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Improved speed sensorless control for induction motor drives using rotor flux angle estimation

Introduction. *In the typical field-oriented control (FOC) method, the variation of machine resistance is not considered when calculating the rotor flux angle. This omission affects the accuracy of the control method during motor operation, leading to potential performance degradation.* ***Problem****. Neglecting stator resistance variations in the voltage model-based FOC technique can cause rotor flux angle estimation deviation. This inaccuracy impacts motor speed control, especially under varying operating conditions where resistance changes due to temperature fluctuations.* ***Goal.*** *This paper aims to improve the accuracy of rotor flux angle estimation in the voltage model-based FOC technique by incorporating a real-time stator resistance estimation process.* ***Methodology.*** *The proposed research integrates a model reference adaptive system to estimate the stator resistance and replaces the rated resistance value in the rotor flux angle calculation algorithm of the FOC technique. The effectiveness of the method is evaluated by using MATLAB/Simulink simulations, where the estimated resistance value is compared with the actual resistance value, and the motor speed control performance is analyzed. Simulation* ***results*** *demonstrate that the proposed method significantly enhances the accuracy of rotor flux angle estimation by adapting to changes in stator resistance. This improvement ensures better motor speed control performance, reducing deviations between the actual and reference speeds under different operating conditions.* ***Scientific novelty*** *of this research lies in integrating real-time stator resistance estimation into the rotor flux angle calculation process of the voltage model-based FOC technique, addressing a key limitation in typical FOC approaches.* ***Practical value.*** *By improving the accuracy of rotor flux angle estimation, the proposed method enhances the stability and efficiency of motor speed control. This ensures better performance in industrial applications where precise motor control is essential under varying operating conditions.* References 27, figures 11.

Keywords: **induction motor drive, field-oriented control, model reference adaptive system, stator resistance.**

Вступ*. У типовому методі управління з орієнтацією по полю (FOC) зміна опору машини не враховується під час розрахунку кута потоку ротора. Цей недолік впливає на точність методу керування під час роботи двигуна, що призводить до потенційного зниження продуктивності.* ***Проблема****. Нехтування змінами опору статора у методі FOC на основі моделі напруги може призвести до відхилення оцінки кута потоку ротора. Ця неточність впливає на керування швидкістю двигуна, особливо в умовах експлуатації, коли опір змінюється через коливання температури.* ***Метою*** *даної роботи є підвищення точності оцінки кута потоку ротора в методі FOC на основі моделі напруги шляхом включення процесу оцінки опору статора в реальному часі.* ***Методика****. Пропоноване дослідження інтегрує адаптивну систему з еталонною моделлю для оцінки опору статора та замінює номінальне значення опору в алгоритмі розрахунку кута потоку ротора методом FOC. Ефективність методу оцінюється за допомогою моделювання MATLAB/Simulink, де розрахункове значення опору порівнюється з фактичним значенням опору, а потім аналізується характеристика керування швидкістю двигуна.* ***Результати*** *моделювання показують, що запропонований метод значно підвищує точність оцінки кута потоку ротора за рахунок адаптації змін опору статора. Це покращення забезпечує більш ефективне управління швидкістю двигуна, зменшуючи відхилення між фактичною та заданою швидкостями у різних робочих умовах.* ***Наукова новизна*** *даного дослідження полягає в інтеграції оцінки опору статора в реальному часі в процес розрахунку кута потоку ротора методом FOC на основі моделі напруги, що усуває ключове обмеження типових підходів FOC.* ***Практична значимість****. Підвищуючи точність оцінки кута потоку ротора, запропонований метод підвищує стабільність та ефективність управління швидкістю двигуна. Це забезпечує більш високу продуктивність у промислових застосуваннях, де точність управління двигуном необхідна в змінних робочих умовах.* Бібл. 27, рис.11.

