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Implementation of sensorless indirect vector control of induction motor with closed-loop current control

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Abstract

The paper focuses on the development and testing of an advanced induction motor control method. This method, known as indirect rotor flux-oriented vector control, allows independent control of motor torque and flux, providing high dynamic performance similar to that of a DC motor. Additionally, the implemented system is sensorless, eliminating physical rotor position sensors, which reduces complexity and cost while increasing system reliability. The proposed system uses a rotor flux estimation algorithm, based on mathematical models, which provides the necessary information for vector orientation in the absence of a sensor. Additionally, closed-loop current control improves stability and accuracy of the control by correcting output current deviations from reference values. Thus, the system provides fast and accurate response in the presence of load variations and external disturbances. Simulations and experimental tests were carried out in the Simulink environment, where the proposed model was evaluated under various operating conditions. The results demonstrate the efficiency of the system and the validity of the method for industrial applications where precise and robust induction motor control is required.

Keywords: three-phase induction machine, vector-control, rotor flux estimator

Introduction

Induction motors have been and continue to be widely used in industrial applications due to their robustness, durability and low maintenance compared to other types of electric machines. However, precise control of these motors presents significant challenges, as motor parameters vary with operating conditions and dynamics are complex. Indirect rotor flux oriented vector control has emerged as an effective solution to enable superior dynamic performance comparable to that of DC motors by decoupling torque and flux components, thus providing better motor handling in transient regimes and variable load.

The literature includes numerous studies and researches that explore various methods of implementing vector control for induction motors. The flux-orientation method was originally proposed by Blaschke in the 1970s, and has since been extended and improved in many directions, including sensorless implementations to reduce the complexity and cost of industrial systems. The removal of flux sensors, for example, has become an important research direction due to the potential to simplify the control

system and increase its reliability in difficult operating environments. Estimating the rotor flux through mathematical models of the motor and using adaptive algorithms has proven to be an effective method to eliminate flux sensors, with sufficient accuracy for most industrial applications, [1], [2].
Closed-loop current control is also a key element in ensuring the stability and accuracy of the system. This approach allows rapid compensation of variations and disturbances by continuously adjusting the current, thus providing superior performance in induction motor control, [3]. Recent studies show that the integration of closed-loop current control with sensorless vector control methods leads to improved system performance under real operating conditions, [4].
With the help of the Matlab/Simulink platform, it is possible to develop and simulate the control models of induction motors, thanks to its ability to represent the mathematical complexity of the systems and to allow testing of different operating scenarios before physical implementation. This paper aims to study and implement indirect vector control of a flux sensorless induction motor with closed-loop current control using advanced simulations in Simulink to evaluate the performance and robustness of the proposed method.

Mathematical model

The mathematical model of the asynchronous motor is written in stator notation and describes the dynamic behavior of the machine based on electrical and mechanical equations. Typically, the vector representation for currents, voltages and fluxes is used within a system of fixed axes relative to the stator (d,q), which allows voltages and currents to be treated as scalar quantities for each of these two perpendicular axes. Thus, the stator and rotor voltage equations are, [4],

$$\begin{aligned} u_{ds} &= R_s \cdot i_{ds} + \frac{d\psi_{ds}}{dt} \\ u_{qs} &= R_s \cdot i_{qs} + \frac{d\psi_{qs}}{dt} \\ 0 &= R_r \cdot i_{dr} + \frac{d\psi_{dr}}{dt} + \omega_r \cdot \psi_{qr} \\ 0 &= R_r \cdot i_{qr} + \frac{d\psi_{qr}}{dt} - \omega_r \cdot \psi_{dr} \end{aligned} \tag{1}$$

The stator and rotor flux components are,

$$\begin{aligned} \psi_{ds} &= L_s \cdot i_{ds} + L_{sr} \cdot i_{dr} \\ \psi_{qs} &= L_s \cdot i_{qs} + L_{sr} \cdot i_{qr} \\ \psi_{dr} &= L_r \cdot i_{dr} + L_{sr} \cdot i_{ds} \\ \psi_{qr} &= L_r \cdot i_{qr} + L_{sr} \cdot i_{qs} \end{aligned} \tag{2}$$

Where, $U_{ds}, I_{ds}, \psi_{ds}$ - d-axis components,

$U_{qs}, I_{qs}, \psi_{qs}$ - q axis components.

