

AN ADVANCED RF-MRAS TECHNIQUE APPLYING TO SPEED SENSORLESS CONTROL

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ABSTRACT

Reference frame model reference adaptive system (RF_MRAS) is a typical method to generate an estimated speed signal for motor control without a speed encoder. The primary principle of the RF-MRAS method is to use two voltage and current structures to develop one kind of estimated rotor flux signal and then compare the difference between them for adapting control to an estimated speed signal. However, during operation, due to the increase in temperature, the stator resistance of the motor will change, affecting the speed control performance. This paper proposes an enhanced solution for the RF-MRAS technique based on the parallel integration of stator resistance estimation into the control model to increase motor performance. In this research, the stator voltage calculated from the DC-link voltage and switching pulses is proposed to be provided to the RF-MRAS model as the input. The paper's objective is that the estimated speed should match the actual operating speed even under variable stator resistance conditions. The performance of the proposed model is investigated through various three case simulations, and the achievement results demonstrated its effectiveness under different operating conditions.

Keywords: Field-oriented control, induction motor, current model, stator resistance, MRAS.

1. INTRODUCTION

Three-phase induction motors (TPIM) are widely used for many industrial applications due to their high reliability, relatively low cost, and minimal maintenance requirements [1-3]. Typical methods are scalar control (SC) and field-oriented control (FOC). Scalar control focuses on regulating the average speed of the induction motor without complex transformations. SC regulates the voltage and frequency supplied to the motor to control its speed, making it more straightforward and cost-effective for applications where high accuracy is not so important [4, 5]. In contrast, FOC is a prominent strategy in the vector control group because it considers both the amplitude and angular position of the space vectors of motor elements, such as voltage and flux, and is used in high-performance situations [6-9].

The FOC controller's signals necessitate measurement sensors such as current, voltage, or speed sensors to ensure optimal performance in controlling induction motor systems [10-12]. Nevertheless, challenges like sensor longevity, investment costs, and environmental constraints can impede sensor usage during measurement [13]. Sensorless control is vital for lowering investment costs and reducing the control system's size while enhancing the induction motor system's reliability [14-16]. The Model Reference Adaptive System (MRAS) control method relies on mathematical models of various motors to estimate system states and parameters. This technique determines the speed and other motor parameters, such as flux current and voltage, using mathematical models alongside the actual system's responses. This straightforward solution is widely used across

numerous domains, including electric motor control, automation systems, industrial applications, robotic control systems, and renewable energy [17-19].

In the MRAS model, stator current and voltage are vital inputs for rotor speed estimation. The stator resistance (R_s) is another critical parameter whose impact on speed estimation is pronounced. Changes in R_s can influence the accuracy of these estimations, but adaptation of convergence parameters may be employed at both high and low-speed ranges [20]. R_s may vary over time in real-world applications due to factors like temperature changes, coil aging, or supply voltage variations. If not correctly estimated and adjusted, these variations can cause significant issues in the control system's functionality. The study in [21] implemented a Kalman Filter in FOC to oversee speed, revealing that it is reliable across various speed ranges. Nonetheless, this observer is particularly sensitive to stator resistance variations, especially at lower speeds.

This study introduces an improved model framework utilizing the Model Reference Adaptive System (RF-MRAS) within the FOC strategy for rotor speed estimation. A stator resistance estimator is included to accommodate variations in the motor's stator resistance. A communicating Proportional-Integral (PI) controller evaluates both rotor speed and R_s . Details of the methodology are outlined in Section 3. Section 4 showcases MATLAB/Simulink simulations of the TPIM drive using the FOC approach. The paper concludes with a discussion of results and insights for future research.