Ключові слова: **привод асинхронного двигуна, полеорієнтоване управління, адаптивна система еталонної моделі, опір статора.**

Introduction. The rotor flux angle is a crucial factor in the functioning and vector control methods of induction motors (IMs). It indicates the alignment of the rotor's magnetic field concerning the stator's magnetic field, and precise estimation of this angle is vital for achieving peak motor performance. Within the IM model, the rotor flux angle is integral in separating torque and flux control, enabling accurate and independent tuning of torque and flux during motor operation [1–5].

Problems and the relevance. The field-oriented control (FOC) method [6–9] is a widely used approach for determining the rotor flux angle. However, this method's control strategy relies heavily on the machine parameters, particularly the stator resistance. Furthermore, variations in stator resistance are not accounted for when computing the rotor flux angle, thereby impacting the precision of the control method during operation.

Review of recent publications about rotor flux estimation. Model reference adaptive systems (MRAS) have been extensively developed to calculate the rotor flux and its angle in IMs [10–13]. Two elementary models are utilized in the MRAS method: the current model (CM, the adaptive model) and the voltage model (VM, the reference model). The CM, sensitive to rotor resistance parameters [14, 15], relies on the stator current signal and rotor speed to ascertain the rotor flux angle. Conversely, the VM, which depends on the stator resistance parameter [16, 17], uses both voltage and current signals to estimate rotor flux. A significant challenge in MRAS modeling is the variation in stator resistance due to temperature fluctuations, which can impact motor precision. As the stator winding temperature changes, the resistance alters, necessitating an adaptive approach to estimate this parameter accurately. These adaptive mechanisms bolster the resilience of MRAS models, mainly during low-speed functions where the precise determination of stator resistance is vital for sustaining performance [18, 19]. When the stator resistance is not accurately estimated, it leads to errors in the calculated stator flux, affecting the torque output and stability of the motor drive [20]. The authors [21] considered a rotor flux estimator based on the MRAS model, which also depends on the stator resistance (R_s) of the motor, and found that the estimated R_s value is susceptible to changes in IM parameters. This estimated R_s serves as an input to the speed estimator. The relationship between temperature-induced resistance changes and control accuracy is further supported by the findings in [22, 23], highlighting the challenges in maintaining accurate rotor speed and flux estimates in the face of R_s drift. The estimated R_s is considered a solution to improve the reliability of the flux estimate.

The goal of the paper. This study introduces an enhanced rotor flux-based model reference adaptive system (RF-MRAS) to estimate the rotor flux and determine the R_s of the IM. This estimated resistance is then used to update the R_s in the rotor flux angle calculation within the FOC technique, which traditionally overlooks variations in R_s [24, 25]. The proposed approach enhances the precision of rotor flux angle estimation, accommodating changes in stator resistance during motor speed regulation and ensuring alignment between the actual and target speeds across various operational scenarios. Furthermore, simulation results have confirmed the validity of this analysis.

Mathematical models for IMs within the [*α*/*β*] coordinate framework. The connection between the electrical parameters of an IM is influenced by several nonlinear factors [26]. These parameters include the stator current, flux linkage, and voltage. To study the dynamic performance of the IM, a mathematical model is formulated within the static coordinate framework [*α*/*β*]. This model illustrates the interaction between the voltage, current, and flux linkage of both the stator and rotor. The primary mathematical equations defining the IM system are:

$$\begin{bmatrix} \boldsymbol{u}_s^s \\ 0 \end{bmatrix} = [\boldsymbol{A}] \begin{bmatrix} \boldsymbol{i}_s^s \\ \boldsymbol{\psi}_r^s \end{bmatrix} + [\boldsymbol{B}] \frac{\mathrm{d}}{\mathrm{d}t} \begin{bmatrix} \boldsymbol{i}_s^s \\ \boldsymbol{\psi}_r^s \end{bmatrix}, \qquad (1)$$

with matrices:

