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Application of the model reference adaptive system method in sensorless control for elevator drive systems using 3-Phase permanent magnet synchronous motors

Tran Van Khoi, An Thi Hoai Thu Anh, Tran Trong Hieu
Department of Electrical Engineering, University of Transport and Communications, Hanoi, Vietnam

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ABSTRACT

Improving sensorless control performance in elevator drive systems using three-phase permanent magnet synchronous motors (PMSM) has become increasingly popular to reduce costs and enhance system stability. The primary operation of the elevator involves motor mode when the cabin moves upward and shifts to generator mode or braking mode under the influence of gravity when moving downward. This presents significant challenges for sensorless control. To address these issues, the model reference adaptive system (MRAS) based on the mathematical d-q axis model of the PMSM is proposed to estimate rotor speed and position. Combined with field-oriented control (FOC), this method optimizes performance and precisely controls motor torque without requiring physical sensors. Additionally, a low-pass filter is employed to process input signals, such as voltage and current, to improve estimation accuracy and optimize speed response. Simulation results from MATLAB/Simulink demonstrate highly accurate speed responses, particularly under continuous load variations.

Corresponding Author:

An Thi Hoai Thu Anh
Department of Electrical Engineering, Faculty of Electrical-Electronic Engineering, University of Transport and Communications
No. 3 Cau Giay, Lang Commune, Dong Da District, Hanoi, Vietnam
Email: htanh.ktd@utc.edu.vn

1. INTRODUCTION

High-rise buildings, central to urbanization, demand efficient transportation like elevators. Early 20th-century elevators utilized DC motors for speed control via voltage adjustment, but they faced issues such as large size, frequent maintenance, and low efficiency [1]. By the mid-20th century, semiconductor technology had advanced, enabling inverters to control speed and torque more effectively in induction motors. This became prevalent despite inefficiencies under light or no load and slow response due to asynchronous operation [2]. By the late 20th and early 21st centuries, rare-earth magnets (NdFeB, SmCo) enabled the development of compact, efficient permanent magnet synchronous motors (PMSMs) with high performance, which were widely adopted in modern elevators [3], [4]. Today, high-rise elevators are rapidly transitioning to PMSM [5].

Materials and electronic technology advances, including cheaper semiconductor chips, drive efforts to optimize energy use and efficiency [6]. Traditional elevators use gearboxes for speed and torque control, but modern gearless systems enhance performance and reduce costs like friction and energy loss. Speed sensors such as encoders are costly, maintenance-intensive, and unreliable in harsh environments, prompting a shift to sensorless speed estimation (observer estimation) [7]. Observers are classified into two types: non-feedback and feedback-based [8]–[11]. Non-feedback observers predict states using input signals but lack accuracy. Feedback observers, such as Kalman EKF, model reference adaptive system (MRAS), sliding mode observer (SMO), and Luenberger observer, are more precise. However, Kalman EKF demands high-cost hardware, SMO causes chattering at low speeds, and the Luenberger observer is limited to linear systems. MRAS, with its simplicity, adaptability, and efficiency, is preferred for modern systems [12].

Abdelnaby *et al.* [13] developed and compared the combination of MRAS with Pi and MRAS with fuzzy for PMSM motors. Mishra *et al.* [14] designed and developed an MRAS algorithm to eliminate the issues caused by back-EMF. Badini and Verma [15] used MRAS and calculated it without relying on motor parameters, allowing operation in all four quadrants. Eskola and Tuusa [16] based their research on MRAS to develop a simple algorithm to address stability issues in the zero-speed region. Nicola and Nicola [17] implemented MRAS on a digital signal processor (DSP) system to demonstrate its effectiveness. Quoc and Anh [18] use the error signal between the measured stator current and the model-calculated current as the reference–response quantity in the MRAS; the fuzzy controller adjusts the adaptive gain in real time to reduce chattering and improve the accuracy of speed estimation. Zou *et al.* [19] propose a sensorless control strategy for the PMSM based on a SMO integrated with a Super-Twisting Algorithm whose gain is adaptive to the motor speed (STASMO) to suppress the chattering inherent to the switching function of a conventional SMO while maintaining the robustness of state observation. Hussain and Bazaz [20] proposed a neural network observer design for sensorless control of the induction motor drive. However, the existing studies have not proposed or implemented the development of a MRAS observer combined with a low-pass filter to stabilize and eliminate disturbances in the axial and quadrature voltages and currents for gearless elevators. The study focuses on a 30-story residential building in the King Crown Infinity Urban Area, Ho Chi Minh City, Vietnam. This approach enhances the smoothness of the speed feedback signal, allowing it to closely follow the reference speed and thereby improve the elevator's operational efficiency. Therefore, this paper proposes using a low-pass filter to clean the voltage and current signals before they enter the observer. This helps improve the accuracy of the variable estimations and makes it easier for the MRAS observer to adjust the Kp and K_i parameters. Finally, the validity and correctness of the proposed method will be verified through simulations conducted in MATLAB/Simulink.

