MODELING AND SIMULATION OF AN INDUCTION MOTOR

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Abstract

Due to their affordability, dependability, and longevity, induction motors are among the most widely used motors. The induction motor is modeled and simulated within a stationary reference frame using the qd0 transformation theory. The motor's dynamic activity is captured by the differential equations of the system. MATLAB/SIMULINK is used to carry out simulations, which concentrate on important motor output parameters as phase current, motor speed, and electromagnetic torque. The benefits of applying the qd0 transformation theory to motor modeling are amply illustrated by the simulation results.

Keywords: *Dynamic modeling, induction machine, stationary reference frame, MATLAB/SIMULINK*

I. INTRODUCTION

Since their creation, asynchronous motors, especially those with squirrel-cage rotors—have become much more common. Numerous industrial applications, robotics, home appliances (particularly single-phase motors), and related sectors use these motors as actuators [1]. Their straightforward design, sturdy construction, affordability, great efficiency, dependability, and exceptional self-starting ability are the primary reasons for their rising popularity [2].

Analysis of induction motors is usually carried out in a steady-state, treating the motor as a second-order electromechanical system [3]. The motor's steady-state and transient behavior are both described by the dynamic model. Including the application of scalar control techniques, this model is helpful for simulating asynchronous motor drives and assessing their transient performance [4]. Additionally, it facilitates the creation of sophisticated asynchronous motor drive control techniques including direct torque control (DTC) and vector control [5].

The motor may draw excessive currents, generate oscillatory torques, induce voltage dips, and even create harmonics in the power system during startup or other operating situations. Predicting these occurrences requires precise modeling of the asynchronous motor [6]. A few models have been created, but the d-q axis model has been extensively tested and shown to be accurate and dependable for examining transient behavior [7].

Although there are three often used reference frame speeds, it has been shown that the d and q axes' speeds can vary [8]:

a. The d and q axes stay stationary in the stationary qd0 reference.
b. Rotor reference frame, in which the d and q axes move in tandem with the rotor's speed.
c. The synchronously rotating reference frame, where the d and q axes rotate at synchronous speed.

For studying multi-machine systems and performing stability analysis in controller design, it is typically best to linearize the motor output equations around an operating point within the synchronously rotating reference frame [9]. In this reference frame, steady-state variables remain constant and do not oscillate over time. This paper discusses the induction machine model within the stationary reference frame, as well as the impact of varying mechanical loads on the motor's output variables [10].

II. INDUCTION MACHINE MODEL IN qd0 STATIONARY REFERENCE FRAME

Induction machine loads and other power system components are commonly simulated in the synchronously rotating reference frame of the system for power system analysis [11]. However, simulating the induction machine and its related converter in a fixed reference frame is more practical for transient analysis involving variable-speed drives [12]. The equations for the machine in the stationary reference frame may be obtained by either using ejωte^ {j\omega t}ejωt for the relevant variables [13], [14] or by setting the reference frame speed, ω\omegaω, to zero. An extra superscript, "s" for variables in the stationary frame and "e" for those in the synchronously rotating frame, is used to distinguish between the variables in the stationary and synchronously revolving reference frames [15]. These frames' corresponding circuit representations are displayed in Fig. 1.