$$[\boldsymbol{A}] = \begin{bmatrix} R_s & 0 \\ -L_m/T_r & 1/T_r - j\omega_r \end{bmatrix}; \; [\boldsymbol{B}] = \begin{bmatrix} \frac{L_s L_r - L_m^2}{L_r} L_s & L_m/L_r \\ 0 & 1 \end{bmatrix},$$

where $\boldsymbol{u}_s^s$ is the stator voltage vector; $\boldsymbol{i}_s^s$ is the stator current vector; $\boldsymbol{\psi}_r^s$ is the rotor flux vector; $T_r = L_r/R_r$ is the time rotor constant; R_s, R_r are the stator and rotor resistances; L_s, L_r, L_m are the stator, rotor and mutual inductances; ω_r is the rotor angular velocity.

A. Apply the typical VM to calculate rotor flux in the FOC technique corresponding to speed sensorless control. A speed sensorless induction motor drive (IMD) using the FOC technique consists of voltage/current sensors [27] integrated into the converter. The IMD consists of key components: the IM for converting electrical into mechanical energy, with rotor flux dynamics crucial for speed control; the application-dependent load; the inverter power supply, a 3-phase voltage source inverter for AC voltage and frequency to manage speed and torque; and the sensing system for indirect speed estimation. The FOC controller separates torque and flux components of stator current for independent motor control, regulated by a PI controller. A new rotor flux controller estimates rotor flux. Figure 1 shows these components' interconnection.

Rotor flux calculation in IM is essential to control strategies, especially in sensorless applications. Rotor flux using a VM is advantageous because it does not depend on rotor parameters. The block diagram for estimating rotor flux vector components using the VM is depicted in Fig. 2.

Equation (2) describes the rotor flux estimation:

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} \psi_{r\alpha(VM)} \\ \psi_{r\beta(VM)} \end{bmatrix} = \frac{L_r}{L_m}\begin{bmatrix} u_{s\alpha} \\ u_{s\beta} \end{bmatrix} - \frac{L_r}{L_m} R_{s\_est} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} - a_1 \frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix}; \qquad (2)$$

with $a_1 = \left(L_s L_r - L_m^2\right)/L_m$,

where $\psi_{r\alpha(VM)}$, $\psi_{r\beta(VM)}$ are the rotor flux components in the VM on the coordinate axis [*α*/*β*].

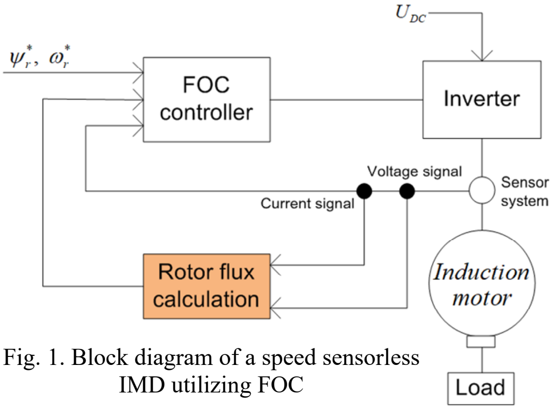

Fig. 1. Block diagram of a speed sensorless IMD utilizing FOC

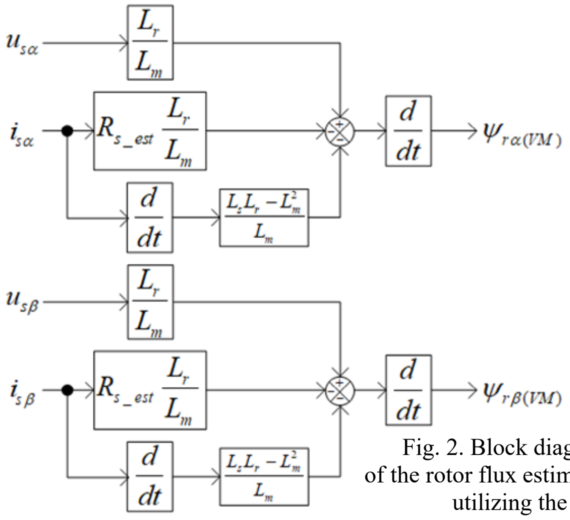

Fig. 2. Block diagram of the rotor flux estimator utilizing the VM

B. Sensorless technique based on RF-MRAS. Figure 3 shows the rotor flux-based speed observer in the improved RF-MRAS model for speed estimation.

