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Modeling and simulation of scalar and vector control strategies for industrial induction motor applications

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Abstract

This study addresses the challenge of selecting an effective control strategy for induction motor drives to achieve optimal performance under varying operating conditions. Although induction motors are widely used in industrial applications due to their efficiency and durability, there remains a gap in understanding the comparative performance of scalar control and field-oriented control (FOC), particularly in terms of dynamic response and steady-state operation across different speeds and load conditions. To bridge this gap, the study employed MATLAB/Simulink to model and simulate both control techniques using standard industrial motor parameters. Scalar control was implemented using a constant voltage-to-frequency (V/f) ratio approach, while FOC was designed to decouple torque and flux components for enhanced motor control. The performance of both methods was evaluated under startup, transient, and varying load conditions. The findings revealed that scalar control offers a simple and reliable solution for steady-state and low-to-medium performance applications, although it experiences slower dynamic response and transient oscillations during startup. In contrast, FOC demonstrated faster stabilization, improved transient response, and more precise control during dynamic load changes, making it more suitable for high-performance industrial applications. The study therefore provides valuable insight into the strengths and limitations of each control strategy, assisting engineers in selecting the most appropriate method for specific induction motor drive applications.

Keywords: Control Strategy; Induction Motor drives; Load conditions; Model; Dynamic Load changes

1. Introduction

Induction motors are commonly used in industries because they are strong, dependable, and affordable. These motors play a key role in sectors like manufacturing, automotive, and processing by powering equipment such as pumps, conveyors, compressors, and machine tools. As noted in [1], about 90% of industrial applications worldwide rely on induction motors due to their efficiency and ability to work well in various conditions.

However, controlling induction motors is not always easy because of their complex and non-linear behavior. Basic control methods like scalar control (also called Voltage/Frequency control) are simple and cost-effective, making them suitable for general uses like fans, compressors, and blowers [1]. But these methods are not ideal for tasks that need precise control of speed and torque, as scalar control cannot separate the control of torque and flux, leading to poor performance in demanding situations.

To address these challenges, advanced methods such as Field-Oriented Control were introduced. Vector control allows separate control of torque and flux, resulting in quicker and more precise responses. This makes it perfect for applications like robotics, electric vehicles, and machine tools [2]. By transforming the motor's three-phase currents into a two-axis system, it enhances motor performance and enables control like that of a conventional DC motor.

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2. Review of related literature

2.1. Theoretical Background of Induction Motor Drive Systems

Induction motors are widely used in industrial applications because of their durability, reliability, low cost, and efficiency. They operate based on the principle of electromagnetic induction introduced by Michael Faraday. An induction motor mainly consists of a stator and a rotor. When a three-phase AC supply is applied to the stator windings, a rotating magnetic field is produced, creating induced current and torque in the rotor [3]. The motor operates below synchronous speed due to slip, which is necessary for torque production [4].

Induction motors are valued for their good speed regulation, high starting torque, robustness, and low maintenance requirements. They are commonly applied in conveyor systems, compressors, HVAC systems, and industrial machinery [1]. However, they may experience lower power factors and reduced efficiency under light loads, which has encouraged the development of advanced control methods such as vector control [5].

2.2. Types of Induction Motors

The two major types of induction motors are squirrel cage induction motors and wound rotor induction motors. Squirrel cage induction motors are the most common due to their simple construction, low cost, durability, and minimal maintenance requirements [8]. They are highly efficient and widely used in pumps, fans, compressors, and conveyors [14]. However, they have limited speed control capability and relatively lower starting torque compared to wound rotor motors [12], [13].

Wound rotor induction motors use rotor windings connected to external resistors through slip rings, allowing improved speed control and higher starting torque [16]. These motors are suitable for cranes, hoists, conveyors, and applications requiring variable speed operation [17]. Despite their advantages, they are more expensive, less efficient, and require greater maintenance due to the use of brushes and slip rings [19].

