

SCALAR CONTROL OF INDUCTION MOTOR DRIVES BASED ON ROTOR FLUX ADAPTATION

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Abstract. *This paper proposes a speed-sensorless closed-loop scalar control strategy for three-phase induction motor drives based on a rotor-flux model reference adaptive system (RF-MRAS). The proposed approach enhances the conventional constant V/f control by introducing a closed-loop slip compensation mechanism, eliminating both the mechanical speed sensor and the proportional-integral based speed controller. Rotor speed is estimated via the adaptive mechanism of the RF-MRAS using the deviation between the rotor flux vectors obtained from the voltage and current models. The rotor flux angle obtained from the voltage model is then used to estimate the synchronous speed so that slip estimation and compensation can be performed. To reduce the high frequency noise due to the differentiation of the flux angle, a first-order low-pass filter is included in the compensation loop. Extensive simulation studies under load torque disturbances and dynamic speed reference profiles show that the proposed method can achieve accurate speed tracking, robust performance, and stable operation compared with the typical open-loop scalar control. The results show that the proposed scheme is an effective low-complexity alternative for speed sensorless induction motor drive applications.*

Keywords: *Induction motor, speed sensorless, scalar control, speed estimation.*

1. Introduction

Three-phase induction motor (IM) drives are widely used in industrial settings because of their durability, low cost, and limited maintenance needs. Over recent decades, several control methods have been introduced to improve both the dynamic and steady-state behavior of IM drives, with direct torque control (DTC), field-oriented control (FOC), and scalar control (SC) remaining the most commonly implemented techniques.

DTC offers fast torque feedback and relatively simple control structures but suffers from torque ripple, current distortion, and variable switching frequency. Recent advances address these issues via switchboard-based strategies, constant switching frequency operation, intelligent control, sensorless control, and predictive control [1]. A DTC scheme based on minimum voltage vector error was proposed to reduce torque ripple and current THD while maintaining fast dynamics and nearly constant average switching frequency [2]. Advanced control structures have also been studied to improve DTC. To improve the control performance of the motor drive system, an improved DTC strategy with a synthetic controller is presented [3]. A fuzzy DTC scheme with a magnetic flux estimator (MRAS) and slip-mode speed controller has been developed to reduce the torque and

flux ripple and to improve the stator current waveforms and stability under different operating conditions [4]. Moreover, a DTC optimization method based on a genetic algorithm is proposed to tune PID coefficients and enhance speed feedback [5]. Nevertheless, DTC still has drawbacks in torque smoothness and switching performance, especially at low speed.

In high-performance IM drives, FOC dominates because it decouples torque and flux control, enabling precise speed regulation over a wide operating range. To enhance the dynamic response and accuracy of FOC-based drives, advanced current regulation techniques have been developed [6], and fault-tolerant control strategies have been proposed to improve reliability under sensor faults [7]. Additionally, FOC has been coupled with neural network-based approaches to improve current regulation accuracy under different operating conditions [8]. However, FOC-based drives are generally based on cascaded PI controllers and multiple sensors, which increases the system complexity and reduces the robustness in the event of sensor faults or parameter uncertainties [9].

Compared with other methods, SC based on the constant V/f principle provides a simple and economical solution; therefore, it is widely applied in systems requiring low- and medium-performance operation [10]. Typical open-loop scalar control (OSC) lacks feedback, resulting in poor speed regulation and high sensitivity to load disturbances. To address these issues while preserving SC's simple structure, several improved strategies have been proposed. A passivity-based scalar control with adaptive high starting torque was developed to enhance sensorless, observerless induction motor starting performance [11]. Another study introduced a scalar control with normalized adaptive control to improve starting performance and dynamic response, also with a sensorless, observerless structure [12]. A steady-state model-based scalar control method derived from rotor-flux-oriented vector control was developed to improve magnetizing current regulation and full-load starting [13]. Moreover, a closed-loop adaptive high-starting-torque scalar control scheme using cascade normalized adaptive passivity-based control was introduced to improve tran-

sient behavior under high-torque operation [14]. Although these methods improve the starting and transient performance of SC, accurate speed regulation and strong load-disturbance rejection over a wide operating range remain challenging. More recently, an improved rotor slip compensation method for SC of IM drives was proposed in [15]. In this method, the synchronous speed is obtained from the current model, while the virtual rotor speed is estimated using CB-MRAS. The slip compensation component is then derived from the difference between these two speed quantities to improve speed tracking under load variations. However, this approach mainly relies on a virtual speed compensation mechanism.

