"Modeling and Control of Induction Motor Using Indirect Field-Oriented Control (IFOC) with PWM-Based Voltage Source Inverter"

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ABSTRACT

This thesis presents the modeling and control of an induction motor drive using the Indirect Field-Oriented Control (IFOC) strategy. The proposed system employs a decoupled control structure, allowing independent regulation of torque and flux components through dq-axis transformation. A closed-loop control scheme is developed, consisting of an outer speed loop and inner current control loops, implemented using PI controllers. The reference voltages are generated in the synchronous reference frame and applied to the motor through a PWM-based voltage source inverter. The proposed approach ensures fast dynamic response, precise speed regulation, and reliable operation, making it well suited for application in AC electric locomotive traction systems.

Keywords: Voltage source inverter, traction systems, induction motors, (PWM) pulse width modulation

Introduction

Induction motors are widely used in modern AC electric locomotives due to their robustness, high efficiency, and low maintenance requirements. In railway traction systems, they are essential for providing high starting torque, reliable operation, and efficient performance over a wide speed range. However, induction motors are nonlinear systems with strong coupling between torque and flux, making precise control challenging. Conventional control methods such as V/f control are simple but suffer from poor dynamic performance and limited accuracy, especially under rapidly changing load conditions typical in traction applications. [1]

To address these limitations, advanced control techniques such as Field-Oriented Control (FOC) have been developed. In particular, Indirect Field-Oriented Control (IFOC) enables independent control of torque and flux by transforming motor variables into a rotating dq reference frame. This approach provides fast dynamic response and accurate speed control, which are critical for AC locomotive drives. [2-3]

This thesis focuses on the modeling and control of an induction motor using the IFOC method. The system is implemented in MATLAB/Simulink and includes speed and current control loops, coordinate transformations, and a PWM-based inverter. The proposed control strategy aims to achieve high-performance operation suitable for electric traction systems.

CONTROL STRUCTURE AND WORKING PRINCIPLE OF INDIRECT FIELD-ORIENTED CONTROL (IFOC)

An induction motor drive based on the Indirect Field-Oriented Control (IFOC) system consists of an outer speed control loop and inner current control loops, enabling decoupled control of torque and flux. The reference speed is compared with the measured rotor speed to generate a speed error, which is processed by a PI controller to produce the reference torque current i_q^*. The flux-producing current reference i_d^* is provided separately, allowing independent regulation of the rotor flux. The measured stator currents are transformed from the three-phase (abc) system into the stationary αβ frame using Clarke transformation, and then into the rotating dq frame using Park transformation. These dq currents are compared with their respective reference values, and the errors are processed through PI controllers to generate voltage commands v_d^* and v_q^*.The voltage references are then converted back to the three-phase system using inverse Park transformation and applied to the PWM-based voltage source inverter, which drives the induction motor. Fig.1

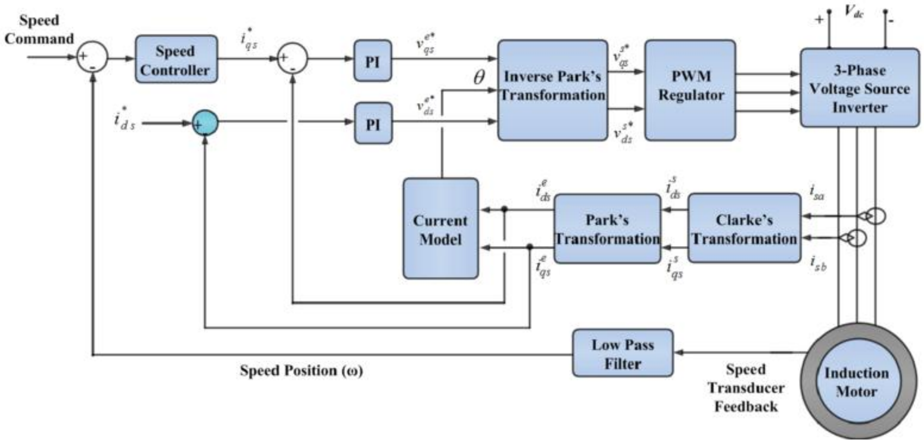

Fig. 1 Block Diagram of Indirect Field-Oriented Control (IFOC) System for Induction Motor Drive

The rotor flux angle θ, required for coordinate transformations, is obtained indirectly through slip frequency calculation, making the system an indirect field-oriented control scheme. Feedback signals including motor currents and rotor speed are used to ensure closed-loop operation and high dynamic performance. Fig.2

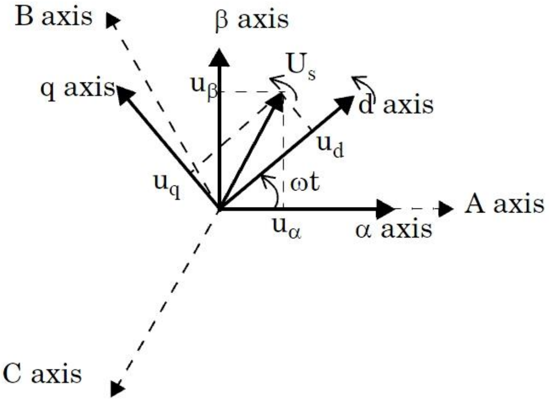

Fig. 2 Clarke Transformation (abc → αβ)