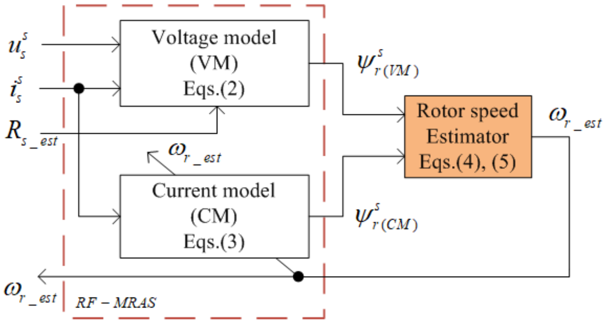

Fig. 3. Block diagram of the speed estimation using RF-MRAS

This improved model consists of the reference model (VM), represented in (2), and the adaptive model (CM), based on the relationship between the stator current, the rotor flux, and the rotor speed represented in (3), together with an adaptive mechanism to minimize the error between the 2 models, as shown in (4, 5):

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} \psi_{r\alpha(CM)} \\ \psi_{r\beta(CM)} \end{bmatrix} = \begin{bmatrix} -1/T_r & -\omega_{r\_est} \\ \omega_{r\_est} & -1/T_r \end{bmatrix} \begin{bmatrix} \psi_{r\alpha(CM)} \\ \psi_{r\beta(CM)} \end{bmatrix} + \frac{L_m}{T_r}\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix}, \qquad (3)$$

where $\psi_{r\alpha(CM)}$, $\psi_{r\beta(CM)}$ are the rotor flux components in CM on the coordinate axis [α/β].

Equation (4) shows the discrepancy, termed as the error, between the outputs of the 2 estimators:

$$\xi_{RF\text{-}MRAS} = \psi_{r\alpha(CM)}\cdot\psi_{r\beta(VM)} - \psi_{r\beta(CM)}\cdot\psi_{r\alpha(VM)}. \tag{4}$$

The RF-MRAS technique estimates speed via the PI controller:

$$\omega_{r\_est} = K_p\cdot\xi_{\omega_{RF-MRAS}} + K_i\int\xi_{\omega_{RF-MRAS}}\mathrm{d}t\,, \tag{5}$$

where K_p, K_i are the gain constants for the proportional and integral components, respectively.

C. Stator resistance estimation using RF-MRAS. During motor operation, temperature increases affect the stator resistance, altering the R_s parameter of (2) in section A of the VM and causing rotor flux estimation errors. This research proposes a method to estimate R_s integrated with speed estimation. Figure 4 illustrates the fundamental block diagram of the R_s estimator based on RF-MRAS, which includes a reference function f ($\boldsymbol{i}_s^s$, $\boldsymbol{u}_s^s$, R_{s_est}) and an adaptive function f ($\boldsymbol{i}_s^s$, ω_{r_est}). The PI controller processes the deviation between them. The output, R_{s_est}, adjusts to minimize the error.

The parameter R_{s_est} is expected to enhance the precision of the rotor flux estimation approach, which depends on the RF-MRAS model. The PI stage determines the R_s value:

$$\xi_R = [\psi_{r\alpha(RF)} - \psi_{r\alpha(CM)}]i_{s\alpha} + [\psi_{r\beta(RF)} - \psi_{r\beta(CM)}]i_{s\beta}; \tag{6}$$

$$R_{s\_est} = K_p f\left(\xi_R\right) + K_i\int f\left(\xi_R\right)\mathrm{d}t\,. \tag{7}$$

