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## CONSTRUCTION OF A LIBRARY OF ELECTRICAL MACHINES USING ECOSIMPRO

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### Abstract

*With the aim of studying, analysing and designing control systems for electrical components, a library of models has been developed for the dynamic simulation of these systems. This library not only includes models of electrical machines, but also a series of electrical, electronic, mechanical and calculation elements which take part in control systems of this type. This paper briefly describes some of the models developed and refers to some of the characteristics of the simulation tool used, EcosimPro. This is an object-oriented modelling tool with characteristics that make it suitable for modelling complex physical systems. The source code generated by this software is Visual C++ which, once compiled, creates a file that can be executed independently. An example of this is given in the modelling and simulation of an induction motor controlled using field co-ordinates and some of the results obtained are shown.*

**Key words:** Simulation, EcosimPro, object-oriented modelling of physical systems, electrical machines, control using field co-ordinates, electronic components.

### 1. INTRODUCTION

Dynamic simulation is a widely used tool in the study, analysis and design of control systems in complex plants. In the particular case of electrical machines, the control system includes power electronics systems and fast calculation and control mechanisms. The simulation tool adopted must be capable of reliably modelling and simulating very different systems, such as steady-state systems and discrete event systems. Models of electrical machines are steady-state and the dynamics are fast and generally non-linear. The models of power

electronics, on the other hand, are non-linear discrete event systems. There are tools for modelling steady-state systems and there are other, specific tools for modelling electronic circuits. Among the first group we have Matlab with its Simulink toolbox, which some authors have used to develop models of electrical machines and they have documented their work in literature on the subject. One such person is the author Chee-Mun Ong in his book *Dynamic Simulation of Electrical Machinery Using Matlab/Simulink* [1]. On the other hand, in 1998, the Canadian companies Hydro-Quebec and Teqsim International Inc developed a specific toolbox on the subject called "Powersys". This toolbox comes with an in-built library of models of electrical machines and of some electronic components for simulations with Matlab [4]. For many years specific programs have been available for modelling and simulating electronic circuits, such as PSPICE developed by the Microsim Corporation and EWB (Electronic Workbench) and, because they are very widely used, many electronic components manufacturers offer their products so that they can be simulated.

A tool was needed that could jointly model and simulate electronic circuits and complex steady-state plants, combining the characteristics offered by software packages specific for each purpose. EcosimPro offered a good solution for modelling the proposed systems. Being a new tool, it presented the disadvantage of not having libraries of electronic components and electrical machines. The development of a library was therefore undertaken in order to acquire a tool for the study, analysis and design of electrical machine control systems.

This presentation is organised in the following way: section 2 addresses the simulation tool used, EcosimPro. Section 3 discusses the model of the induction motor using steady state co-ordinates and describe the modelling of power electronics and other elements. Section 4 presents as an example the model

of an induction motor with the mechanisms for control using field co-ordinates. Section 5 shows some curves obtained by simulation and section 6 sets out the conclusions of the work.

## 2. THE SIMULATION TOOL USED

With the intention of presenting a general overview of EcosimPro, some of its relevant characteristics are described [2].

One of the special features of this simulation tool is that each physical component (object) can be modelled independently of others and, subsequently, a system can be assembled by connecting the different elements of which it is comprised, in a way similar to the topology of the real system [3]. The tool symbolically processes the equations of the models in accordance with the specified topology and with the boundary conditions of the system, generating the equations which are used for the simulation with powerful integrating algorithms. This allows higher level programming, leaving the user with the task of modelling the components and defining the system topology. As an example, let's take a circuit formed by two resistors  $R_1$  y  $R_2$  and a power source with a voltage and current of  $v(t)$  and  $i(t)$ , respectively. Depending on how the resistors are connected, in series or in parallel, the system equation will either be Eq (1) or (2). This symbolic processing is automatically carried out by the software and the user only has to model the components (resistors and power source) and define the topology.

$$v(t) = i(t)(R_1 + R_2) \quad (1)$$

$$v(t) = i(t) \frac{R_1 + R_2}{R_1 R_2} \quad (2)$$

Another illustrative example which highlights the characteristics of the tool is the modelling of an electric motor. If we apply a power source to the terminals in this model, it will generate mechanical energy on the shaft. However, if we do the opposite, in other words make the machine rotate by applying a torque on the shaft, then the model will function as a generator and produce electrical energy at the terminals. It is the same model; the only thing that has changed is the direction of the flow of electricity.

