International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 16, No. 3, September 2025, pp. 1586~1597
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v16.i3.pp1586-1597

Direct torque control of induction motor using a novel sliding mode control

Ngoc Thuy Pham, Duc Thuan Le, Phu Diep Nguyen
Department of Electrical Engineering Technology, Industrial University of Ho Chi Minh City, Ho Chi Minh City, Vietnam

Article Info

Article history:

Received Mar 10, 2024
Revised May 30, 2025
Accepted Jul 23, 2025

Keywords:

Direct torque control
Induction motor
Nonlinear control
Sliding mode control
Vector control

ABSTRACT

Direct torque control (DTC) for induction motor (IM) drive systems is recognized as a powerful control method known for its fast response and simple structure. However, this control method often suffers from several limitations, such as significant torque and current ripple, and sensitivity to variations in motor parameters. To address these issues, this paper proposes a novel sliding mode control strategy for the outer speed loop to improve the quality of DTC-based IM drive systems. Unlike previous approaches, we propose a novel adaptive parameter higher-order sliding mode (HOSM) controller for IM speed control. This approach enhances the drive system's performance by reducing torque ripple (a common issue in DTC), improving dynamic response, eliminating overshoot during transients, and increasing overall system stability. To ensure system stability, Lyapunov stability theory is used to design the control signals. The efficiency of the control law proposed in this paper is evaluated based on simulations performed on MATLAB-Simulink. The results obtained demonstrate that: First, the proposed control model for fast torque and speed responses, ensuring the drive system converges to the desired operating point during transients without encountering the phenomenon of exceeding the threshold. Second, the system maintains stable operation, even in the presence of load disturbances. Third, this method significantly reduces torque ripple, a common problem in IM drive systems using DTC techniques.

Corresponding Author:

Phu Diep Nguyen
Department of Electrical Engineering Technology, Industrial University of Ho Chi Minh City
Ho Chi Minh City, Vietnam
Email: phudiep.tradin@gmail.com

1. INTRODUCTION

Nowadays, IM is widely used in most industrial applications and gradually occupies the market share of DC motors due to its simple structure, low cost, reliable operation, and high efficiency [1]. During a long period of development, scientists around the world have researched and developed various control techniques for IM speed control. Among them, field-oriented control (FOC) and direct torque control (DTC) are two basic control techniques widely used in industrial applications. FOC was invented in 1972 [2]. By separating torque and flux control, this control technique provides a wide speed control range, fast torque response, and high control performance under various operating conditions. Torque and flux oscillation, motor vibration during operation, mechanical noise, and poor control performance during operation at low speed range do not appear with this control technique. However, the relatively complex controller design, strongly affected by load interference or motor parameter changes, is a notable disadvantage of FOC [3], [4]. Meanwhile, DTC was first proposed by Depenbrock [5], Takahashi and Noguchi [6] as a simply designed control technique that allows control of both torque and magnetic flux. In addition to some advantages such as less dependence on IM parameters, fast response, DTC is also known for its simple design because it does not require coordinate system transformation, as well as current component control design [7]. However, DTC has disadvantages that seriously affect the transmission system as well as hardware devices, such as: high switching frequency, torque oscillation, mechanical noise, low control efficiency in the low-speed range, motor vibration [8]-[10]. To improve the performance of the transmission system using DTC, many different solutions have been proposed by scientists around the world, such as replacing delay control steps and switching commands using a neuron, fuzzy logic control, GA, [11]-[19]. This is considered one of the great solutions in nonlinear systems [14]. However, the use of AI has a major disadvantage in requiring a microcontroller with strong computing speed, fast response, and complex hardware configuration. This increases the cost and makes it difficult to apply widely in industrial production. Several other control strategies have been proposed for speed controllers to improve the phenomenon of torque ripple, which creates shaking of the rotor shaft, especially at low speeds [20]-[37]. This approach allows for simple drive system design, improved performance, reduced hardware requirements, and high practicality for industrial applications. However, simulation and experimental results in these strategies show that the torque ripple phenomenon still remains relatively significant. Another approach to enhance the performance of IMDs using the direct torque control strategy and improve the torque ripple problem is to improve the quality of the IM flux observer proposed in [38]-[42]. However, these strategies still show that the improvement of the ripple issue has not been fully addressed.

First-order sliding mode control (FOSMC) is a widely recognized robust control method developed for nonlinear systems with uncertainties. This approach exhibits strong resistance to disturbances and uncertainties, provided that these elements satisfy the matching condition – meaning they affect the system through the same channel as the control input. Key advantages of FOSMC include its relatively simple design structure and its ability to reduce the order of the system's state equations once on the sliding surface. However, FOSMC also possesses inherent limitations. Specifically, its applicability is limited to systems with a relative degree of one with respect to the control input. Furthermore, an inherent drawback is the 'chattering' phenomenon, characterized by high-frequency oscillations of the control signal with finite amplitude. This can excite unmodeled high-frequency dynamics and degrade system performance.

To surmount the previously mentioned limitations of FOSMC, the higher-order sliding mode control (HOSMC) technique has emerged [43], [44]. HOSMC provides distinct advantages by circumventing the relative degree one constraint, improving precision in discrete-time implementations, and attenuating the chattering phenomenon [44], [45]. In contrast to conventional FOSMC, which frequently utilizes Lyapunov stability theory for its design, HOSMC algorithms are typically developed using homogeneity concepts [44]. Nevertheless, a comprehensive investigation into the analysis and development of these HOSMC algorithms, along with their effective integration with established nonlinear control theory, remains an area requiring further exploration. Lyapunov theory is broadly acknowledged as a cornerstone in the analysis of nonlinear systems and serves as a potent methodology for the design of nonlinear feedback controllers [46], [47]. Consequently, recent research endeavors have concentrated on the analysis and design of HOSMCs through the application of Lyapunov functions. Certain studies [48], [49] have demonstrated the successful adaptation of Lyapunov's methodology for second-order discontinuous algorithms. As an illustration, various types of Lyapunov functions, encompassing weakly differentiable, strongly differentiable, and non-differentiable forms, have been put forward for well-known HOSM algorithms such as twisting and super-twisting. Despite these advances, endeavors to construct Lyapunov functions for general HOSM algorithms have been limited, and their success has not paralleled that achieved for second-order sliding modes. Sanchez and Moreno [50] proposed a generalized framework for the construction of Lyapunov functions applicable to HOSMs. A significant limitation of this methodology, however, lies in its reliance on obtaining explicit solutions for the associated differential inclusion (DI), a dependency that substantially restricts its practical application to systems whose order does not exceed two. More recently, novel avenues of research have materialized [51], with the objective of broadening the scope of Lyapunov function development to encompass systems of arbitrary order. Furthermore, alternative strategies have been investigated for the formulation of HOSMC techniques leveraging established nonlinear control paradigms [52]. Such a strategy initially employs a continuous control law to achieve finite-time stabilization for an ideal (unperturbed) chain of integrators. Subsequently, a Lyapunov-based redesign is incorporated, utilizing a discontinuous control mechanism, to bolster the robustness characteristics of the closed-loop system. The controller synthesized through this process demonstrates efficacy in rejecting matched, bounded uncertainties and disturbances, which the nominal continuous control law, operating in isolation, is unable to adequately address.