2.3. Control Techniques for Induction Motor Drives

Several control techniques are used to improve the performance of induction motor drives. The major methods include Scalar (V/f) Control, Vector or Field-Oriented Control (FOC), and Direct Torque Control (DTC). Scalar control, also known as Volts-per-Hertz (V/f) control, maintains a constant ratio between voltage and frequency to preserve magnetic flux [21]. It is simple, cost-effective, and widely used in applications such as pumps, fans, and blowers where precise speed control is not essential [23]. However, scalar control has limitations, including poor dynamic response, low accuracy, and weak load regulation [20]. Vector control, also referred to as Field-Oriented Control (FOC), is a more advanced technique that independently controls torque and flux components of the motor [25]. Using Clarke and Park transformations, the motor currents are transformed into rotating reference frames for precise control [1]. FOC provides fast dynamic response, smooth low-speed operation, and high efficiency, making it suitable for electric vehicles, robotics, and CNC machines [26], [27], [29]. The two major forms of vector control are Direct Vector Control (DVC) and Indirect Vector Control (IVC), both designed to improve motor performance under varying operating conditions [11]. Direct Torque Control (DTC) is another advanced control technique that directly regulates torque and flux without complex coordinate transformations. It offers rapid torque response and high efficiency, though it may introduce torque ripple during operation.

2.4. Power Electronics Controllers in Motor Drives

Power electronics controllers play an important role in induction motor drives by regulating voltage and frequency supplied to the motor. Inverters convert DC power into AC power with adjustable frequency and voltage for motor speed control [1]. Voltage Source Inverters (VSIs) are commonly used because of their efficiency and ease of control [33]. Converters, including rectifiers and DC-DC converters, are also used to regulate power flow within motor drive systems [34]. Modern power electronics improve energy efficiency, reduce losses, and enhance motor performance in industrial applications [35].

2.5. Related Studies on Induction Motor Control

Several researchers have proposed advanced control techniques for improving induction motor performance. Zhang et al. (2018) investigated adaptive robust control strategies for induction motors under parameter uncertainties and load disturbances [36]. Their study showed improved speed tracking and system stability, although the method involved complex algorithms and parameter tuning requirements. Ghosh et al. (2020) explored Model Predictive Control (MPC) for induction motor drives [37]. The study demonstrated that MPC improved dynamic response and operational flexibility by predicting future motor behavior and adjusting control actions accordingly. Li et al. (2015) proposed the use of first-order Auto-Disturbance Rejection Controllers (ADRCs) for induction motor speed control [38]. Their findings revealed improved robustness against disturbances and reduced computational complexity compared to conventional proportional-integral (PI) controllers. However, the study noted that some ADRC approaches still involve computational challenges in real-time implementation [38].

Overall, the reviewed literature shows that advanced control methods such as FOC, MPC, and ADRC significantly improve induction motor performance compared to traditional scalar control, particularly in applications requiring high precision, fast response, and efficient operation.

3. Methodology

The first step in modeling an induction motor is transforming the three-phase voltages into a two-phase system. This is done using Clarke's and Park's transformations. Under unbalanced conditions, the three-phase voltages V_a, V_b, and V_c can be expressed as [41]:

$$V_a = \sqrt{2}V_{rms}sin(\omega t) \quad (6)$$

$$V_b = \sqrt{2}V_{rms}sin\left(\omega t - \frac{2\pi}{3}\right) \quad (7)$$

$$V_c = \sqrt{2}V_{rms}sin\left(\omega t + \frac{2\pi}{3}\right) \quad (8)$$

V_a V_b and V_c are then converted to $\alpha - \beta$ (stationary reference) frame using Clarke's transformation [41]:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \quad (9)$$

The park's transformation converts the stationary $\alpha - \beta$ quantities into a rotating d-q frame [41]:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix}\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \quad (10)$$

Also, for the three-phase current instantaneous value of the stator and rotor can be calculated into a two-phase system using Clarke's and Park's transformations [41].