The general equation of motion and the expression of the electromagnetic torque are,

$$\frac{d\omega_r}{dt} = \frac{p}{J}\left(T_e - T_L\right) \tag{3}$$

$$T_e = \left(\frac{3p}{2}\right)\left(\frac{L_m}{L_r}\right)\left(\psi_{rd} i_{sq} - \psi_{rq} i_{sd}\right) \tag{4}$$

Where, T_e, T_L - electromagnetic torque and load torque.

Rotor flux estimator

For the indirect vector control with rotor flux orientation of the asynchronous motor, the proposed model uses a rotor flux estimation algorithm, based on mathematical models derived directly from the machine equations. With such models the partial state estimators are determined. These rotor flux estimation models provide the information needed for vector orientation in the absence of a sensor. For this paper, the "VI" estimator variant was chosen, an estimator that uses the stator voltage (V) and current (I) measurements to approximate the rotor flux. This type of estimator is relatively simple to implement and is used in applications where flux sensors are not available but indirect control of the induction motor is required.

In such situations, the mathematical model is determined from the motor equations written in the state space, [5], [6],

$$\dot{x} = A \cdot x + B \cdot u \tag{5}$$

Where: x – the vector of state variables,

u – system input (control).

If the stator currents and rotor fluxes (6) are chosen as state variables, then equations (1) are modified as follows,

$$x = \begin{bmatrix} i_{sd} & i_{sq} & \psi_{rd} & \psi_{rq} \end{bmatrix}^T \tag{6}$$

$$u = \begin{bmatrix} u_{sd} & u_{sq} \end{bmatrix}^T$$

$$A = \begin{bmatrix} -\left(\frac{1}{\sigma T_s} + \frac{1-\sigma}{\sigma T_r}\right) & 0 & \frac{L_m}{\sigma L_s L_r T_r} & \frac{L_m}{\sigma L_s L_r}\omega \\ 0 & -\left(\frac{1}{\sigma T_s} + \frac{1-\sigma}{\sigma T_r}\right) & -\frac{L_m}{\sigma L_s L_r}\omega & \frac{L_m}{\sigma L_s L_r T_r} \\ \frac{L_m}{T_r} & 0 & -\frac{1}{T_r} & -\omega \\ 0 & \frac{L_m}{T_r} & \omega & -\frac{1}{T_r} \end{bmatrix} \tag{7}$$

$$B = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{8}$$

Where, $T_s = \frac{L_s}{R_s}$ - stator time constant,

$T_r = \frac{L_r}{R_r}$ - rotor time constant,

$\sigma = 1 - \frac{L_m^2}{L_s L_r}$ - leakage coefficient.

Following the performed calculations, the mathematical model of the rotor flux estimator "VI" becomes,

$$\frac{d\hat{\Psi}_{rd}}{dt} = \frac{L_r}{L_m} u_{sd} - \frac{L_r}{L_m} R_s i_{sd} + \frac{L_m^2 - L_s L_r}{L_m} \frac{di_{sd}}{dt} \tag{9}$$

$$\frac{d\hat{\Psi}_{rq}}{dt} = \frac{L_r}{L_m} u_{sq} - \frac{L_r}{L_m} R_s i_{sq} + \frac{L_m^2 - L_s L_r}{L_m} \frac{di_{sq}}{dt} \tag{10}$$

Where, $\hat{\Psi}_{rd}$ and $\hat{\Psi}_{rq}$ - d and q-axis estimated rotor linkage fluxes.

From the mathematical model (9) and (10) we can see the dependence of the "VI" estimator on all the main parameters of the asynchronous motor, except for the rotor resistance. However, the involvement of the stator resistance in the mathematical model of the flux estimator may lead to errors in the estimation of the rotor flux. Being a temperature-dependent parameter, correction filters are used in practical applications to compensate for errors in the estimation of the rotor flux. Fig.1 shows the "VI" estimator, where the stator currents are in the derivative form in relation to time and also the internal reaction term is missing.

