqrt{[\omega_h^2 - (\omega_h - \omega)^2]^2 + [\Gamma\omega_h(\omega_h - \omega)]^2}} \quad (25)$$

Considering the effect of band-stop filter phase deviation: it we obtain:

$$M_{BS} = \frac{1}{2} I_m H[j(\omega_h - \omega)] \sin[(\omega - \omega_h)t + \varphi_1] + \frac{1}{2} I_m H[j(\omega_h + \omega)] \sin[(\omega + \omega_h)t + \varphi_2] \quad (26)$$

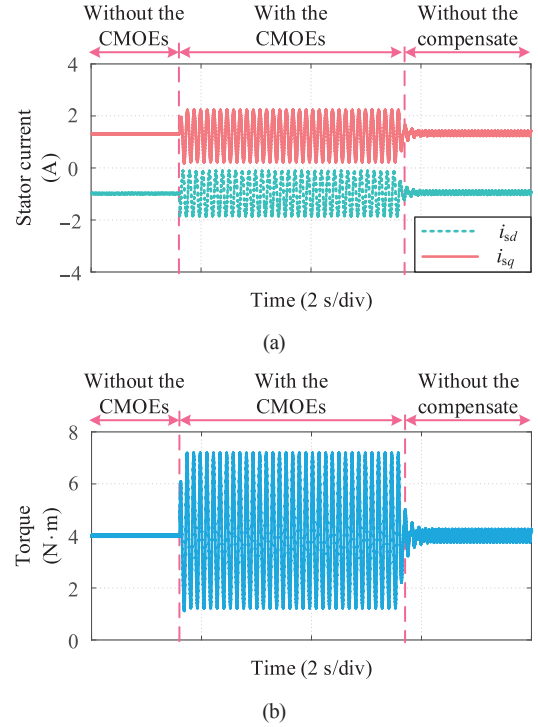


Fig. 5. Performance of the proposed method without amplitude attenuation and phase deviation compensation. (a) Stator current. (b) Motor torque.

$$K_{BS} = \frac{1}{2} I_m H[j(\omega_h - \omega)] \cos[(\omega - \omega_h)t + \varphi_1] - \frac{1}{2} I_m H[j(\omega_h + \omega)] \cos[(\omega + \omega_h)t + \varphi_2] \quad (27)$$

where M_{BS} , K_{BS} , φ_1 and φ_2 are the intermediate component that considers the influence of the band-stop filter and the phase deviation caused by the band-stop filter, respectively, as given by:

$$\varphi_1 = \arctan\left[\frac{\Gamma\omega_h(\omega_h - \omega)}{\omega^2 - 2\omega_h\omega}\right] \quad (28)$$

$$\varphi_2 = \arctan\left[\frac{\Gamma\omega_h(\omega_h + \omega)}{2\omega_h\omega + \omega^2}\right] \quad (29)$$

After using the same method, there is:

$$i_{saes_BS} = M_{BS} i_{ha} + K_{BS} i_{hp} = \frac{1}{2} I_m H[j(\omega_h - \omega)] \sin(\omega t + \varphi_1) + \frac{1}{2} I_m H[j(\omega_h + \omega)] \sin(\omega t + \varphi_2) \quad (30)$$

According to (30), although the band-stop filter based on the SOGI can remove the component at frequency ω_h , it introduces significant amplitude attenuation and phase deviation to the components at frequencies $(\omega + \omega_h)$ and $(\omega - \omega_h)$, thereby degrading the suppression performance for CMOEs.

Simulations were conducted to investigate the impact of the band-stop filter on the proposed method, with the test results shown in Fig. 5. As observed from Fig. 5, when CMOEs is introduced into the current sensor, noticeable pulsations oc-

cur in the d -axis and q -axis current components as well as in the motor torque, thereby degrading the performance of the IPMSM drive system. Although the proposed method reduces current and torque pulsations to some extent, the suppression performance of CMOEs remains insufficient to meet system requirements due to the amplitude attenuation and phase deviation introduced by the band-stop filter.

B. Amplitude Attenuation and Phase Deviation Compensation

From the analysis in the previous section, it is known that the band-stop filter based on the SOGI introduces significant amplitude attenuation and phase deviation, thereby affecting the performance of the proposed method. To address this, a simple yet effective amplitude-and-phase compensation strategy is employed to mitigate these distortions, thereby ensuring the reliable performance of the proposed method under various operating conditions.

Let the injected signal frequency be equal to the stator current frequency, it is given by:

$$\omega_h = \omega \quad (31)$$

Substituting (31) into (24), (25), (28), and (29) :

$$H[j(\omega_h - \omega)] = \frac{|\omega_h^2 - (\omega_h - \omega)^2|}{\sqrt{[\omega_h^2 - (\omega_h - \omega)^2]^2 + [\Gamma\omega_h(\omega_h - \omega)]^2}} = 1 \quad (32)$$

$$H[j(\omega_h + \omega)] = \frac{|\omega^2 - (\omega_h + \omega)^2|}{\sqrt{[\omega_h^2 - (\omega_h + \omega)^2]^2 + [\Gamma\omega_h(\omega_h + \omega)]^2}} = \frac{3}{\sqrt{9 + 4\Gamma^2}} \quad (33)$$

$$\phi_1 = \arctan\left[\frac{\Gamma\omega_h(\omega_h - \omega)}{\omega^2 - 2\omega_h\omega}\right] = 0 \quad (34)$$

$$\phi_2 = \arctan\left[\frac{\Gamma\omega_h(\omega_h + \omega)}{2\omega_h\omega + \omega^2}\right] = \arctan\left(\frac{2\Gamma}{3}\right) \quad (35)$$

With (30), (32), (34), and (35), it is obtained that:

$$i_{\text{saes_BS}} = M_{\text{BS}} i_{\text{ha}} + K_{\text{BS}} i_{\text{hp}} = \frac{1}{2} I_m \sin(\omega t) + \frac{1}{2} I_m \frac{3}{\sqrt{9 + 4\Gamma^2}} \sin(\omega t + \phi_2) \quad (36)$$