Notwithstanding its benefits, this particular methodology necessitates an initially formulated continuous controller that ensures finite-time convergence. Furthermore, the resultant closed-loop dynamics do not exhibit homogeneity. Consequently, the objective of developing a genuinely homogeneous higher-order sliding mode control (HOSMC) strategy, grounded in Lyapunov stability theory, remains an area that requires comprehensive resolution. The principle of homogeneity is of paramount importance for the evolution of HOSMC, as it endows the system with favorable characteristics and streamlines the evaluation of both finite-time stability and operational accuracy. Deviating from established quasi-continuous and nested HOSM control strategies, the HOSM controller detailed in the current work is formulated through the utilization of specifically chosen homogeneous control Lyapunov functions (CLFs). Such CLFs facilitate an iterative process for generating continuously differentiable functions, thereby circumventing the requirement for sophisticated mathematical formalisms often linked with Lyapunov functions that lack continuous differentiability. Through the adoption of a theoretical foundation rooted in Lyapunov methods, the design process for HOSM controllers can be significantly advanced. This not only enables the formulation of a diverse range of homogeneous control laws but also concurrently permits a more thorough exploration of complex nonlinear system behaviors that have historically presented analytical difficulties within the scope of prevailing HOSM methodologies. This approach ultimately facilitates the development of robust controllers with a simplified structure, ensuring that the closed-loop system maintains homogeneity

To address the issues analyzed above, this paper presents a novel sliding mode control strategy for the outer speed loop to enhance the robustness and performance of DTC-based IM drive systems. First, a nonlinear sliding surface is designed to track the IM speed error. Compared to traditional linear sliding surfaces, this approach enables finite-time convergence, which is an essential feature in applications requiring high precision and fast response. Additionally, the nonlinear sliding surface offers greater flexibility in shaping the system dynamics during the sliding motion, helping to reduce overshoot and improve settling time. Next, a higher-order sliding mode (HOSM) control law is designed using Lyapunov stability theory to determine the system's virtual control input. This approach effectively mitigates the chattering phenomenon and ensures the stability of the drive system. The resulting control action, filtered through the system's inherent integration layers in HOSM, leads to significantly smoother state trajectories compared to first-order sliding mode controllers. Finally, an adaptive sliding control gain for the HOSM controller is designed. Using a gain update law, the controller autonomously determines an appropriate gain value at each moment to compensate for current uncertainties and disturbances, without requiring prior knowledge of their upper bounds. This significantly simplifies controller design, making it more practical while substantially reducing the amplitude and frequency of high-frequency control signals. Consequently, the proposed method minimizes chattering while maintaining system stability and convergence. This ensures that the control gain is dynamically adjusted to adapt to operating conditions, IM parameter variations, and external disturbances. With this strategy, the control becomes more adaptive, allowing for better speed regulation, providing accurate compensation of bounded smooth uncertainties/disturbances along with their derivatives to known functions, eliminating overshoot, optimizing transient response, and minimizing torque ripple problems commonly found in IM drive systems using DTC techniques.

The subsequent section offers a concise overview of DTC: i) Section 3 elaborates on the enhanced DTC methodology specifically applied to the IMDs; ii) Thereafter, an examination of the research findings, procured via simulations conducted in the MATLAB-Simulink environment, is detailed in section 4; and iii) Section 5 encapsulates the primary contributions stemming from this study and incorporates a relevant discussion.

2. IM DYNAMICS UNDER DTC: A MATHEMATICAL REPRESENTATION

A system's dynamics can be represented in state-space form by the mathematical expressions as shown in (1).

$$\begin{cases} \mathrm{dx/dt} = Ax(t) + Bu(t) \\ y(t) = Cx(t) \end{cases} \tag{1}$$

In these equations, the variables x, u, and y are defined as (2).

$$x = [i_{s\alpha} \quad i_{s\beta} \quad \varphi_{r\alpha} \quad \varphi_{r\beta}]^T;\ u = [u_{s\alpha} \quad u_{s\beta}]^T;\ y = [i_{s\alpha} \quad i_{s\beta}]^T \tag{2}$$

With $i_{s\alpha}, i_{s\beta}, u_{s\alpha}, u_{s\beta}, \varphi_{r\alpha}, \varphi_{r\beta}$ are components of the stator's current, stator's voltage, and rotor's flux in the $\alpha - \beta$ reference frame.

$$A = \begin{bmatrix} -\lambda & 0 & \frac{K}{T_r} & K\Omega_r \\ 0 & -\lambda & -K\Omega_r & \frac{K}{T_r} \\ \frac{L_m}{T_r} & 0 & \frac{-1}{T_r} & -\Omega_r \\ 0 & \frac{L_m}{T_r} & \Omega_r & \frac{-1}{T_r} \end{bmatrix};\ B = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix};\ C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{3}$$

with:

$$\lambda = \frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma T_r}; K = \frac{1-\sigma}{\sigma L_m}; \sigma = 1 - \frac{L_m^2}{L_r L_s}; T_r = \frac{L_r}{R_r} \quad (4)$$

Based on the dynamics of the induction motor in the stator fixed reference frame, the stator flux can be estimated as (5).

$$\begin{cases} \varphi_{s\alpha} = \int_0^t (u_{s\alpha} - R_s i_{s\alpha}) dt \\ \varphi_{s\beta} = \int_0^t (u_{s\beta} - R_s i_{s\beta}) dt \end{cases} \quad (5)$$

The stator flux linkage phase is given by (6).

$$\varphi_s = \sqrt{\varphi_{s\alpha}^2 + \varphi_{s\beta}^2} \quad (6)$$

Torque can be calculated as (7).

$$T_e = \frac{3}{2} p \left(i_{s\beta} \varphi_{s\alpha} - i_{s\alpha} \varphi_{s\beta} \right) \quad (7)$$

A voltage source inverter is capable of generating six distinct active vectors, which are subsequently denoted as $V_{i=1-6}$. The two zero-voltage vectors are V_0 and V_7. Division of the complex plane into six angular Sectors $S_{i=1-6}$as shown in Figure 1. The conventional DTC algorithm described by Figure 2, and the corresponding switching table, which defines the voltage vector selection for each sector, is presented in Table 1.