Sensorless control has become a major research focus for eliminating mechanical speed sensors, thereby reducing cost and improving reliability. Among sensorless methods, model reference adaptive system (MRAS) techniques are attractive due to their simple structure and satisfactory estimation accuracy. A sensorless indirect vector control of induction machines using a stator current-based MRAS speed estimator offers good speed tracking at low speed, during speed reversal, load changes, parameter uncertainty, and regenerative operation [16]. An improved current-based MRAS with stator resistance tuning was proposed for sensorless speed control of three-phase induction motor drives [17]. In this method, the stator resistance tuning mechanism was integrated into the CB-MRAS algorithm to enhance virtual current estimation under stator resistance mismatch [17]. An improved current-based MRAS with stator resistance tuning was proposed for sensorless speed control of three-phase induction motor drives [18]. In addition, a rotor flux-based MRAS speed observer has been applied to sensorless indirect field-oriented control of induction motor traction drives for EV/HEV applications, showing satisfactory speed regulation under various driving profiles [19]. These works confirm the effectiveness of MRAS-based estimation, but their use is largely confined to sensorless vector control drives and not to closed-loop scalar control with rotor-flux-based slip compensation.

A recent study reported an improved scalar control method based on slip compensation from virtual speeds for three-phase induction motor drives [20]. Although this method improves speed tracking under load variations, it mainly relies on a virtual speed compensation mechanism. In contrast, this paper presents a speed-sensorless closed-loop scalar control (SS-CSC) method based on an RF-MRAS framework. By integrating rotor flux estimation and adaptive slip compensation into the SC architecture, the proposed method achieves closed-loop speed regulation without mechanical speed sensors or traditional PI-based speed controllers. Instead, a low-complexity compensation loop with a first-order low-pass filter is used to provide stable slip compensation while suppressing high-frequency noise caused by flux angle differentiation. Therefore, the proposed strategy preserves the simplicity of SC while improving the speed tracking accuracy and robustness against varying load and operating conditions.

The main contributions of this paper can be summarized as follows:

- A speed-sensorless closed-loop scalar control structure based on RF-MRAS is proposed for induction motor drives.
- The rotor speed is estimated using the RF-MRAS adaptive mechanism driven by the deviation between the rotor flux vectors obtained from the voltage and current models, thereby eliminating the need for a mechanical speed sensor.
- The rotor flux angle of voltage model is used to calculate the synchronous speed and the slip compensation component.
- The slip compensation loop is implemented in a first-order low-pass filter to filter out the high-frequency noise caused by differentiating the flux angle.
- The proposed method improves the speed tracking and load disturbance rejection while maintaining the simple scalar control structure.

The remainder of this paper is organized as follows. Section 2 presents the IM model and the

typical OSC structure. Section 3 describes the proposed RF-MRAS-based SS-CSC method and its slip compensation mechanism. Section 4 discusses the simulation results under load disturbances and dynamic speed references. Finally, Section 5 concludes the paper.

2. Induction Motor Drive based on Scalar Control

2.1. Dynamic Model in the Stationary $\alpha\beta$ Reference Frame

The dynamic behavior of the IM is described using a rotor flux-oriented model in the stationary $[\alpha, \beta]$ reference frame. This modeling approach enables a clear separation between the electrical dynamics and the flux evolution.

