Simulink implementation of the open-loop scalar command for a three-phase induction machine model

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Abstract

This paper describes step by step the modelling and simulation of the open loop scalar command for a three-phase induction machine with known parameters, which operates in motor regime. In order to change the electromagnetic torque and implicitly the rotor speed, in this paper the solution of applying a positive mechanical torque from outside the machine was chosen, without dynamically adjusting the supply voltage. The chosen mathematical model for the induction machine is the one described by Krause's equations, written in a stationary reference frame. The simulations were done on the Matlab/Simulink simulation environment and the behaviour of the machine was monitored under the working conditions listed above.

Keywords: three-phase induction machine, open-loop command, Simulink model

1 Introduction

The induction machine is an essential component in an electric drive, playing a crucial role in a variety of industrial, commercial, and residential applications. It is used in various fields due to its efficiency, reliability, and versatility. Constructively, they are similar to classic asynchronous motors, designed to operate at constant speed. What differs is the field of industrial applications, in which the machine is used as an electromechanical conversion element with adjustable speed, in which case the performance of the machine in dynamic mode is of particular interest, [1].

This paper describes the modelling and simulation of the open-loop scalar command for a three-phase induction machine operating in motor mode. The mathematical model is implemented on specialized electrical and electromechanical systems simulation software. One of the common tools used for this purpose is MATLAB/Simulink [2], but there are others such as PSCAD, EMTDC, or dedicated software for simulating electrical circuits and control systems.

Control is achieved by applying a constant voltage to the induction machine, without dynamically adjusting this voltage according to its operating conditions. In order to change the electromagnetic torque and implicitly the speed of the rotor, in this paper the solution of applying a mechanical torque from outside the machine was chosen. This type of control may be simpler to implement, but it does not provide the same precision and efficiency as a closed-loop command that uses feedback to adjust

parameters in real time. However, this command is preferred where stationary speeds are used for long periods of time or in undemanding drive systems, [3], [4].

2 Mathematical model of the three-phase induction machine

In this paper, the mathematical model of the three-phase induction machine chosen for implementation on the Matlab/Simulink simulation environment represents one of the multiple variants that can be found in the specialized literature. Thus, the Krause model was chosen for the equivalent circuit, [1],
Stator and rotor voltage equations in arbitrary reference frame are,

$$U_{ds} = R_s i_{ds} + p\lambda_{ds} - \omega_e \lambda_{qs} \tag{1}$$

$$U_{qs} = R_s i_{qs} + p\lambda_{qs} + \omega_e \lambda_{ds} \tag{2}$$

$$U_{os} = R_s i_{os} + p\lambda_{os} \tag{3}$$

$$U_{dr} = R_r i_{dr} + p\lambda_{dr} - (\omega_e - \omega_r)\lambda_{qr} \tag{4}$$

$$U_{qr} = R_r i_{qr} + p\lambda_{qr} + (\omega_e - \omega_r)\lambda_{dr} \tag{5}$$

$$U_{or} = R_s i_{or} + p\lambda_{or} \tag{6}$$

where, $U_{ds}, I_{ds}, \lambda_{ds}$ - d-axis components,

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

$U_{os}, I_{os}, \lambda_{os}$ - 0- axis and usually represent the unbalances in the system. In case of balanced voltages, the zero-axis currents, voltages and flux are zero under normal operating conditions.
Since, in electrical systems, certain parameters are represented by the unit of measure ohms, electric fluxes and inductances will be replaced by flux linkages per second and leakage reactance, thus,

$$\Psi = \omega_b \lambda \text{ and } X = \omega_b L \tag{7}$$

where, $\omega_b = 2\pi f_{rated}$ - motor angular electrical base frequency,

f_{rated} - the rated frequency.