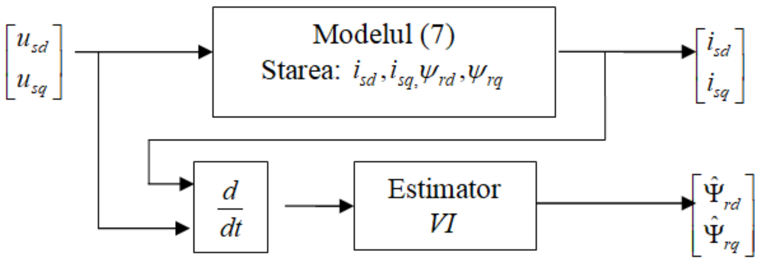


Figure 1. “VI” Estimator

Simulation results

The purpose of testing in the Matlab/Simulink simulation environment is to evaluate the performance and robustness of an advanced control method for induction motor. Specifically, the aim is to validate the operation of the indirect vector control, with rotor flux orientation, implemented in sensorless mode, with closed circuit current control, [7].

The objectives of the simulation are: checking the stability of the flux estimation in various operating regimes, including load and speed variations; closed loop current control validation; the dynamic response of the induction motor to speed and load control under different operating conditions. All these tests were done on a three-phase induction motor, with known parameters, Table1.

Table 1. The three-phase induction motor parameters

Parameter	**Value**
p	2
J	0,04 [kgm^2]
R_s	2,71[Ω]
R_r	3,53[Ω]
L_s	0,268[Ω]
L_r	0,274[Ω]
L_m	0,265[Ω]

The general block diagram of this paper can be structured to reflect the main functional components of the control system, Fig.2.

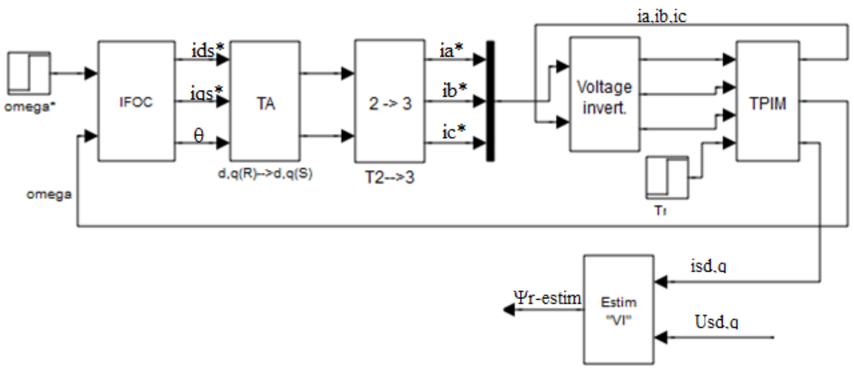


Figure 2. The block diagram of the control system

In the "IFOC" control block, the two components that produce the electromagnetic torque (active quantities) are decoupled by orthogonality from the quantities that produce the magnetization flux (reactive quantities), (12) and (13). This block has no information about the flux, but its value is imposed by the system design through a flux generator and also in this block its position is determined in relation to the fixed stator system θ_e (11), Fig.3.

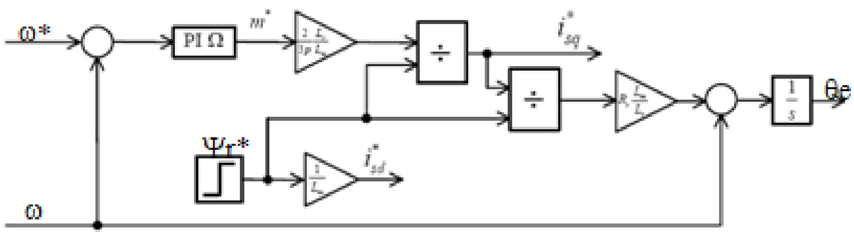


Figure 3. The block "IFOC" using rotor flux and torque to produce command currents

$$\theta_e = \int \left(\omega_r + \frac{R_r L_m}{L_r} \frac{i_{sq}^*}{\Psi_r^*} \right) dt \tag{11}$$

$$i_{sd}^* = \frac{1}{L_m} \Psi_r^* \tag{12}$$

$$i_{sq}^* = \frac{2}{3p} \frac{L_r}{L_m} \frac{1}{\Psi_r^*} m* \tag{13}$$

The "TA" block performs the coordinate transformation of the stator electric current from the mobile rotor system to the fixed stator system, using the position θ_e, determined in the command block.