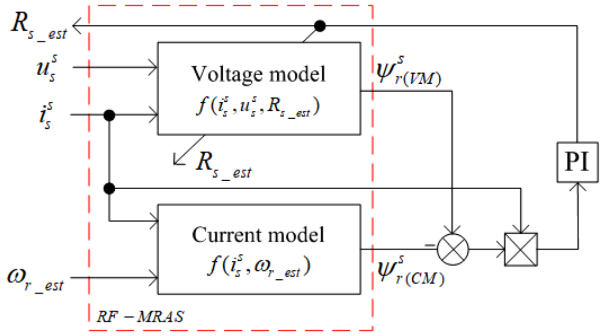

Fig. 4. Block diagram of the estimating stator resistance using RF-MRAS

Simulation results. The performance of the improved method is assessed through simulations of the IMD. The parameters for IM are: pole pairs – 2; rated speed – 1420 rpm; R_s = 3.179 Ω; R_r = 2.118 Ω; L_s = 0.209 H; L_r = 0.209 H; L_m = 0.192 H.

The sensitivity to changes in motor parameters was tested at a low-speed reference speed value increasing from 0 rpm to 300 rpm at 0.5 s. The motor was operated at a load of 14.8 N·m after 1 s (full load). Two cases considered the influence of the stator resistance on the VM-based flux estimator. The stator resistance was assumed to be unchanged and increased by 20 % from the nominal value, while the other parameters remained the same.

The 1st case simulated the operation of the IMD corresponding to the improved FOC method with rotor flux based on the VM. Figure 5 shows the performance of the motor when R_s is constant, showing the reference speed and the motor's actual speed; the control system maintained the motor speed closely following the reference value in a stable manner despite small overshoots during starting and at maximum load. The stator current stabilizes quickly after speed and load changes, with a slight initial spike when the speed changes, indicating that the system responds quickly and sensitively. Figures 6, 7 show that the components of the rotor flux vector components in [α/β] from the CM also remain accurate and well maintained, ensuring efficient operation of the system.

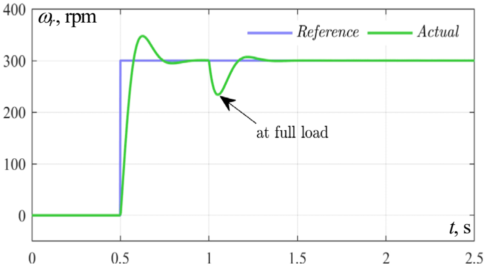

Fig. 5. Reference speed and actual speed of the IM

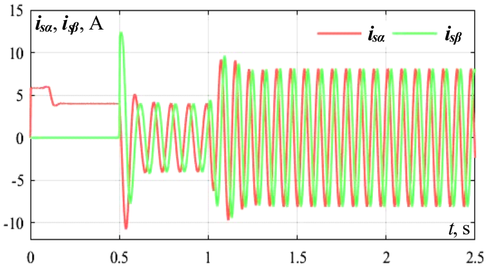

Fig. 6. Stator current vector of the IM $\boldsymbol{i}_{s\alpha}$, $\boldsymbol{i}_{s\beta}$

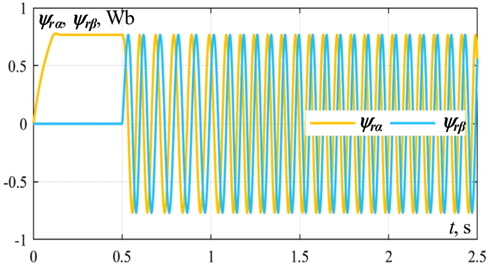

Fig. 7. Rotor flux vector from the VM for improved FOC technique: $\boldsymbol{\Psi}_{r\alpha}$, $\boldsymbol{\Psi}_{r\beta}$

In the 2nd case, when the stator resistance increases by 20 % from the nominal value at 1.3 s, this change affects the rotor flux and rotor speed in the RF-MRAS technique. Although the initial change in R_s leads to a deviation between the reference value and the estimated value, the estimator has shown good adaptability, accurately adjusting to the change in R_s. The simulation results show (Fig. 8) that the difference between the actual and estimated stator resistance is negligible. The rotor flux and stator current vectors remain stable (Fig. 9, 10). Although the estimated speed in Fig. 11 still closely follows the actual speed and is very close to the reference speed, ensuring high accuracy in both the transient and steady-state responses.