The connection of the different objects is made through so-called ports, in which there are variables defined as accessible. In the case of electrical components, we have sought to give the ports a physical resemblance to the nodes or points of connection of two or more components. In these ports it will be the current and voltage variables that are present. The language (EL) enables restrictions to be defined for the variables of different objects connected to the same port. Such restrictions

correspond to the physical laws that govern in the case of these variables. In the case of electrical systems, the sum of the currents of different objects connected through one of their ports must be equal to zero, as expressed by Eq (3). In their turn, the voltages in the ports of different connected objects must be the same, as expressed by Eq (4).

$$\sum_{i=1}^n i_i(t) = 0 \quad (3)$$

$$v_1(t) = v_2(t) = v_i(t) = \dots v_n(t) \quad (4)$$

Where:

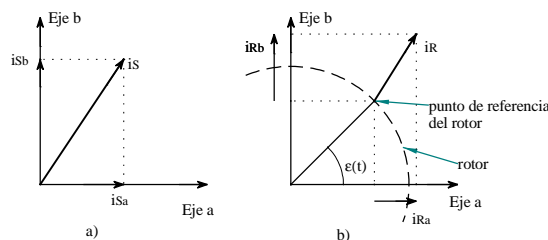
$i_i$ : current in the port of the  $i^{\text{th}}$  connected object

$v_i$ : voltage in the port of the  $i^{\text{th}}$  connected object

## 3. MODELS

### 3.1 Model of the Induction Motor using Steady State Co-ordinates

In the model of the induction motor, as it is presented in the bibliography [5], the electrical and magnetic variables are represented as vectors. These vectors occur in the representation of the variables in a rotational or steady-state system of orthogonal co-ordinates. In the case of the analysis of control using field co-ordinates, this system of co-ordinates is rotational and field-oriented. In this work we need a general model and the vectors will therefore be referred to a steady-state system whose axes are *axis a* and *axis b*, as shown in Figure 1.



**Fig. 1:** Breakdown of the electrical variables according to a system of steady-state axes:

- breakdown of the stator current
- breakdown of the rotor current

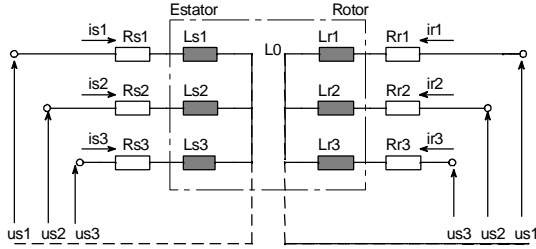
Analysing the stator circuit shown in Figure 2 and considering the effects of the current which circulates through a rotor conductor located in an angular position, we obtain Eq (5).

$$u_s = R_s i_s + L_s \frac{di_s}{dt} + L_0 \frac{d(i_r e^{j\epsilon})}{dt} \quad (5)$$

where:

$u_s$ : vector which represents the voltage in the stator

$i_S$  : vector which represents the current in the stator  
 $i_R$  : vector which represents the current in the rotor  
 $R_S$  : total resistance of the stator circuit  
 $L_S$  : total inductance of the stator circuit  
 $L_0$  : mutual inductance  
 $e$  : angular position of a point of the rotor considered



**Fig. 2:** Wiring diagram of an induction motor

Carrying out an analysis similar to the previous one, but this time for a single squirrel cage type rotor circuit, we obtain Eq (6).

$$0 = R_R i_R + L_R \frac{di_R}{dt} + L_0 \frac{d(i_S e^{-je})}{dt} \quad (6)$$

The expression for the motor torque  $T_m$  is addressed in the aforementioned bibliography and shown in Eq (7).