The Clarke transformation converts three-phase (abc) quantities into a two-axis stationary reference frame (αβ). This transformation reduces system complexity and serves as an intermediate step for Park transformation in vector control systems. Fig.3

$$\begin{bmatrix} \vartheta_\alpha \\ \vartheta_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \vartheta_a^* \\ \vartheta_b^* \\ \vartheta_c^* \end{bmatrix} \tag{1}$$

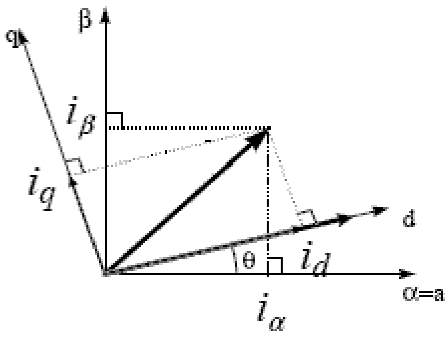

Fig.3 Park Transformation (αβ → dq)

The Park transformation can be interpreted as a rotation of the stationary αβ reference frame by an angle θ, resulting in a synchronously rotating dq frame aligned with the rotor flux. This geometric interpretation simplifies the understanding of decoupled control in induction motor drives.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (2)$$

θ_e— electrical angle

In indirect field-oriented control (IFOC), the rotor flux angle θ is not measured directly but estimated through electrical angular speed.

The electrical speed is obtained as the sum of rotor mechanical speed and slip speed.

$$\omega_e = \frac{d\theta_e}{dt} \qquad (3)$$

$$\omega_e = \omega_r + \omega_{slip} \qquad (4)$$

The slip speed is calculated based on the torque-producing current and rotor flux. The rotor flux angle is then obtained by integrating the electrical angular speed. This estimated angle is used in the Park transformation to align the rotating reference frame with the rotor flux, enabling decoupled control of torque and flux.[5]

Matlab/Simulink Implementation Of Ifoc

The Simulink implementation of the Indirect Field-Oriented Control (IFOC) system are given. It includes speed, flux, and torque control loops, along with Clarke and Park transformations for converting currents into the dq reference frame. A flux observer and angle estimator provide the required rotor flux and electrical angle for control. The system generates voltage references for PWM-based inverter operation, ensuring decoupled control of torque and flux. Fig.4

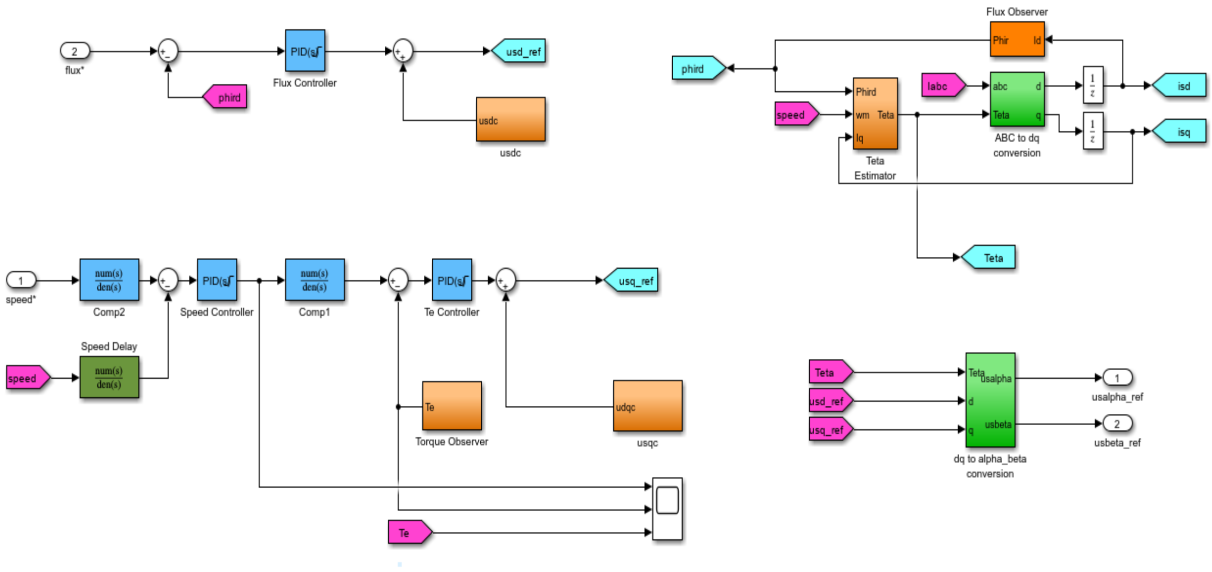

Fig. 4 Simulink Implementation of IFOC for Induction Motor

Results And Discussion

The simulation results demonstrate the dynamic performance of the induction motor drive under the Indirect Field-Oriented Control (IFOC) strategy. The obtained waveforms include stator voltage, stator currents, rotor speed, and electromagnetic torque. Fig.5