The "TPIM" asynchronous motor is fed from a time-modulated, current-controlled voltage inverter. In this specific case, a bang-bang control is used for the motor currents. At the entrances of the block “Voltage Invert.” the prescribed instantaneous values of the currents on the three phases and the measured values of the currents must be applied. When the actual current deviates from the prescribed current, the bang-bang control rapidly turns on and off the transistors in the inverter to correct this error, resulting in a rapid variation of the voltage applied to the motor. Thus, this type of inverter generates phase voltages applied to the motor through closed-loop current control, ensuring accurate performance and rapid adaptation to dynamic load requirements.

The "Estim VI" rotor flux estimator block, Fig.4, has as inputs the stator quantities on the two orthogonal axes d-q of the electric voltages and currents. The output is an estimated value of the rotor flux, under the conditions of sensorless system operation.

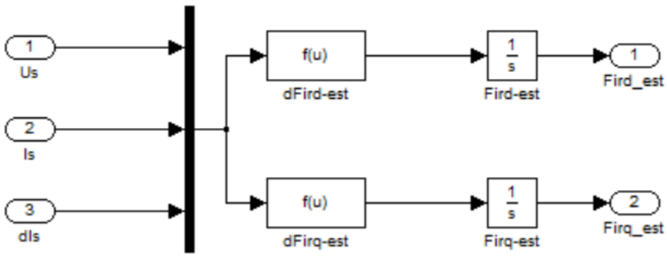
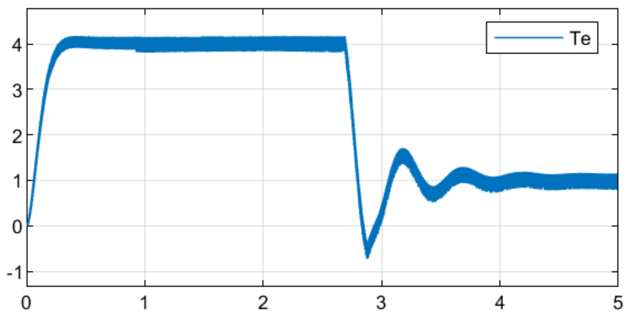


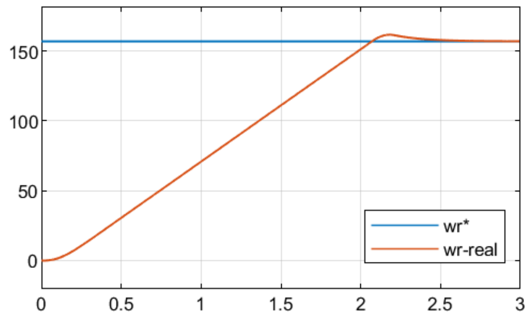
Figure 4. Rotor flux estimator block "VI"

To carry out the simulations, it was considered that the induction motor starts at idle, and after $t = 0{,}5s$ a load torque is applied $T_L = 1Nm$. In the evaluation of the performance of the system operation, the prescribed values of the speed and the rotor flux are made through a step type signal. The interpretation of the graphs regarding the variation of the speed and the estimated rotor flux are important for understanding the performances of the indirect vector control system, in a sensorless system. The three analyzed scenarios assume variations of stator resistance (R_s), rotor resistance (R_r) and supply frequency (f), respectively their impact on the magnetic and mechanical characteristics.

With the prescribed values of the asynchronous motor from Table 1, the mechanical characteristics of Fig. 5 were initially obtained and the magnetic characteristic from Fig. 6, in transitory regime. It can be seen that both the speed and the estimated rotor flux converge towards the imposed reference value, $\omega_r^* = 157 rad/sec$ and $\psi_r^* = 0{,}8Wb$.



a) electromagnetic torque



b) rotor speed

Figure 5. Mechanical characteristics of the asynchronous motor

Stator resistance (R_s) plays a critical role in maintaining stability of rotor speed and estimated rotor flux in an indirect vector control system. Its value influences both the accuracy of rotor flux estimation and the overall system performance. After performing several simulations in which the value of R_s changed by (+-50%) from the prescribed value, $R_s = 1{,}35\Omega; R_s = 4{,}06\Omega$, it was found that the system can maintain the stability of the rotor speed, its characteristic not being influenced, Fig.5. Also, the voltage drop across R_s of the "VI" estimator is correctly compensated, so that the estimated rotor flux is constant and its variations are minimal, Fig.6.