Table 1. Switching logic for direct torque control

$E\phi$	E_T	N					
		S_1	S_2	S_3	S_4	S_5	S_6
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_7	V_0	V_7	V_0	V_7	V_0
	-1	V_6	V_1	V_2	V_3	V_4	V_5
0	1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_5	V_6	V_1	V_2	V_3	V_4

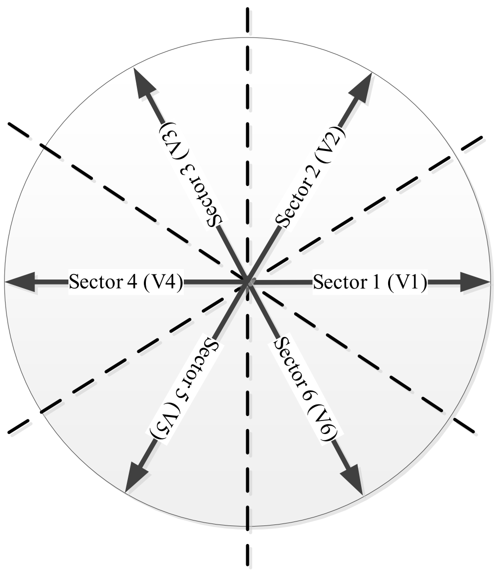


Figure 1. Division of the complex plane into six angular sectors

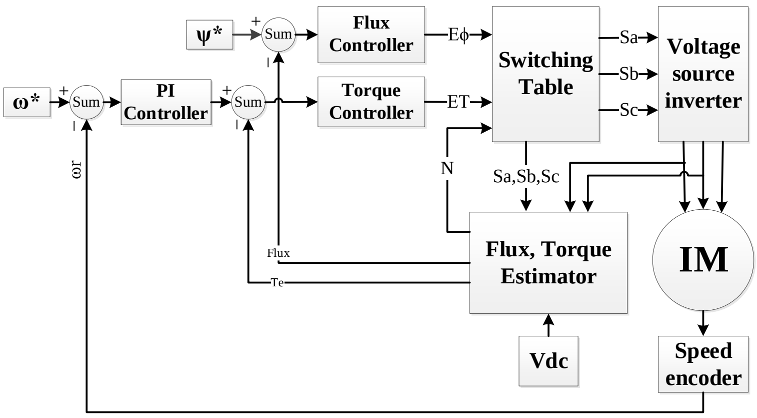


Figure 2. The conventional DTC algorithm

3. A NEW ADAPTIVE HOSMC STRATEGY FOR INDUCTION MOTOR DTC

This section introduces an enhanced adaptive higher-order sliding mode (AHOSM) methodology specifically developed for three-phase induction motor drive systems. This approach facilitates the design of resilient control strategies that can accommodate variations in parameters and effectively counteract disturbances. Improvements in the stability and robustness of the developed control algorithm are achieved by continually adjusting the coefficients of the virtual control vectors during system operation and by incorporating the integral components of the system's error-tracking mechanism into the control architecture. Utilizing this technique renders the control process more adaptable, permitting precise regulation of the motor speed to adhere to a predefined desired trajectory. Consequently, this method significantly mitigates most overshoot issues that often arise during startup, reversal, or in the presence of external load fluctuations. The proposed strategy not only bolsters responsiveness and enhances stability but also aids in prolonging the operational life of the motor and its associated parts by lessening mechanical stress during speed changes. Furthermore, by enabling precise speed control along a predetermined trajectory, this approach significantly contributes to mitigating the torque ripple phenomenon - a challenge of DTC method.

The tracking errors are defined as (7).

$$\varepsilon_{\omega} = (\omega_r^* - \omega_r) + k_{\omega} \int_0^{t\int} (\omega_r^* - \omega_r) dt \tag{7}$$

To ensure the stability of the outer control loops, virtual inputs denoted as i_{sq} are employed. The dynamics of these tracking errors are described by (8).

$$\frac{d\varepsilon_r}{dt} = \frac{d\omega_r^*}{dt} - \left[\frac{3}{2} P \frac{\delta\sigma L_s}{J}(\psi_s i_{sq}) - \frac{T_L}{J} - B_1\omega_r\right] + k_{\omega}(\omega_r^* - \omega_r) \tag{8}$$

The Lyapunov function is selected as (9).

$$V = \frac{1}{2}\varepsilon_{\omega}^2 \tag{9}$$

its derivative can obtain:

$$\frac{dV}{dt} = \varepsilon_{\omega}\frac{d\omega_r}{dt} = \varepsilon_{\omega}\left[\frac{d\omega_r^*}{dt} - k_t\psi_s i_{sq} + \frac{T_L}{J} + B_1\omega_r + k_{\omega}(\omega_r^* - \omega_r)\right] \tag{10}$$

where: $k_t = \frac{3}{2} P \frac{\delta\sigma L_s}{J}$. To satisfy $\frac{dV}{dt} < 0$. Then:

$$\left[\frac{d\omega_r^*}{dt} - k_t\psi_s i_{sq} + \frac{T_L}{J} + B_1\omega_r + k_{\omega}(\omega_r^* - \omega_r)\right] = v_{AHOSM} \tag{11}$$

combining (10) and (11), the virtual control vector i_{sq} is designed as (12):

$$i_{sq} = \frac{1}{k_t \psi_s}\left[\frac{d\omega_r^*}{dt} + \frac{T_L}{J} + B_1\omega_r + k_\omega(\omega_r^* - \omega_r) - v_{AHOSM}\right] \quad (12)$$

where k_ω is a positive constant, v_{AHOSM} is an adaptive high-order sliding mode (AHOSM) controller proposed in this paper and designed as follows:

A nonlinear sliding surface is selected to track the IM speed error:

$$s = (\omega_r^* - \omega_r) + k_\omega \int_0^{t\int} (\omega_r^* - \omega_r)dt \quad (13)$$

The sliding control function is designed as (14).

$$v_{AHOSM} = -\alpha_A \frac{s'' + 2\left(s' + |s|^{2/3} sat(s)\right)\left(|s'| + |s|^{2/3}\right)^{-1/2}}{|s''| + 2\left(|s'| + |s|^{2/3}\right)^{1/2}} \quad (14)$$

An adaptive coefficient designed to enhance the system's tolerance is used instead of the fixed coefficient a in the proposed HOSM sliding control function based on the proposed Lyapunov stability theory as (15).

$$\alpha_A = \frac{1}{2} sat(|s|) + \frac{3}{2} k_3 |s|^{1/2} sat(|s|) + k_3^2 |s|; \quad k_3 > 0 \quad (15)$$

Combining (10), (12), (14) we get (16).

$$\frac{dV}{dt} = -\varepsilon_\omega v_{AHOSM} < 0 \quad \forall \varepsilon_\omega \quad (16)$$

Reference torque can be calculated as (17).

$$T_e^* = \frac{3}{2} P \frac{L_m}{L_r} i_{sq} \varphi_s \quad (17)$$

4. RESULTS AND DISCUSSION

Figure 3 illustrates the block diagram of the control system. In this study, the performance of the suggested AHOSM algorithm for the IM drive system is evaluated and benchmarked against an IM drive system that employs conventional DTC. To verify the efficacy of the developed algorithm, MATLAB/Simulink software is utilized. The parameters for the induction motor are as follows: 400 V, 50 Hz, 4-pole, 1430 rpm, Rs = 1.405 Ω, Rr = 1.395 Ω, Ls = 0.005839 H, Lr = 0.005839 H, Lm = 0.1722 H, J = 0.0131 kg.m2, B1=0.002985.

