DYNAMIC MODEL OF A THREE-PHASE ASYNCHRONOUS MOTOR USING MATLAB/SIMULINK

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Abstract
The purpose of this paper is to develop a generalized model using Matlab/Simulink program to study the dynamic behavior of a three-phase induction motor. Dynamic models are used to better understand the behavior of an induction motor in both transient and steady-state conditions. The dq axis transformation theory is applied in the rotor reference frame to study the dynamics of the motor. A model has been developed using the Matlab/Simulink software for dynamic modeling of a 4-pole induction motor with a power of 0.75 kW, power factor cosφ=0.76, efficiency η=73%, rated current I1=2.05 A. The developed model is used for research the influence of changes in stator resistance, moment of inertia and load torque. The results show that the torque characteristic curve and rotor speed of an induction motor depend on the rotor resistance and moment of inertia. All differential voltages, currents and magnetic fluxes between the stationary stator and the moving rotor are also modeled.

Keywords: Matlab/Simulink software, induction motor, dq transformation, modelling, current, torque, speed.

Introduction

In electrical machine theory, it is known that any multi-phase electrical machine with an n -phase stator winding and an m -phase rotor winding can be represented by a two-phase model. Therefore, the mathematical description of the processes in a rotating electrical machine is based on examining its two-phase model.

The voltage and torque equations describing the dynamic state of an asynchronous motor change over time. Solving these differential equations can involve some complexities. Dynamic modeling establishes all the mechanical equations for varying inertia, torque, and speed over time. It also models all differential voltages, currents, and magnetic fluxes between the stationary stator and the rotating rotor [1, 2].

Dynamic models (mathematical models) are used to better understand the operating modes of an asynchronous motor in transient and steady states. This mathematical model, created with MATLAB/Simulink, represents a three-phase asynchronous motor, including the transformation from a three-phase system to a d-q axis system (Figure 1). The main advantage of MATLAB/Simulink is that the modeling of electromechanical processes can be performed simply and quickly using the program's functional blocks [3].

Controlling three sinusoidal currents is a complex task, but there is no need to control all three currents. This task can be simplified using Clark (E. Clark) and Park (R. H. Park) transformations for stator currents. First, Clark transformation is used to convert the three-phase system to a two-phase system, and then Park transformation is used to convert to the rotor coordinate system [4].

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Clark transformation is intended to convert currents from a three-phase stationary coordinate system to a two-phase stationary coordinate system. Park transformation is intended to convert currents from a two-phase stationary coordinate system to a rotating coordinate system along the rotor flux vector, where variables are referred to the stationary current system. Park inverse transformation is intended to convert stationary currents from the rotating coordinate system to a two-phase stationary coordinate system [5].

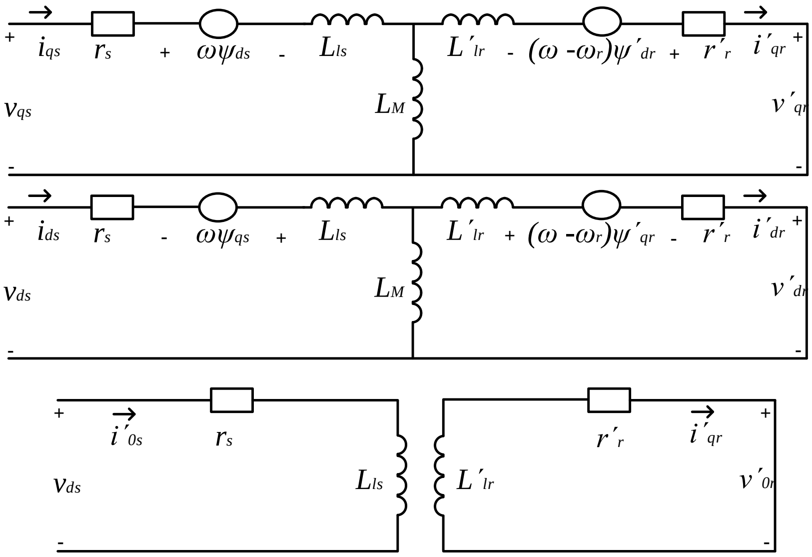

Figure 1. dq0 Transformation Scheme of an Asynchronous Motor

Thus, each individual equation among the model equations can be easily implemented in a single block, allowing all machine variables to be available for monitoring and verification purposes. In this study, the model of the asynchronous motor is brought into the stator and rotor variable coordinate systems for dynamic characteristic modeling using MATLAB/Simulink [6].