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (11)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (12)$$

In the d-q reference frame, the stator and rotor windings are aligned along two perpendicular axes: the d-axis and the q-axis. This alignment eliminates mutual magnetic coupling between the windings, meaning there is no flux linkage between them [42]. Each winding's flux linkage depends on its own current and the current of the other winding on the same axis. Focusing on the d-axis of the stator, we see that the flux linkage includes both the magnetizing flux and leakage flux, both of which result from the winding's own current, denoted as i_d [42]. Additionally, due to the rotor current in the winding on same axis (noted as i_{rd}), only the magnetizing flux links to the stator winding, as no leakage flux crosses the air gap between them. Applying this logic leads to the following flux equations for the induction motor model [42].

For the stator windings:

$$\varphi_{sd} = L_s i_{sd} + L_m i_{rd} \quad (13)$$

$$\varphi_{sq} = L_s i_{sq} + L_m i_{rq} \tag{14}$$

Rotor windings:

$$\varphi_{rd} = L_r i_{rd} + L_m i_{sd} \tag{15}$$

$$\varphi_{rq} = L_r i_{rq} + L_m i_{sq} \tag{16}$$

Where $L_s = L_{ls} + L_m$ for the stator winding,

While $L_r = L_{lr} + L_m$ for the rotor winding.

The equations for the stator and rotor voltages are derived from basic electromagnetic principles applied to the motor's windings in the d-q frame. For example, the stator voltage equation follows Faraday's law, which states that the voltage v induced in a conductor equals the rate of change of magnetic flux linkage φ over time [41]:

$$v = Ri + \frac{d\varphi}{dt} \tag{17}$$

Where:
v represent the voltage across the winding
R is the resistance of the winding
i represents the current through the winding
φ is the magnetic flux linkage.

By applying faraday's law to the stator's d-axis, the stator d-axis winding in the d-q frame:

Therefore, the d-axis stator-voltage is:

$$v_{sd} = R_s i_{sd} + \frac{d\varphi_{sd}}{dt} \tag{18}$$

Where:
v_{sd} represents d-axis stator-voltage
R_s represents stator winding resistance
i_{sd} represents the d-axis stator-current, and
φ_{sd} represents d-axis component of the stator flux linkage.

Since the d-q reference frame rotates at a certain angular velocity ω an additional term is introduced to account for the effect of this rotation on the stator flux linkage. The change in the flux linkage in a rotating reference frame introduces a voltage proportional to the angular velocity ω and the flux linkage on the q-axis φ_{sq}:

$$V_{induced} = -\omega_e \varphi_{sq} \tag{19}$$

Where $V_{induced}$ is induce voltage

Combining these terms gives the final equation for the d-axis stator voltage. The voltage equations for the rotor and stator in the d-q frame are given in equation [41].

3.1. Field Oriented Control (FOC)

Field-Oriented Control (FOC) for induction machines assumes that the flux linkage phasor (φ_r) position of the rotor is known. This phasor is oriented at an angle θ_f from the stationary reference frame,

Where θ_f is the field angle.

Using this information, the stator currents are transformed into q and d axes in the synchronous reference frame through a mathematical transformation.

$$\begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} cos\theta_f & \cos\left(\theta_f - \frac{2\pi}{3}\right) & \cos\left(\theta_f + \frac{2\pi}{3}\right) \\ sin\theta_f & \sin\left(\theta_f - \frac{2\pi}{3}\right) & \sin\left(\theta_f + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} \tag{45}$$

Where the stator current phasor i_s is gotten as

$$i_s = \sqrt{\left(i_{qs}\right)^2 + (i_{ds})^2} \tag{46}$$

Where the stator phase angle is $\theta_s = tan^{-1}\left(\frac{i_{qs}}{i_{ds}}\right)$

The stator current contributes to generating both the rotor flux (φ_r) and torque (T_e). To produce rotor flux effectively, the current component responsible for flux generation must align with φ_r [1].