2. THE THREE-PHASE INDUCTION MOTOR MODEL BASED ON THE FIELD-ORIENTED CONTROL

2.1. The mathematical model

Several nonlinear factors influence the connection among the electrical parameters of the TPIM, and the equations below illustrate the mathematical model of the motor in the stationary coordinate system $[\alpha, \beta]$ as follows [22, 23]:

$$\begin{cases} \vec{u}_s = R_s \vec{i}_s + \left(\frac{L_s L_r - L_m^2}{L_r} \right) L_s \frac{d\vec{i}_s}{dt} + \frac{L_m}{L_r} \frac{d\vec{\psi}_r}{dt} \\ 0 = -\vec{i}_s \frac{L_m}{T_r} + \vec{\psi}_r \left(\frac{1}{T_r} - jp\omega_m \right) + \frac{d\vec{\psi}_r}{dt} \end{cases} \quad (1)$$

The electromagnetic torque produced by the induction motor is illustrated as follows:

$$T_e = T_L + \frac{J}{p} \frac{d\omega}{dt} \quad (2)$$

Where \vec{u}_s is the stator voltage vector; \vec{i}_s, \vec{i}_r are the stator and rotor current vectors, respectively; $\vec{\psi}_s, \vec{\psi}_r$ are the stator and rotor magnetic flux vectors; R_s, R_r are the stator and rotor resistances; L_s, L_r are the stator and rotor inductances; L_m is the magnetizing inductance; T_r is the time rotor constant; $\omega_r = p\omega_m$ is the rotor speed, ω_m is the mechanical speed; T_L is load torque; J is moment of inertia.

2.2. Field-Oriented Control Method

The basic configuration of a motor drive utilizing inverter technology comprises four essential components: the motor-connected load, the controller, the inverter, and the sensors. Each element is crucial in ensuring efficient and precise motor speed regulation, as illustrated in Figure 1.

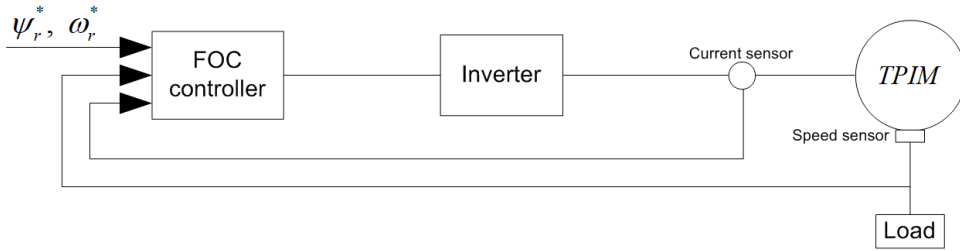


Figure 1. Control structure of TPIM.

This research implements an FOC method in a TPIM drive system to manage flux and torque separately. This configuration includes current sensors and a voltage source inverter, and it uses feedback loops to align the motor speed with a reference speed via control voltage signals. The FOC method [22], depicted in Figure 2, converts the three-phase stator current into $[\alpha, \beta]$ coordinates using Clarke and Park transformations, allowing the rotor flux and flux angle to be calculated. A PI controller monitors multiple feedback loops and processes the speed and flux differences to generate control inputs, which are then converted into voltage signals. These signals regulate the inverter switching via SPWM, ensuring effective control of the drive system speed.