2. MODELING OF THE SENSORLESS CONTROL SYSTEM FOR ELEVATORS

The first step in research is developing algorithms and system models. Figure 1 shows the structure of a 3-phase PMSM elevator drive system. With ω, θ representing the speed and angle, respectively, u_{sa}, u_{sb}, u_{sc}, i_{sa}, i_{sb}, and i_{sc} represent the voltage and current in phases a, b, and c.

Permanent magnet synchronous motors (PMSM) are preferred in elevator systems for their high efficiency and stable torque. PMSM modelling utilizes the d-q frame, employing fundamental equations for current, flux, and torque [21]. The d-q frame is central to the MRAS model.

$$\frac{di_{sd}}{dt} = \frac{1}{L_s}U_{sd} - \frac{R_s}{L_s}i_{sd} + \omega_r i_{sq} \quad (1)$$

$$\frac{di_{sq}}{dt} = \frac{1}{L_s}U_{sq} - \frac{R_s}{L_s}i_{sq} - \omega_r i_{sd} - \frac{\lambda}{L_s}\omega_r \quad (2)$$

i_{sd}, i_{sq}, U_{sd}, and U_{sq} represent the *d*-axis and *q*-axis currents and voltages, respectively, and R_s is the stator resistance.

Model reference adaptive system (MRAS) is a sensorless observer in PMSM control, which estimates rotor speed and position without the use of physical sensors. It compares a reference model with an adjustment model for optimization [22]. Based on (1) and (2) of the PMSM motor model, the estimation model can be derived from the adjustment model:

$$\frac{d\hat{\imath}_{sd}}{dt} = \frac{1}{L_s}U_{sd} - \frac{R_q}{L_s}\hat{\imath}_{sd} + \widehat{\omega}_r\hat{\imath}_{sq} \quad (3)$$

$$\frac{d\hat{\imath}_{sq}}{dt} = \frac{1}{L_s}U_{sq} - \frac{R_s}{L_s}\hat{\imath}_{sq} - \widehat{\omega}_r\hat{\imath}_{sd} - \frac{\lambda}{L_s}\widehat{\omega}_r \quad (4)$$

With $\hat{\imath}_{sd}$, $\hat{\imath}_{sq}$, $\widehat{\omega}_r$ representing the observed d-axis and q-axis currents and the observed rotor speed, respectively.

The output current error is:

$$\begin{cases} e_d = i_{sd} - \hat{\imath}_{sd} \\ e_q = i_{sq} - \hat{\imath}_{sq} \end{cases} \quad (5)$$

With e_d, e_q representing the errors in the d-axis and q-axis currents between the actual and the observed currents. Adaptive control (PI controller):

$$\hat{\omega}_r = K_i \int (e_q \hat{\imath}_{sd} - ed\hat{\imath}_{sq} - \frac{\lambda}{L_s} e_q) + K_p (e_q \hat{\imath}_{sd} - ed\hat{\imath}_{sq} - \frac{\lambda}{L_s} e_q) \quad (6)$$

With K_i and K_p being the tuning parameters of the PI controller, aiming to minimise the error between the actual and observed current.