According to the auxiliary angle formula of trigonometric functions, (36) can be expressed as:

$$i_{\text{saes_BS}} = \frac{1}{2} I_m H_x \sin(\omega t + \zeta) \quad (37)$$

where H_x and ζ represent the amplitude attenuation and the phase deviation, respectively, and it holds that:

$$H_x = \sqrt{\left[1 + \frac{3}{\sqrt{9 + 4\Gamma^2}} \cos(\phi_2)\right]^2 + \left[\frac{3}{\sqrt{9 + 4\Gamma^2}} \sin(\phi_2)\right]^2} \quad (38)$$

$$\zeta = \arctan\left[\frac{\frac{3}{\sqrt{9 + 4\Gamma^2}} \sin(\phi_2)}{1 + \frac{3}{\sqrt{9 + 4\Gamma^2}} \cos(\phi_2)}\right] \quad (39)$$

According to (38) and (39), Γ and ϕ_2 are fixed, making H_x and ζ constant as well. This means that when the injected signal frequency matches the stator current frequency, the amplitude attenuation and phase deviation caused by the SOGI-based band-stop filter are constant.

To compensate for the amplitude attenuation caused by the band-stop filter, it is obtained that:

$$H_c = \frac{2}{H_x} \quad (40)$$

For the phase deviation caused by the band-stop filter, a method based on signal delay is used to compensate it. According to (39), the signal delay time can be calculated as:

$$\tau = \frac{\zeta}{\omega} = \frac{\arctan\left[\frac{\frac{3}{\sqrt{9 + 4\Gamma^2}} \sin(\phi_2)}{1 + \frac{3}{\sqrt{9 + 4\Gamma^2}} \cos(\phi_2)}\right]}{\omega} \quad (41)$$

where τ represents the signal delay time.

Assuming the system sampling period is T_s , the number of delay cycles required can be expressed as:

$$N = \frac{\tau}{T_s} = \frac{\zeta}{T_s \omega} \quad (42)$$

According to (40) and (42), an effective compensation for amplitude attenuation and phase deviation can be achieved.

Subsequently, the compensation method was verified, and the test results are shown in Fig. 6 and Fig. 7. In Fig. 6, with the load and CMOEs set to 3 N·m and 1 A respectively, and the speed command varied as 200 r/min → 400 r/min → 200 r/min, the results show that the adopted method effectively compensates for amplitude attenuation and phase deviation (see Fig. 6(a) and Fig. 6(b)), enabling the estimated current to accurately track the actual current (see Fig. 6(c), Fig. 6(d), and Fig. 6(e)).

Additionally, the efficacy of the compensation method was further examined under dynamic load variations. As illustrated in Fig. 7, with a constant speed command of 300 r/min and CMOEs set to 1 A, the load torque was varied in a sequence of 3 N·m → 6 N·m → 3 N·m. The results clearly demonstrate that the adopted compensation strategy maintains robust performance in this scenario, effectively correcting both amplitude attenuation and phase deviation induced by the band-stop filter despite the changing load conditions. Consequently, the estimated current successfully mitigates the signal distortions introduced by the filter, providing precise and reliable current feedback. This accurate current information is crucial, as it directly ensures the consistent and reliable performance of the CMOEE process across diverse operational profiles.

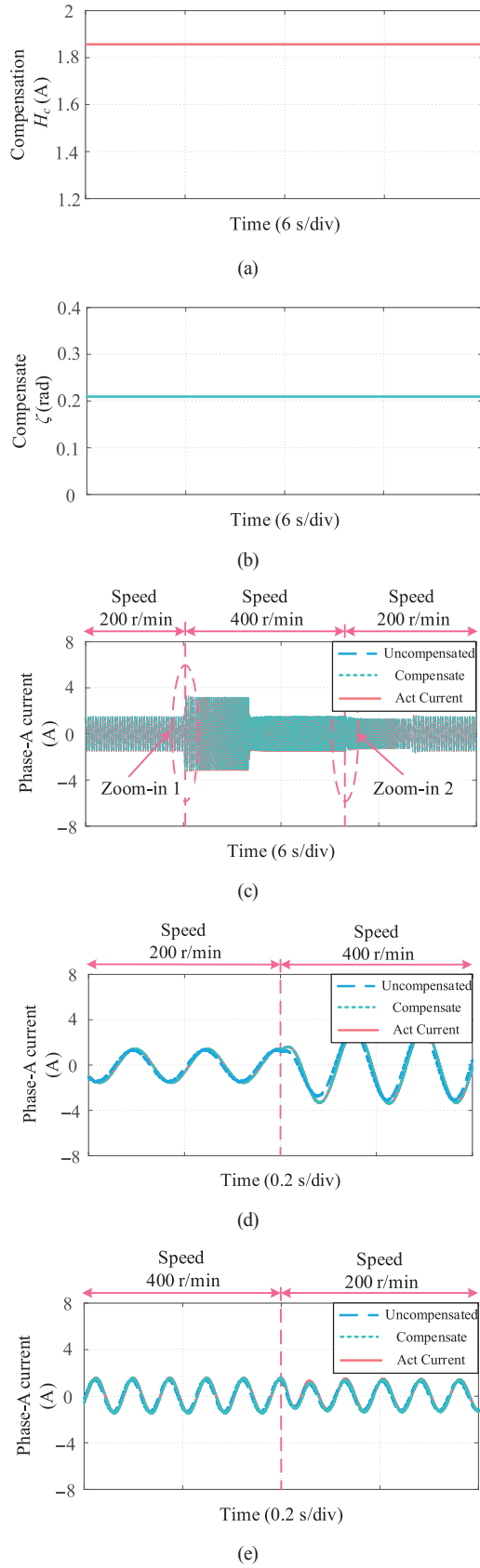


Fig. 6. Performance comparison of phase current estimation with and without amplitude attenuation and phase deviation compensation under speed command variations. (a) Amplitude compensation. (b) Phase compensation. (c) The phase-A current. (d) The zoom-in 1. (e) The zoom-in 2.