By breaking down the stator current phasor along φ_r, the flux-producing component can be identified. Meanwhile, the component perpendicular to this alignment generates torque [21]. Therefore:

$$\varphi_r \propto i_f \tag{47}$$

$$T_e \propto \varphi_r \cdot i_T \propto i_f \cdot i_T \tag{48}$$

In steady-state conditions, these flux and torque components remain constant (DC), as their relative speed with respect to the rotor field is zero [45]. Aligning φ_r with the synchronous reference frame ensures these components become DC values, making them ideal for control purposes [40].

To achieve this, the rotor flux position must be continuously determined. The field angle θ_f is calculated as:

$$\theta_f = \theta_{sl} + \theta_r \tag{49}$$

Where θ_r is the rotor position and θ_{sl} is the slip angle [26]. Alternatively, it can be derived in terms of time and speed:

$$\theta_f = \int \omega_s dt = \int (\omega_r + \omega_{sl}) dt \tag{50}$$

FOC relies on determining the rotor flux position at each instant, which divides them into indirect vector control and direct vector control methods. In direct vector control, the field angle is obtained through terminal voltages, currents, Hall sensors, or flux-sensing windings [46]. Indirect vector control (IVC) estimates the rotor flux position based on rotor position and machine parameters, eliminating the need for external measurements [35].

3.2. Derivation of Indirect FOC for Induction Motor

To derive indirect FOC, we assume a current source inverter, where the stator phase currents are inputs, allowing stator dynamics to be ignored [47]. The dynamic equations for the induction motor in the synchronous reference frame, with rotor flux as the state variable, are defined by [41]:

$$R_r i_{qr} + p\varphi_{qr} + \omega_{sl}\varphi_{dr} = 0 \tag{51}$$

$$R_r i_{dr} + p\varphi_{dr} - \omega_{sl}\varphi_{qr} = 0 \tag{52}$$

Where p is $\frac{d}{dt}$

Where the slip speed ω_{sl} is defined as [45]:

$$\omega_{sl} = \omega_s - \omega_r \tag{53}$$

The rotor flux linkages along the q and d axes are expressed as [41]:

$$\varphi_{qr} = L_r i_{qr} + L_m i_{qs} \tag{54}$$

$$\varphi_{dr} = L_r i_{dr} + L_m i_{ds} \tag{55}$$

Where L_r represents the rotor inductance, L_m represent the mutual inductance.

To simplify the analysis, the rotor flux phasor φ_r is aligned with the d axis. This alignment reduces the complexity of the setting [40]:

$$\varphi_r = \varphi_{dr} \tag{56}$$

$$\varphi_{qr} = 0 \tag{57}$$

$$p\varphi_{qr} = 0 \tag{58}$$

Substituting equations (55) to (57) into (51) and (52), we derive the simplified rotor equations [41]:

$$R_r i_{qr} + \omega_{sl}\varphi_r = 0 \tag{59}$$

$$R_r i_{dr} + p\varphi_r = 0 \tag{60}$$

From equation (54) and (55), the rotor currents are determined as [41]

$$i_{qr} = -\frac{L_m}{L_r} i_{qs} \tag{61}$$

$$i_{dr} = -\frac{L_m}{L_r} i_{qs} + \frac{\varphi_r}{L_r} \tag{62}$$

Substituting the values of i_{qr} and i_{dr} from the equations (61) and (62) into equations (59) and (60), we obtain [40]:

$$\omega_{sl} = \frac{R_r}{L_r}\left(\frac{L_m}{L_r} i_{qs}\right) \tag{63}$$

And from equation (50):

$$\omega_{sl}\varphi_r = -R_r i_{qr} \tag{64}$$

Here:

$$i_T = i_{qs} \tag{65}$$

$$i_f = i_{ds} \tag{66}$$

The rotor time constant T_r is given by:

$$T_r = \frac{L_r}{R_r} \tag{67}$$

Using these rotor currents, the torque expression is derived as [41]:

$$T_e = \frac{3}{4}\frac{P}{L_r}\varphi_r i_{qs} \tag{68}$$

This equation (68) demonstrates that torque is proportional to the product of rotor flux linkage and the q-axis stator current, like the air gap torque in DC motors. When rotor flux linkage (φ_r) is constant, torque directly depends on the torque-producing stator current component (i_{qs}) [40]. This transforms the induction motor's control model into an equivalent separately excited DC motor [40].