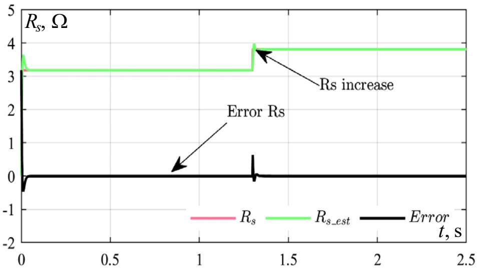

Fig. 8. Actual/estimated and error between stator resistance using RF-MRAS

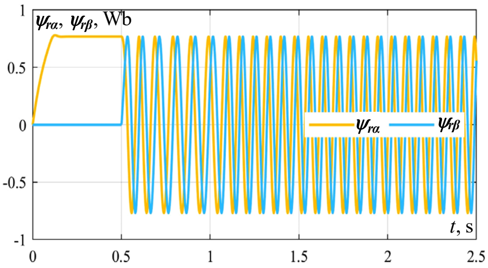

Fig. 9. Rotor flux vector based on improved FOC technique using RF-MRAS: $\boldsymbol{\Psi}_{r\alpha}$, $\boldsymbol{\Psi}_{r\beta}$

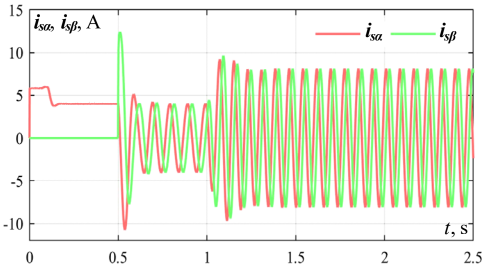

Fig. 10. Stator current vector of the IM based on improved FOC using RF-MRAS: $\boldsymbol{i}_{s\alpha}$, $\boldsymbol{i}_{s\beta}$

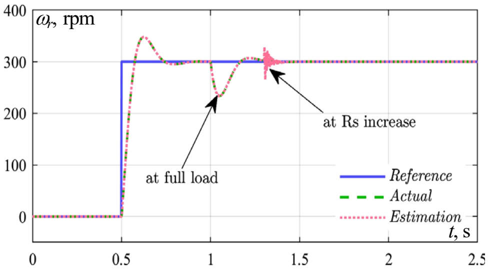

Fig. 11. Reference/actual/estimated speed of the IM based on improved FOC using RF-MRAS

The improved FOC system works well in both cases, ensuring accurate speed and fast response. When R_s changes, the system takes some time to adjust but still provides the accuracy of the speed estimate. The difference between the actual R_s and the estimated R_s is negligible, proving the stability of the estimator.

Conclusions. The proposed method focuses on accurately estimating the R_s to improve the accuracy of estimated speed in sensorless control systems and aims at a more comprehensive approach. Specifically, the method improves the accuracy of the rotor flux angle, which is the core element of FOC in motor speed control. Since the rotor flux angle plays an important role in ensuring the separation of torque and flux control, any deviation in this value due to the change in R_s can cause deterioration in the control performance. Therefore, optimizing both the estimation of R_s and the flux angle will significantly improve the accuracy and stability of the vector control system, not only under normal operating conditions but also when R_s changes significantly due to the influence of temperature or other environmental factors. The simulation results show that the proposed method can adapt to the change in R_s, ensuring that both the rotor speed and the flux angle are accurately estimated, thus improving the performance of sensor and sensorless control systems.

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Conflict of interest. The authors declare that they have no conflicts of interest.

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