In Figure 1, the d-q equivalent circuit for the induction machine is represented, and the equations (1) - (6) written in the stationary reference frame for a symmetrical three-phase induction machine are modified as follows,

$$\frac{d\Psi_{ds}}{dt} = \omega_b \left[U_{ds} + \frac{R_s}{x_{ls}} (\Psi_{md} - \Psi_{ds}) \right] \tag{8}$$

$$\frac{d\Psi_{qs}}{dt} = \omega_b \left[U_{qs} + \frac{R_s}{x_{ls}} (\Psi_{mq} - \Psi_{qs}) \right] \tag{9}$$

$$\frac{di_{os}}{dt} = \frac{\omega_b}{x_{ls}}\left[U_{os} - R_s i_{os}\right] \tag{10}$$

$$\frac{d\Psi_{dr}}{dt} = \omega_b\left[U_{dr} - \frac{\omega_r}{\omega_b}\Psi_{qr} + \frac{R_r}{x_{lr}}\left(\Psi_{md} - \Psi_{dr}\right)\right] \tag{11}$$

$$\frac{d\Psi_{qr}}{dt} = \omega_b\left[U_{qr} + \frac{\omega_r}{\omega_b}\Psi_{dr} + \frac{R_r}{x_{lr}}\left(\Psi_{mq} - \Psi_{qr}\right)\right] \tag{12}$$

$$\frac{di_{or}}{dt} = \frac{\omega_b}{x_{lr}}\left[U_{or} - R_r i_{or}\right] \tag{13}$$
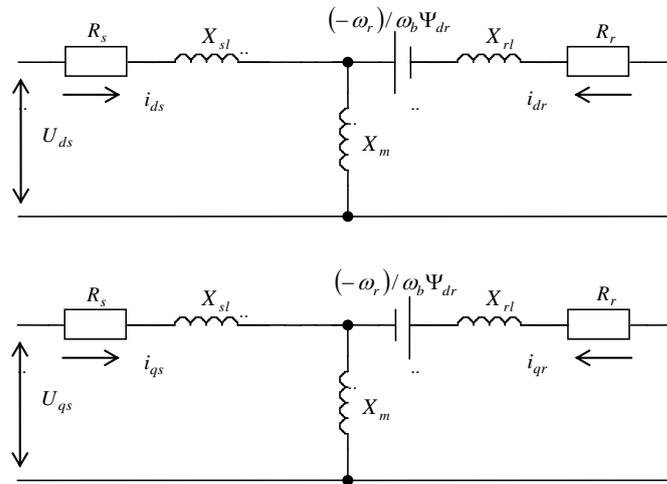
Figure 1. (d–q) equivalent circuit of the induction machine in stationary reference frame

The expressions of flux linkages and electrical currents from equations (8)-(13) are,

$$\Psi_{ds} = x_{ls}i_{ds} + \Psi_{md}, \quad i_{ds} = \frac{1}{x_{ls}}\left(\Psi_{ds} - \Psi_{md}\right) \tag{14}$$

$$\Psi_{qs} = x_{ls}i_{qs} + \Psi_{mq}, \quad i_{qs} = \frac{1}{x_{ls}}\left(\Psi_{qs} - \Psi_{mq}\right) \tag{15}$$

$$\Psi_{dr} = x_{lr}i_{dr} + \Psi_{md}, \quad i_{dr} = \frac{1}{x_{lr}}\left(\Psi_{dr} - \Psi_{md}\right) \tag{16}$$

$$\Psi_{qr} = x_{lr}i_{qr} + \Psi_{mq}, \quad i_{qr} = \frac{1}{x_{lr}}\left(\Psi_{qr} - \Psi_{mq}\right) \tag{17}$$

$$\Psi_{md} = x_M\left[\frac{\Psi_{ds}}{x_{ls}} + \frac{\Psi_{dr}}{x_{lr}}\right], \quad \Psi_{mq} = x_M\left[\frac{\Psi_{qs}}{x_{ls}} + \frac{\Psi_{qr}}{x_{lr}}\right] \tag{18}$$

$$x_M = \frac{1}{\dfrac{1}{x_m} + \dfrac{1}{x_{ls}} + \dfrac{1}{x_{lr}}} \tag{19}$$

where, Ψ_{ds}, Ψ_{qs} - d and q flux linkages,

Ψ_{md}, Ψ_{mq} - d and q magnetizing flux linkages,

x_{ls}, x_{lr} - stator and rotor leakage reactance,

ω_r - stator angular electrical frequency,

ω_r - rotor angular electrical speed.

The electromagnetic torque equation has the form,

$$T_e = \frac{3}{2} \frac{p}{2\omega_b} \left(\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds} \right) \tag{20}$$

where, p – number of pole.