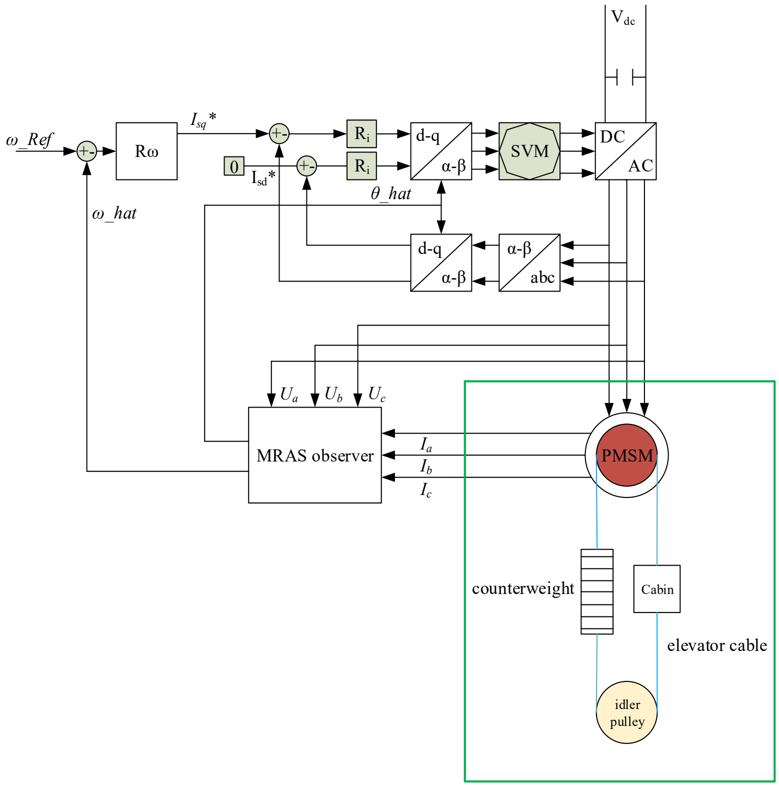

Figure 1. System model structure of the elevator drive using PMSM motor

3. CONTROL DESIGN

The field-oriented control (FOC) controller was chosen as the primary control system due to its ability to precisely control speed and torque, with less output distortion and reduced harmonic distortion [23]. Additionally, it provides independent control of torque and speed, which is especially important when applying speed estimation methods like MRAS, as the estimated speed must be synchronized and accurate with the actual speed.

3.1. MRAS observer design

The MRAS observer estimates the motor's rotor speed without needing sensors, reducing costs and increasing the system's durability. From (1) to (4), we can represent the model as shown in Figure 2. The input includes voltages u_{sa}, u_{sb}, u_{sc}, and output measurements are i_{sa}, i_{sb}, i_{sc}. In the a-b-c coordinate system, sinusoidal current and flux make calculations complex. To simplify and reduce the time-varying components, the a-b-c system is transformed into the d-q system using Clarke and Park transformations before being introduced into the MRAS model [24].

– Voltage transformation from a-b-c system to d-q system:

$$\begin{cases} U_d = \frac{2}{3}\left(U_a\,cos(\theta) + U_b\,cos\left(\theta - \frac{2\pi}{3}\right) + U_c\,cos\left(\theta + \frac{2\pi}{3}\right)\right) \\ U_q = \frac{2}{3}\left(U_a\,sin(\theta) + U_b\,sin\left(\theta - \frac{2\pi}{3}\right) + U_c\,sin\left(\theta + \frac{2\pi}{3}\right)\right) \end{cases} \quad (7)$$

– Current transformation from a-b-c system to d-q system:

$$\begin{cases} I_d = \frac{2}{3}\left(I_a\,cos(\theta) + I_b\,cos\left(\theta - \frac{2\pi}{3}\right) + I_c\,cos\left(\theta + \frac{2\pi}{3}\right)\right) \\ I_q = \frac{2}{3}\left(I_a\,sin(\theta) + I_b\,sin\left(\theta - \frac{2\pi}{3}\right) + I_c\,sin\left(\theta + \frac{2\pi}{3}\right)\right) \end{cases} \quad (8)$$

With u_a, u_b, u_c being the voltages in phases a, b, c, i_a, i_b, i_c being the currents in phases a, b, c, and θ being the rotor position angle.