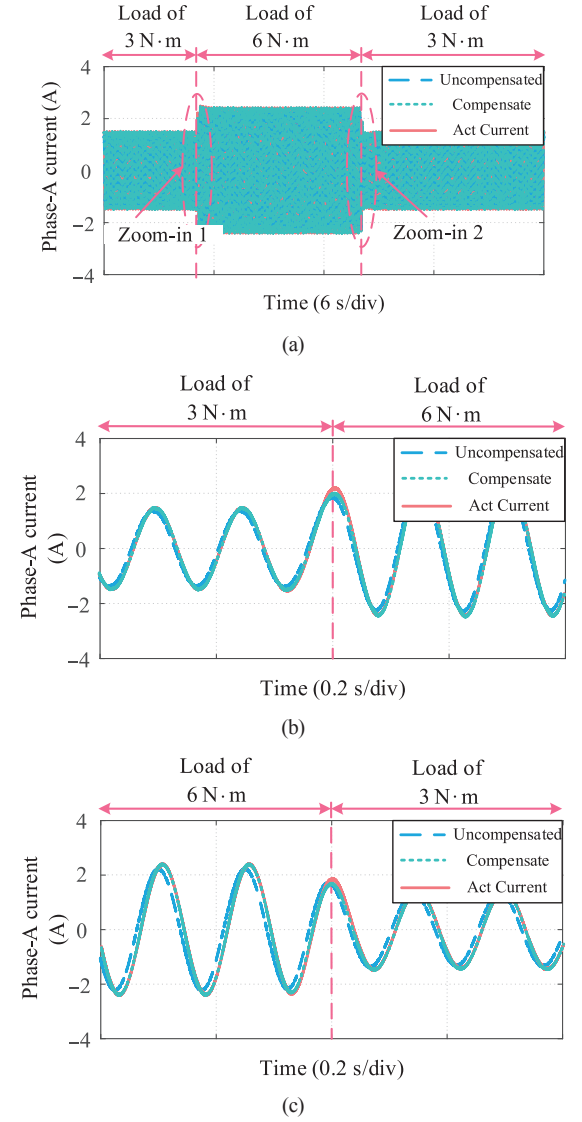


Fig. 7. Performance comparison of phase current estimation with and without amplitude attenuation and phase deviation compensation under load variations. (a) The phase-a current. (b) The zoom-in 1. (c) The zoom-in 2.

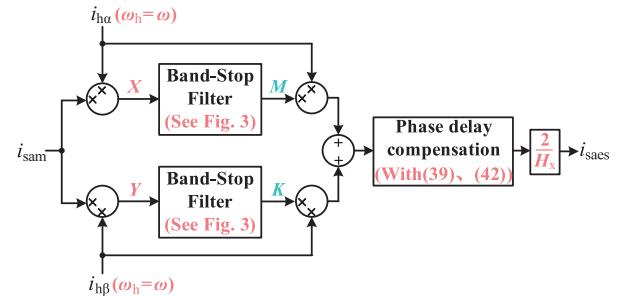


Fig. 8. Implementations of the proposed method.

C. Specific Implementation of the Studied CMOEE Method

According to the above analysis, the concrete implementation of the studied CMOEE method is depicted in Fig. 8. As shown in the figure, the scheme requires only two band-stop filters combined with a concise compensation mechanism, resulting

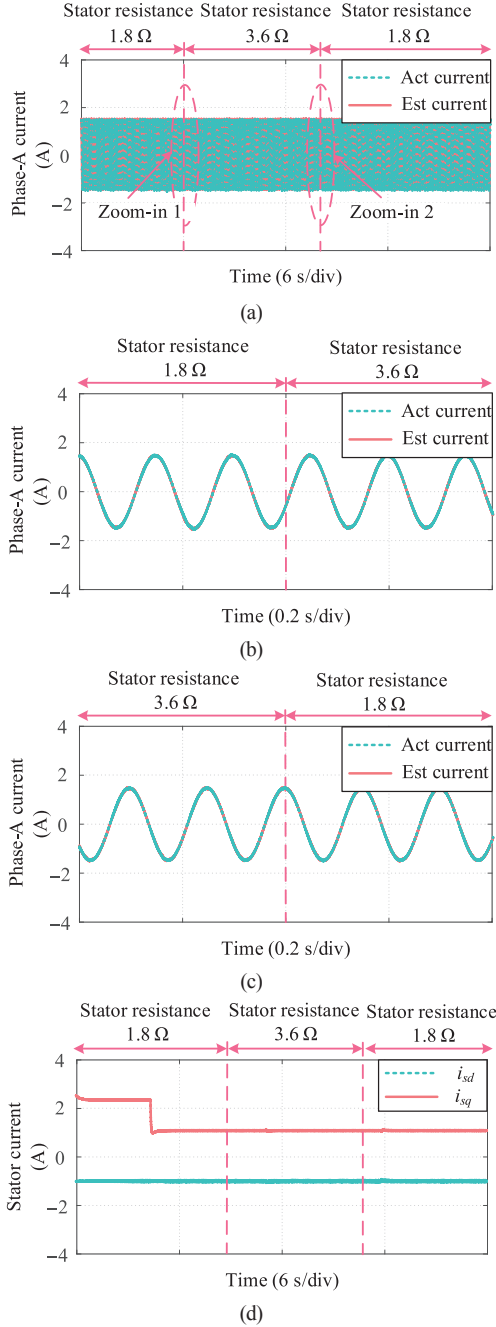


Fig. 9. Performance of the proposed method under stator resistance variations. (a) The phase-A Current. (b) The zoom-in 1. (c) The zoom-in 2. (d) d -axis and q -axis current component.

in a simple and clear overall structure. This design is not only easy to implement but also features a low computational burden.