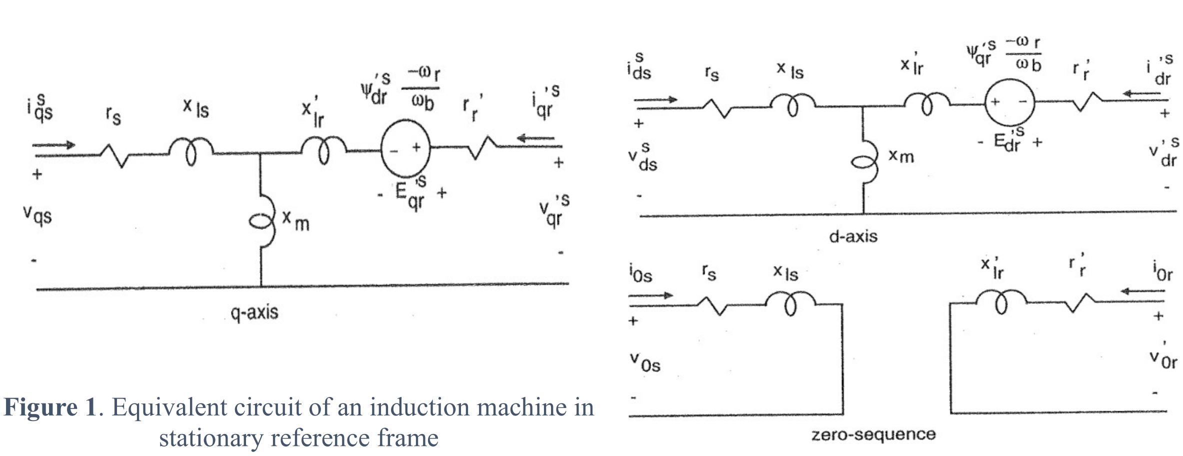

Figure 1. Equivalent circuit of an induction machine in stationary reference frame

III. SIMULINK IMPLEMENTATION

The model equations of the three-phase induction machine are rearranged in the following form for the simulation:

Equations in the Stationary Reference Frame
These equations represent the variation of magnetic linkage and current in the stationary axis:

$$\psi qs^{s} = \omega b \int \left(vqs^{s} + \left(\frac{rs}{xls}\right)(\psi mq^{s} - \psi qs^{s})\right) dt \quad (1)$$

$$\psi ds^{s} = \omega b \int \left(vds^{s} + \left(\frac{rs}{xls}\right)(\psi md^{s} - \psi ds^{s})\right) dt \quad (2)$$

$$i0s = \left(\frac{\omega b}{xls}\right) \int (v0s - i0s \cdot rs) dt \quad (3)$$

Equations in the Rotor Reference Frame
These equations model the components in a coordinate system that moves with the rotor.

$$\psi qr'^{s} = \omega b \int \left(vqr'^{s} + \left(\frac{\omega r}{\omega b}\right) \cdot \psi dr'^{s} + \left(\frac{rr'}{xlr'}\right)(\psi mq^{s} - \psi qr'^{s})\right) dt \quad (4)$$

$$\psi dr'^{s} = \omega b \int \left(vdr'^{s} - \left(\frac{\omega r}{\omega b}\right) \cdot \psi qr'^{s} + \left(\frac{rr'}{xlr'}\right)(\psi md' - \psi dr'^{s})\right) dt \quad (5)$$

$$i0r' = \left(\frac{\omega b}{xlr'}\right) \int (v0r' - i0r' \cdot rr') dt \quad (6)$$

Magnetic Linkages (Flux Linkage)
Flux linkages are expressions that describe the interaction of currents in the stator and rotor through magnetic coupling.

$$\psi mq^{s} = xm \left(iqs^{s} + iqr'^{s} \right) \quad (7)$$

$$\psi md^{s} = xm \left(ids^{s} + idr'^{s} \right) \quad (8)$$

$$\psi qs^{s} = xls \cdot iqs^{s} + \psi mq^{s} \quad (9)$$

Implying that,

$$i^{s}_{(qs)} = \frac{\left(\psi^{s}_{(qs)} - \psi^{s}_{(mq)}\right)}{X_{(ls)}} \quad (10)$$

$$\psi^{s}_{(ds)} = X_{\left(\{ls\} i^{s}_{\{ds\}}\right)} + \psi^{s}_{(md)} \quad (11)$$

Implying that,

$$i^s_{(ds)} = \frac{\left(\psi^s_{(ds)} - \psi^s_{(md)}\right)}{X_{(ls)}}$$

$$\psi^s_{(qr)} \ = \ X'_{(lr)} \, i'^s_{(qr)} \ + \ \psi^s_{(mq)} \tag{12}$$

Implying that,

$$i'^s_{(qr)} \ = \ \left(\psi'^s_{\{qr\}}\right) - \frac{\psi^s_{(mq)}}{X'_{(lr)}}$$