3.3. Implementation of Power Electronics Controllers for Variable Speed Drive Systems

Power electronics controllers are critical for ensuring the efficient and precise operation of Variable Speed Drive (VSD) systems. They control motor speed, torque, and efficiency by converting electrical energy and regulating its delivery to the motor. A typical VSD system consists of three main components: a rectifier, a DC link, and an inverter. The rectifier converts the AC supply to DC, while the DC link stabilizes the voltage, and the inverter transforms the DC into variable-frequency AC to control the motor speed [41]. In this project, the focus is on the inverter, particularly the Voltage Source Inverter (VSI) configured with Pulse Width Modulation (PWM) techniques. The inverter adjusts the amplitude and frequency of the AC voltage, allowing for precise motor control [49]. In contrast, Field-Oriented Control (FOC), enhances performance by decoupling the motor's flux and torque components, allowing separate control of these variables. This results in improving dynamic performance and efficiency, especially under varying loads. The inverter generates synchronized three-phase voltage waveforms aligned with the rotor flux, ensuring accurate speed and torque regulation even during rapid changes in load [39]. To enhance the system's performance, the inverter's switching sequences are optimized to reduce losses and minimize electromagnetic interference. Simulation using MATLAB/Simulink allows for detailed analysis of these controls. Such simulations validate their ability to improve motor performance while identifying potential challenges, such as harmonic distortion or thermal stress in components. The use of d-q transformations in these simulations simplify the control strategy by representing the motor's dynamic behavior in a stationary reference frame [20].

4. Results

This research explores the control and application of an induction motor drive system using MATLAB/Simulink. Induction motors are popular in many applications because of their simple design, durability, and affordability. However, ensuring they operate efficiently requires precise regulation of key parameters such as speed, current, and torque. To achieve optimal performance, effective control is crucial.

The study involves simulating two widely used control methods: vector and scalar control. Scalar control regulates the motor by managing the magnitude of voltage and frequency, making it suitable for basic applications. However, for more demanding and high-performance scenarios, vector control is preferred.

Vector control (FOC) works by aligning the stator current with the rotor's magnetic field. This alignment enables the independent regulation of two critical components: torque and flux. By decoupling these components, vector control provides superior control over motor speed and torque. Its ability to respond quickly and maintain precision makes it ideal for advanced applications requiring high performance and efficiency.

4.1. Simulation Results of FOC of Induction Motor Drive

This simulation employs Field-Oriented Control (FOC) to manage an induction motor drive. A detailed model was developed using MATLAB/Simulink, building upon a pre-existing demo model available in the Simulink library. Modifications were made to tailor the model to the specific needs of this research. The FOC technique makes it possible to independently regulate the torque and flux of the motor, enabling accurate and dynamic operation—a feature that is very advantageous in high-performance applications. To create the simulation, a model block from the Simulink library was selected and adjusted to include custom parameters and control logic, as illustrated in Figure 8 [50]. These modifications ensured that the model aligned with the objectives of this study. The simulation outcomes highlight the motor's dynamic response, torque regulation, and speed stability when operated under the FOC method.

4.2. Simulation studies of Scalar Control for Induction Motor Drive

This simulation examines scalar control for an induction motor drive using a modified MATLAB/Simulink model based on the Simulink library [50]. Scalar control maintains a constant voltage-to-frequency ratio, ensuring stable motor flux and smooth operation, making it suitable for moderate performance needs [1]. The base model was customized with specific parameters and control algorithms for this study.