More importantly, the proposed method suppresses the CMOEs in the natural coordinate system (the abc -frame), without requiring any motor parameters, thereby avoiding the adverse effects caused by variations in motor parameters.

To verify the performance of the proposed method under motor parameter variations, simulations were conducted, with the test results shown in Fig. 9. In Fig. 9, the speed command, load, and CMOEs are set to 200 r/min, 3 N·m, and 1 A, respectively. Additionally, the stator resistance is increased from 1.8 Ω to 3.6 Ω

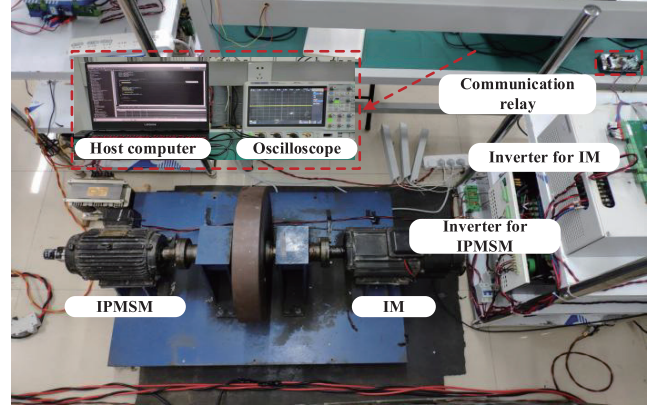


Fig. 10. Experimental set-up of the interior permanent magnet synchronous motor drives.

TABLE I
PARAMETERS OF THE EXPERIMENTAL SET-UP OF THE IPMSM DRIVES

Parameter	Value	Parameter	Value
Rated power (kW)	3	Rated voltage (V)	380
Rated current (A)	6	Stator resistance (Ω)	1.8
d -axis inductance (mH)	38	q -axis inductance (mH)	142
Pole pairs	2	Inertia ($\text{kg} \cdot \text{m}^2$)	3.13

and then decreased back to 1.8 Ω . As can be seen from Fig. 9, when the stator resistance changes, the current estimation performance remains unaffected, thereby ensuring the CMOEE capability of the proposed method. This indicates that, since the proposed method does not rely on motor parameters, it exhibits strong robustness against variations in motor parameters.

V. EXPERIMENTAL TEST VERIFICATION

A. Experimental Test Bench

To further validate the performance of the proposed CMOEE method, a low-power IPMSM drive system experimental platform was constructed for testing. The experimental setup is shown in Fig. 10. As illustrated, the platform consists of a test motor (3 kW IPMSM), a load motor (3.3 kW induction motor), inverters (DZ-dAC), a DC power source (Chroma 62180D-600), a DSP controller (TMS320F28335), a communication relay board, an oscilloscope, and other components. The test motor and the load motor are coupled via a flywheel. Two separate inverters supply power to the test motor and the load motor, respectively. Meanwhile, the communication relay board is used for serial communication to acquire experimental data and transmit it to the host computer. Furthermore, the parameters of the IPMSM drive system experimental platform are listed in Table I.

B. Current Estimation Performance

Experiments were conducted to investigate the current estimation performance of the proposed method. As shown in Fig. 11, the speed command, load, and CMOEs are set to 300 r/

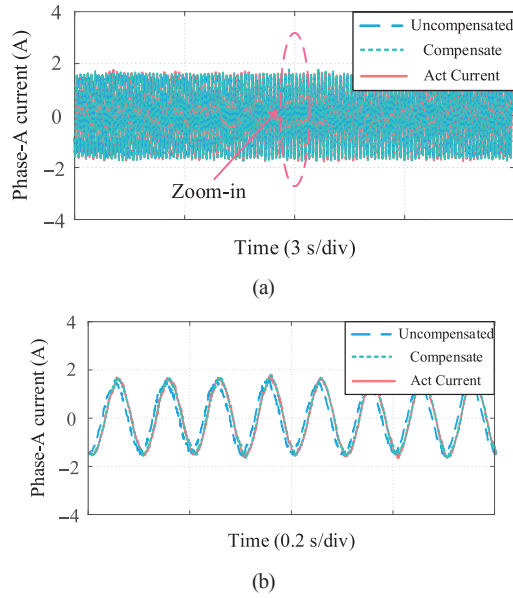


Fig. 11. Performance comparison of phase current estimation with and without amplitude attenuation and phase delay compensation under steady state. (a) The phase-A current. (b) The zoom-in.

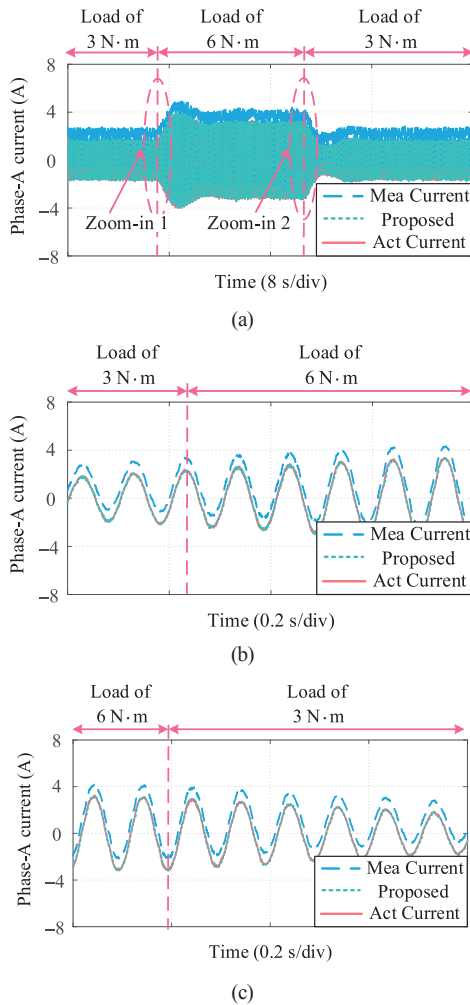


Fig. 12. Phase current estimation performance of the proposed method under load variations. (a) The phase-A current. (b) The zoom-in 1. (c) The zoom-in 2.