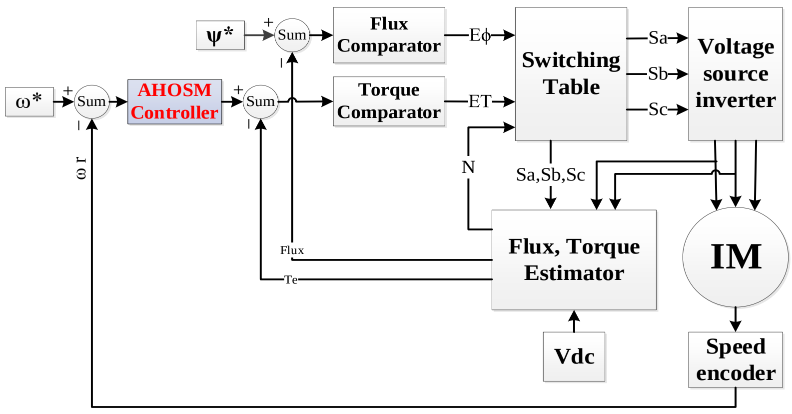
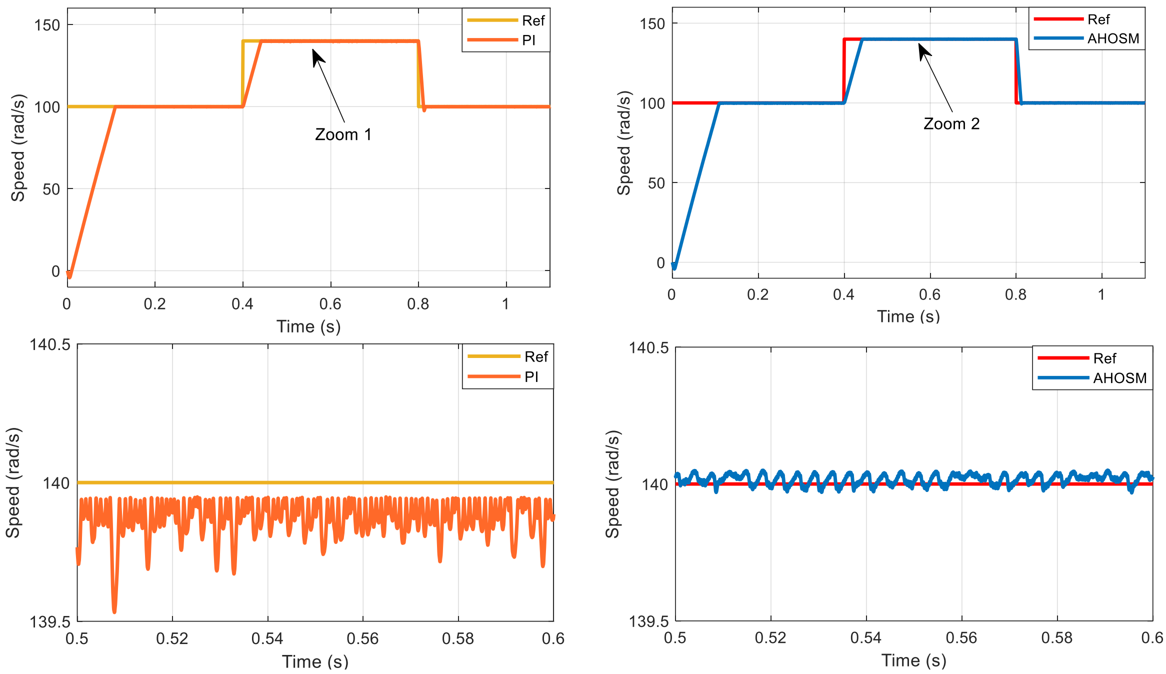


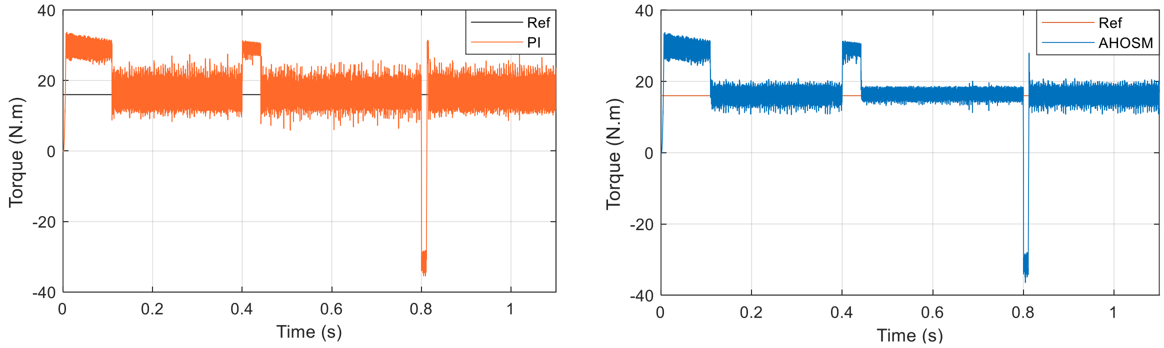
Figure 3. Simulation model of the AHOSM algorithm-based DTC

Case 1: In this scenario, the IM speed initially rises from 0 rad/s to 100 rad/s and subsequently to 140 rad/s at t = 0.4 s. It then reduces to 100 rad/s at t = 0.8 sec. The torque remains constant at 16 N.m (approximately 2/3 of the rated load torque). The characteristics for speed and torque are depicted in Figures 4 and 5, respectively. The outcomes presented in Figure 4, along with Zoom 1 and Zoom 2, indicate that: the control strategy introduced in this work yields an excellent speed response. The rotor's speed consistently tracks the reference speed, exhibiting minimal error and a low oscillation amplitude. In contrast, the conventional PI method results in a slower speed response, a considerable discrepancy between the feedback rotor speed and the reference value, and significant oscillation amplitude throughout operation. As illustrated by the electromagnetic torque in Figure 5, the proposed algorithm mitigates the torque ripple issue, maintaining a low and consistently stable oscillation amplitude during operation.



