EcosimPro/PROOSIS permanent magnet *aircraft starter and trapezoidal current control*
ELECTRIC SYSTEMS LIBRARY

V. Pordomingo López

Empresarios Agrupados Internacional. S.A. Magallanes, 3. 28015 Madrid. Spain. *(email: vpo@empre.es)*

1. INTRODUCTION

Traditionally, when designing and building aircraft the electrical system needs to comply with several requirements. In this sense, the generator that is used shall be the main element. Furthermore, most of the designs try to benefit from its presence to use it as actuator whenever necessary. Therefore, this component can be used to generate electrical power from the mechanical energy of the main motors and viceversa, that is, creating mechanical power by using electrical batteries (APU).

This document summarises the modelling process developed in EcosimPro [1]/Proosis [2] with the ELECTRIC SYSTEMS library [3] to study this type of system. A brief presentation of the components used is shown, followed by a detailed description of the equations for the permanent magnet and wound rotor synchronous motor. Finally, an analysis of the results is presented to show the system behaviour and response upon slight modifications of certain control parameters and boundary variables.

2. MODEL OF THE SYNCHRONOUS MOTOR

The **permanent magnet synchronous motor** is the most widespread in this type of application. Its compact size and low weight, reliability and ease of control make it the most suitable option. There are several types available in the market. Their main difference lies in the type of rotor:

- Wound rotor: These are the most commonly used motors. The wound rotor creates sine electromotive forces on the stator.
- Grooved rotor: These units have compact rotors where the various poles are separated by grooves. This type of rotor generates trapezoidal induced electromotive forces on the stator.

The motor used in the model presented herein is of wound rotor type, so the induced electromotive forced on the stator are of sine type.

There are several ways to model this type of motor, either establishing the stator domain or the rotor domain as the reference by means of the corresponding Park's transformation. For the case presented in this document, the model has been expressed as a function of the motor line voltages, and taking the fixed shafts connected to the stator as a reference. Thus, the equations that serve to calculate the electrical behaviour of the motor are shown below:

$$\frac{di_a(t)}{dt} = \frac{1}{3L_S}(2v_{ab} + v_{bc} - 3R_S i_a(t) + \lambda p \omega_r(-2\phi'_a + \phi'_b + \phi'_c))$$

$$\frac{di_b(t)}{dt} = \frac{1}{3L_S}(-v_{ab} + v_{bc} - 3R_S i_a(t) + \lambda p \omega_r(\phi'_a - 2\phi'_b + \phi'_c))$$

$$\frac{di_c(t)}{dt} = -(\frac{di_a(t)}{dt} + \frac{di_b(t)}{dt})$$

This model presents the current derivatives as the main variables. Therefore, its behaviour shall be determined by the voltages at its ends. Besides, when it operates in combination with a power source, it can function as a motor or a generator, depending on the sign of the torque that is applied to the shaft. In addition, this model is highly intuitive since it can be adapted without any significant modifications to any type of permanent magnet synchronous motor by simply changing the induced flows that are shown as independent variables.

Thus, in order to model a grooved rotor motor, it will be necessary to define an induced flux on the stator winding of each phase that complies with the following equation:

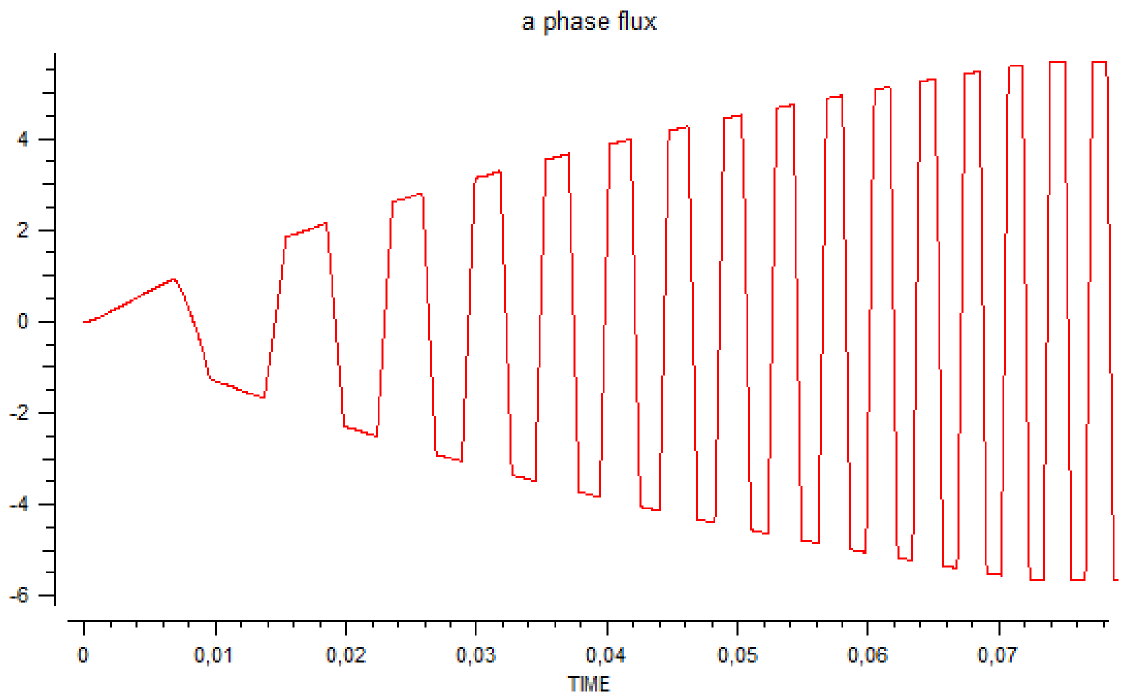

Figure 1 Induced flux during startup

It can be seen that the speed increase during the startup transient causes an increase in the current of the induced flux. During steady state conditions, the rotor grooves generate a trapezoidal flux with constant amplitude, as shown in the following figure:

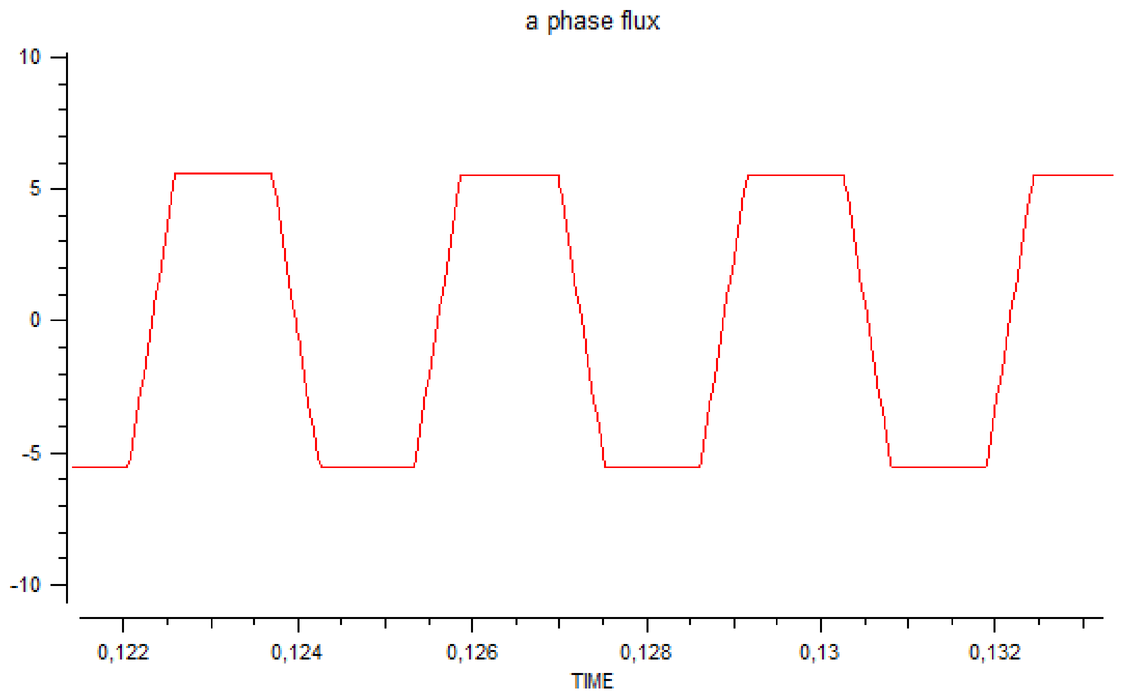

Figure 2 Steady state induced flux.