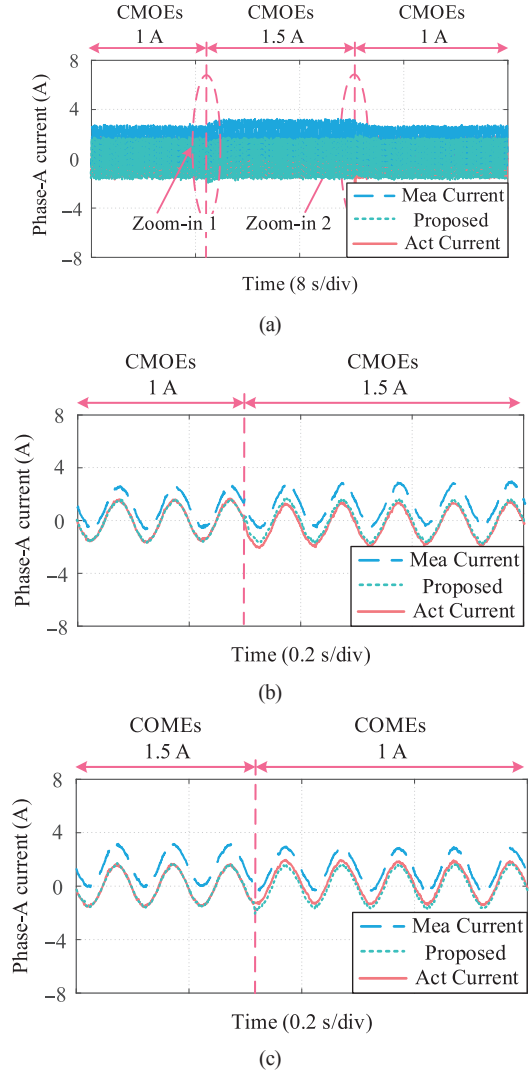


Fig. 13. Phase current estimation performance of the proposed method under the variations of CMOEs. (a) The phase-A current. (b) The zoom-in 1. (c) The zoom-in 2.

min, 3 N·m, and 1 A, respectively. According to the test results, under these operating conditions, when the proposed method does not incorporate amplitude and phase compensation, the estimated current exhibits noticeable deviation from the actual current, thereby degrading the CMOEE performance (see Fig. 11). In contrast, after introducing the amplitude and phase compensation into the proposed method, the estimated current effectively tracks the actual current, indicating that with compensation, the proposed method provides satisfactory current estimation performance and ensures reliable CMOEE.

Subsequently, experiments were carried out to validate the current estimation performance of the proposed method under varying load conditions, with the test results shown in Fig. 12. In Fig. 12, the load varies from 3 N·m to 6 N·m and then back to 3 N·m, while the speed command and CMOEs are set to 200 r/min and 1 A, respectively. As can be observed from Fig. 12, under these conditions, the proposed method exhibits satisfactory current estimation performance and dynamic response.

Finally, considering that CMOEs may vary during actual

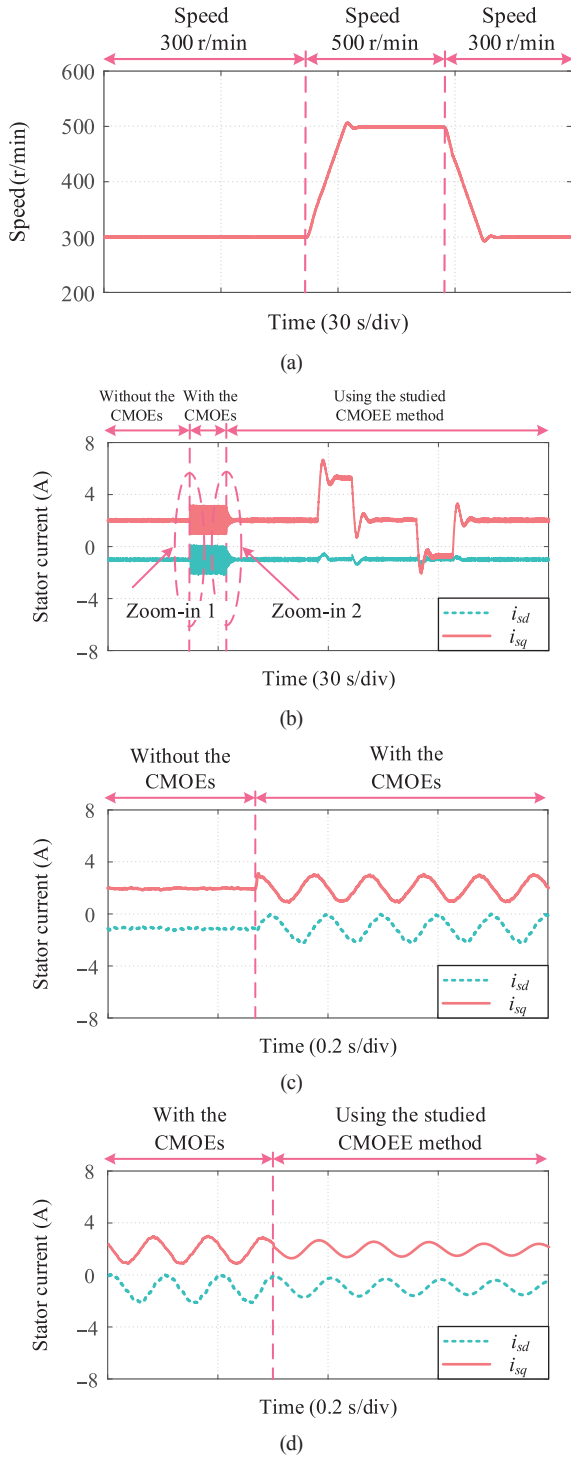


Fig. 14. Performance of the IPMSM drives with the proposed method under speed command variations. (a) The motor speed. (b) d -axis and q -axis current component. (c) The zoom-in 1. (d) The zoom-in 2.