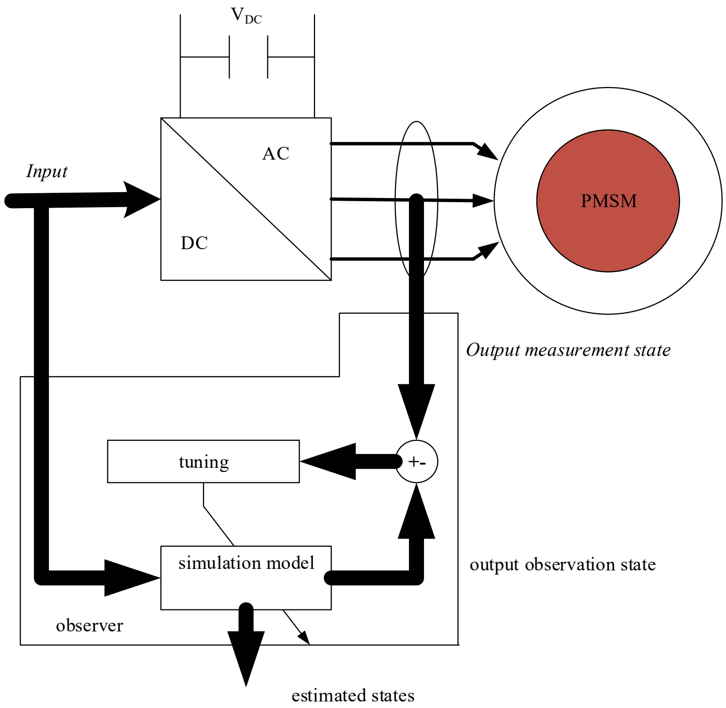

Figure 2. Description of the MRAS observer design structure

Although with (4), (5), and (6), we can build the MRAS observer to handle load disturbances and some significant types of noise affecting the actual voltage and current used for building the speed observation system, we will use a low-pass filter at the input of the d-q voltage and current before feeding them into the MRAS observer. This will help the system control the noise and prevent it from affecting the quality of the observed variables, such as speed and the rotor angle theta [25].

The general equations for both voltage and current in the d-q system are:

$$\begin{aligned} U_{d,filtered}(k) &= (1-\alpha)\cdot U_{d,filtered}(k-1) + \alpha \cdot U_d(k) \\ U_{q,filtered}(k) &= (1-\alpha)\cdot U_{q,filtered}(k-1) + \alpha \cdot U_q(k) \\ I_{d,filtered}(k) &= (1-\alpha)\cdot I_{d,filtered}(k-1) + \alpha \cdot I_d(k) \\ I_{q,filtered}(k) &= (1-\alpha)\cdot I_{q,filtered}(k-1) + \alpha \cdot I_q(k) \end{aligned} \quad (9)$$

With $U_{d,filtered}(k)$, $U_{q,filtered}(k)$, $I_{d,filtered}(k)$, $I_{q,filtered}(k)$ as filtered values from the previous step and α as the filtering coefficient ($0<\alpha<1$), a smaller α produces smoother but slower signals, while a larger α results in faster responses but less smooth signals, $U_d(k), U_q(k), I_d(k), U_q(k)$ are pre-filter input values.

A low-pass filter removes unwanted components, such as electromagnetic interference or high-frequency oscillations, thereby smoothing axial and quadrature voltage signals. This filtering reduces rapid fluctuations, ensuring signal accuracy before entering the observer and improving speed estimation and overall system performance. Figure 3 shows the structure of the MRAS observer using a low-pass filter.