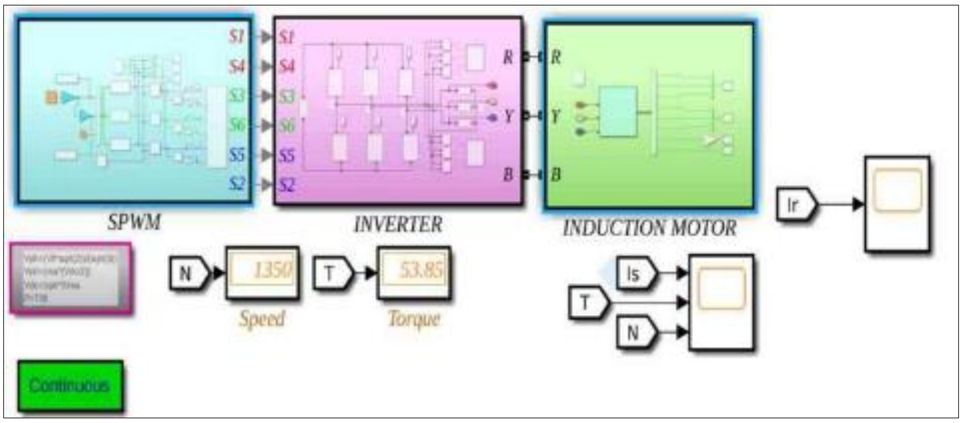

Figure 1 Scalar Control of induction motor [50]

4.3. Stator Current

The stator current simulation in figure 2 shows distinct characteristics during motor operation. Initially, there is a high-amplitude oscillation in the current waveform across all three phases, which gradually stabilizes within 0.2 seconds. This transient behavior during the acceleration phase is expected due to the rapid changes in motor speed and the corresponding demand for current. Once stabilized, the currents exhibit a balanced sinusoidal waveform with constant amplitude, indicating steady-state operation under load. The initial oscillations are caused by the motor's response to starting-torque requirements and control system dynamics. The steady sinusoidal waveform shows a well-functioning scalar control system, as it maintains balanced phase currents with minimal distortion. However, the slight variations in waveform amplitude could indicate small harmonic components or control imperfections. These ripples might affect efficiency or performance in applications requiring precise current control.

4.4. Electromagnetic Torque

The torque simulation reveals an initial spike reaching 160 Nm, followed by oscillations that stabilize at 60 Nm within 0.1 seconds, indicating effective damping and control. This transient behavior is typical during motor startup due to current surges or control loop adjustments. The steady-state torque demonstrates consistent performance with minimal ripples, likely caused by harmonics, inverter switching, or feedback noise. The quick stabilization shows the effectiveness of the scalar control strategy. Overall, the motor exhibits excellent responsiveness, stability, and reliability.