motor operation, which could potentially affect the performance of the proposed method, this study further validates the current estimation capability of the approach under dynamic CMOEs variations through experimental tests. The results are shown in Fig. 13, where the CMOEs is stepped sequentially from 1 A to 1.5 A and back to 1 A. The experimental data demonstrate that the proposed method maintains excellent cur-

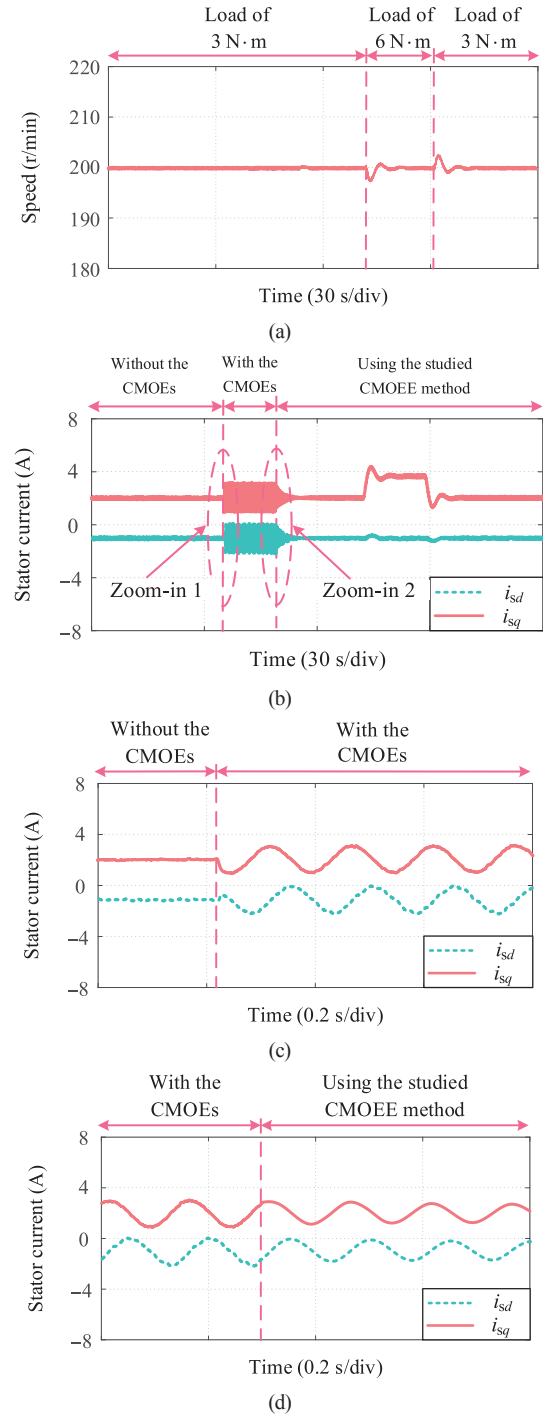


Fig. 15. Performance of the IPMSM drives with the proposed method under load variations. (a) The motor speed. (b) d -axis and q -axis current component. (c) The zoom-in 1. (d) The zoom-in 2.

rent estimation performance even when the CMOEs changes. This characteristic ensures the robustness of the method in practical applications, as it does not rely on a fixed ideal parameter. Therefore, even if the CMOEs fluctuates during motor operation, the proposed method can still provide accurate and reliable current estimation, thereby effectively ensuring the CMOEE performance and enhancing the overall stability and reliability of the control system.

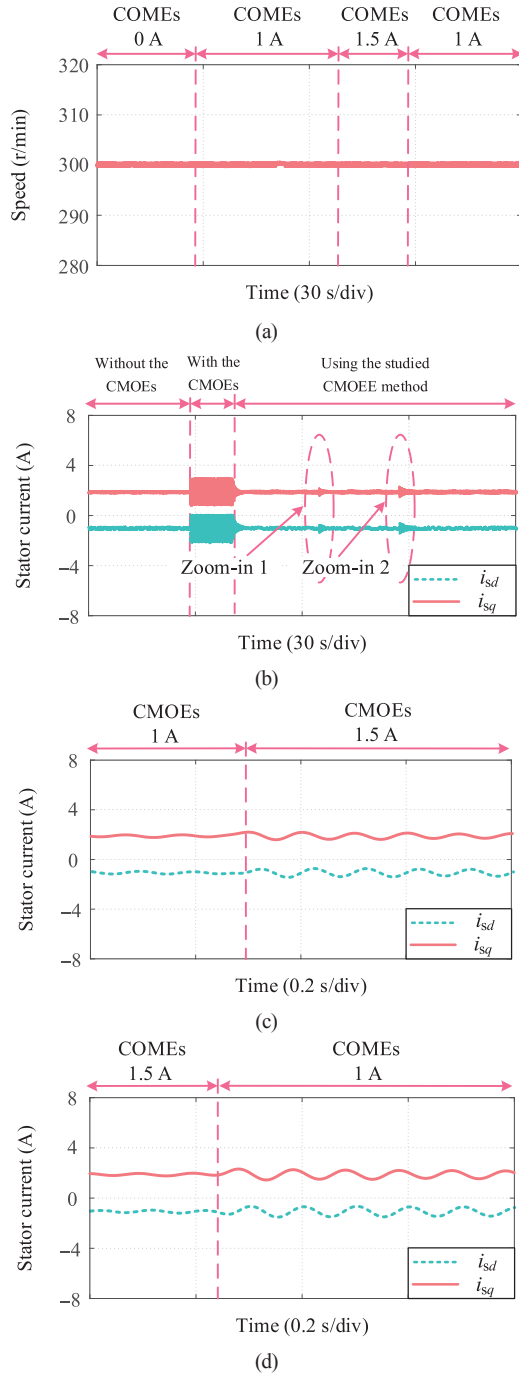


Fig. 16. Performance of the IPMSM drives with proposed method under the variations of CMOEs. (a) The motor speed. (b) d -axis and q -axis current component. (c) The zoom-in 1. (d) The zoom-in 2.