(a) (b)

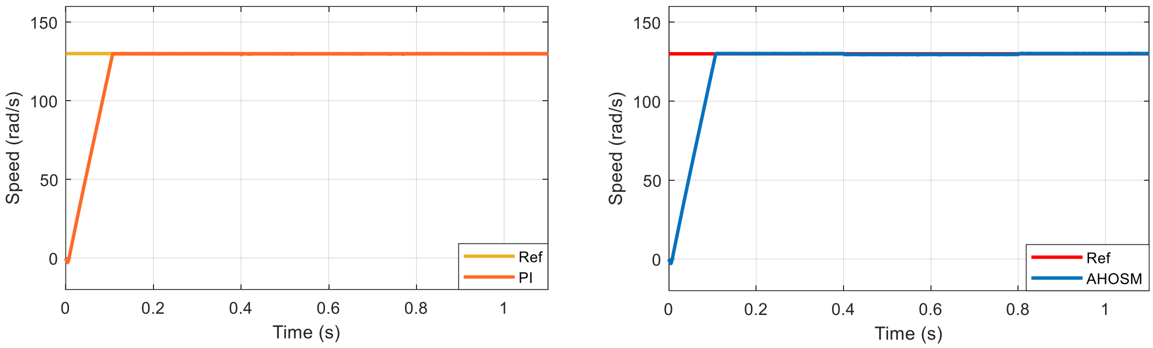
Figure 4. Comparison of motor speed responses during step changes: (a) utilizing a conventional PI controller (Zoom 1) and (b) employing the AHOSM controller (Zoom 2)



(a) (b)

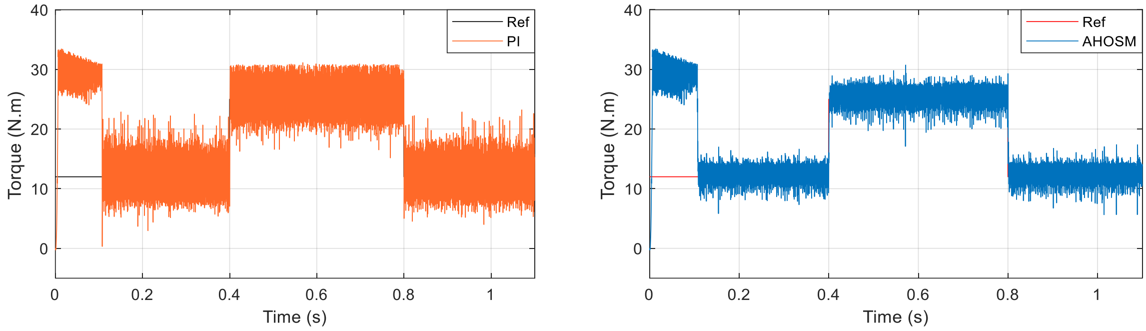
Figure 5. Depiction of electromagnetic torque behavior: (a) PI controller, and (b) AHOSM controller

Case 2: Under these conditions, the motor speed is maintained at a steady 138 rad/s. Simultaneously, the electromagnetic torque is elevated from 12 N.m to 25 N.m at t = 0.4 sec, and subsequently reduced to 12 N.m at t = 0.8 sec. The respective speed and torque response characteristics for this scenario are presented in Figures 6 and 7. The torque response shown in Figure 7 further substantiates that the AHOSM algorithm put forth by the authors markedly enhances the performance of the IM drive system with DTC. The issue of torque ripple is considerably alleviated, with the oscillation amplitude diminished by over 50% when compared to the traditional PI technique.



(a) (b)

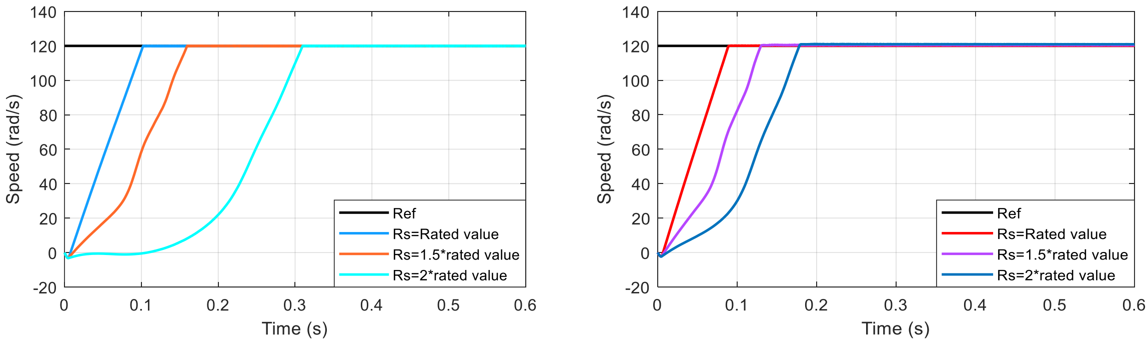
Figure 6. Illustration of motor speed dynamics under step changes: (a) employing a conventional PI controller, and (b) utilizing the AHOMS controller



(a) (b)

Figure 7. Representation of electromagnetic torque characteristics: (a) PI control and (b) AHOSM control

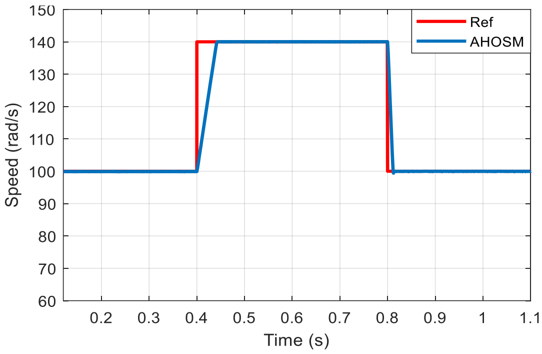
Case 3: In this instance, the stator resistance of the motor is altered, increasing to 150% and then 200% of its nominal value. The motor speed is held constant at 120 rad/s, and the motor load torque is also maintained at the rated load torque (25 N.m). The speed response is displayed in Figure 8. The investigation findings reveal that even with variations in the motor's stator resistance, the IM drive system employing the AHOSM method demonstrates a highly favorable speed response. This underscores the adaptability and stability of the drive system proposed by the authors in this research.