II. MODEL OF THE ASYNCHRONOUS MOTOR

The model equations can be derived from the dq0 transformation scheme of the asynchronous electrical motor shown in Figure 1. The current-related equations associated with this scheme can be obtained as follows [7, 8]:

$$\psi_{ds} = L_s\, i_{ds} + L_m\, i_{dr} \quad (1)$$

$$\psi_{qs} = L_s\, i_{qs} + L_m\, i_{qr} \quad (2)$$

$$\psi_{dr} = L_r\, i_{dr} + L_m\, i_{ds} \quad (3)$$

$$\psi_{qr} = L_r\, i_{qr} + L_m\, i_{qs} \quad (4)$$

Then, by substituting the values of the flux linkages, we can determine the currents:

$$i_{ds} = \frac{L_r}{D}\psi_{ds} - \frac{L_m}{D}\psi_{dr}\,; \quad (5)$$

$$i_{qs} = \frac{L_r}{D}\psi_{qs} - \frac{L_m}{D}\psi_{qr}\,; \quad (6)$$

$$i_{dr} = -\frac{L_m}{D}\psi_{ds} + \frac{L_s}{D}\psi_{dr}\,; \quad (7)$$

$$i_{qr} = -\frac{L_m}{D}\psi_{qs} + \frac{L_s}{D}\psi_{qr}\,; \quad (8)$$

Here

$$D = L_s\, L_r - L_m^2; \quad (9)$$

To find the voltages, we use the following formulas:

$$v_{ds} = R_s\, i_{ds} + p\psi_{ds} \tag{10}$$

$$v_{qs} = R_s\, i_{qr} + p\psi_{qr} \tag{11}$$

$$v_{dr} = R_r\, i_{dr} + p\psi_{dr} + \omega_m \psi_{qr} \tag{12}$$

$$v_{qr} = R_r\, i_{qr} + p\psi_{qr} + \omega_m \psi_{dr} \tag{13}$$

Based on the above equations, the torque and rotor speed can be determined as follows:

$$T_e = \frac{3}{2}\, p\, I_m \left(i_{qs}\, i_{dr} - i_{ds}\, i_{qr}\right) \tag{14}$$

$$\omega_r = \int \frac{P}{2J}(T_e - T_L) \tag{15}$$

Here, p- is the number of poles; J- the moment of inertia (kg/m²). For a squirrel-cage rotor asynchronous motor, the rotor voltages UqrU_{qr}Uqr and UdrU_{dr}Udr are zero in the magnetic flux equations, as the rotor bars are considered to be short-circuited. After calculating the torque and speed equations using the dq-axis currents and stator currents, the applied voltages to the electrical motor (stator) should be derived through dq-axis transformation [1-3]. In a balanced condition, the three-phase stator voltages of the asynchronous machine can be expressed as follows:

$$U_a = \sqrt{2}\, U_{rms}\, sin(\omega t) \tag{16}$$

$$U_b = \sqrt{2}\, U_{rms}\, \sin(\omega t - \frac{2\pi}{3}) \tag{17}$$

$$U_c = \sqrt{2}\, U_{rms}\, \sin(\omega t + \frac{2\pi}{3}) \tag{18}$$

These three-phase voltages are transmitted to the synchronous rotating coordinate system in only two phases (dq-axis transformation). This can be done using the following two equations:

$$\begin{bmatrix} U_\alpha \\ U_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & 1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} \tag{19}$$