The rotor flux and stator voltage equations can be expressed in vector form as shown in Equations (1) and (2).

$$\vec{u}_S = R_S \vec{i}_S + \left(\frac{L_S L_R - L_M^2}{L_R} \right) \frac{d\vec{i}_S}{dt} + \frac{L_M}{L_R} \frac{d\vec{\lambda}_R}{dt} \quad (1)$$

$$0 = -\frac{L_M R_R}{L_R} \vec{i}_S + \left(\frac{R_R}{L_R} - j\Omega_R \right) \vec{\lambda}_R + \frac{d\vec{\lambda}_R}{dt} \quad (2)$$

where, $\vec{u}_S$ is the stator voltage vector; $\vec{i}_S$ is the stator current vector; $\vec{\lambda}_R$ is the rotor flux vector; Ω_R is the rotor angular velocity; R_S and R_R are the stator and rotor resistances, respectively; L_S , L_R , and L_M are the stator, rotor, and magnetizing inductances, respectively.

By combining Equations (1) and (2), the stator current dynamics in the stationary reference frame can be derived as given in Equations (3)–

(6).

$$i_{S\alpha} = J_1 \int \left[\frac{u_{S\alpha}}{L_M} - \frac{R_S}{L_M} i_{S\alpha} + \frac{L_M \Omega_R}{L_R} i_{S\beta} + \frac{R_R}{L_R} i_{R\alpha} + \Omega_R i_{R\beta} \right] dt \quad (3)$$

$$i_{S\beta} = J_1 \int \left[\frac{u_{S\beta}}{L_M} - \frac{L_M \Omega_R}{L_R} i_{S\alpha} - \frac{R_S}{L_M} i_{S\beta} - \Omega_R i_{R\alpha} + \frac{R_R}{L_R} i_{R\beta} \right] dt \quad (4)$$

$$\lambda_{R\alpha} = L_M i_{S\alpha} + L_R i_{R\alpha} \quad (5)$$

$$\lambda_{R\beta} = L_M i_{S\beta} + L_R i_{R\beta} \quad (6)$$

where, $i_{S\alpha}$ and $i_{S\beta}$ denote the α - and β -axis stator current components, respectively; $i_{R\alpha}$ and $i_{R\beta}$ are the corresponding rotor current components; $u_{S\alpha}$ and $u_{S\beta}$ represent the stator voltage components in the stationary reference frame; $\lambda_{R\alpha}$ and $\lambda_{R\beta}$ are the rotor flux linkage components. The coefficient J_1 is defined as $J_1 = \frac{L_M L_R}{L_S L_R - L_M^2}$.

2.2. Typical Open-Loop Scalar Control

The typical open-loop scalar control (OSC) is commonly used for IM drives due to its simplicity and low implementation cost. Its operating principle is based on preserving a constant relationship between the stator voltage amplitude V and the supply frequency f . Accordingly, when the frequency command changes, the voltage magnitude is adjusted in the same proportion so that $V/f = \text{constant}$. This condition helps keep the air-gap flux approximately unchanged within the normal operating region of the motor.

Under this condition, the electromagnetic characteristics of the IM remain nearly unchanged over a wide speed range, provided that

magnetic saturation and parameter variations are negligible. As a result, the motor can operate with acceptable performance without requiring flux or speed feedback.

Figure 1 illustrates the overall structure of the OSC IM drive. The reference speed Ω_{ref} is first converted into a corresponding stator frequency command through the V/f block. Based on this frequency, a voltage reference signal is generated to satisfy the constant V/f relationship. This reference voltage is then applied to the inverter via sinusoidal pulse-width modulation (SPWM), as depicted in Figure 2.

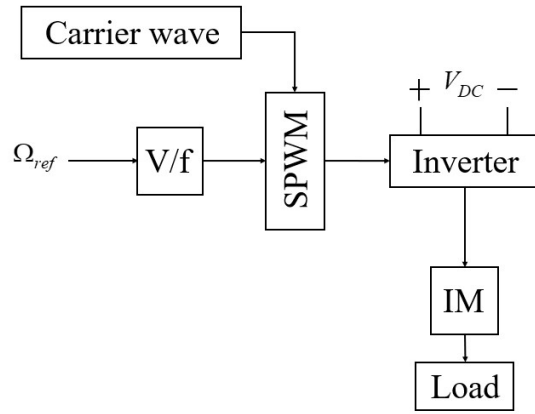


Figure 1: Block diagram of the OSC scheme for IM drive.