From the fundamental equation of the machine's motion, we get the rotor angular electrical speed, [4],

$$\omega_b \frac{d(\omega_r / \omega_b)}{dt} = \frac{P}{2J} \left(T_e + T_{mec} - T_L \right) \tag{21}$$

where, J - moment of inertia,

T_{mec} - mechanical torque,

T_L - load torque.

Another expression of the above equation, replacing J-moment of inertia with H-inertia constant,

$$H = \frac{J\omega_b^2}{2S_b} \tag{22}$$

where S_b - power in VA.

3 Simulink implementation

The implementation of the mathematical model will be done on the Matlab/Simulink simulation environment, [2], [5]. The machine used in the simulation is a three-phase induction machine with a short-circuited rotor, with known parameters, Table 1. The three-phase system of electric voltages and currents are transformed into a two-phase d-q system, and the general equations of the machine are adapted to the stationary reference frame, [1].

Table 1. Machine parameters

Parameter	Value
P	2
J	2,8 [kgm^2]
f_{rated}	50 [Hz]
R_s	0,206[Ω]
R_r	0,086[Ω]
x_{ls}	0,178[Ω]
x_{lr}	0,178[Ω]
x_m	4,861[Ω]

Fig. 2 shows the block diagram, where both input and output quantities are highlighted. Thus, the induction machine is powered by a three-phase voltage system, at nominal frequency and a mechanical torque act on it which is applied in the same direction of rotation as the rotor rotation. Also, it was considered that the neutral of the stator voltage system varies, and this shortcoming was solved by introducing a small capacity capacitor, between points s and g, Fig.3. As output quantities we have electromagnetic torque and rotor speed.
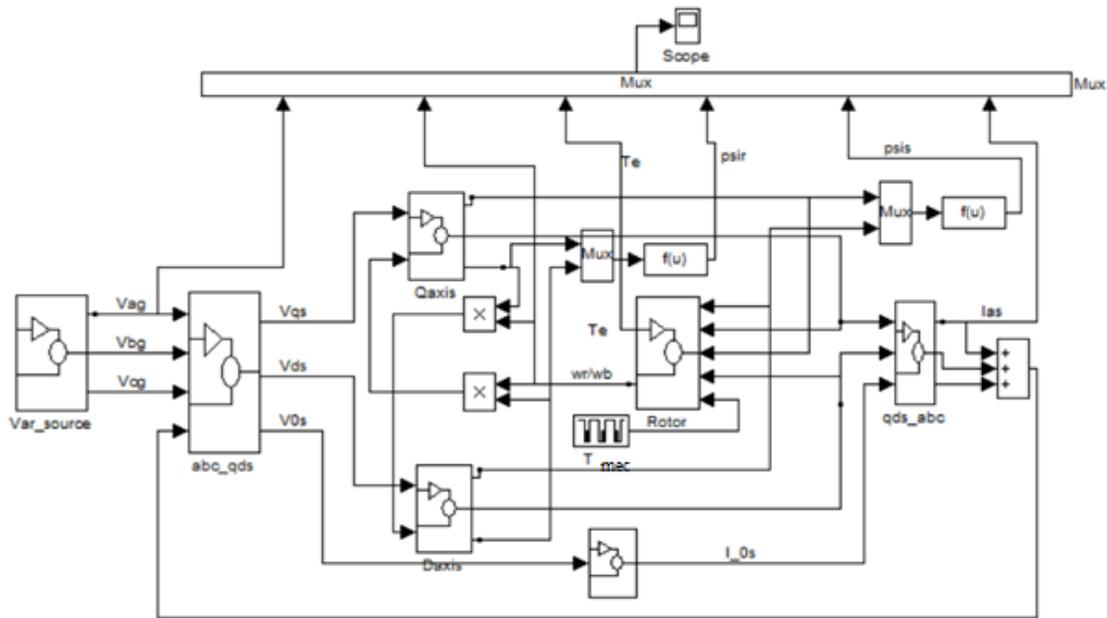
Figure 2. Block diagram of the studied model
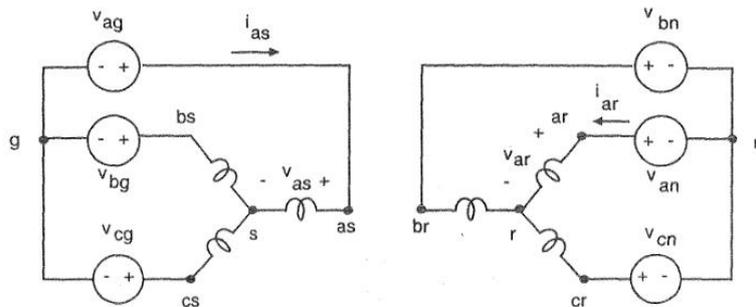
Figure 3. Connecting the machine's armatures

