Tema A1b Automatización y Control Mecánico:

"Induction motor modeling in MATLAB"

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R E S U M E N

Distintos tipos de motores son implementados en los trenes motrices de los vehículos eléctricos. En los recientes modelos disponibles en el mercado se ha implementado el motor síncrono de imanes permanentes. Sin embargo, diversos factores concernientes a la disponibilidad de la materia prima de los imanes permanentes han ocasionado el interés en motores que no dependan de dichos componentes. Una de las alternativas más viable en estos momentos es el motor de inducción. El modelo matemático del motor de inducción es presentado y simulado Simulink de Matlab. El objetivo del modelo obtenido es para aplicaciones en el diseño de motores eléctricos para tracción de vehículos.

Palabras Clave: Motor de inducción, Espacio de estados, Vehículos eléctricos.

A B S T R A C T

(Different types of motors are implemented in powertrains of electric vehicles. In the last commercial vehicles available in the market, the synchronous permanent magnets motors were the most used. However, different aspects concerning with the raw material availability for the magnets motivated the use of other types of motors. One of the most optimal options available right now is the induction motor. The state space induction motor is described and simulated in Simulink. This model is going to be used for the first steps of the design of induction motors for traction applications

Keywords: Electric induction motor, state space model, electric vehicles.

1. Introduction

Electrification of vehicles has become an important tool in overcoming environmental and mobility problems in the cities. The core of the electric powertrain is the electric motor. Most of the commercial available models of electric cars use a synchronous permanent magnet motor. Synchronous motor has good performance for traction applications, but the permanent magnets are made of rare earth elements, such as neodymium. There is an increasing effort for develop motors which do not require the use of rare earth elements [4]. Another type of motor used in traction applications is the Induction Moto (IM), it is the most used electric machine in industry in a wide area of applications.

1.1. Requirements in the traction motors.

Designing motors for traction applications is a big challenge because of the special requirements that those machines must meet. Meanwhile electric motors for industrial applications operate close to specific point. In a vehicle the range of operation is wide, and the motor efficiency must be highest as possible over the whole operation range. The weight and volume of the motors are important parameter and in a new design, a smaller and lighter machine is always desirable [1]. The environmental operation condition is another special requirement, the electric motor will work with water, dirt, and another extreme condition.
To achieve a new design for a specific application, the designer must be able to predict the behavior of the new design. An important tool to start with the design of a new machine is the analytical model, which is simple enough to

understand the basic operation of an electric motor and gives a good prediction for the first stage of the design process [1]. In the section 2, the state space of the induction motor is presented in detail, the equivalent circuit of the induction machine is showed, and the equations are explained. In section 3, the analysis of stability and observability is developed, as is explained in this section, the IM is observable for any measurable stator currents and angular rotor speed, and open loop observer is shown. In section 4 the simulations for the state space model and for the observer are made and compared with the results presented in the reference.

2. Model of Induction Motor

There are three main techniques used in electric motors modeling: analytic equations, finite element method and magnetic equivalent magnetic circuit [1]. In this section the analytic equations of the model in the state space is described in detail. This model is useful in the first stage of the design of electric motors and is useful to understand the electromagnetics process involved in transformation of electric energy into mechanical work.

2.1. The Equivalent Circuit of Induction Motor.

The equivalent circuit is a representation with basic elements that describes the energy transformation and losses in the induction motor.
In Figure 1, the parameters in the stator side are: R_s, stator resistance; X_1, stator leakage reactance; X_m, magnetizing reactance and R_c, core resistance. The rotor resistance, R_r; rotor leakage reactance, X_2 are influence for the current induced in the rotor [3].

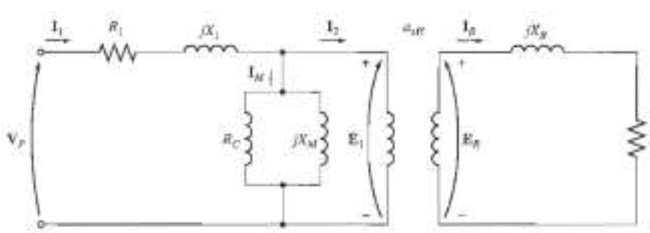

Figure 1 – Real Equivalent Circuit of Induction Motor.

Even when the circuit of Figure 1 is useful to understand the electromagnetic process involved in the IM, it is necessary a simpler model to write the basic equations that describe the dynamic of the system. In Figure 2 shows the equivalent circuit per phase that can be used for analysis.