Implying that,

$$i'^s_{(qr)} \ = \ \left(\psi'^s_{(qr)}\right) - \frac{\psi^s_{\{mq\}}}{X'_{\{lr\}}}$$

$$\psi'^s_{(dr)} \ = \ X'_{(lr)} \, i'^s_{(dr)} \ + \ \psi^s_{(md)}$$

Implying that,

$$i'^s_{(dr)} \ = \ \left(\psi'^s_{(dr)}\right) - \frac{\psi^s_{(md)}}{X'_{(lr)}} \tag{13}$$

Implying that,

$$i'^s_{(dr)} \ = \ \left(\psi'^s_{(dr)}\right) - \frac{\psi^s_{(md)}}{X'_{(lr)}}$$

Where,

$$\frac{1}{X_M} = \frac{1}{X_m} + \frac{1}{X_{(ls)}} + \frac{1}{X'_{(lr)}} \tag{14}$$

$$\psi^s_{(mq)} \ = \ X_M \left(\left(\frac{\psi^s_{(qs)}}{X_{(ls)}} \right) + \frac{\left(\psi'^s_{(qr)}\right)}{X'_{\{lr\}}} \right) \tag{15}$$

And

$$\psi^s_{(md)} \ = \ X_M \left(\left(\frac{\psi^s_{(ds)}}{X_{(ls)}} \right) + \frac{\left(\psi'^s_{(dr)}\right)}{X'_{(lr)}} \right) \tag{16}$$

The torque equation is:

$$T_{em} = \frac{3}{2}\frac{p}{2\omega_b}\left(\psi_{ds}^s i_{qs}^s - \psi_{qs}^s i_{ds}^s\right) \tag{17}$$

Rotor motion equation

$$J\frac{d\omega_r}{dt} = T_{em} + T_{mech} - T_{damp} \tag{18}$$

IV. DESCRIPTION OF PARAMETERS AND CALCULATIONS

The following parameters are used for the dynamic modeling and analysis of an induction machine:

- **Rr = 0.39 Ω** — Rotor resistance
- **Rs = 0.19 Ω** — Stator resistance
- **Lls = 0.21 mH** — Stator leakage inductance
- **Llr = 0.6 mH** — Rotor leakage inductance
- **Lm = 4 mH** — Magnetizing inductance
- **fb = 100 Hz** — Base (or nominal) frequency
- **p = 4** — Number of poles
- **J = 0.0226 kg·m²** — Moment of inertia of the rotor

Using these parameters, the following calculations are performed:

- **Lr = Llr + Lm**

  This represents the total rotor inductance, combining rotor leakage and magnetizing inductances.

- **Tr = Lr / Rr**

  This is the rotor time constant, calculated by dividing the total rotor inductance by the rotor resistance.

- **wb = 2 × π × fb**

The base angular frequency in radians per second, corresponding to the base electrical frequency.

- **Xls = wb × Lls**

The stator leakage reactance, calculated by multiplying the base angular frequency by the stator leakage inductance.

- **Xlr = wb × Llr**

The rotor leakage reactance, similarly calculated with the rotor leakage inductance.

- **Xm = wb × Lm**
-

The magnetizing reactance computed using the magnetizing inductance.

- **Xm*** (denoted as Xmstar)

The combined magnetizing reactance is calculated from the parallel combination of the stator leakage reactance, the magnetizing reactance, and the rotor leakage reactance using the formula:

$$X_m^* = \frac{1}{\frac{1}{X_{ls}} + \frac{1}{X_m} + \frac{1}{X_{lr}}}$$

These parameters and derived values are fundamental for simulating the dynamic and steady-state behavior of an induction machine in vector control or dynamic analysis.

ASYNCHRONOUS PARAMETERS

LR	0.0046
TR	0.0118
WB	628.3185
XLS	0.1319
XLR	0.3770
XMSTAR	0.0941

V. DESCRIPTION OF THE ASYNCHRONOUS MACHINE SIMULATION MODEL (SIMULINK)

This block diagram represents a simulation model of a three-phase asynchronous machine in MATLAB Simulink. The system is designed to analyze the performance of the motor under specific input conditions.