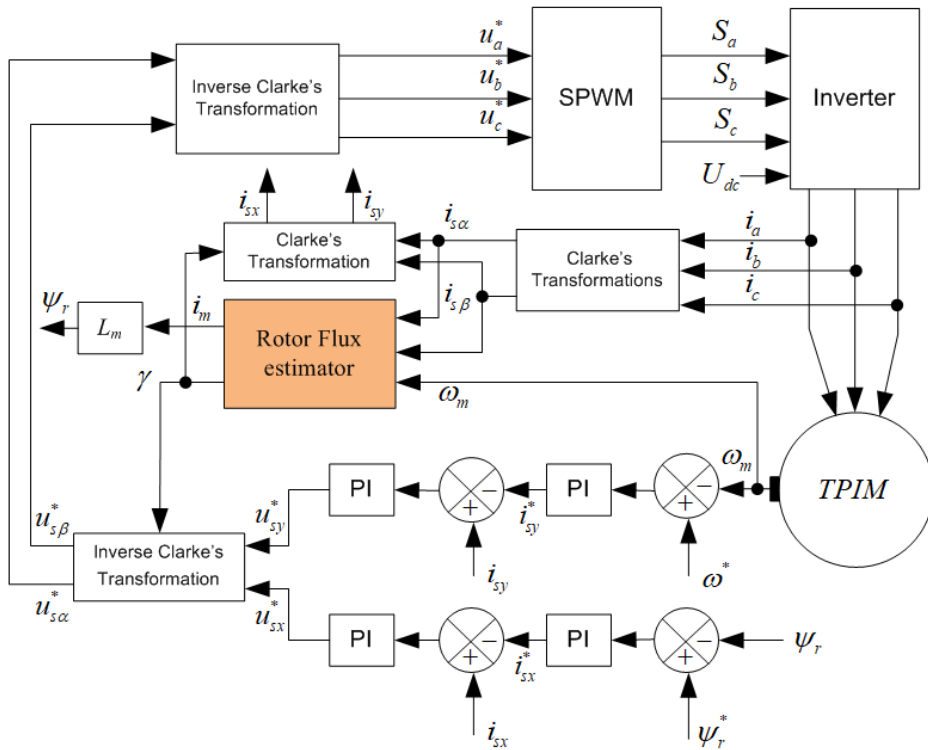


Figure 2. Diagram of TPIM drive system using FOC technique.

2.3. The proposed RF_MRAS integrating stator resistance estimation

Figure 3 illustrates the block diagram of the proposed RF-MRAS method for predicting the speed and stator resistance of TPIM. The voltage model, also known as the reference model, consists of the stator equations. In this model, the stator voltage is proposed to be determined from the DC-link voltage and switching pulses. The current model, known as the adaptive model, is based on the rotor equations of TPIM.

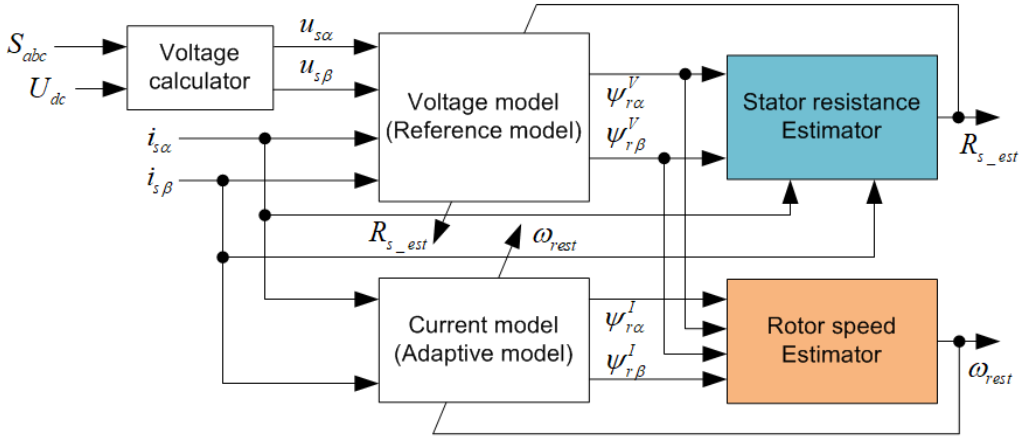


Figure 3. Block diagram of RF-MRAS integrating stator resistance estimation.

Figure 4 displays the schematic of a speed sensorless control system for an induction motor, utilizing the RF-MRAS method while incorporating stator resistance estimation via the FOC approach.