The block diagram in Fig. 2 contains four main blocks, as follows: the three voltages that supply the stator of the machine are determined, the transformation of the three-phase system into a two-phase d-q0 system in the stationary reference frame and vice versa, using the Clark and Park transformation equations and the block that models the induction machine in d-q stationary reference frame. Also, the block diagram includes a module that makes it possible to determine and visualize on the oscilloscope the real stator electrical currents.

The unit vectors $\cos\theta_e$ and $\sin\theta_e$ are calculated in the block in Fig. 4, using the integration formula,

$$\theta_e = \int \omega_e dt \text{, where } \omega_e = 2\pi f_{rated} \, [rad/\sec] \text{ and } f_{rated} = 50Hz \text{ .}$$
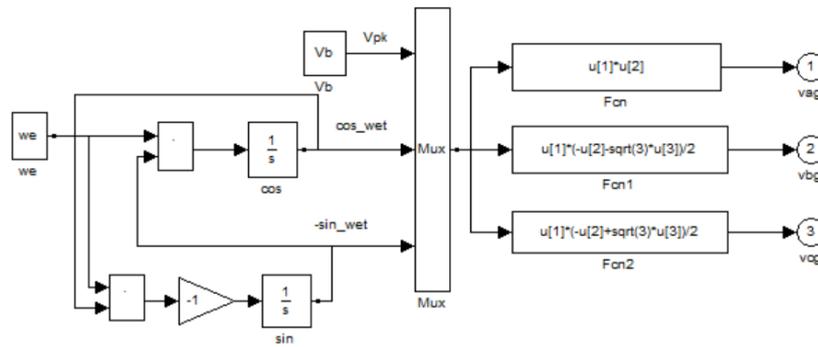
Figure 4. Frequency generator

Thus, the three-phase system of voltages is obtained, applied to the machine's stator, at the nominal frequency, which will later be converted into a two-phase stationary frame. In Fig. 5 is presented a block diagram where the calculation option of the fluxes and currents in the stator and rotor on the d axis was chosen, according to equations (8)-(13). Modeling and simulating the same quantities on the q axis is done in the same way.
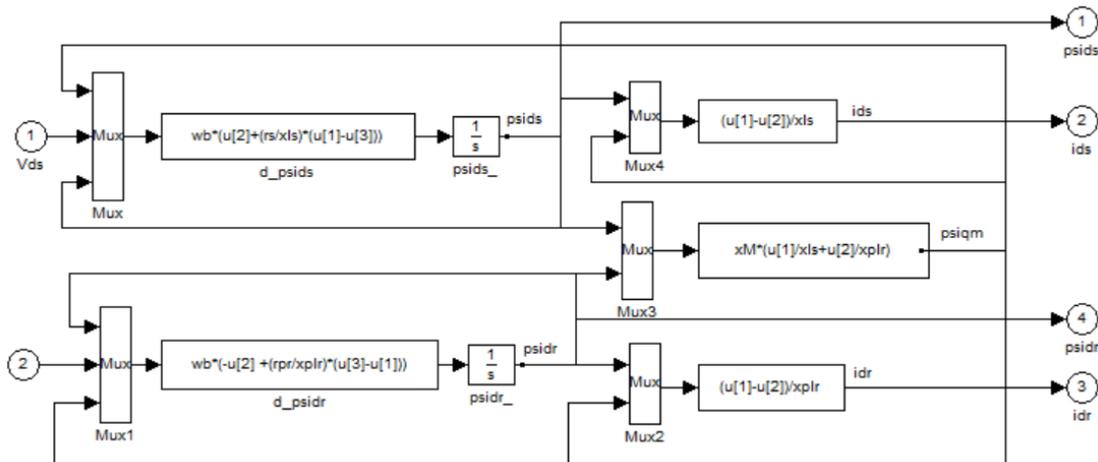
Figure 5. Block diagram d-axis elements