Inputs:

- Three-Phase Supply (Faz A, Faz B, Faz C):
  - These inputs simulate a balanced three-phase power supply.
  - Parameters: 380V, 120° phase difference, 1 Hz frequency.
- Synchronous Frequency:
  - A constant value of 100 is provided to represent the synchronous speed of the rotating magnetic field (in rad/s or RPM, depending on the setup).
- Rotor Speed Reference (TI):
  - A constant value of 100 is fed into the asynchronous machine model to define the desired or actual speed of the rotor.

Core Block:

- Model of Asynchronous Machine:
  - This block simulates the dynamic behavior of the asynchronous motor.
  - Inputs: Phase voltages (vao, vbo, vco), excitation frequency (we), and rotor speed (TI).
  - Outputs:
    - ia, ib, ic: Phase currents.
    - Te: Electrical torque produced by the motor.
    - wr: Rotor speed output.

Signal Processing & Visualization:

- Current Graph:
  - Phase currents are grouped using a MUX block and plotted.
- Electrical Torque:
  - Output torque (Te) is displayed using a numeric display (value shown: 101).
- Rotor Speed:
  - Rotor speed (wr) is displayed (value shown: 194.8).
- Graphs:

- Input Voltage Graph: Shows input voltages to the motor.
- WR & WE: Displays both rotor speed and excitation frequency.
- TE & TI: Displays electrical torque and input speed reference.

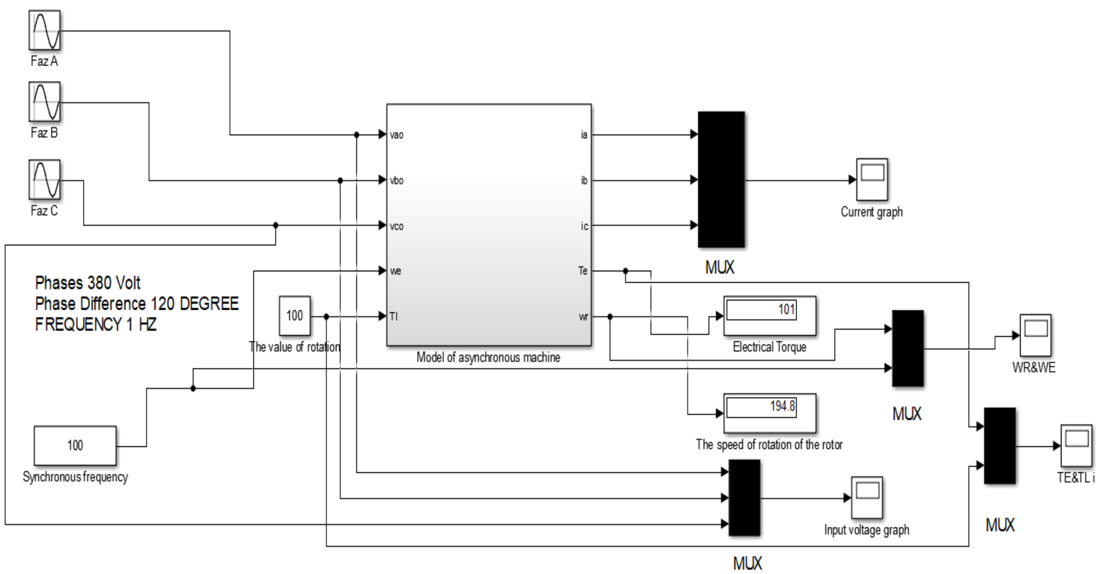

Figure 2. Simulation model of a three-phase asynchronous machine in MATLAB Simulink

Description of Voltage Transformation from ABC to DQ Reference Frame (Simulink)

This Simulink model performs the transformation of three-phase voltages from the **ABC reference frame** (stationary frame) to the **DQ reference frame** (rotating frame), which is commonly used in vector control of electric machines.

Inputs:

- **van, vbn, vcn** (Input voltages):
  - These are the three-phase voltages applied to the stator, coming from the power supply or inverter.
  - They are grouped using a **MUX block**.
- **cos(θ - e)** and **sin(θ - e)**:
  - These represent the cosine and sine of the angle difference between the rotor electrical angle and a reference angle.
  - They are used for coordinate transformation (Park Transformation).