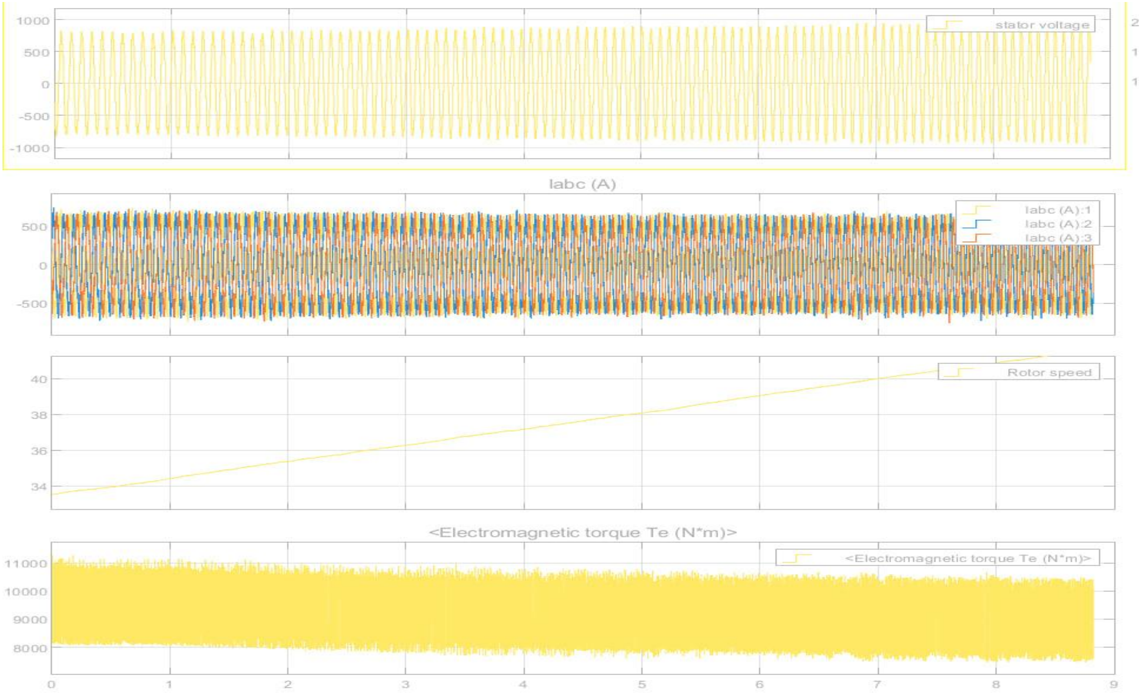

Fig. 5 Simulation Results of Induction Motor under IFOC Control

From the results, it can be observed that as the rotor speed increases, the stator voltage also increases proportionally. At the initial stage, the stator voltage is approximately 91.4 V and continues to rise with speed until it reaches the rated value of about 2150 V. This behavior corresponds to the constant V/f control region. Beyond this point, in the field weakening region, the stator voltage remains nearly constant despite further increase in speed.The stator current behavior also confirms proper operation of the control system. At the starting condition, the stator current reaches approximately 510 A, providing high starting torque required for traction applications. As the motor approaches nominal operation, the current decreases to around 390 A. At maximum speed, the current slightly increases and stabilizes at approximately 410 A, indicating effective torque control in the field weakening region.[6-7]

Furthermore, the stator current frequency increases proportionally with speed. Starting from near zero frequency, it rises continuously and reaches the nominal frequency of 46 Hz, and further increases up to approximately 86 Hz at maximum speed. This confirms that the inverter correctly adjusts the supply frequency according to the speed demand.The rotor speed curve shows a smooth and stable increase without oscillations, indicating good dynamic response and proper tuning of the control system. The electromagnetic torque remains within the expected range and does not exhibit significant instability, demonstrating effective decoupling of torque and flux.

Overall, the results confirm that the implemented IFOC strategy provides stable operation, accurate speed tracking, and efficient control of the induction motor over a wide speed range, including both constant torque and field weakening regions. These characteristics make the system highly suitable for AC electric locomotive applications.

Conclusion

This thesis investigated the modeling and control of an induction motor using the Indirect Field-Oriented Control (IFOC) strategy. The dq-based mathematical model enabled decoupled control of torque and flux, and the complete control system was implemented in MATLAB/Simulink. The simulation results demonstrate that the stator voltage increases with speed up to its rated value and remains constant in the field-weakening region. The stator current decreases from its initial value and stabilizes at higher speeds, while the rotor frequency increases proportionally with speed. The rotor speed accurately tracks the reference value, and the electromagnetic torque remains stable throughout operation.

The results obtained in this study confirm the effectiveness of the Indirect Field-Oriented Control (IFOC) method for controlling an induction traction motor. The proposed approach ensures fast dynamic response, precise speed regulation, and reliable operation, making it well suited for application in AC electric locomotive traction systems.

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