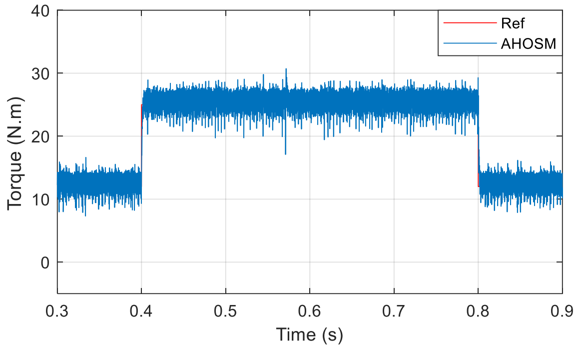
(a) (b)

Figure 8. Motor speed behavior under varying stator resistance: using (a)-PI and (b)-AHOSM controller

Case 4: In this study, a comprehensive investigation is conducted to evaluate the effectiveness of the proposed AHOSM algorithm in comparison with an artificial neural network-based strategy presented in [32]. Figure 9(a) illustrates the speed response of the AHOSM algorithm under rated load conditions, allowing for a direct comparison with the results reported in [32]. The findings indicate that the AHOSM algorithm, despite its simplicity and lack of complex computations or high hardware requirements, delivers significantly better speed response than the approach in [32]. The motor speed consistently follows the reference speed without any noticeable speed ripple oscillations during operation. Figure 9(b) presents the torque response of the AHOSM algorithm at a fixed speed of 138 rad/s, serving as a basis for comparison with the results in [32]. The results clearly demonstrate that, in contrast to the neural network-based approach in [32], which requires extensive computations, the proposed AHOSM algorithm achieves a higher-quality drive system, characterized by stable torque and lower oscillation amplitude.



(a)



(b)

Figure 9. Performance of the proposed AHOSM algorithm: (a) under variable speed conditions and (b) under variable load torque conditions

Thus, through the survey results and evaluation analyses performed in the above cases, we see that: With the proposed control strategy, the gain update law can autonomously determine a sufficiently large gain value dynamically to compensate for the level of uncertainties and disturbances without requiring prior knowledge of their upper bound. This makes the controller design easier and more practical. Instead of using a fixed large gain, the adaptive higher-order sliding mode (AHOSM) approach can achieve: Smoother response due to reduced oscillation amplitude; Potential energy savings by avoiding unnecessarily large control signals when disturbances are small; Reduced actuator wear and tear since the control signal is less aggressive; Maintained robustness: despite the varying gain, the adaptive laws are formulated using Lyapunov stability principles to ascertain that the gain consistently remains at a sufficient level for sustaining the sliding mode operation and to secure the system's resilient stability when faced with uncertainties and disturbances. This contributes to improving the performance of IM drive systems using DTC.

5. CONCLUSION

This paper proposes a new sliding mode control technique using high-order sliding mode control combined with an adaptive coefficient based on Lyapunov stability theory for IM drive systems using DTC. The proposed strategy has brought about many interesting results. In particular, the ripple torque problem that often appears when using DTC has been significantly improved. High dynamic response and adaptability to changes in load and motor parameters. With an extremely simple design and low computational volume, the AHOSM strategy can be applied to high-quality drive systems without requiring too much hardware design cost. However, the use of DTC technique with a traditional switchboard still cannot completely eliminate the ripple torque problem. This is considered a limitation of this paper and a new research direction in the future that the author and his colleagues hope to carry out to further enhance the performance of IM drive systems using DTC. On the other hand, in the near future, the authors will build hardware to evaluate the performance of the control strategy that the group proposed and apply it to specific industrial applications.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Ngoc Thuy Pham	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓	
Duc Thuan Le		✓		✓	✓	✓		✓		✓	✓			
Phu Diep Nguyen	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author, [NP], upon reasonable request.

REFERENCES

[1] P. Vas, *Sensorless vector and direct torque control*. Oxford University PressOxford, 1998. doi: 10.1093/oso/9780198564652.001.0001.

[2] M. Yano, S. Abe, and E. Ohno, "History of power electronics for motor drives in Japan," *IEEE Conference on the History of Electronics (CHE)*, pp. 1–11, 2004.

[3] D. Arun Dominic and T. R. Chelliah, "Analysis of field-oriented controlled induction motor drives under sensor faults and an overview of sensorless schemes," *ISA Transactions*, vol. 53, no. 5, pp. 1680–1694, Sep. 2014, doi: 10.1016/j.isatra.2014.04.008.

[4] R. Kumar, S. Das, and A. Bhaumik, "Speed sensorless model predictive current control of doubly-fed induction machine drive using model reference adaptive system," *ISA Transactions*, vol. 86, pp. 215–226, Mar. 2019, doi: 10.1016/j.isatra.2018.10.025.

[5] M. Depenbrock, "Direct self-control (DSC) of inverter-fed induction machine," *IEEE Transactions on Power Electronics*, vol. 3, no. 4, pp. 420–429, Oct. 1988, doi: 10.1109/63.17963.

[6] I. Takahashi and T. Noguchi, "A new quick-response and high-efficiency control strategy of an induction motor," *IEEE Transactions on Industry Applications*, vol. IA-22, no. 5, pp. 820–827, Sep. 1986, doi: 10.1109/TIA.1986.4504799.

[7] N. El Ouanjli, A. Derouich, A. El Ghzizal, A. Chebabhi, and M. Taoussi, "A comparative study between FOC and DTC control of the doubly fed induction motor (DFIM)," in *2017 International Conference on Electrical and Information Technologies (ICEIT)*, Nov. 2017, pp. 1–6. doi: 10.1109/EITech.2017.8255302.

[8] T. Sutikno, N. R. N. Idris, and A. Jidin, "A review of direct torque control of induction motors for sustainable reliability and energy efficient drives," *Renewable and Sustainable Energy Reviews*, vol. 32, pp. 548–558, Apr. 2014, doi: 10.1016/j.rser.2014.01.040.

[9] X. Wu, W. Huang, X. Lin, W. Jiang, Y. Zhao, and S. Zhu, "Direct torque control for induction motors based on minimum voltage vector error," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 5, pp. 3794–3804, May 2021, doi: 10.1109/TIE.2020.2987283.

[10] S. Usha *et al.*, "Performance enhancement of sensorless induction motor drive using modified direct torque control techniques for traction application," *Alexandria Engineering Journal*, vol. 108, pp. 518–538, Dec. 2024, doi: 10.1016/j.aej.2024.07.095.

[11] S. Gdaim, A. Mtibaa, and M. F. Mimouni, "Direct torque control of induction machine based on intelligent techniques," *International Journal of Computer Applications*, vol. 10, no. 8, pp. 29–35, Nov. 2010, doi: 10.5120/1500-2017.

[12] S. Gdaim, A. Mtibaa, and M. F. Mimouni, "Design and experimental implementation of DTC of an induction machine based on fuzzy logic control on FPGA," *IEEE Transactions on Fuzzy Systems*, vol. 23, no. 3, pp. 644–655, Jun. 2015, doi: 10.1109/TFUZZ.2014.2321612.