Transformation Process:

1. **Gain Block:**
    - Multiplies the 3-phase voltages by a constant matrix:
    - This step transforms the voltages from the **ABC** frame to **αβ (alpha-beta)** stationary frame.
    - The output is two components: vqs and vds (in αβ frame).
2. **DE-MUX Block:**
    - Splits the αβ voltages into two separate signals: vqs and vds.
3. **Park Transformation:**
    - The αβ voltages are then transformed into DQ voltages using the following equations:
        - $vds = v\alpha \cdot co\,s(\theta - e) + v\beta \cdot si\,n(\theta - e)\, v_{ds} = v_{\alpha} \cdot \cos(\theta - e) + v_{\beta} \cdot \sin(\theta - e)\, vds = v\alpha \cdot cos(\theta - e) + v\beta \cdot sin(\theta - e)$
        - $vqs = -v\alpha \cdot si\,n(\theta - e) + v\beta \cdot co\,s(\theta - e)\, v_{qs} = -v_{\alpha} \cdot \sin(\theta - e) + v_{\beta} \cdot \cos(\theta - e)\, vqs = -v\alpha \cdot sin(\theta - e) + v\beta \cdot cos(\theta - e)$
    - This is implemented using four **Product blocks** and two **Sum blocks**.

Outputs:

- **vds**, **vqs**:
    - These are the direct and quadrature axis voltages in the rotating DQ frame.
    - Output at ports labeled 1 (vds) and 2 (vqs).

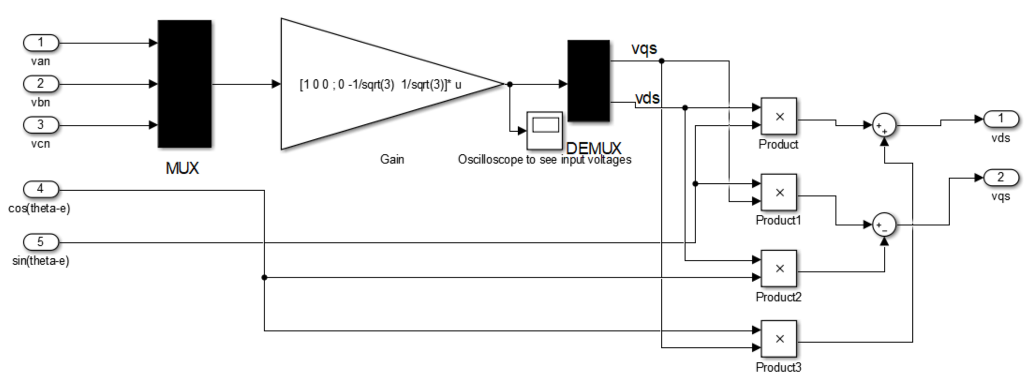

Figure 3. Description of Voltage Transformation from ABC to DQ Reference Frame (Simulink)

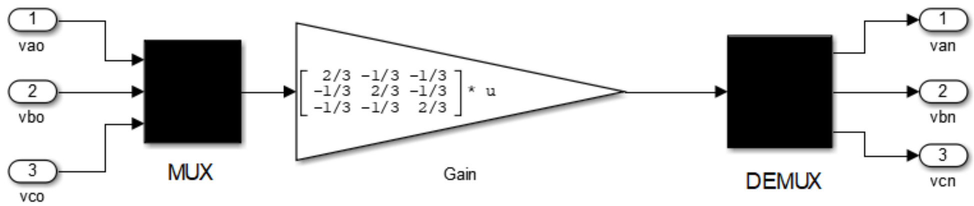

Figure 4. Description of Zero-Sequence Voltage Elimination (Line-to-Neutral Conversion)

This is a **Simulink block diagram**, and it appears to represent a **vector control (field-oriented control)** model of an **induction motor** or similar AC machine. Here's a breakdown of the key components and signals:

Inputs (Left Side):

1. **vqs** – Quadrature-axis stator voltage
2. **vds** – Direct-axis stator voltage
3. **we** – Electrical angular speed
4. **Tl** – Load torque

Functional Blocks:

Each block performs specific electromagnetic or transformation calculations:

- **Fqs, Fds, Fqr, Fdr** – Flux linkage blocks for quadrature/direct axes, stator and rotor sides.
- **Fmq, Fmd** – Magnetizing inductance or flux coupling blocks (mutual flux computations).
- **Te block** – Calculates electromagnetic torque using
- **wr block** – Calculates rotor speed ωr\omega_rωr based on load torque

Outputs (Right Side):

1. **Te** – Electromagnetic torque
2. **iqs** – Stator quadrature-axis current
3. **ids** – Stator direct-axis current
4. **iqr** – Rotor quadrature-axis current
5. **idr** – Rotor direct-axis current
6. **wr** – Rotor angular speed

Coupling & Feedback:

The model has multiple feedback loops:

- Currents (iqs, ids, iqr, idr) are fed back into flux models.
- Rotor speed (wr) is fed back into the flux computation of the rotor.
- The mechanical dynamics block at the bottom calculates wr using Te and Tl.

Possible Use Case:

This structure is typical for:

- **Simulation of vector control algorithms**
- **Dynamic modeling of AC induction machines**
- **Validation of control strategies using field-oriented control (FOC)** in Simulink

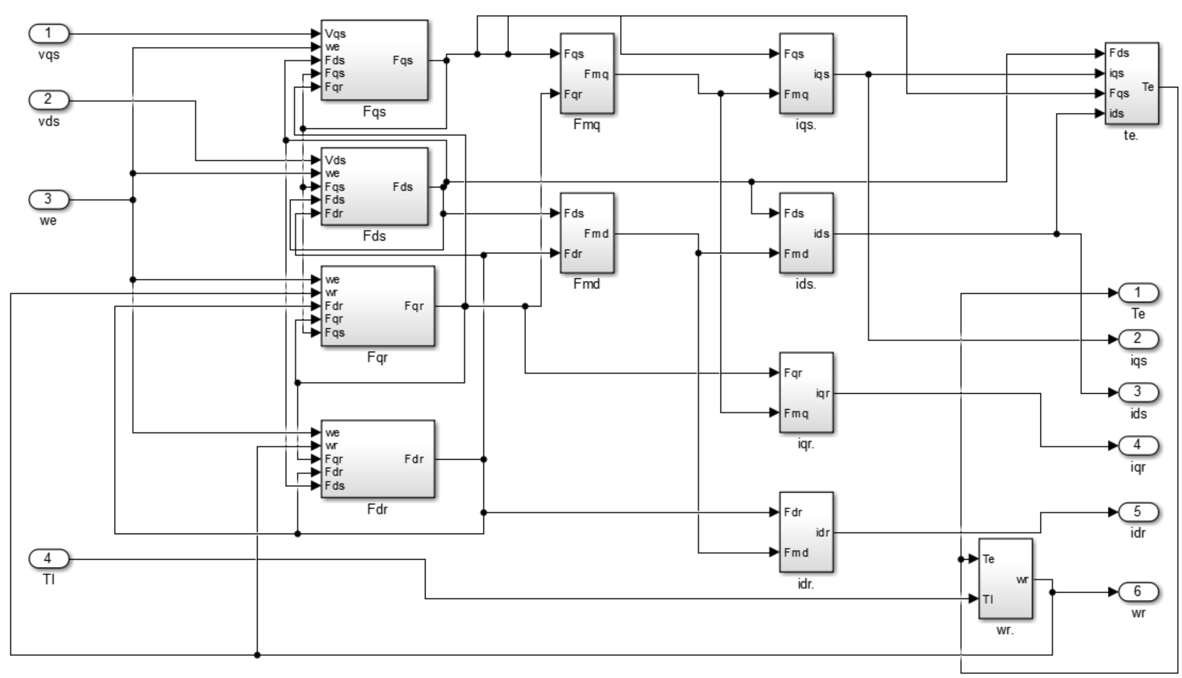

Figure 5. Vector control (field-oriented control)

VI. RESULTS

Figure 6. Current Graph

Description of the Current Graph:

The image shows a Simulink scope output representing a three-phase current waveform over a simulation time of 10 seconds. The graph likely corresponds to the stator currents of a three-phase induction motor or a similar AC machine in a balanced condition.