In this case, the voltages along the direct and quadrature axes are as follows:

$$\begin{bmatrix} U_d \\ U_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \cos\theta \\ -\cos\theta & \cos\theta \end{bmatrix}\begin{bmatrix} U_\alpha \\ U_\beta \end{bmatrix} \tag{20}$$

The instantaneous values of the stator and rotor currents in the three-phase system are calculated using the following transformation:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{21}$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & 0 \\ -1/2 & -\sqrt{3}/2 \\ -1/2 & \sqrt{3}/2 \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{22}$$

III. DYNAMIC MODEL OF THE ASYNCHRONOUS MOTOR

In this section, a three-phase asynchronous motor model is simulated using MATLAB/Simulink. The model is implemented using the set of equations provided in Section II. The complete Simulink diagram of the asynchronous motor model is shown in Figure 2

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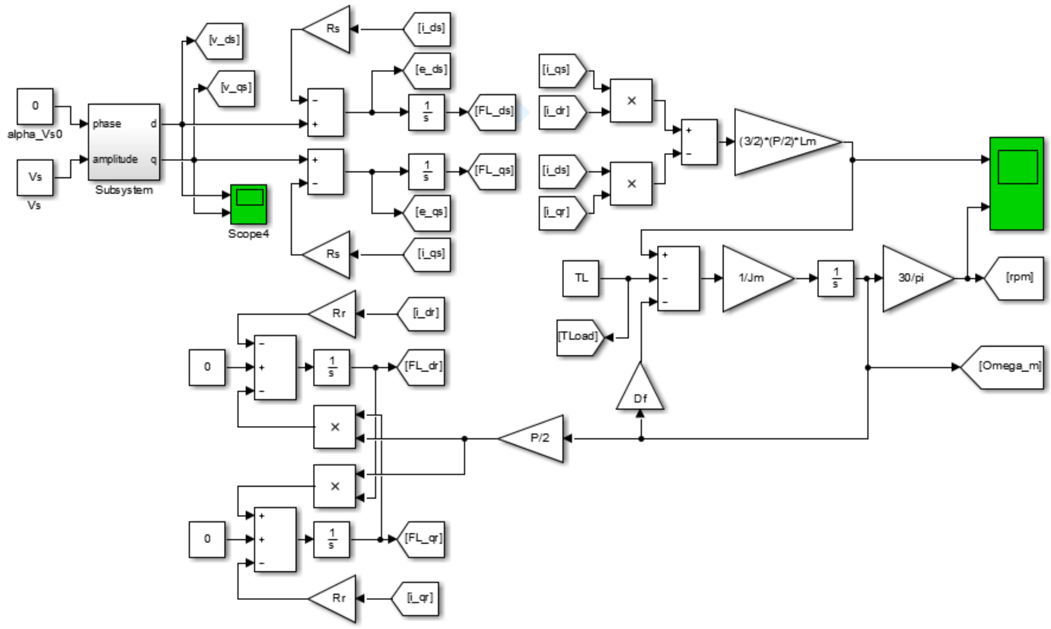

Figure 2. MATLAB/Simulink Model of the Three-Phase Asynchronous Motor

In this model, the simulation of the three-phase stator voltages begins by forming the equations (16, 17, 18). Then, these balanced voltages are transformed into two-phase voltages associated with the synchronously rotating frame using the Clark and Park transformations, as described in equations (19, 20). Next, the dq flux linkages and current equations are implemented as shown below. Using the flux linkages ψds\psi_{ds}ψds, ψqs\psi_{qs}ψqs, ψdr\psi_{dr}ψdr, and ψqr\psi_{qr}ψqr from equations (1)-(4), the MATLAB/Simulink model can be constructed. Figures 3 and 4 illustrate the internal structure of the dq model of the asynchronous motor, which is used to calculate the stator and rotor flux linkages. Figure 5 shows the Simulink blocks used to calculate the currents iqsi_{qs}iqs, idsi_{ds}ids, iqri_{qr}iqr, and idri_{dr}idr according to equations (5)-(9). Figure 6 shows the implementation of the electromagnetic torque TeT_eTe and angular speed ωr\omega_rωr, as expressed in equations (14) and (15).