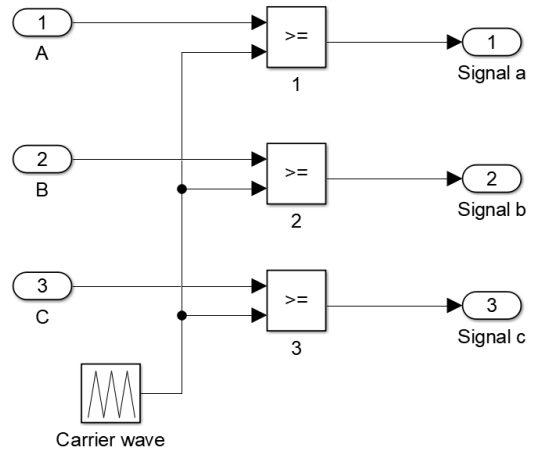


Figure 2: Principle of SPWM for voltage synthesis in OSC.

This comparison determines the switching states of the power devices. When the reference signal is greater than the carrier signal, the switch is ON and OFF otherwise. This switching principle can be written in the mathematical form as Equation (7).

$$\begin{cases} v_{\text{ref}}(t) > v_{\text{carrier}}(t) \Rightarrow \text{Switch ON} \\ v_{\text{ref}}(t) \leq v_{\text{carrier}}(t) \Rightarrow \text{Switch OFF} \end{cases} \quad (7)$$

where, $v_{\text{ref}}(t)$ denotes the sinusoidal reference voltage signal generated by the V/f control block, and $v_{\text{carrier}}(t)$ represents the high-frequency carrier signal used in the SPWM process.

Although the structure of the OSC is simple, it cannot compensate the slip variation inherently. In particular, as the load torque increases, the rotor slip increases resulting in a large difference between the actual rotor speed and the reference speed. This drawback becomes more serious in the applications requiring the accurate speed control or in the applications with the variable load conditions. The above intrinsic drawbacks motivate the development of improved OSC strategies with closed-loop characteristics. In the next section, an improved scheme based on the RF-MRAS framework is proposed to overcome these drawbacks while maintaining the simple nature of the SC approach.

3. Proposed Speed-Sensorless Closed-Loop Scalar Control

In closed-loop scalar control (CSC), the measured speed feedback signal was generally obtained from the speed sensor. The input of the PI controller was the error between the reference speed and the rotor speed. The PI speed controller adjusted the output control frequency to keep the rotor speed near the reference speed. This means that the PI controller acted as a slip compensation mechanism. However, a drawback of PI speed controllers is their dependence on the

Kp and Ki coefficients. Additionally, speed sensors mounted on the motor shaft have significant durability drawbacks due to mechanical friction.

With the proposed speed-sensorless CSC (SS-CSC) structure, the mechanical speed sensor is completely eliminated. Instead, the control strategy relies exclusively on measured electrical quantities, namely the stator currents and stator voltages. The measured three-phase quantities $[a, b, c]$ are first transformed into the stationary reference frame $[\alpha, \beta]$ using the Clarke transformation, which provides a convenient representation for observer design and control implementation. This transformation is expressed in Equation (8).

$$\begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \quad (8)$$

where, X_a , X_b , and X_c denote the three-phase quantities in the a -, b -, and c -phase coordinate system, respectively. The variables X_α and X_β represent the corresponding components in the stationary $\alpha\beta$ reference frame. In this study, X can represent either the stator voltage or stator current.

Based on the transformed stator quantities, the proposed RF-MRAS observer is constructed using two fundamental models, namely the voltage model (VM) and the current model (CM). Among them, the VM is selected as the reference model because it directly employs the measured stator voltages and stator currents as input signals. Since these quantities are obtained from physical sensors, the rotor flux vector estimated by the VM can be regarded as a reliable representation of the actual operating condition of the IM.