2.2. Estate space model.

There are two main different state space models of induction motors [5]. The fixed frame model and the rotating frame model. The fixed frame model was chosen because it clarifies that the control inputs, u_{sa}, u_{sb}, directly affect the dynamics of the stator currents which control the rotor speed and the rotor flux. The IM used in electric vehicles works with three phase voltages. Nevertheless, it is possible to simplify the three phases in two projections along axes a-b in the stator and d-q in the rotor. Writing the equations for the equivalent circuits of each one of the axes we have Equations (1)-(4)

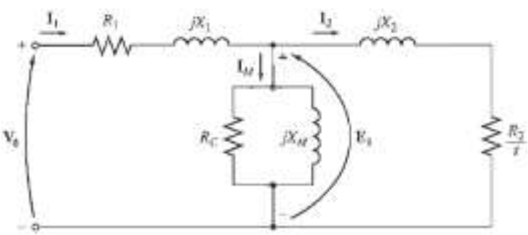

Figure 2 – Simplified Equivalent Circuit of Induction Motor.

$$\dot{\psi}_{ra} + R_s i_{sa} = u_{sa} \tag{1}$$

$$\dot{\psi}_{rb} + R_s i_{sb} = u_{sb} \tag{2}$$

$$\dot{\psi}_{rd'} + R_s i_{rd'} = 0 \tag{3}$$

$$\dot{\psi}_{rq'} + R_s i_{sq'} = 0 \tag{4}$$

The angular position, angular speed the electric torque and the load torque are related by the equations

$$\dot{\delta} = \omega \tag{5}$$

$$J\dot{\omega} = T_e - T_L \tag{6}$$

$$T_e = \frac{M}{L_r}(\psi_{ra} i_{sb} - \psi_{rb} i_{sa}) \tag{7}$$

With equations (1) - (7), as is developed in full detail in [5] the fixed frame state space model is given for equations (8) - (12).

$$\frac{d\omega}{dt} = \mu(\psi_{ra} i_{sb} - \psi_{rb} i_{sa}) - \frac{T_L}{J} \tag{8}$$

$$\frac{d\psi_{ra}}{dt} = -\alpha\psi_{ra} - \omega\psi_{rb} + \alpha M i_{sa} \tag{9}$$

$$\frac{d\psi_{rb}}{dt} = -\alpha\psi_{rb} + \omega\psi_{ra} + \alpha M i_{sb} \tag{10}$$

$$\frac{di_{sa}}{dt} = -\gamma i_{sa} + \frac{u_{sa}}{\sigma} + \beta\alpha\psi_{ra} + \beta\omega\psi_{rb} \tag{11}$$

$$\frac{di_{sb}}{dt} = -\gamma i_{sb} + \frac{u_{sb}}{\sigma} + \beta\alpha\psi_{rb} - \beta\omega\psi_{ra} \tag{12}$$

3. Analysis of the state space model

In practical applications it is needed to know the value of the state space variables to be able to predict the behavior of the output. In an induction motor is easy to measure the currents in the stator (i_{sa}, i_{sb}) and the angular speed of the rotor (ω). However, the magnetic fluxes (ψ_{ra}, ψ_{rb}) are difficult to measure [2]. To solve this issue and observer can be implemented to estimate the fluxes with the known state space variables.

3.1. Observability.

The rotor fluxes are no measurable and therefor it is necessarily to know if the fluxes are observable with the variables known. If the steady state is supposed and constant angular speed implies that the angular speed change is zero and the systems is reduced to:

$$\begin{bmatrix} \frac{d\psi_{ra}}{dt} \\ \frac{d\psi_{rb}}{dt} \\ \frac{di_{sa}}{dt} \\ \frac{di_{sb}}{dt} \end{bmatrix} = \begin{bmatrix} -\alpha & -\omega & \alpha M & 0 \\ \omega & -\alpha & 0 & \alpha M \\ \beta\alpha & \beta\omega & -\gamma & 0 \\ -\beta\omega & \beta\alpha & 0 & -\gamma \end{bmatrix} \begin{bmatrix} \psi_{ra} \\ \psi_{rb} \\ i_{sa} \\ i_{sb} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1/\sigma & 0 \\ 0 & 1/\sigma \end{bmatrix} \begin{bmatrix} u_{sa} \\ u_{sb} \end{bmatrix}$$

$$\begin{bmatrix} i_{sa} \\ i_{sb} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \psi_{ra} \\ \psi_{rb} \\ i_{sa} \\ i_{sb} \end{bmatrix} \tag{13}$$

And therefor by the linear observability test we can say that the system is observable for any i_{sa}, i_{sb} and ω. In Figure 3 an open loop observer is shown.