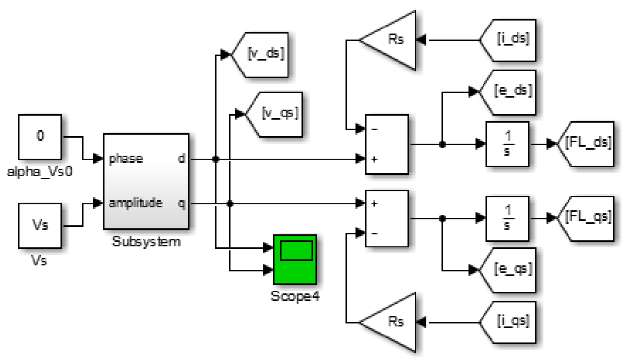

Figure 3. Block for Calculating Stator Flux Linkages

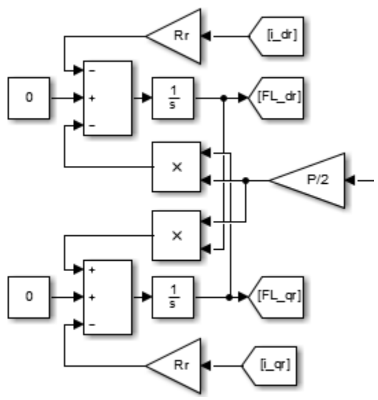

Figure 4. Block for Calculating Rotor Flux Linkages

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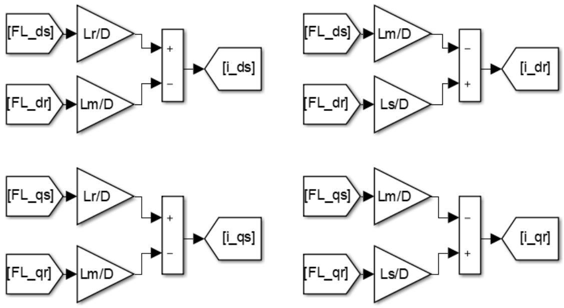

Figure 5. Implementation of dq Current Equations

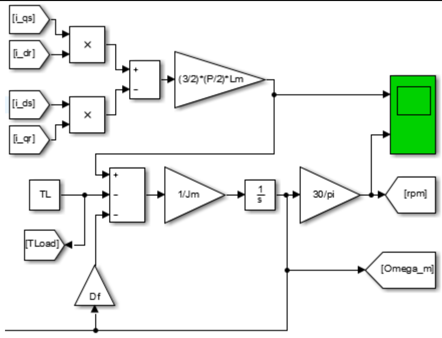

Figure 6. Implementation of Torque and Angular Speed

IV. RESULTS OF DYNAMIC MODELING

Using this model, an asynchronous motor of type AIR71B4 with a power rating of 0.75 kW was tested. The modeling results for the asynchronous motor are as follows: U = 230 V, 2p = 4, f = 50 Hz; Rs = 15.7 Ω, Rr = 8.4 Ω, Lls = 0.005 H, Llr = 0.025 H, Lm = 0.61 H, J = 0.017 kg/m², T_e = 5.3 Nm.

The simulation results show that (Table 1), for the electric motor, the useful power P2=757P_2 = 757P2=757 W, efficiency η=77\eta = 77%η=77, power factor cos ϕ=0.75\cos \phi = 0.75cosϕ=0.75, stator current I1=2I_1 = 2I1=2 A, and rotor speed n=1365n = 1365n=1365 rpm are achieved (Figure 7).

The technical characteristics of the existing AIR71B4 electric motor are: useful power P2=750P_2 = 750P2=750 W, efficiency η=73\eta = 73%η=73, power factor cos ϕ=0.76\cos \phi = 0.76cosϕ=0.76, nominal current I1=2.05I_1 = 2.05I1=2.05 A, and speed n=1390n = 1390n=1390 rpm.