Accordingly, the rotor flux components in the stationary reference frame $[\alpha, \beta]$, estimated by the VM, are described in Equations (9) and (10).

$$\frac{d\lambda_{R\alpha}^{\text{VM}}}{dt} = J_2 (u_{S\alpha} - R_S i_{S\alpha}) - J_2 J_3 \frac{di_{S\alpha}}{dt} \quad (9)$$

$$\frac{d\lambda_{R\beta}^{\text{VM}}}{dt} = J_2 (u_{S\beta} - R_S i_{S\beta}) - J_2 J_3 \frac{di_{S\beta}}{dt} \quad (10)$$

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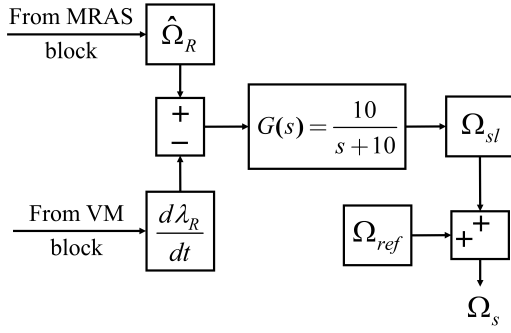


Figure 4: Slip speed estimation and compensation scheme using first-order low-pass filtering.

To suppress high-frequency noise introduced by the differentiation of the rotor flux angle, the slip speed signal is passed through a first-order low-pass filter with the transfer function given in Equation (18).

$$G(s) = \frac{10}{s+10} \quad (18)$$

where, $G(s)$ denotes the transfer function of the first-order low-pass filter in the Laplace domain.

The slip speed estimation procedure is illustrated in Figure 4, which is based on the difference between the electrical angular speed acquired from the differentiation of the rotor flux angle and the estimated rotor electrical angular speed provided by the RF-MRAS. To remove the high-frequency components introduced by the numerical differentiation and measurement noise, the raw slip speed signal is low-pass filtered by a first-order filter. The filtered slip speed is fed back to the synchronous speed generation block, which allows a smooth and stable slip compensation without oscillations of the SC loop.

Although the speed reference is not directly compared with a measured mechanical speed, the proposed scheme still operates with feedback signals. The stator voltage and current measurements are used by the RF-MRAS observer to estimate the rotor speed, which is then employed to compute the slip compensation. Therefore, the control structure can be interpreted as an

Table 1: Parameters of the IM.

Parameter	Value	Unit
Rated power P_{rated}	2200	W
Rated voltage V_{rated}	380	V
DC-link voltage V_{DC}	540	V
Rated frequency f_{rated}	50	Hz
Stator resistance R_S	3.179	Ω
Rotor resistance R_R	2.118	Ω
Magnetizing inductance L_M	0.192	H
Stator inductance L_S	0.209	H
Rotor inductance L_R	0.209	H
Stator time constant T_S	0.0657	s
Rotor time constant T_R	0.0987	s
Moment of inertia J	0.047	kg·m ²
Number of pole pairs p	2	–

indirect closed-loop SC scheme with observer-based feedback.

4. Simulation Results

The proposed SS-CSC strategy has been evaluated by extensive simulations on the IM drive. The tests considered steady state accuracy, load disturbance rejection and dynamic tracking performance under different speed references and load conditions. The motor parameters are given in Table 1.

4.1. Scenario 1: OSC under Load Torque Variation

In the first test case, the IM drive operates using the typical OSC approach. The reference speed follows a piecewise trajectory with setpoints of 73 rad/s, 104 rad/s, and 83 rad/s during the intervals 0-1.5 s, 1.5-4 s, and 4-7 s, respectively, as depicted in Figure 5b. At the same time, the load torque is increased stepwise at approximately $t = 3$ s and $t = 5$ s, as illustrated in Figure 5a.