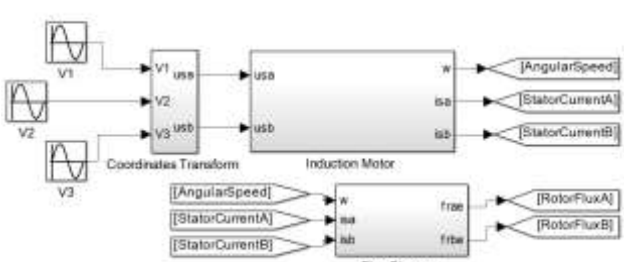

Figure 3 – Observer for the rotor flux.

4. Simulation in Matlab

The state space model was implemented in Matlab/Simulink using a function block, as shown in the Figure 4. In Figures 5 and 6 the comparation of the simulation using the model of Figure 3 and the results publish in [5] are depicted.

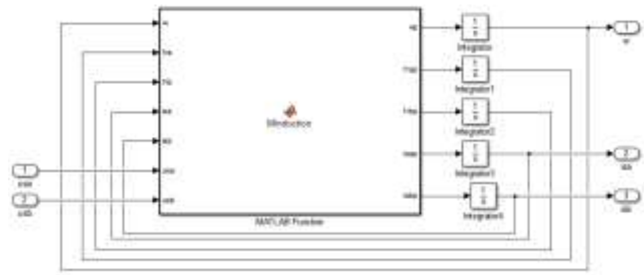

Figure 4 – Simulink bloc of Induction Motor.

Figure 4 shows the angular speed and the rotor flux modulus of this simulation, the simulation of [5] is showed in the Figure 5, the results are identical in both cases.

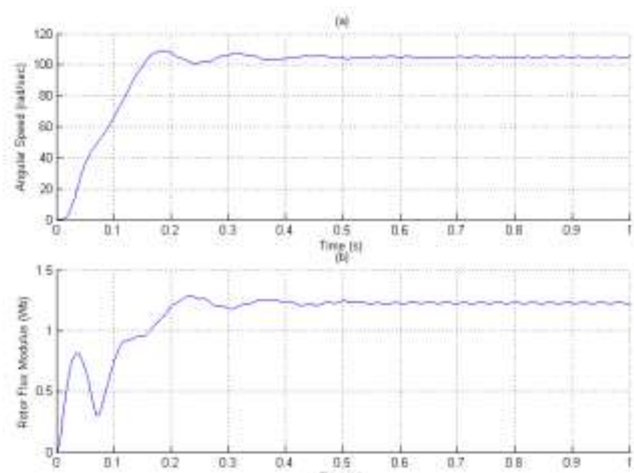

Figure 5 – Results of the simulation.

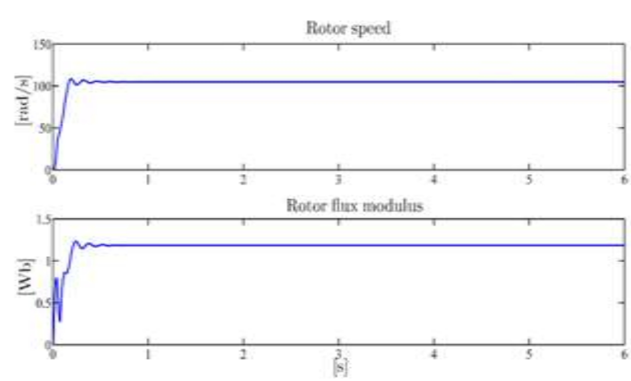

Figure 6 – Results in the reference [5].

The parameters of the simulation are listed in the Table1. The simulation was done with the assumption is a zero-load condition and with a voltage V=110 (V) with a frequency of 16.7 (Hz).

Table 1 – Parameter in the simulation.

Parameter	Value	Units
J	0.0075	Kgm^2
R_s	5.3	Ω
R_r	3.3	Ω
Ls	0.365	H
L_r	0.375	H
M	0.34	H

5. Parameter Estimation of Induction Motors

Parameter Estimation could be used in designing new motor to identify the values of the physical properties of a motor with the desired performance. This is especially useful for new designer who can learn by doing inverse engineering as the parameter of the motor are no published in the datasheet.

The identification process proposed in this section comprise of a linear parameterization and the implementation of a Recursive Least Square Estimation block.

5.1. Linear Parameterization.

The goal of the lineal parameterization is rearranging the model of the IM in the form show in the equation [2].

$$y = \varphi^T\theta \tag{14}$$

where φ is a vector of signals from our system and, θ is the parameter vector.