Table 1 Operating Characteristics Data

№	P_2, w	n, rev / min	cosφ	η, %	I_1, A	M, Nм
1	154	1476	0,27	54	1,32	1
2	230	1465	0,35	63	1,35	1,5
3	305	1454	0,43	68	1,4	2
4	377	1442	0,5	72	1,45	2,5
5	450	1430	0,56	74	1,53	3
6	520	1417	0,62	76	1,62	3,5
7	587	1403	0,66	76	1,71	4
8	654	1390	0,7	77	1,82	4,5
9	720	1375	0,73	77	1,94	5
10	757	1365	0,75	77	2	5,3
11	780	1355	0,76	76	2,1	5,7

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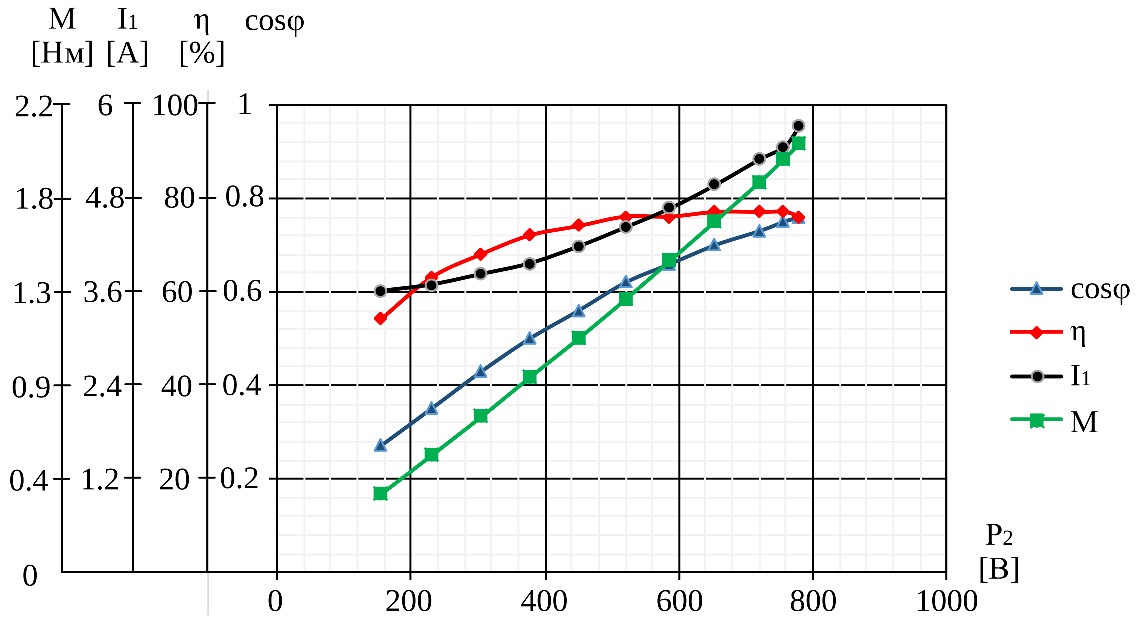

Figure 7. Operating Characteristics of the Motor

Various operating characteristics of the asynchronous motor, including consumed power, electromagnetic torque, rotor speed, and currents in the three-phase stator windings, are illustrated in the time-domain graphs (Figures 8 to 10).

The obtained data allow for the evaluation of the transient characteristics of the AIR71B4 motor during startup. The key findings are as follows:

The time to reach steady state is 0.5 seconds.

The maximum recorded amplitude value of the motor stator current is 11 A.

The steady-state values for motor speed and torque are 1365 rpm and 5.3 Nm, respectively.

The maximum recorded amplitude value of the motor torque is 12 Nm.