The corresponding speed response is shown in Figure 5b. When the load torque increases, the rotor speed gradually departs from the reference trajectory. This effect is attributed to the absence of any slip compensation mechanism in the

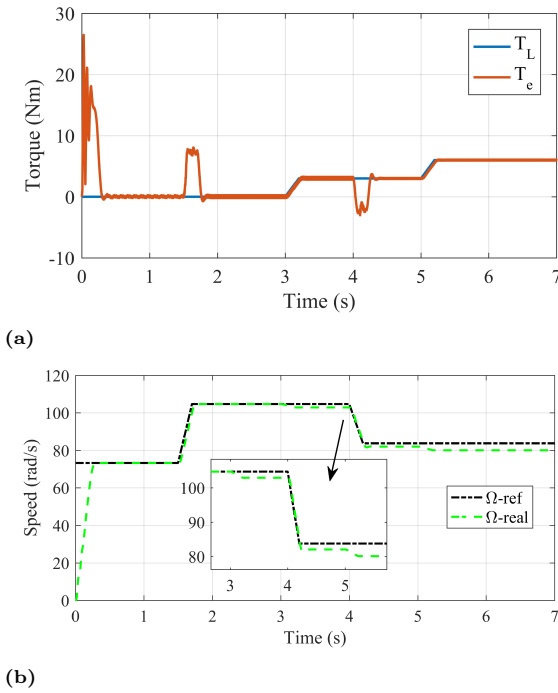


Figure 5: Performance of OSC under load torque disturbance: a) Torque; b) Speed.

OSC scheme. Since the excitation frequency remains fixed, the increase in load torque results in a larger rotor slip, which consequently reduces the actual rotor speed. The discrepancy between the reference and the actual speed becomes evident after $t = 3$ s and further increases following the second torque disturbance at $t = 5$ s.

These observations reveal the intrinsic limitation of OSC. Although maintaining a constant V/f ratio preserves the air-gap flux approximately constant, the method lacks the capability to compensate for load-induced slip variations, resulting in poor speed regulation when the mechanical load changes.

4.2. Scenario 2: Proposed SS-CSC under Load Torque Variation

In the second scenario, the proposed SS-CSC strategy is implemented under the same reference speed and load torque conditions as those

applied in Scenario 1, allowing a direct performance comparison.

As shown in Figure 6a, the load torque increases at $t = 3$ s and $t = 5$ s. In contrast to the OSC scheme, the proposed approach employs an RF-MRAS observer to estimate the rotor speed and derive the corresponding slip component. This estimated slip is then fed back in the control structure to modify the excitation frequency.

The acquired speed response is depicted in Figure 6b. With the increase of the load torque, the rotor speed decreases temporarily due to the sudden change of the mechanical load. The control system, however, quickly brings the speed back to the reference value within about 0.1 s.

The slip signal produced by the compensation mechanism is depicted in Figure 6c. By incorporating a filtering stage, the slip signal can evolve smoothly without any noticeable oscillations. Thus, the proposed control structure is able to track the speed accurately in the presence of load disturbances. Moreover, the estimated rotor speed by the RF-MRAS observer is in close agreement with the actual rotor speed during the simulation that confirms the effectiveness of the estimation process.

However, the slip signal is typically injected directly into the control loop, which may cause transient speed oscillations. The proposed method introduces slip filtering, resulting in smoother compensation and improved speed stability.

4.3. Scenario 3: Trapezoidal Speed Reference with Quadratic Load Torque Variation

To further evaluate the robustness of the proposed control strategy, Scenario 3 considers a dynamic operating condition in which the reference speed follows a trapezoidal waveform. In this case, the load torque varies according to the square of the rotor speed, as illustrated in Figure 7a. Such a condition introduces simultaneous variations in both the speed command and the mechanical load.