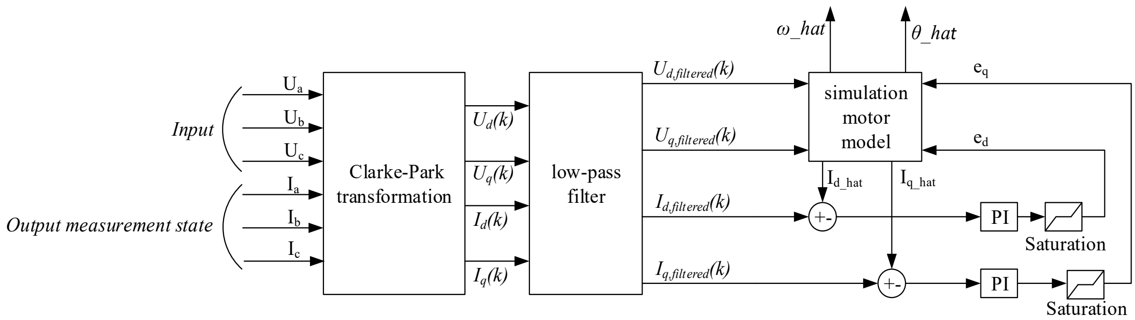

Figure 3. The structure of the MRAS observer using a low-pass filter

4. SIMULATION AND RESULT EVALUATION

To verify the system's stability when using the MRAS observer, simulations are conducted in MATLAB Simulink with the following parameters in Table 1. The simulation script is shown in Figure 4:

Phase 1: The elevator is in standby mode with its doors open on floor1. Fifteen people enter, taking 1 second each, for a total waiting time of 17 seconds.
Phase 2: The elevator reaches its rated speed of 2.5 m/s in 2.5 seconds.
Phase 3: The elevator moves at 2.5 m/s until floor 29, then begins deceleration, which takes 31.6 seconds.
Phase 4: The elevator decelerates and stops at floor 30 in 2.5 seconds.
Phase 5: Elevator doors open and remain on standby for 17 seconds.
Total simulation time: 71 seconds.

Table 1. Simulation parameters

Quantity	Symbol	Value
Power Rated	Pmax	15 Kw
AC Rated	Vac	291 V
DC Rated	Vdc	411 V
Current Rated	Idm	37.5 A
Resistance	Rs	0.144 Ω
Pole	p	40
Moment of inertia	J	0.00075 kg·m²
Friction coefficient	F	0.05 N·m·s
Flux linkage	λ	0.133 V·s
Armature inductance	La	0.00209 H
Reference torque	T	160 N.m
Reference speed	ω	80 rpm

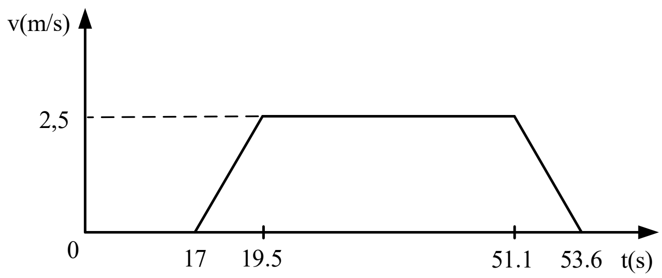

Figure 4. Elevator speed trajectory graph

Figure 5 illustrates the PMSM motor's speed response when using the MRAS observer. The figure shows that the speed response is quite good, with the feedback speed closely tracking the reference speed. However, there are slight oscillations during the transition phases, though they are negligible.

To verify the system's stability under the influence of noise and external parameters, we suddenly change the load at time t = 30 s. Figure 6 shows a portion of the running cycle, illustrating the speed response when the load is abruptly changed. When the load is changed, the speed exhibits some oscillations, but they are relatively small. However, the level of oscillation is still acceptable. Additionally, when the load changes, we see more significant oscillations in the deceleration region towards 0, but the speed quickly adjusts to the reference speed. This demonstrates that, with the MRAS observer, the system can still maintain good stability even in the presence of sudden external disturbances. The torque curve is represented in Figure 7.