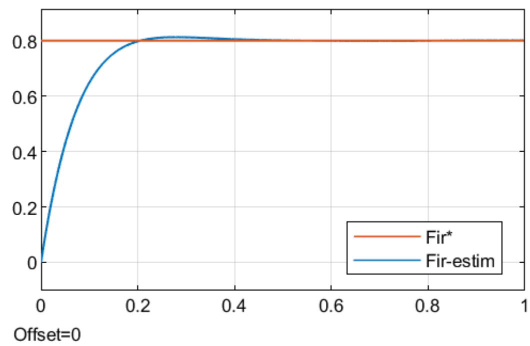


Figure 6. Characteristic of the estimated rotor flux

Rotor resistance (R_r) is an essential parameter in induction motor operation, having a significant impact on torque, speed characteristic and accuracy of rotor flux estimation. In an indirect vector control system, R_r is used in the calculation of synchronous speed and rotor flux orientation. If the value of R_r changes by ($\pm$50%) of the prescribed value, ($R_r = 1{,}77\Omega$; $R_r = 5{,}3\Omega$), the characteristic from Fig.7 and Fig.8 are obtained. Thus, for a lower value ($R_r = 1{,}77\Omega$), the motor shows a faster response of the rotor speed, in transient mode. If the resistance value is higher, $(R_r = 5{,}3\Omega)$, then the system response is slower, Fig.7.

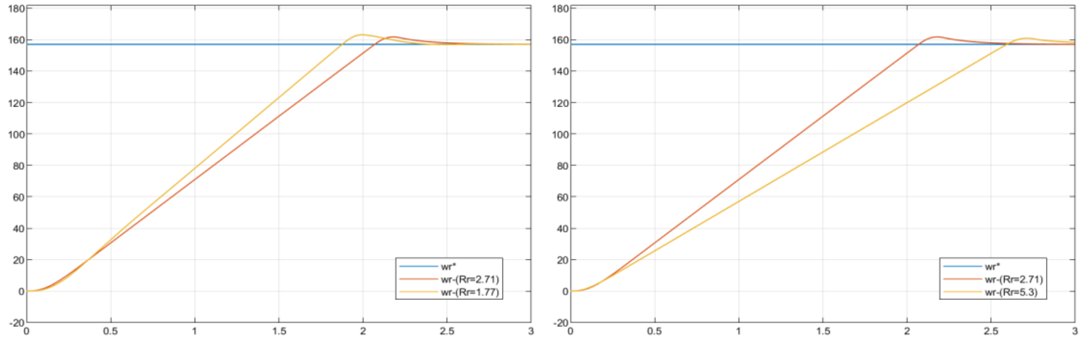


Figure 7. Rotor speed characteristics for $R_r = 1{,}77\Omega; R_r = 5{,}3\Omega$

The changes made on the rotor resistance have a negative impact on the rotor flux characteristics, Fig.8, observing the instability of the system.