$$T_m = \frac{2}{3} L_0 z_p \Im \left[ i_S (i_R e^{je})^* \right] \quad (7)$$

where:

$z_p$  : number of pairs of poles

$T_m$  : generated motor torque

$\Im$  : imaginary part of the argument between square brackets

$(i_R e^{je})^*$  : conjugated complex of  $(i_R e^{je})$

The kinetics of the model is expressed in Eq (8).

$$\frac{de}{dt} = \mathbf{w} \quad (8)$$

where:

$\mathbf{w}$  : angular electrical velocity

The mechanical velocity on the motor axis,  $\mathbf{w}_m$ , will be as expressed in Eq (9).

$$\mathbf{w}_m = \frac{\mathbf{w}}{z_p} \quad (9)$$

Newton's law for rotational movements is expressed in Eq (10).

$$T_m = J \frac{d\mathbf{w}_m}{dt} + T_L \quad (10)$$

$$T_L = T_L(t, \mathbf{e}, \mathbf{w}_m, \dot{\mathbf{w}}_m) \quad (11)$$

where:

$T_L$  : load torque

$J$  : moment of inertia of the rotating mass

Eq (11) shows that the load torque can be a non-linear function of the time, position, velocity and acceleration of the rotor shaft.

It is advisable to express the vectors that represent the variables in accordance with a system of steady-state co-ordinates whose axes are *axis a* and *axis b*, as shown in Figure 1. A breakdown of the electrical variables in the system of co-ordinates is shown in Eq (12), (13) and (14).

$$\mathbf{u}_S = u_{Sa} + j u_{Sb} \quad (12)$$

$$\mathbf{i}_S = i_{Sa} + j i_{Sb} \quad (13)$$

$$\mathbf{i}_R e^{je} = i_{Ra} + j i_{Rb} \quad (14)$$

By replacing Eq (9), (12), (13) and (14) with Eq (5), (6), (7), (8) and (10), developing derivatives, operating and separating the real and imaginary parts, we obtain the system of equations expressed in (15) which are the equations that define the model of the induction motor in steady-state co-ordinates.

$$\begin{aligned} u_{Sa} &= R_S i_{Sa} + L_S \frac{di_{Sa}}{dt} + L_0 \frac{di_{Ra}}{dt} \\ u_{Sb} &= R_S i_{Sb} + L_S \frac{di_{Sb}}{dt} + L_0 \frac{di_{Rb}}{dt} \\ 0 &= R_R i_{Ra} + L_R \frac{di_{Ra}}{dt} + L_R i_{Rb} \mathbf{w} \\ &\quad + L_0 \frac{di_{Sa}}{dt} + L_0 i_{Sb} \mathbf{w} \\ 0 &= R_R i_{Rb} - L_R i_{Ra} \mathbf{w} + L_R \frac{di_{Rb}}{dt} \\ &\quad + L_0 \frac{di_{Sb}}{dt} - L_0 i_{Sa} \mathbf{w} \\ j \frac{d\mathbf{w}}{dt} + T_L &= \frac{2}{3} L_0 z_p (i_{Sa} i_{Rb} - i_{Sb} i_{Ra}) \\ \mathbf{w}_m &= \frac{\mathbf{w}}{z_p} \end{aligned} \quad (15)$$

Clarke's transform for voltages and currents is defined in Eq (16) and (17), respectively. The reverse transform for the same variables does not need to be defined because the simulation tool does it on the basis of the direct transforms defined in Eq (16) and (17).

$$\begin{bmatrix} u_{Sa} \\ u_{Sb} \end{bmatrix} = \begin{bmatrix} \frac{3}{2} & 0 & 0 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \quad (16)$$

$$\begin{bmatrix} i_{Sa} \\ i_{Sb} \end{bmatrix} = \begin{bmatrix} \frac{3}{2} & 0 & 0 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} \quad (17)$$

where:

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} : \text{three-phase motor voltage vector}$$

$$\begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} : \text{three-phase motor current vector}$$

Eq (15), (16) and (17) represent the electrical, dynamic and kinematic behaviour of the induction motor in steady-state co-ordinates. These equations are suitable for introducing into the model because they do not require any additional algebraic treatment to arrange them in order and to find a solution for the simulation. This task is carried out by the tool, thus simplifying the work of the user. Nor is it necessary to define the input and output variables, because this function is carried out by the tool in accordance with the boundary conditions.