C. IPMSM Drive System Using the Studied Method

Subsequently, experimental tests were conducted to evaluate the performance of the IPMSM drive system using the proposed method. First, the performance of the IPMSM drive system under varying speed commands was experimentally validated. Under this operating condition, the speed command varied from 200 r/min to 400 r/min and then back to 200 r/min. The test results are shown in Fig. 14. As depicted, when CMOEs is present in the IPMSM drive system, significant pul-

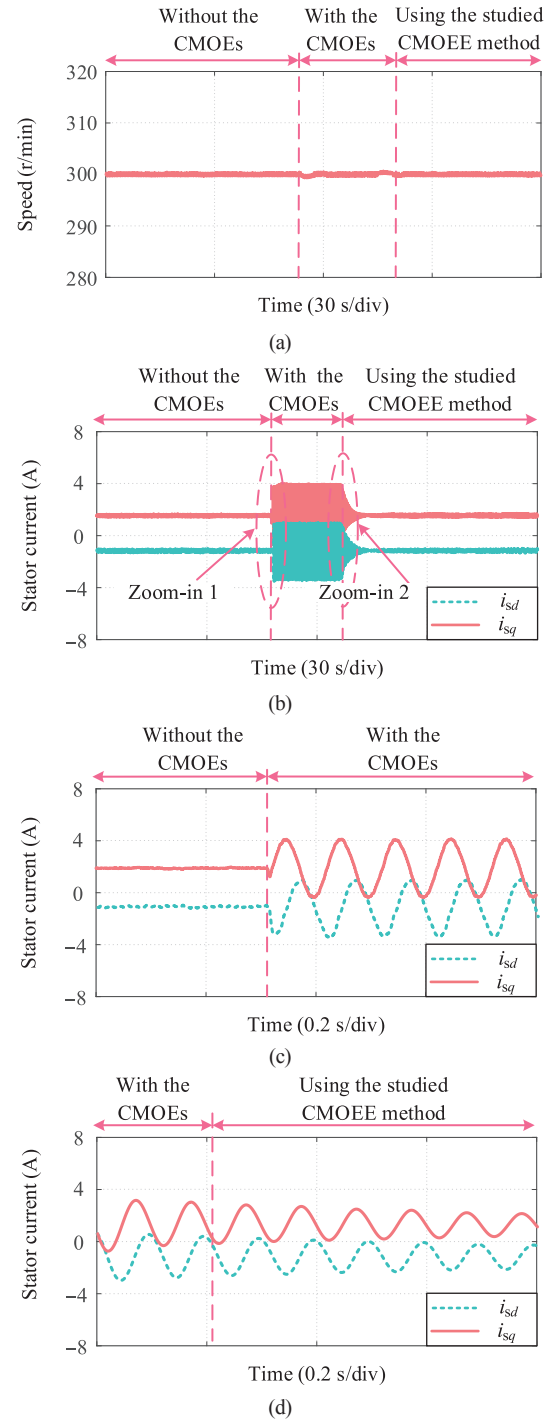


Fig. 17. Performance of the IPMSM drives with the proposed method when two current sensors suffer from CMOEs. (a) The motor speed. (b) d -axis and q -axis current component. (c) The zoom-in 1. (d) The zoom-in 2.

sations occur in the d -axis and q -axis current components, degrading the control performance of the drive system. However, after applying the proposed method, the pulsations in the d -axis and q -axis current components are effectively suppressed, significantly mitigating the adverse effects of CMOEs on the IPMSM drive system. Moreover, with the proposed method, the system maintains good dynamic response even under varying speed command conditions.

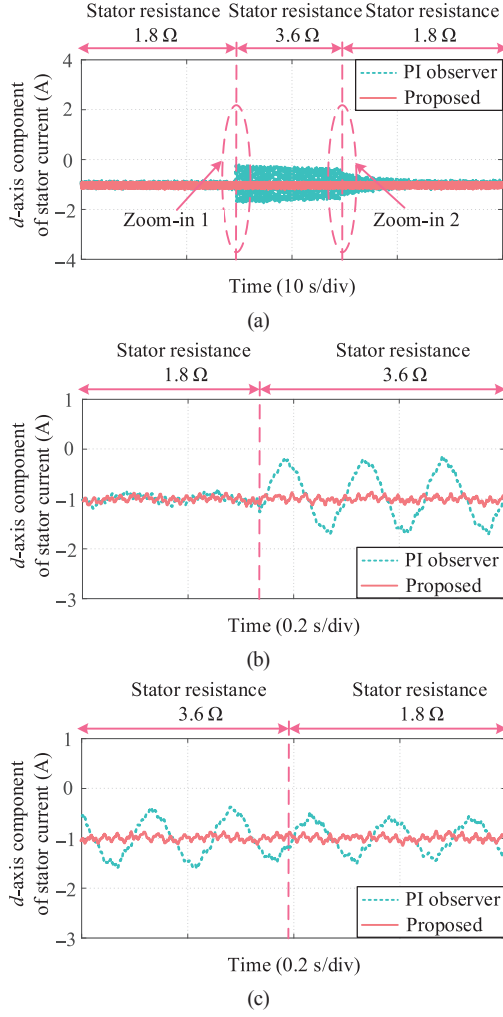


Fig. 18. Performance comparison of d -axis component between the PI-type observer-based method and the proposed method under stator resistance variations. (a) Overall performance comparison. (b) The zoom-in 1. (c) The zoom-in 2.

Subsequently, the performance of the IPMSM drive system under varying load conditions was investigated, with the test results shown in Fig. 15. In Fig. 15, the speed command is set to 200 r/min, and the load is increased from 3 N·m to 6 N·m and then reduced back to 3 N·m. According to the test results, under varying load conditions, the proposed method also provides satisfactory CMOEE performance and maintains good dynamic response.