Key Observations:

- Waveform Type: Sinusoidal, indicating proper operation of the motor under steady-state conditions.
- Phases: There are three distinct curves (commonly colored blue, red, and yellow), each representing one of the three-phase currents: iai_aia, ibi_bib, and ici_cic.
- Phase Shift: The three waveforms are 120 degrees apart, confirming a balanced three-phase system.
- Amplitude: Peak values appear around ±600 A (amperes), with a transient spike near simulation start (at t=0t = 0t=0).
- Transient Response: At the beginning (0–0.5s), a short disturbance appears, likely due to startup transients or load change, before stabilizing into a steady sinusoidal regime.

- Simulation Time: The graph spans from 0 to 10 seconds as shown in the time axis (horizontal).

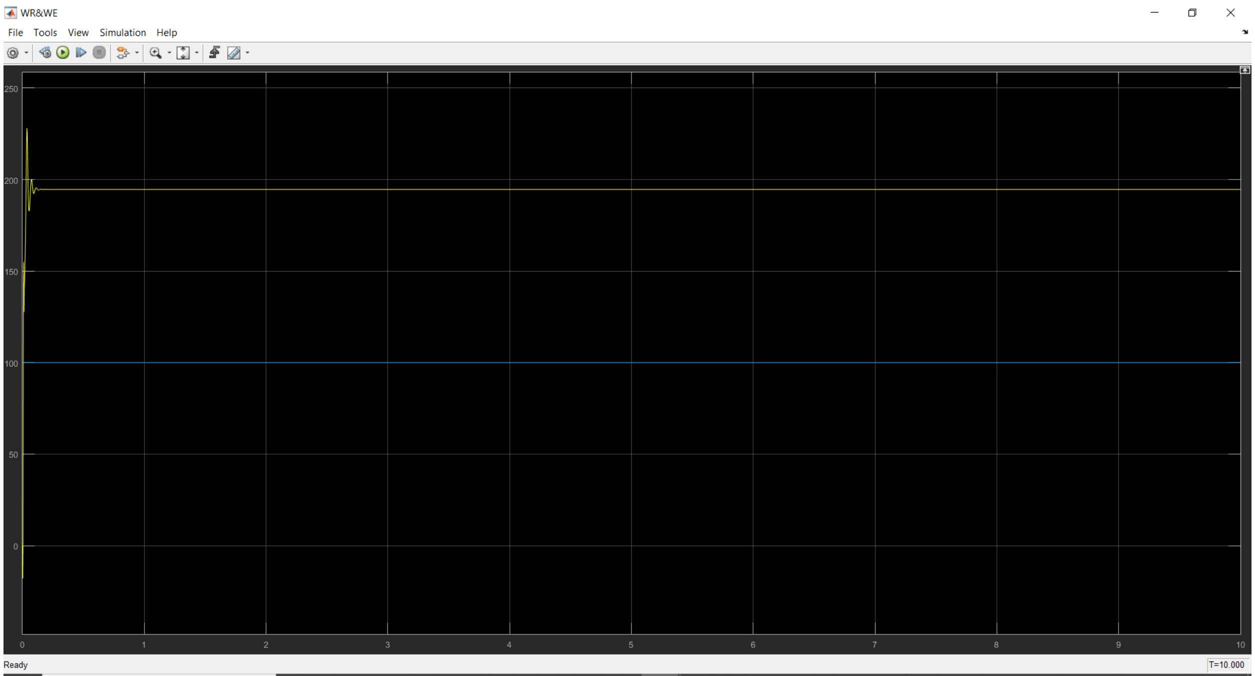

Figure 7. WR & WE Graph

WR & WE Graph Description

This Simulink scope output displays the behavior of two variables over time, likely:

- WR – Rotor speed
- WE – Electrical angular speed (synchronous speed)

Key Observations:

- X-Axis: Simulation time (0 to 10 seconds)
- Y-Axis: Speed in rad/s or rpm (not explicitly labeled, but typical for such simulations)
- Yellow Curve (WR):
    - Starts from 0 and rapidly increases.
    - Stabilizes around 200 units after a short transient (around 0.5s).
    - This is the rotor speed, indicating a successful speed ramp-up.
- Blue Curve (WE):
    - Remains constant throughout the simulation at 100 units.
    - Represents the synchronous speed, indicating a fixed frequency reference.