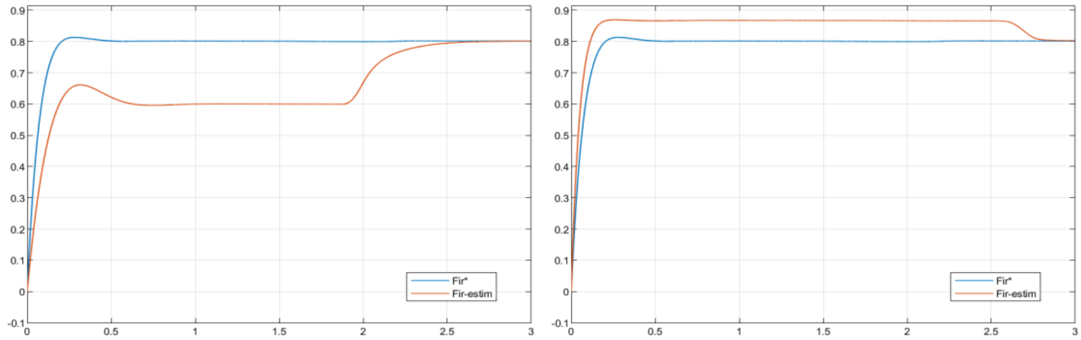


Figure 8. Rotor flux characteristics for $R_r = 1{,}77\Omega; R_r = 5{,}3\Omega$

Another parameter for which the system stability is checked is the frequency, $(f = 10Hz; f = 60Hz)$, respectively the reference applied to the rotor speed, $(\omega_r^* = 2\pi f\ rad/s)$. From Fig. 9 it can be seen that the rotor speed characteristics converge towards the estimated value, the faster the lower the frequency. The influence of frequency on the characteristic of the estimated rotor flux can be seen in Fig. 10, where the instability of the system is visible for high frequencies. At low frequencies the graph remains unchanged, Fig. 6.

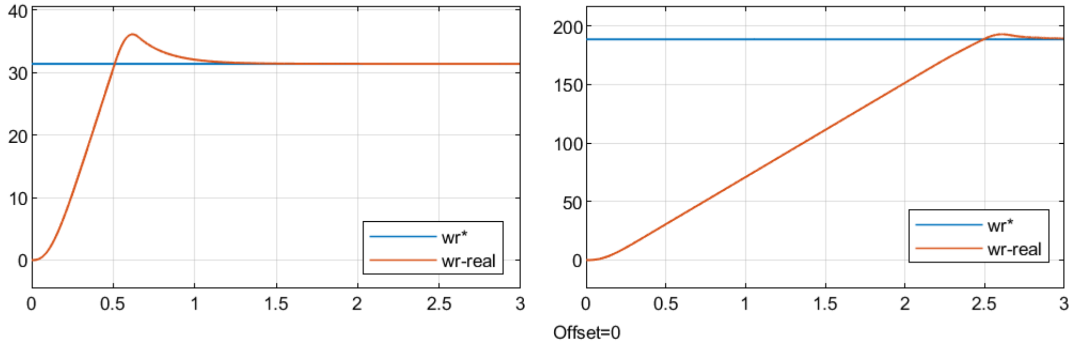


Figure 9. Rotor speed characteristics for $f = 10Hz; f = 60Hz$

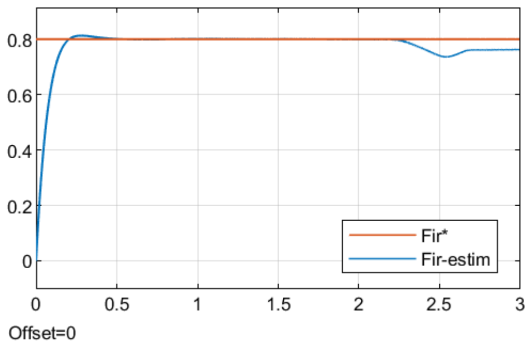


Figure 10. Rotor rotor flux characteristics for $f = 10Hz; f = 60Hz$

Conclusions

The paper highlighted the advantages and challenges of implementing indirect vector control of sensorless induction motors with emphasis on parameter variation, the use of a rotor flux estimator and overall system performance.

The variation of the parameters, especially the rotor resistance, can affect the accuracy of the flux and torque separation. It has been observed that significant parameter variations reduce the performance of the IFOC algorithm, highlighting the need for a robust model or real-time adaptation method.

The rotor flux estimator based on the volt-ampere (VI) integration technique has demonstrated the ability to provide accurate estimates under normal operating conditions. It is also relatively simple to implement and is used in applications where flux sensors are not available, but indirect control of the induction motor is required.

IFOC has proven to be an effective solution, providing accurate motor control even in the absence of sensors. Simulations have shown that the method provides good dynamic performance, but practical implementation requires additional compensations for the effects of parameter variation.

By integrating closed-loop current control, fast and robust system regulation was achieved, demonstrating the applicability of this solution in demanding industrial environments with high performance and reliability requirements.

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