### 3.2 Modelling Power Electronics

Power electronics is modelled based on the models of simple elements such as diodes, switches resistors, capacitors, etc, and the circuits are subsequently assembled in accordance with the topology of the physical system to be modelled. Simple models of the electronic components have been built because the objective of this work was not to obtain component models with great exactitude, particularly the semiconductors, but this tool can be used to build models with the precision and exactness required. The complexity of each model (object) is encapsulated in the actual model and is transparent to the user; only the parameters defined as accessible can be accessed.

The simulation language allows the user to define a basic class from which other models can be obtained by inheritance. An electrical element with two terminals is the simplest basic class defined and for which the basic properties of the element are

established. One of the properties which must be fulfilled, for example, is that the current that goes into one port or terminal is the same that comes out of the other. From this basic class we can define elements such as resistors, capacitors, diodes, inductors, etc.

### 3.3 Modelling other Elements

Other elements such as mechanical elements, sensors, controllers, etc, are modelled in much the same way as the power electronics elements. For the mechanical elements, we have to define mechanical ports in which mechanical variables such as velocity, torque and position are accessible so that elements of this type can be connected.

## 4. MODELLING A CONTROL SYSTEM FOR AN ELECTRICAL MACHINE

Figure 3 shows an example of a system which includes a certain variety of models which have been developed. This system contains the blocks necessary to simulate the control of an induction motor using field co-ordinates. As can be seen in Figure 3, the system includes all the electronics, current sensors and calculation blocks. Inputs to these blocks are the stator currents in field co-ordinates that we want to impose on the motor,  $i_{Sq}$  e  $i_{Sd}$  (current in quadrature and in accordance with direct axis), and the outputs from the blocks which are used as feedback for the control system are the currents that run through the stator in field co-ordinates  $i_{Sq}$  e  $i_{Sd}$  and the magnetising current  $i_{mR}$ . To assemble a speed control system, for example, it would only be necessary to aggregate a speed controller which actuates on the inputs  $i_{Sq}$  and  $i_{Sd}$  and takes feedback from the outputs of the block  $i_{Sq}$  and  $i_{Sd}$ . The system shown also has a model of an induction motor and a tachometer. It can be seen in Figure 3 that we have modelled blocks which function in reverse; this is due to the characteristics of the language.

The following is the function of each of the blocks shown in Figure 3:

**ab2dq:** Block which transforms an orthogonal system of steady-state co-ordinates into another similar block but in field co-ordinates or vice versa (Park's direct and reverse transforms).

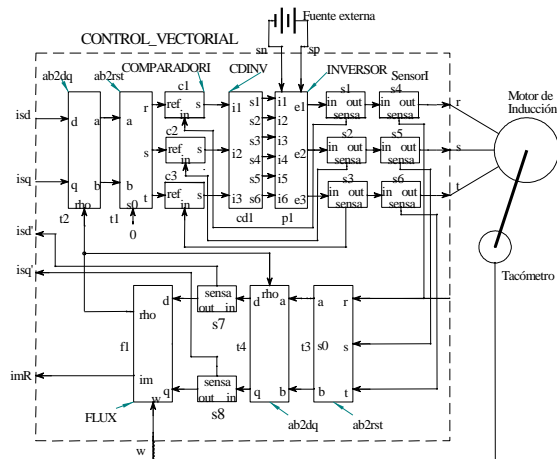


Fig. 3: Control blocks in field co-ordinates

**ab2rst:** Block which carries out the transformation of a two-phase system into a three-phase system and vice versa (Clarke's direct and reverse transforms).

**FLUX:** Flux estimator block

**COMPARADORI:** Model of a comparator of current with hysteresis. The parameters in this block are the thresholds of hysteresis, the inputs are the signals from the current sensors, and the outputs are three lines for the control of the inverter branches.