When the motor operates at a constant speed ranging from 0 to 80 rpm, and the torque is set to a constant value with a 30-second load application time, the acceleration and deceleration phases are entirely normal. However, after 30 seconds, the torque tends to increase to meet the initial set torque. Additionally, with the current waveforms, we need to implement decoupled control of the two currents I_{sd} and I_{sq} to facilitate control. However, this problem does not include weak flux control, meaning $I_{sd} < 0$, so the ideal case is $I_{sd} = 0$, as shown in Figure 8. Both currents exhibit oscillations, with I_{sq} oscillating around a value of 20 by a small amount and I_{sd} oscillating around a value of 0 by a small amount. This behavior occurs because the MRAS observer uses a PI controller to try to reach the desired speed, causing slight oscillations in the feedback speed. As a result, the responses of I_{sd} and I_{sq} also experience slight oscillations. This phenomenon is standard in the system.

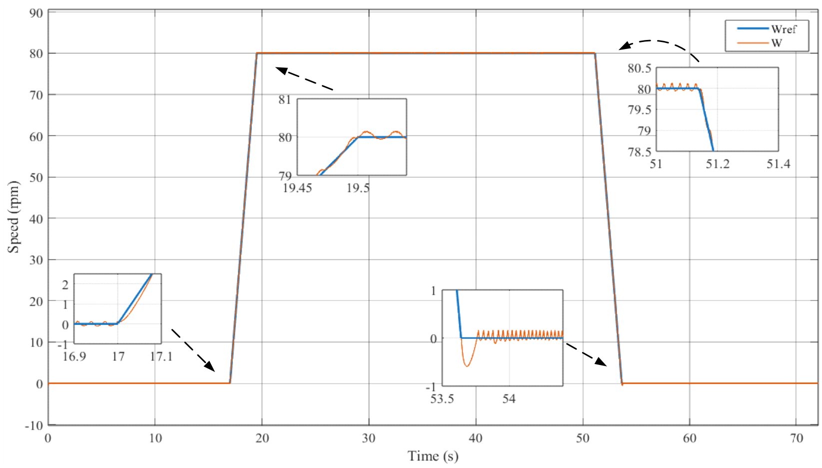

Figure 5. Speed response

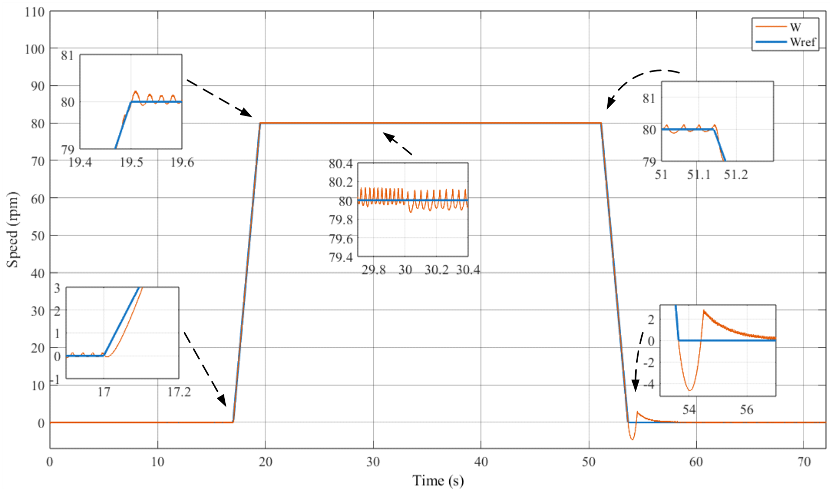

Figure 6. Speed response when the load is changed

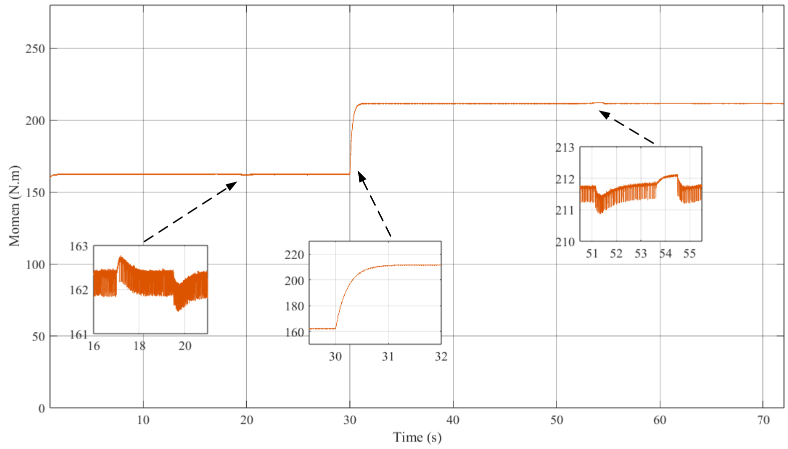

Figure 7. The result of the torque curve is as follows

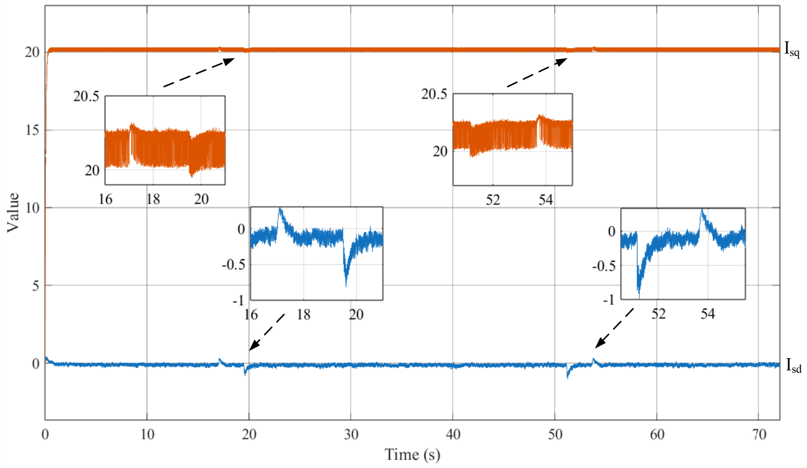

Figure 8. The current response of I_{sd} and I_{sq}

5. CONCLUSION

In this study, the authors investigated a sensorless speed estimation method based on the MRAS model observer for permanent magnet synchronous motors used in elevators, combined with a low-pass filter to improve the performance and responses of elevators in residential buildings. The simulation results show that this method optimizes energy efficiency and cost, ensuring torque and system stability under various operating conditions. This opens up new research directions in the design and operation of elevators, contributing to the sustainable development of future transportation technologies.