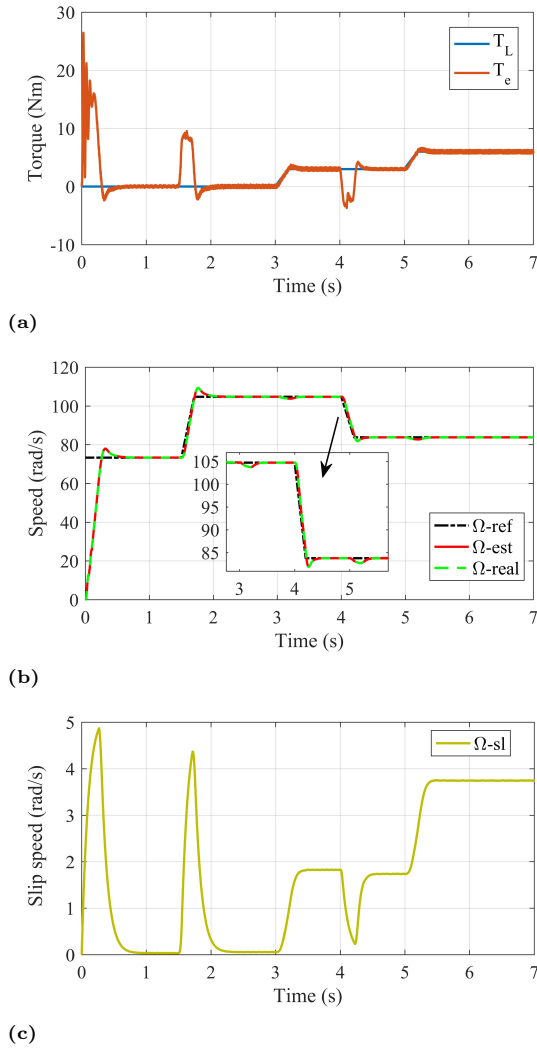


Figure 6: Performance of the proposed SS-CSC under load torque disturbance: a) Torque; b) Speed; c) Slip speed.

However, the proposed control scheme provides stable operation during the whole simulation period. The rotor speed response shown in Figure 7b indicates that the drive system is able to follow the trapezoidal reference profile with small deviations in the transition periods between different speed levels.

The corresponding slip signal in Figure 7c is smooth and continuous over the whole operating range. The above behavior demonstrates that the slip compensation mechanism is well suited for time-varying operating conditions and

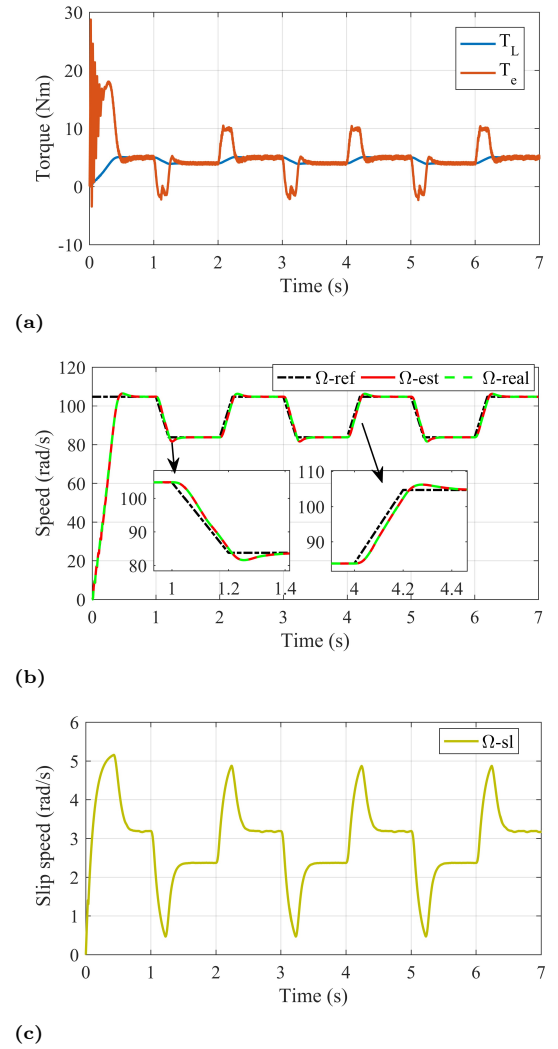


Figure 7: Dynamic performance of the proposed SS-CSC under trapezoidal speed reference with quadratic load torque variation: a) Torque; b) Speed; c) Slip speed.

maintains accurate speed tracking even under quadratic load torque variation.