[13] M. Elgbaily, F. Anayi, and M. Packianather, "Genetic and particle swarm optimization algorithms based direct torque control for torque ripple attenuation of induction motor," *Materials Today: Proceedings*, vol. 67, pp. 577–590, 2022, doi: 10.1016/j.matpr.2022.08.293.

[14] S. Mahfoud, A. Derouich, N. El Ouanjli, and M. El Mahfoud, "Enhancement of the direct torque control by using artificial neuron network for a doubly fed induction motor," *Intelligent Systems with Applications*, vol. 13, p. 200060, Jan. 2022, doi: 10.1016/j.iswa.2022.200060.

[15] H. Benbouhenni, "Improved switching selection for DTC of induction motor drive using artificial neural networks," *Acta Electrotechnica et Informatica*, vol. 18, no. 1, pp. 26–34, Mar. 2018, doi: 10.15546/aeei-2018-0004.

[16] A. Dris, M.Bendjebbar, Aek.Belaidi, and H. Benbouhenni, "DTC-ANN control with two level inverter associated by different observers (MRAS and KUBOTA) for Induction machine drives," *International Journal of Neural Networks and Advanced Applications*, vol. 5, 2018.

[17] F. Aymen, N. Mohamed, S. Chayma, C. H. R. Reddy, M. M. Alharthi and S. S. M. Ghoneim, "An improved direct torque control topology of a double stator machine using the fuzzy logic controller," in *IEEE Access*, vol. 9, pp. 126400-126413, 2021, doi: 10.1109/ACCESS.2021.3110477.

[18] B. Singh, P. Jain, A. P. Mittal, and J. R. P. Gupta, "Neural network based DTC IM drive for electric vehicle propulsion system," in *2006 IEEE Conference on Electric and Hybrid Vehicles*, Dec. 2006, pp. 1–6. doi: 10.1109/ICEHV.2006.352276.
[19] S. Gdaim, A. Mtibaa, and M. F. Mimouni, "Artificial neural network-based DTC of an induction machine with experimental implementation on FPGA," *Engineering Applications of Artificial Intelligence*, vol. 121, p. 105972, May 2023, doi: 10.1016/j.engappai.2023.105972.
[20] H. Li, B. Bilgin, and A. Emadi, "An improved torque sharing function for torque ripple reduction in switched reluctance machines," *IEEE Transactions on Power Electronics*, vol. 34, no. 2, pp. 1635–1644, Feb. 2019, doi: 10.1109/TPEL.2018.2835773.
[21] M. V. de Paula and T. A. dos S. Barros, "A sliding mode DITC cruise control for SRM with steepest descent minimum torque ripple point tracking," *IEEE Transactions on Industrial Electronics*, vol. 69, no. 1, pp. 151–159, Jan. 2022, doi: 10.1109/TIE.2021.3050349.
[22] G. H. B. Foo and X. Zhang, "Robust constant switching frequency-based field-weakening algorithm for direct torque controlled reluctance synchronous motors," *IEEE Transactions on Industrial Informatics*, vol. 12, no. 4, pp. 1462–1473, Aug. 2016, doi: 10.1109/TII.2016.2585646.
[23] P. K. Reddy, D. Ronanki, and P. Perumal, "Efficiency improvement and torque ripple minimisation of four-phase switched reluctance motor drive using new direct torque control strategy," *IET Electric Power Applications*, vol. 14, no. 1, pp. 52–61, Jan. 2020, doi: 10.1049/iet-epa.2019.0432.
[24] T. Husain, A. Elrayyah, Y. Sozer, and I. Husain, "Unified control for switched reluctance motors for wide speed operation," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 5, pp. 3401–3411, May 2019, doi: 10.1109/TIE.2018.2849993.
[25] A. Xu, C. Shang, J. Chen, J. Zhu, and L. Han, "A new control method based on DTC and MPC to reduce torque ripple in SRM," *IEEE Access*, vol. 7, pp. 68584–68593, 2019, doi: 10.1109/ACCESS.2019.2917317.
[26] H. Sun, A. F. Moghaddam, P. Sergeant, and A. Van den Bossche, "A novel driving method for switched reluctance motor with standard full bridge inverter," *IEEE Transactions on Energy Conversion*, vol. 35, no. 2, pp. 994–1003, Jun. 2020, doi: 10.1109/TEC.2020.2968758.
[27] Y. Zhang, Y. Cheng, Y. Chen, and H. Sun, "Direct torque control of switched reluctance motor driven by full bridge power converter," *IEICE Electronics Express*, vol. 21, no. 17, p. 21.20240359, Sep. 2024, doi: 10.1587/elex.21.20240359.
[28] J. Jeyashanthi and J. BarsanaBanu, "ANN-based direct torque control scheme of an IM drive for a wide range of speed operation," *Neural Network World*, vol. 31, no. 6, pp. 395–414, 2021, doi: 10.14311/NNW.2021.31.022.
[29] W. M. Utomo, S. Y. Sim, Z. A. Haron, A. A. Bohari, and N. M. Zin, "Online adaptive flux control for space vector PWM-DTC IM drives towards optimum efficiency design," *ARPN Journal of Engineering and Applied Sciences*, vol. 10, no. 19, pp. 9099–9105, 2015.
[30] H. Benbouhenni, "Seven-level direct torque control of induction motor based on artificial neural networks with regulation speed using fuzzy PI controller," *Iranian Journal of Electrical and Electronic Engineering*, vol. 14, no. 1, pp. 85–94, 2018, doi: 10.22068/IJEEE.14.1.85.
[31] F. Mehedi, H. Benbouhenni, L. Nezli, and D. Boudana, "Feedforward neural network-DTC of multi-phase permanent magnet synchronous motor using five-phase neural space vector pulse width modulation strategy," *Journal Européen des Systèmes Automatisés*, vol. 54, no. 2, pp. 345–354, Apr. 2021, doi: 10.18280/jesa.540217.
[32] L. Dube and E. H. E. Bayoumi, "DRNN robust DTC for induction motor drive systems using FSTPI," *Journal Européen des Systèmes Automatisés*, vol. 54, no. 4, pp. 539–547, Aug. 2021, doi: 10.18280/jesa.540403.
[33] Y. Zahraoui, M. Akherraz, C. Fahassa, and S. Elbadaoui, "Induction motor DTC performance improvement by reducing flux and torque ripples in low speed," *Journal of Robotics and Control (JRC)*, vol. 3, no. 1, pp. 93–100, Jan. 2022, doi: 10.18196/jrc.v3i1.12550.
[34] H. Benbouhenni and Z. Boudjema, "Comparative study between neural hysteresis, fuzzy PI, and neural switching table for an IM DTC control," vol. 5, pp. 23–34, 2018.
[35] B. Habib and O. Maurice, "ANFIS speed controller of IM drives with three-level DTC-based neural network," vol. 8, no. 1, pp. 11–17, 2019.
[36] O. Aissa, A. Reffas, A. Krama, R. Benkercha, H. Talhaoui, and H. Abu-Rub, "Advanced direct torque control based on neural tree controllers for induction motor drives," *ISA Transactions*, vol. 148, pp. 92–104, May 2024, doi: 10.1016/j.isatra.2024.03.017.
[37] M. El Haissouf, M. El Haroussi, and A. Ba-Razzouk, "DSP in the loop implementation of an improved sliding mode control for induction motor drive," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 15, no. 1, pp. 53–63, 2024, doi: 10.11591/ijpeds.v15.i1.pp53-63.
[38] A. Choudhury, P. Pillay, and S. S. Williamson, "Modified stator flux estimation based direct torque controlled PMSM drive for hybrid electric vehicle," in *IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society*, Oct. 2012, pp. 2965–2970. doi: 10.1109/IECON.2012.6389425.
[39] N. R. N. Idris and A. H. M. Yatim, "An improved stator flux estimation in steady-state operation for direct torque control of induction machines," *IEEE Transactions on Industry Applications*, vol. 38, no. 1, pp. 110–116, 2002, doi: 10.1109/28.980364.
[40] Y. Wang and Z. Deng, "An integration algorithm for stator flux estimation of a direct-torque-controlled electrical excitation flux-switching generator," *IEEE Transactions on Energy Conversion*, vol. 27, no. 2, pp. 411–420, Jun. 2012, doi: 10.1109/TEC.2012.2188139.
[41] Y. A. Alamri, N. R. Nik Idris, I. Mohd. Alsofyani, and T. Sutikno, "Improved stator flux estimation for direct torque control of induction motor drives," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 7, no. 4, p. 1049, 2016, doi: 10.11591/ijpeds.v7.i4.pp1049-1060.
[42] A. Belbali and S. Makhloufi, "Direct torque control of induction motor with stator flux estimation based on an improved voltage model," *Electronics ETF*, vol. 26, no. 1, pp. 26–33, Jun. 2022, doi: 10.53314/ELS2226026B.
[43] A. Levant, "Universal single-input-single-output (SISO) sliding-mode controllers with finite-time convergence," *IEEE Transactions on Automatic Control*, vol. 46, no. 9, pp. 1447–1451, 2001, doi: 10.1109/9.948475.
[44] A. Levant, "Homogeneity approach to high-order sliding mode design," *Automatica*, vol. 41, no. 5, pp. 823–830, 2005, doi: 10.1016/j.automatica.2004.11.029.
[45] A. Levant, "Higher-order sliding modes, differentiation and output-feedback control," *International Journal of Control*, vol. 76, no. 9–10, pp. 924–941, Jan. 2003, doi: 10.1080/0020717031000099029.
[46] Chunjiang Qian and Wei Lin, "A continuous feedback approach to global strong stabilization of nonlinear systems," *IEEE Transactions on Automatic Control*, vol. 46, no. 7, pp. 1061–1079, Jul. 2001, doi: 10.1109/9.935058.