For equation 7 if the IM model the parameterization is show in equation (15).

$$\dot{\psi}_{ra} = [-\psi_{ra} \quad i_{sa}] \begin{bmatrix} -\alpha \\ \alpha M \end{bmatrix} \tag{15}$$

Where the current i_{sa} is measured for the motor and the flux is estimated with the observer, however to avoid the derivative a filter is operated in both sides of the equation as equation shows.

$$\psi_{ra} \frac{s}{s+\lambda_1} = \frac{1}{s+\lambda_2} [-\psi_{ra} \quad i_{sa}] \begin{bmatrix} -\alpha \\ \alpha M \end{bmatrix} \tag{16}$$

5.2. Recursive Least Square Estimator with Matlab.

Figure [7] shows the implementation of the RLS Estimator block in Matlab/Simulink.

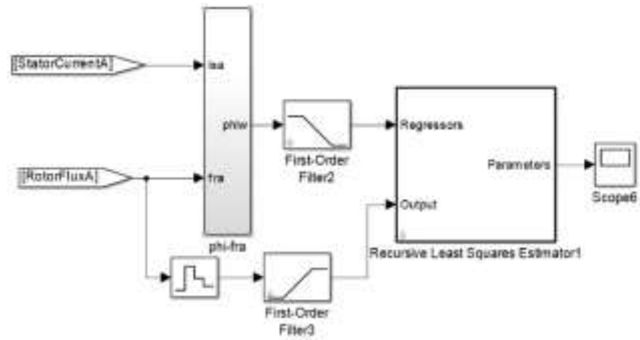

Figure 7 – Results in the reference [5].

The block phi-fra creates the vector φ_f and the Estimator block implements an RLS algorithm. The parameters estimated for this linear regression are showed in Figures [8] and [9]

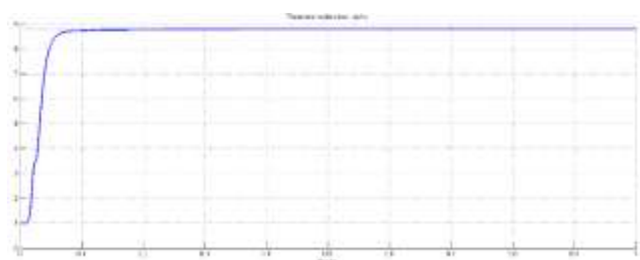

Figure 8 – Parameter Estimation of alpha.

In both cases, the parameters converge to the actual value of the experiment taken for [5]. The input excitation signal was a high frequency three phases voltage source.

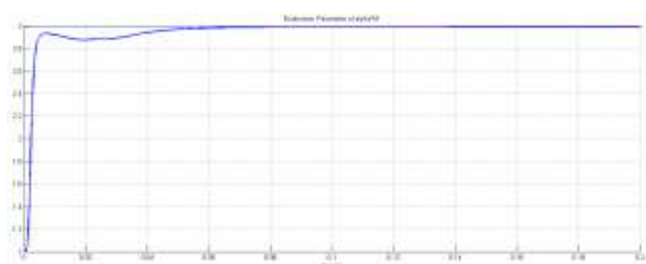

Figure 9 – Parameter Estimation of alpha time M.

The same process implemented for the estimation above, was used in the other equation of the induction motor model. Figure 10 shows the parameter estimation of μ. As we can see in all the graphics of the simulation the convergence time is quite short, this could be just in the simulation but in the actual time if may be necessary more time and a more complex excitation.

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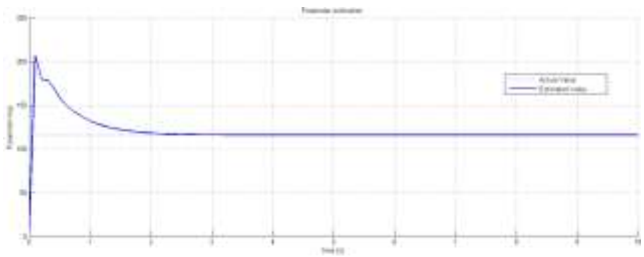

Figure 10 – Parameter Estimation of alpha time μ.

6. Conclusions

Electric vehicles have an increasing breakthrough in the automotive industry, different types of motors have been used in the available models and each one has its advantages and disadvantages in traction applications. Induction motors are a very well study system which has a good performance and characteristics and they are a option without rare earth magnets.
Designing electric motor for traction applications requires high understanding of the electromagnetic phenomena advanced techniques are commonly used for the analysis and simulation of new design however, the computing time in large and making interactions is difficult. An analytical state space model can be used in the first steps of design for quick iterations.
When an already built motor is analyzed it is necessary to know the parameter of the motor, a simple open loop observer with a recursive least square algorithm can be quickly implemented to know the parameter of a specific motor.

The parameterization process shows here is jus the basic configuration of an experiment, but it needs more detailed to become a practical experiment with results.
Simple models, as the showed in this paper, are easy enough to be used in the design of new electric motors and quick implementation of identification experiments.

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