Once the fluxes and currents on the two axes d-q are calculated, according to equations (20)-(22), the electromagnetic torque and the rotor speed can be implemented and determined, Fig.6.
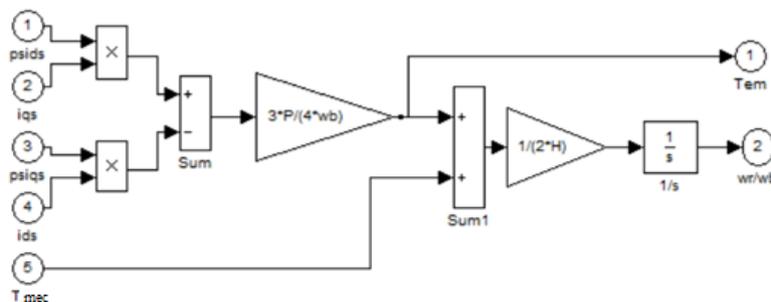
Figure 6. The fundamental equation of motion

The main block diagram, Fig. 2 is therefore built from modules whose sizes can be easily monitored by the Simulink tool „Scope", [6].

4   Simulation results

Once the component modules of the general block diagram are completed, the simulation on the Simulink simulation environment is initiated. The values of all electrical and mechanical parameters were established, considered for the program as input data. The system variables can also be monitored on the oscilloscope or are variables in the calculation of other quantities.

In this paper, we wanted to highlight the variation of the electromagnetic torque, respectively the rotor speed of by applying a mechanical torque from the outside, in the sense of the rotor rotation. Thus, it was opted for this method and not for the classical one, of varying the electric voltage supplying the induction machine.
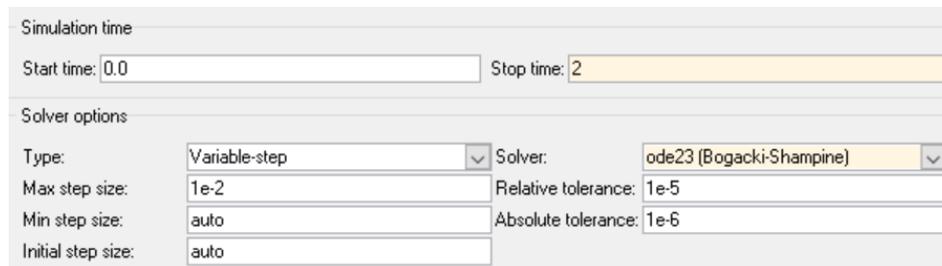
Figure 7. Simulink parameters configuration