During motor operation, variations in CMOEs may affect the performance of the proposed method. To evaluate the IPMSM drive system under varying CMOEs conditions, experiments were conducted, with results presented in Fig. 16. In this test, the CMOEs increased from 1 A to 1.5 A and then returned to 1 A. As shown, even under changing CMOEs, the proposed method still achieves effective CMOEE, ensuring reliable operation of the IPMSM drive system.

In a typical IPMSM drive system, two current sensors are usually used to obtain current information. Therefore, during motor operation, both current sensors may be affected by CMOEs simultaneously. To this end, experiments were used

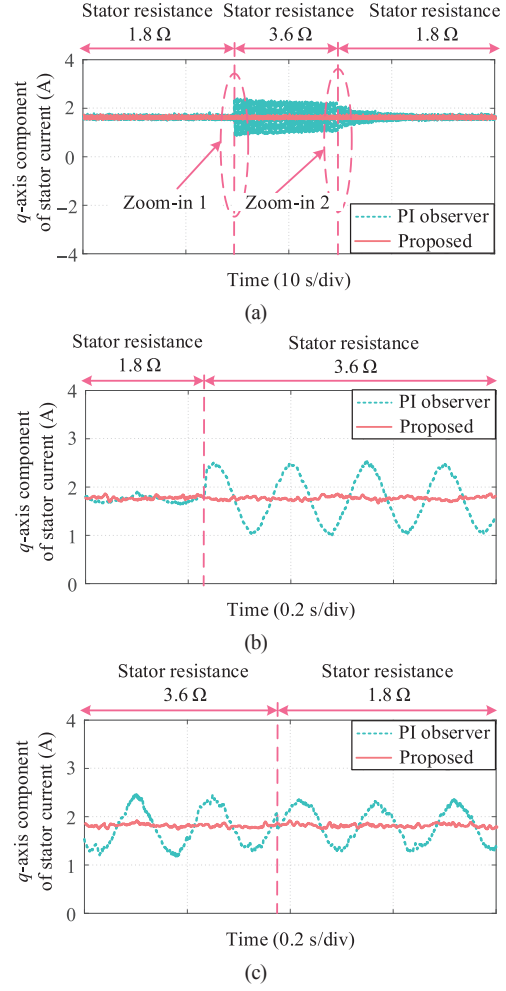


Fig. 19. Performance comparison of q -axis component between the PI-type observer-based method and the proposed method under stator resistance variations. (a) Overall performance comparison. (b) The zoom-in 1. (c) The zoom-in 2.

to explore the performance of the IPMSM drive system when two current sensors are affected by CMOEs at the same time. The test results are shown in Fig. 17.

In Fig. 17, the CMOEs of the phase-A and phase-B current sensors are set to 1 A and 1.5 A, respectively. The test results indicate that when both current sensors are affected by CMOEs simultaneously, the d -axis and q -axis current components exhibit even greater pulsations. Nevertheless, the proposed method is still capable of overcoming the adverse effects caused by the CMOEs.

D. Performance Comparison With CMOEE Method Based on Type PI Observer

Finally, to validate the performance of the proposed method, a comparative evaluation was conducted against the PI-observer-based CMOEE method [21]. The experimental results are presented in Fig. 18 and Fig. 19. Under these test conditions, the stator resistance was varied from 1.8Ω to 3.6Ω and then back to 1.8Ω . As shown in the figures, when the stator resistance changes, the performance of the PI-observer-based method de-

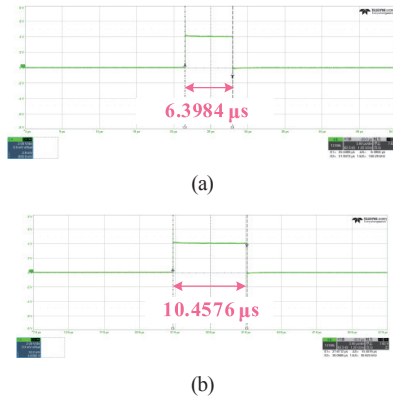


Fig. 20. Performance comparison of computational time between the PI-type observer-based method and the proposed method. (a) Research methods. (b) Methods based on type PI observers.

teriorates, which is manifested as significant pulsations in the d - and q -axis current components. This consequently degrades the performance of the IPMSM drive system. This decline occurs because the method is designed based on a motor model; when motor parameters vary, its CMOEE capability is notably compromised. In contrast, since the proposed method does not involve motor parameters, its CMOEE performance remains unaffected even under motor parameter variations.

Subsequently, a comparative analysis of the computational burden between the PI-observer-based CMOEE method and the proposed method was conducted, with the test results shown in Fig. 20. As can be observed from the figure, the computation time of the PI-observer-based method is 10.4576 μ s, whereas that of the proposed method is only 6.3984 μ s. This indicates that the proposed method imposes a lower computational burden and is easier to implement.

In summary, the proposed method can effectively suppress CMOEs under various operating conditions. Additionally, it is capable of overcoming the adverse effects caused by motor parameter variations and exhibits a lower computational burden.

V. CONCLUSION

The issue of CMOEs can induce estimation inaccuracies and provoke torque ripples, thereby severely degrading the performance of IPMSM drive systems. To address this issue, this paper proposes a CMOEE method based on high-frequency signal injection. The method begins by analyzing the mechanism through which CMOEs affect system performance. Subsequently, it elaborates on the technical approach for CMOEE, which involves injecting specific signals and utilizing a band-stop filter constructed from a SOGI. To address the resultant amplitude attenuation and phase deviation introduced by the filter, a simple yet effective compensation strategy is further introduced, ensuring the reliability of the CMOEE performance. Finally, a low-power experimental platform was established to validate the effectiveness of the proposed method under various operating conditions. Experimental results demonstrate that the proposed method can effectively suppress various CMOEs without altering the drive system structure and without requir-

ing motor parameter information. It is characterized by simple implementation, low computational burden, and strong robustness, providing a practical solution for CMOEE and enhancing the anti-interference capability of IPMSM drive systems.

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