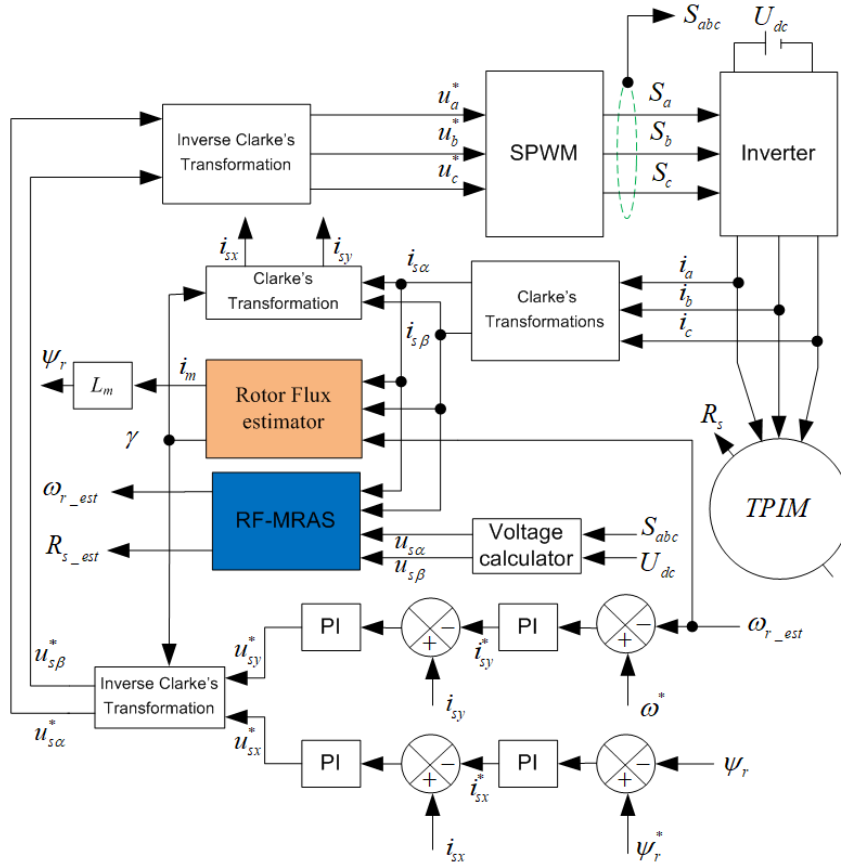


Figure 4. Block diagram of the RF_MRAS combining stator resistance estimation.

Speed estimation with RF-MRAS compares the magnetic flux calculated from the voltage and measured current models. The rotor magnetic flux of the asynchronous motor is determined by formulas (11) and (12) in the RF-MRAS method. The input error of the PI controller is obtained by formula (13). The estimated speed is determined from the output of the PI controller, as shown in formula (14).

$$\psi_{r\alpha}^V = \frac{L_r}{L_m} \left[\int (u_{s\alpha} - R_{s_est} i_{s\alpha}) dt - \left(\frac{L_s L_r - L_m^2}{L_r} \right) i_{s\alpha} \right] \quad (11)$$

$$\psi_{r\beta}^V = \frac{L_r}{L_m} \left[\int (u_{s\beta} - R_{s_est} i_{s\beta}) dt - \left(\frac{L_s L_r - L_m^2}{L_r} \right) i_{s\beta} \right] \quad (12)$$

$$\varepsilon_\omega = \psi_{r\alpha}^I \psi_{r\beta}^V - \psi_{r\beta}^I \psi_{r\alpha}^V \quad (13)$$

$$\omega_{r_est} = K_p \varepsilon_\omega + K_i \int \varepsilon_\omega dt \quad (14)$$