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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
Tran Van Khoi	✓	✓		✓	✓			✓	✓	✓		✓	✓	✓
An Thi Hoai Thu Anh		✓	✓	✓	✓	✓			✓	✓		✓		✓
Tran Trong Hieu		✓	✓	✓		✓	✓		✓		✓		✓	

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

CONFLICT OF INTEREST STATEMENT
The authors state no conflict of interest.

DATA AVAILABILITY
The data supporting the findings of this study are openly available in IJECE.

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BIOGRAPHIES OF AUTHORS

Tran Van Khoi received B.S. and M.S. degree in electrical engineering and automation from the University of Transport and Communications, Hanoi, Vietnam in 2004 and 2009, respectively, and received Ph.D. degree from Beijing Jiaotong University, Beijing, China in 2019. He is currently a lecturer of Electrical and Electronic Faculty in University of Transport and Communications (UTC). His research interests are optimal techniques and energy management strategies. He can be contacted at email: tvkhoi.ktd@utc.edu.vn.

An Thi Hoai Thu Anh received her Engineer (1997), and MSc (2002) degrees in industrial automation engineering from Hanoi University of Science and Technology; and completed PhD degree in 2020 from the University of Transport and Communications (UTC). Now, she is a lecturer at the Faculty of Electrical and Electronic Engineering at the University of Transport and Communications (UTC). Her interests include power electronic converters, electric motor drives, and energy-saving solutions for industry and transportation. She can be contacted by email: htanh.ktd@utc.edu.vn.

Tran Trong Hieu is a fourth-year student majoring in electrical engineering at the University of Transport and Communications (UTC), Vietnam. His current interests include power electronics and electric drive control, which are applied in the transportation and industry. He can be contacted at email: Hieu201503761@lms.utc.edu.vn.