Interpretation:

This output suggests the operation of an induction motor under field-oriented control (FOC). Since the rotor speed (WR) converges and stabilizes around the synchronous speed (WE), this could imply:

- Stable control response
- No speed tracking error after startup
- Balanced torque load and control effort

Figure 8. TE & TL Graph

TE & TL Graph Description

This Simulink scope output appears to display the electromagnetic torque (Te) and the load torque (Tl) over time in an electric motor simulation.

Key Observations:

- X-Axis: Simulation time, from 0 to 10 seconds
- Y-Axis: Torque (likely in Nm, though units aren't explicitly stated)
- Yellow Curve (Te):
    - Starts with a transient oscillation (from 0 to ~1 second).
    - After the initial startup, it settles smoothly around 100 Nm.
    - This represents the electromagnetic torque produced by the motor.

Green Line (Tl):

  - Flat, constant throughout the simulation at approximately 100 Nm.
  - This is the load torque, implying a fixed mechanical load is applied to the motor shaft.

Interpretation:

- The system reaches a torque equilibrium
- This means the motor is producing just enough torque to balance the load torque — a sign of stable operation.
- The initial spike in Te is likely due to motor startup transients, which quickly settle into steady state.

Conclusion:

The motor:

- Starts up correctly;
- Compensation for the applied load;
- Reaches and maintains stable operating condition with no overshoot or instability after 1 second.

VII. CONCLUSION

This study provides in-depth dynamic modeling and simulation of a three-phase asynchronous (induction) motor using the qd0qd0qd0 transformation theory within a stationary reference frame. Induction motors are widely used in industrial, commercial, and domestic applications due to their robustness, low cost, ease of maintenance, and high efficiency. Modeling their behavior under various operating conditions is essential for the development and validation of control strategies. The mathematical model is derived from a set of differential equations representing the electrical and mechanical dynamics of the motor, including the interactions between flux linkages, stator and rotor currents, and electromagnetic torque generation. These equations are implemented in MATLAB/Simulink, which serves as the simulation environment to evaluate motor performance under realistic conditions. The model incorporates voltage transformations from the three-phase ABC frame into the two-axis DQ rotating reference frame using Park and Clarke transformations, enabling simplified analysis of machine variables.

The simulation setup includes key motor parameters such as stator and rotor resistances, leakage and magnetizing inductances, pole number, and mechanical inertia, from which other quantities like reactances, time constants, and base angular frequency are computed. The simulation inputs consist of balanced three-phase voltages and fixed reference values for rotor speed and synchronous frequency. The simulation results are presented in various graphical forms, including time-domain waveforms of stator currents, rotor and synchronous speeds, and the comparison between electromagnetic and load torque. The current stator waveforms exhibit expected sinusoidal characteristics with appropriate phase displacement, verifying balanced and stable motor operation. The rotor speed quickly ramps up to match the synchronous reference speed, indicating proper dynamic response and efficient control. Furthermore, the electromagnetic torque generated by the motor rapidly stabilizes and maintains equilibrium with the mechanical load torque, confirming accurate torque control and load compensation.

The model also effectively demonstrates the benefits of using the stationary reference frame, particularly for analyzing variable-speed drives and vector control implementations. The fixed reference frame simplifies the dynamic equations without losing accuracy, making it well-suited for both steady-state and transient analysis. Through the simulation results, the study validates the applicability of the qd0qd0qd0 transformation for representing motor dynamics and highlights the advantages of using MATLAB/Simulink for such high-fidelity simulations. In summary, this work not only illustrates the fundamental behavior of an induction machine but also lays the groundwork for implementing advanced control strategies such as direct torque control (DTC), field-oriented control (FOC), and other vector-based techniques. This modeling approach can be extended to more complex multi-machine systems and can serve as a powerful educational and research tool in the study of electric machines and power electronics.

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