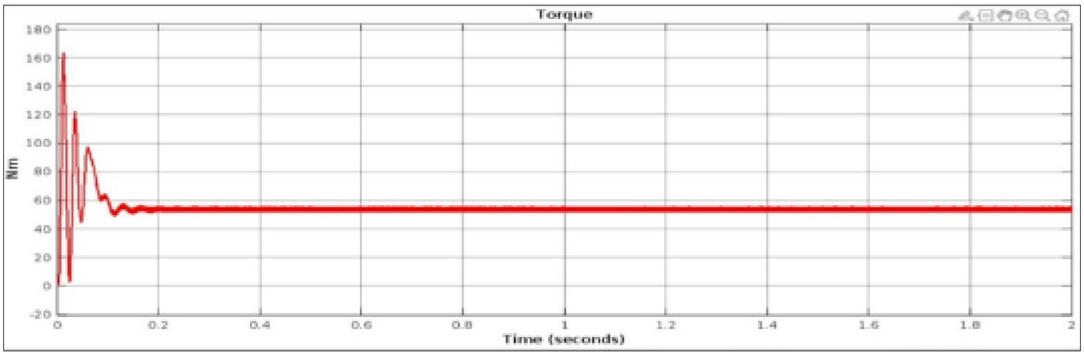

Figure 2 Electromagnetic torque waveform result

4.5. Rotor speed

The speed simulation (figure 3) shows the motor accelerating smoothly to a steady 1400 RPM within 0.3 seconds, with minimal overshoot and rapid stabilization. Minor oscillations during the initial ramp are quickly damped, indicating effective transient handling by the scalar control. Once a steady state is reached, the speed remains constant with no noticeable fluctuations, demonstrating excellent stability and reliable operation under load conditions. This suggests the control system effectively compensates for varying torque. The smooth acceleration and stable speed highlight the system's strong performance, though further tuning could reduce the brief oscillations during startup.

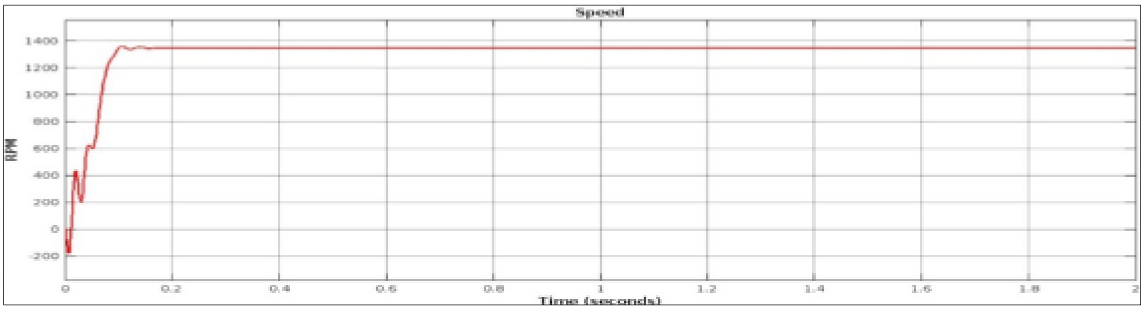

Figure 3 Rotor speed result waveform

5. Conclusion

This research analyzed scalar control and field-oriented control (FOC) methods for induction motors, focusing on their performance under different operational conditions. Scalar control proved effective in maintaining stable operation in steady-state conditions, particularly for applications with low-performance requirements. However, it showed slower dynamic response and transient oscillations during startup. In contrast, FOC exhibited superior performance in dynamic conditions, offering precise control over torque and flux with faster stabilization of rotor speed and currents. The results demonstrate that FOC is better suited for high-performance applications requiring accurate and efficient motor control .

This study contributes to the field of motor control systems by providing a comparative analysis of scalar and field-oriented control methods. It highlights the importance of advanced control techniques like FOC in improving motor efficiency, reducing current distortion, and ensuring smooth dynamic responses. These insights are valuable for researchers and engineers working on modern motor drives for industrial applications. Additionally, the research serves as a reference for selecting appropriate control methods based on specific application needs.

Future Research Prospects

Future research in the field of induction motor drives can focus on several key areas to enhance performance and applicability. One promising direction is the hardware implementation of Field-Oriented Control (FOC). While simulations have validated their effectiveness, experimental testing on real motors could reveal practical challenges such as noise, switching losses, and thermal effects, enabling further optimization of the control strategy.

Another area is the integration of advanced control techniques like Model Predictive Control (MPC) or Artificial Neural Networks (ANNs). These methods can dynamically adapt to changing load conditions and motor parameter variations, offering improved accuracy and robustness compared to traditional FOC. Additionally, incorporating energy-efficient algorithms to reduce power consumption and minimize losses could align motor drives with modern sustainability goals.

Finally, combining motor drives with IoT and AI technologies can allow for real-time monitoring, predictive maintenance, and automated adjustment of control settings, enhancing reliability and reducing downtime in industrial applications. Future research can also explore the use of more advanced simulation tools to model real-world complexities more accurately, bridging the gap between simulation and hardware performance.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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