By integrating the outputs from both the voltage and current models with the stator current, we can determine the error in the stator resistance. This error is then processed through the PI control mechanism to estimate the stator resistance of the motor, as illustrated in equations (15) - (18) below:

$$\psi_{r\alpha}^I = \int \left(\frac{L_m}{T_r} i_{s\alpha} - \frac{1}{T_r} \psi_{r\alpha}^I - \omega_{r_est} \psi_{r\beta}^I \right) dt \quad (15)$$

$$\psi_{r\beta}^I = \int \left(\frac{L_m}{T_r} i_{s\beta} - \frac{1}{T_r} \psi_{r\beta}^I + \omega_{r_est} \psi_{r\alpha}^I \right) dt \quad (16)$$

$$\varepsilon_{R_s} = (\psi_{r\alpha}^V - \psi_{r\alpha}^I) i_{s\alpha} + (\psi_{r\beta}^V - \psi_{r\beta}^I) i_{s\beta} \quad (17)$$

$$R_{s_est} = K_p \varepsilon_{R_s} + K_i \int \varepsilon_{R_s} dt \quad (18)$$

3. SIMULATION RESULTS

The model of TPIM is constructed on the actual machine's framework, with fundamental parameters listed in Table 1. The TPIM drive system's performance is analyzed through simulations in four scenarios at varying speed modes to assess the alterations in the machine model's stator resistance and the virtual speed estimation model.

Table 1. Parameters of TPIM

Parameters	Values
Resistances: stator/rotor	3.358 / 2.506 Ω
Inductances: stator/rotor/magnetizing	0.2192 / 0.2192 / 0.1960 H

The TPIM was programmed to elevate the reference speed from 0 to 400 *rpm* within a 0.5 *s* interval, followed by deceleration to 300 *rpm* at 2.0 *s* and 200 *rpm* at 3.5 *s*. The proposed FOC method was utilized to analyze and assess the TPIM's operational performance under three varying resistance scenarios.

Case study 1: The TPIM operates under variable load with the speed increasing to 400 *rpm* at time 0.5 *s* and decreasing to 200 *rpm*. It starts from 0 at $t = 0$ *s* and gradually reaches the full set value within 1 *s*. Figure 5 demonstrates the effectiveness of the proposed FOC method, with rotor speed estimation using the RF-MRAS model when the motor is supplied with a constant stator resistance. Figure 5(a) shows that the motor speed closely follows the target speed with minimal overshoot. The stator resistance remains constant during the simulation, as depicted in Figure 5(b). Figure 5(c) shows that as the motor accelerates, the electric torque exceeds the load torque, and when the motor stabilizes at the desired speed, the electric torque equals the load torque. The initial motor current is low, around 10 *A*, while the operating current is between 4 *A* and 4.5 *A* during steady-state operation.

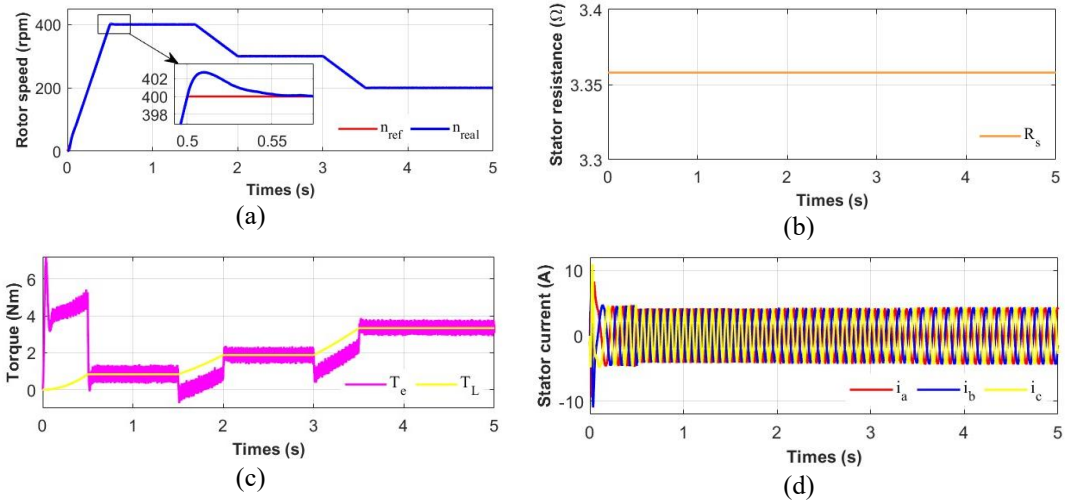


Figure 5. Performance analysis of TPIM under constant stator resistance condition