In Fig. 7, you can view the parameters that have been configured for Simulink, for the optimal functioning of the model proposed in this paper. Depending on the variable visualized on the oscilloscope, the simulation time will be adjusted. Thus, in Fig. 8 (a) shows the variation of the electromagnetic torque over time, where the mechanical torque is zero. If a positive mechanical torque is also applied, then it can be seen in Fig. 8 (b) how the two quantities are directly proportional. From the diagram, it can be seen how, when the mechanical torque stops, the waveform of the currents stabilizes at the steady-state value. In Fig. 8 (c) the steady-state values of the two flux linkages can be monitored, Ψ_s ___ and Ψ_r..... It can be observed the very small influence on the magnetic quantities when applying the mechanical torque, the machine operating stable.
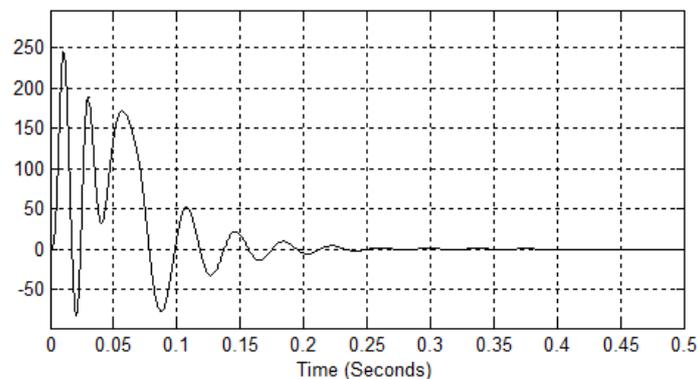
(a) $T_e(t)$
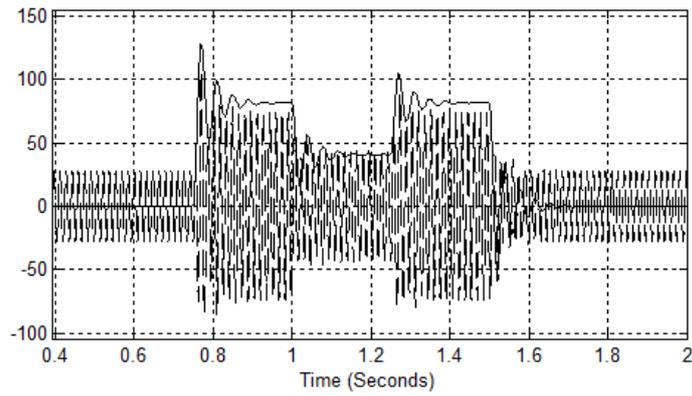
(b) T_e ___$(t); i_s$...(t)
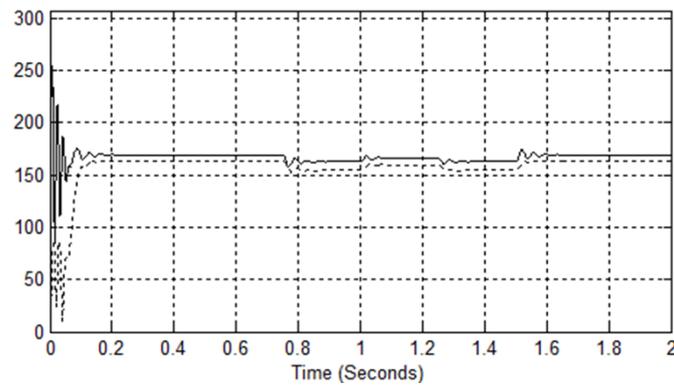
(c) Ψ_s ___$(t); \Psi_r$...(t)

Figure 8. Simulation results

Visualization of the rotor speed variation as a function of time is done on the graph in Fig. 9. In fact, what is observed is a ratio between the rotor speed ω_r and motor angular electrical base frequency ω_b. The unitary value of the variation of the speed ratio is over the entire simulation interval, the small distortions being noticed only when the mechanical torque appears.
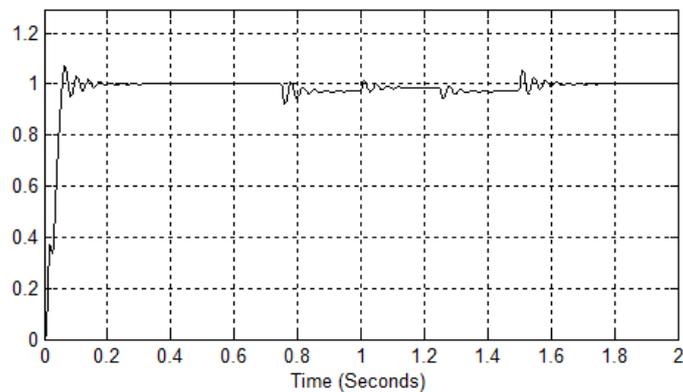
Figure 9. Characteristic $\omega_r/\omega_b(t)$

5 Conclusions

In this paper, the model of the three-phase induction machine written in the stationary reference frame was implemented, using the Matlab/Simulink simulation environment. The realization of a scalar command in the open loop by applying a positive mechanical torque and the behavior of the machine in these operating conditions was pursued. Analyzing each graph separately, Fig. 8 and Fig. 9, it can be concluded that the operation of the three-phase induction machine is stable, the variations being very small. Also, to create the mathematical model of the machine, implemented using Krause equations, the electric inductances and magnetic fluxes were modified, equations (8)-(13). The results of the simulations could be seen on the virtual oscilloscope of Simulink.

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