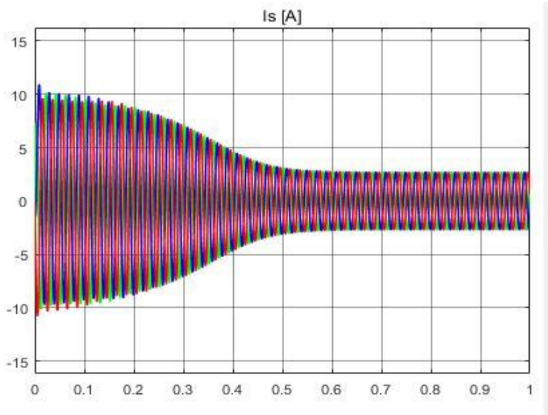

Figure 8. Stator Phase Currents

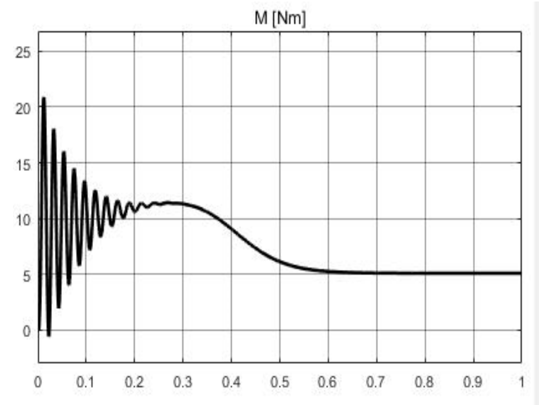

Figure 9. Electromagnetic Torque

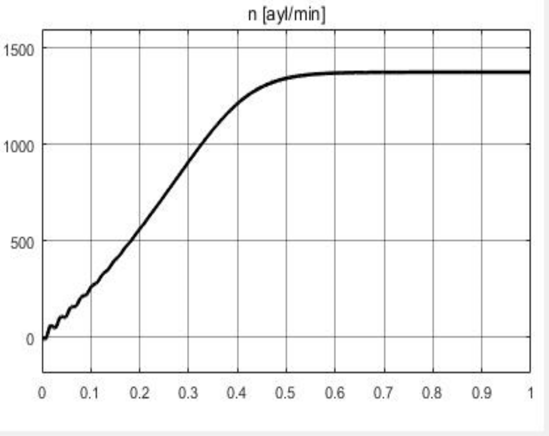

Figure 9. Electromagnetic Torque

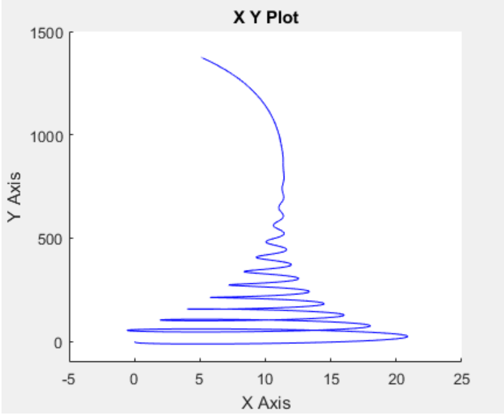

Figure 11. Mechanical Characteristics

CONCLUSION

Asynchronous motors are widely used in various industries and manufacturing sectors. To reduce errors in the design and development of these motors and to minimize operational costs resulting from these errors, it is essential to accurately analyze the dynamic state of the electric motor. Due to the complexity of solving the differential equations of a three-phase asynchronous motor, a dynamic model has been developed using Clark and Park transformations, specifically the d-q axis transformation formulas, in MATLAB/Simulink. Using the developed dynamic model, the characteristics of a 0.75 kW AIR71B4 type asynchronous motor were obtained in both static and dynamic modes. In static mode, the motor's useful power was 757 W, with an efficiency of 77%, a power factor of 0.75, and a stator current of 2 A. In dynamic mode, the transient time of the motor was 0.5 seconds, the startup current factor was 5.5, and the maximum torque relative to the rated torque was 2.26.

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