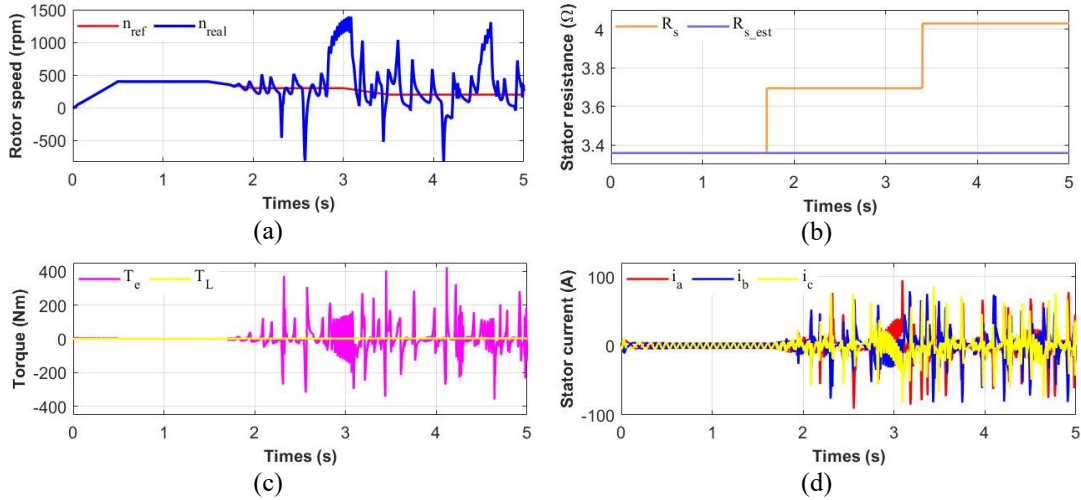


Figure 6. Performance analysis of TPIM under variable stator resistance conditions

Case study 2: This case illustrates the change of the stator resistance (R_s) according to a step function while the stator resistance of RF-MRAS remains the same, Figure 6(b). The sudden change of R_s causes the motor's actual speed to fluctuate strongly compared to the reference speed. Large fluctuations are evident when R_s changes at a time interval of 1.7 s, which proves that the mismatch between R_s and R_{s_est} has negatively affected the speed controllability of the system, Figure 6(a). Figure 6(c) shows that the load torque remains the same, but the electromagnetic torque is affected by the change of R_s , indicating the instability of the control system. The stator current also shows similar large fluctuations when R_s changes, Figure 6(d). Therefore, the control system needs to have a suitable R_s estimation or adjustment mechanism to improve the stability and accuracy of the estimated values, especially when R_s changes during operation.