**CDINV:** Model of an inverter switch circuit. The parameter in this block is the dead time required by the inverter switches, the inputs are the three outputs from the current comparator (COMPARADORI) and the outputs are the six lines to activate the inverter switches.

**INVERSOR:** Model of a three-phase inverter. This block is composed of seven contacts: six inverter contacts and one brake contact.

**SensorI:** Current sensor

**Tacometro:** Analogue tachometer

**Off-site power:** Model of a power source applied to the direct current busbar

## 5. SIMULATION RESULTS

The simulation was carried out for a system that corresponds to that shown in Figure 3. The motor is 1 HP with two pairs of poles, and a constant mechanical load of 4 Ntm. ( $R_S=2.643 \Omega$ ;  $R_R=3.4 \Omega$ ;  $L_S=0.1527$  Hy;  $L_R=0.1527$  Hy;  $L_0=0.1459$  Hy;  $J=0.005$  Kg m<sup>2</sup>).

As input we applied  $i_{sq} = 15$  A ,  $i_{sd} = 10$  A and 500 V dc.

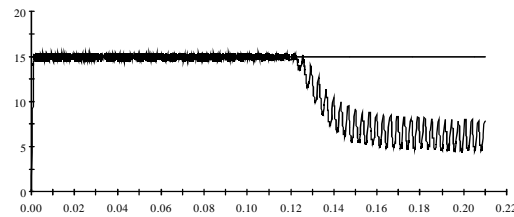


Fig. 4: Current  $i_{sq}$  of the motor and the reference current

Figure 4 represents the current  $i_{sq}$  of the motor and the reference current. We can see that the current  $i_{sq}$  of the motor follows the reference current up to approximately 0.12 s which is the point up to which the speed of the motor and the voltage in the direct current busbar will allow it to go.

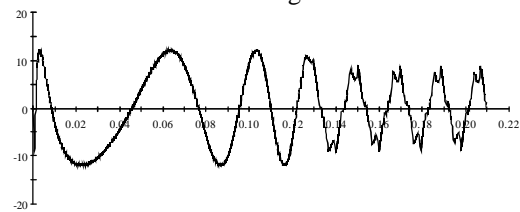


Fig. 5: Current of phase R of the motor

Figure 5 represents the current that runs through phase R of the motor, while Figure 6 shows the speed of the motor shaft. We can see that at first the speed is negative due to the fact that the opposite torque is greater than the motor torque at the beginning of the simulation.

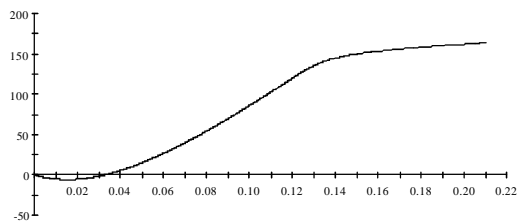
## 6. CONCLUSIONS

Models have been built of different electrical machines, power electronics circuits and blocks for calculation and control. The tool employed is useful and suitable for this work because it allows you to model and simulate systems composed of different types of components: electrical machines, electronic circuits and blocks with programs written in C or Fortran.

Interpretation of the model is simple because the topology and access to variables is very similar to the physical system to be studied. In the models of electronic components, for example, the node voltage and the current that runs through the component can be accessed in the ports. These variables can be entered in graphic form so that the records are similar to those obtained with a measuring instrument.

A graphics tool is available with the simulation tool which enables models to be generated more easily

because it is done by joining blocks chosen from a components library. For example, the electronic circuits are modelled by joining blocks as though they were electric conductors. Each of the blocks



encapsulates the model of an electronic component.

**Fig. 6:** Speed of the motor shaft

It may be concluded that we have successfully created a library for the simulation of control systems for electrical machines and electronic circuits in general, to be used as a tool for studying and analysing these systems. This library can be enriched by debugging some of the models -as in the case of

the power semiconductors, for example- and by incorporating into them the characteristics typical of a particular component, based on the parameters offered by the manufacturer.

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