4.4. Scenario 4: Sinusoidal Speed Reference with Quadratic Load Torque Variation

In the last case, the reference speed is provided as a sinusoidal waveform to simulate continuously changing operating conditions. Sim-

ilar to Scenario 3, the load torque is assumed to vary proportionally to the square of the rotor speed, as shown in Figure 8a. This scenario is used to verify the tracking capability of the proposed method under periodic speed variation and quadratic load torque variation.

The speed response shown in Figure 8b shows that the proposed control method is able to track the sinusoidal reference with high accuracy. The actual rotor speed follows the reference signal

very closely, with only a negligible phase delay and a very small steady-state error.

The estimated slip signal in Figure 8c is smoothly changing during the simulation. The low-pass filtering stage helps to reduce high frequency components that may be caused by the differentiation in the slip estimation. As a result, the control system preserves stable and reliable operation even when both the reference speed and the quadratic load torque vary continuously.

5. Conclusions

This paper presented a SS-CSC strategy for IM drives based on an RF-MRAS framework. The proposed method achieves closed-loop speed regulation without using a mechanical speed sensor and PI-based speed controller, by integrating rotor flux estimation, synchronous speed calculation, and slip compensation. Simulation results under load disturbances and dynamic speed references demonstrate better speed tracking performance and stable operation compared with the typical OSC.

However, the proposed approach still relies on accurate motor parameters such as stator and rotor resistances which are temperature-dependent in operation. Moreover, the differentiation of the rotor flux angle introduces a sensitivity with respect to the measurement noise, requiring appropriate filtering which may affect the dynamic response. Furthermore, the VM-based flux estimation applied in the RF-MRAS structure may be sensitive to stator resistance variations, especially in the low-speed region. Future work will therefore focus on online parameter adaptation and more noise-robust flux estimation techniques such as adaptive stator resistance estimation or hybrid flux observers to increase the robustness under practical operating conditions.

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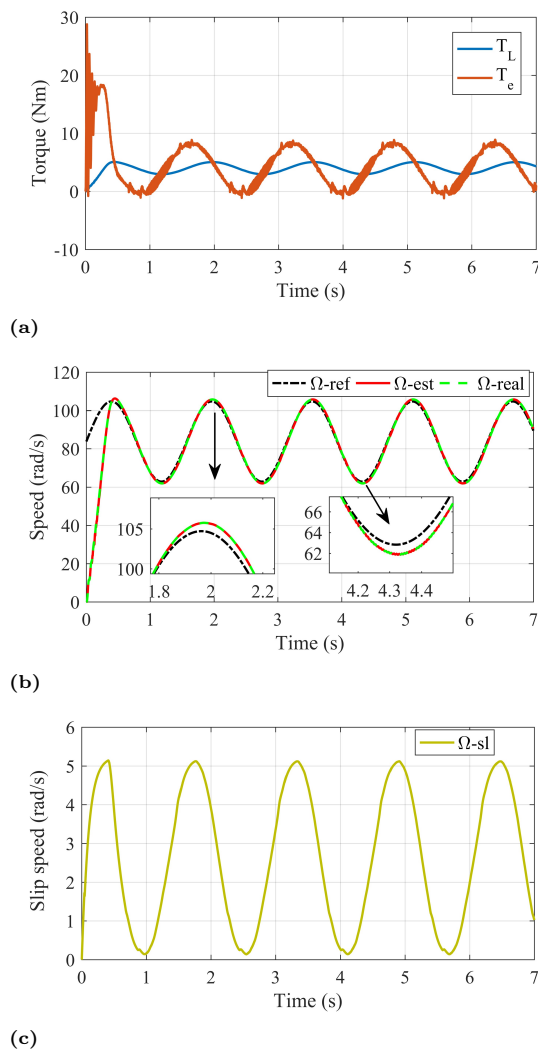


Figure 8: Dynamic response of the proposed SS-CSC under sinusoidal speed reference and quadratic load torque variation: a) Torque; b) Speed; c) Slip speed.

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