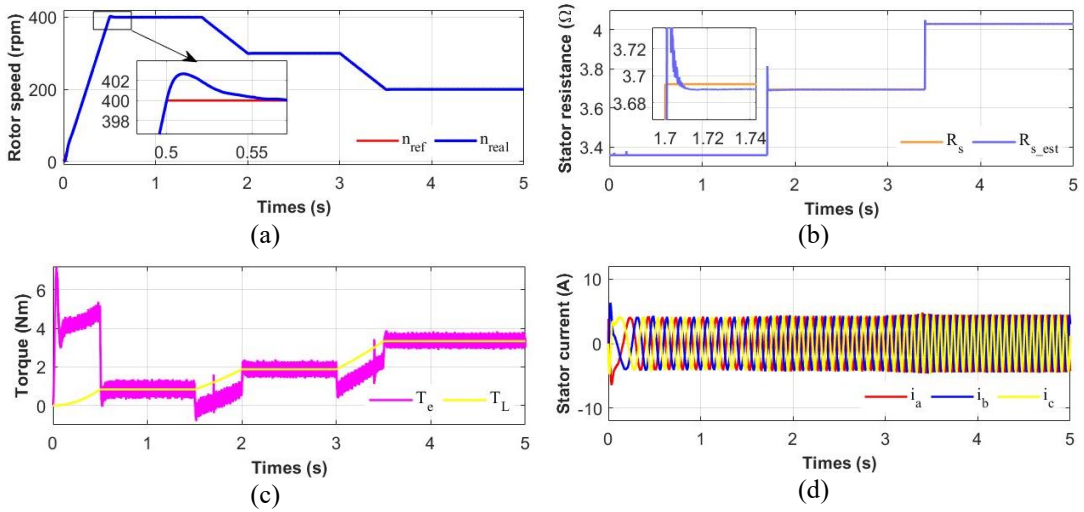


Figure 7. Performance analysis of TPIM under estimated stator resistance conditions

Case study 3: To evaluate the stator resistance estimation function of the proposed method, a multi-slope change of R_s values corresponding to 30% and 50% increments throughout 1.7 s is simulated to evaluate the performance. Figure 7(a) shows that the system achieves fairly good tracking between the actual speed and the reference speed, although there are some small fluctuations around the time of speed change. In Figure 7(b), the R_{s_est} follows the R_s . The electromagnetic torque remains stable and matches the load torque after the motor reaches the desired speed, Figure 7(c). The stator current fluctuates when R_s changes but not too much, and it quickly stabilizes at a suitable value in the steady state. By estimating R_s quickly and accurately, the system maintains the stability of rotor speed, electromagnetic torque, and stator current.

The proposed method is optimal for maintaining the stability and efficiency of TPIM under changing operating conditions.

5. CONCLUSION

The research presents a strategy to enhance rotor flux estimation accuracy by incorporating stator resistance adjustment in the current model. It examines the influence of stator resistance variations on the speed characteristics of TPIM. The stator resistance estimation method using the RF-MRAS technique is validated by accurately estimating resistance values corresponding to actual motor variations. The effectiveness of the proposed FOC method, when combined with stator resistance estimation, is demonstrated through various simulation scenarios.

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TÓM TẮT

MỘT KỸ THUẬT RF-MRAS NÂNG CAO CHO ĐIỀU KHIỂN TỐC ĐỘ KHÔNG SỬ DỤNG CẢM BIẾN

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Hệ thống đáp ứng mô hình khung tham chiếu (RF_MRAS) là một phương pháp điển hình để tạo tín hiệu ước tính tốc độ cho điều khiển động cơ mà không cần cảm biến tốc độ. Nguyên lý chính của phương pháp RF-MRAS là sử dụng hai cấu trúc điện áp và dòng điện để tạo ra cùng tín hiệu từ thông rô-to và sau đó so sánh sự khác biệt giữa chúng để điều khiển đáp ứng tạo ra tín hiệu ước tính tốc độ. Tuy nhiên, trong quá trình vận hành, do nhiệt độ tăng, điện trở stato của động cơ sẽ thay đổi, ảnh hưởng đến hiệu suất điều khiển tốc độ. Bài báo này đề xuất một giải pháp nâng cao cho kỹ thuật RF-MRAS dựa trên tích hợp song song khâu ước tính điện trở stato vào mô hình điều khiển để tăng hiệu suất động cơ. Trong nghiên cứu này, điện áp stato được tính toán từ điện áp liên kết DC và xung chuyên mạch được đề xuất cung cấp cho mô hình RF-MRAS làm đầu vào. Mục tiêu của bài báo là tốc độ ước tính phải phù hợp với tốc độ vận hành thực tế ngay cả trong điều kiện điện trở stato thay đổi. Hiệu suất của mô hình đề xuất được nghiên cứu thông qua ba trường hợp mô phỏng khác nhau và kết quả đạt được đã chứng minh tính hiệu quả của nó trong các điều kiện vận hành đa dạng.

Từ khóa: Điều khiển định hướng từ thông, động cơ cảm ứng, mô hình dòng điện, điện trở stato, MRAS.