[47] A. Polyakov and A. Poznyak, "Reaching time estimation for 'super-twisting' second order sliding mode controller via Lyapunov function designing," *IEEE Transactions on Automatic Control*, vol. 54, no. 8, pp. 1951–1955, Aug. 2009, doi: 10.1109/TAC.2009.2023781.
[48] A. Polyakov and A. Poznyak, "Unified Lyapunov function for a finite-time stability analysis of relay second-order sliding mode control systems," *IMA Journal of Mathematical Control and Information*, vol. 29, no. 4, pp. 529–550, Dec. 2012, doi: 10.1093/imamci/dns007.
[49] T. Sanchez and J. A. Moreno, "Construction of Lyapunov functions for a class of higher order sliding modes algorithms," in *2012 IEEE 51st IEEE Conference on Decision and Control (CDC)*, Dec. 2012, pp. 6454–6459. doi: 10.1109/CDC.2012.6426028.
[50] T. Sanchez and J. A. Moreno, "A constructive Lyapunov function design method for a class of homogeneous systems," in *53rd IEEE Conference on Decision and Control*, Dec. 2014, pp. 5500–5505. doi: 10.1109/CDC.2014.7040249.
[51] M. Harmouche, S. Laghrouche, and Y. Chitour, "Robust and adaptive higher order sliding mode controllers," in *2012 IEEE 51st IEEE Conference on Decision and Control (CDC)*, Dec. 2012, pp. 6436–6441. doi: 10.1109/CDC.2012.6426131.
[52] H. K. Khalil, "*Nonlinear Systems*," 3rd ed., Prentice Hall, Upper Saddle River, 2002.

BIOGRAPHIES OF AUTHORS

Ngoc Thuy Pham is a lecturer in the Department of Electrical Engineering Technology, Industrial University of Ho Chi Minh City (IUH), Ho Chi Minh, Viet Nam. She received the B.Sc. and M.Sc. degrees in Electrical Engineering from Thai Nguyen University of Technology in 1994 and Ho Chi Minh City University of Technology (HCMUT) in 2009, respectively. She earned her Ph.D. degree in Control Engineering and Automation from the Faculty of Electrical Engineering, Ho Chi Minh City University of Transport, in 2020. Her current research interests include power electronics, AC motor drives, intelligent control, multiphase induction motor, sensorless control of multiphase induction motor drives, and embedded systems. She can be contacted at email: ngocpham1020@gmail.com.

Duc Thuan Le is a lecturer in the Department of Electrical Engineering Technology, Industrial University of Ho Chi Minh City (IUH), Ho Chi Minh, Viet Nam. He received the B.Sc. degree in electrical engineering from Thai Nguyen University of Technology in 1994 and the M.Sc. degree in control engineering and automation from Ha Noi University of Transport in 2020. His research interests include the field of power electronics, intelligent control, multiphase induction motor, AC motor drives, and embedded systems. He can be contacted at email: leducthuan@iuh.edu.vn.

Phu Diep Nguyen was born in 1993 in Vietnam. He received his engineer's degree in electrical and electronic engineering from Ho Chi Minh City University of Industry in 2015 and subsequently worked for the Ho Chi Minh City Oil and Gas Single-Member Limited Liability Company. In 2024, he began pursuing the master's program at Ho Chi Minh City University of Industry. His research interests include motor drives, multiphase motors, renewable energy, embedded systems, and intelligent control. He can be contacted at email: phudiep.tradin@gmail.com or diepnp2431@pgr.iuh.edu.vn.