Similarly, it is also possible to model the induced flux with a wound rotor, which, as anticipated, has a sine form:

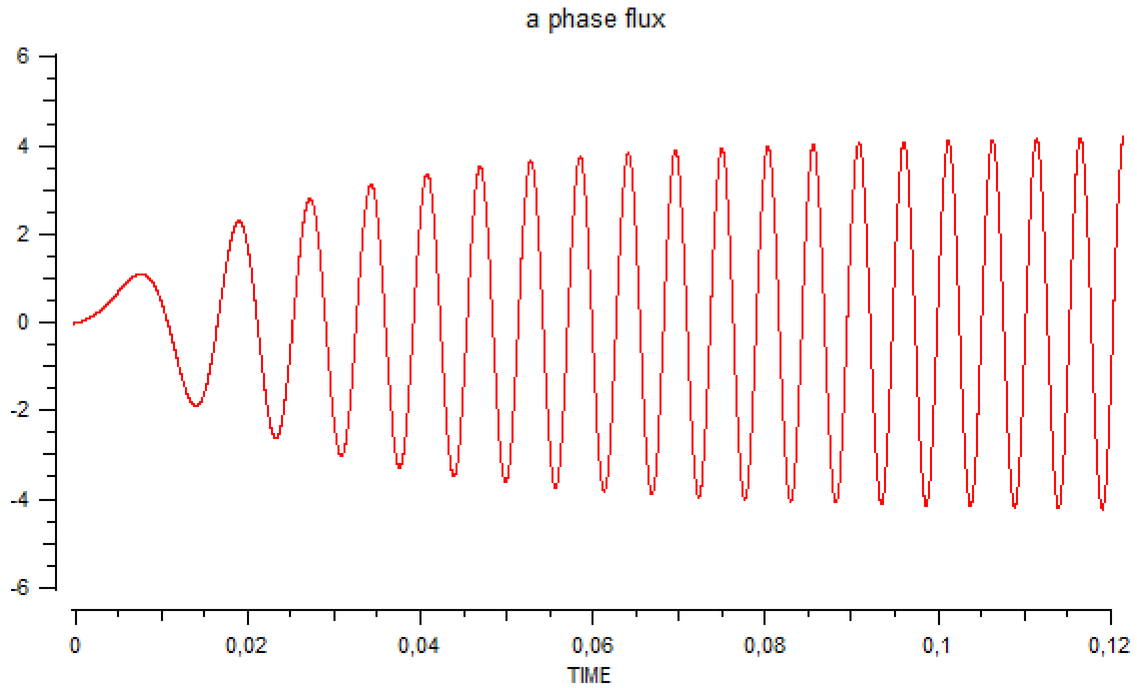

Figure 3 Induced flux for a wound rotor motor.

Once the electrical behaviour has been established, it is necessary to calculate the electromagnetic torque generated by the interaction of the phase currents and the induced flux:

$$T_e = p\lambda(\phi'_a \cdot i_a + \phi'_b \cdot i_b + \phi'_c \cdot i_c)$$

Finally, the mechanical behaviour of the motor is calculated with the corresponding equation that summarises the rotational dynamics of the shaft in accordance with the torque balance that is applied:

$$\frac{d\omega_r(t)}{dt} = \frac{1}{J}(T_e - T_f - F \cdot \omega_r(t) - T_m)$$

$$\frac{d\theta_r(t)}{dt} = \omega_r(t)$$

3. POSITION CONTROL SYSTEM

However, control and power supply are a key part of the use of these units as motors. In order to perform this control, most of the algorithms follow up on the unit shaft using its position, speed and acceleration. Concentric control loops are thus created depending on the needs of each application. In general, the unit can be adequately controlled by applying current to one phase or another depending on the instantaneous

position of the rotor. Therefore, it is enough to use one control loop using the angle as the control variable.

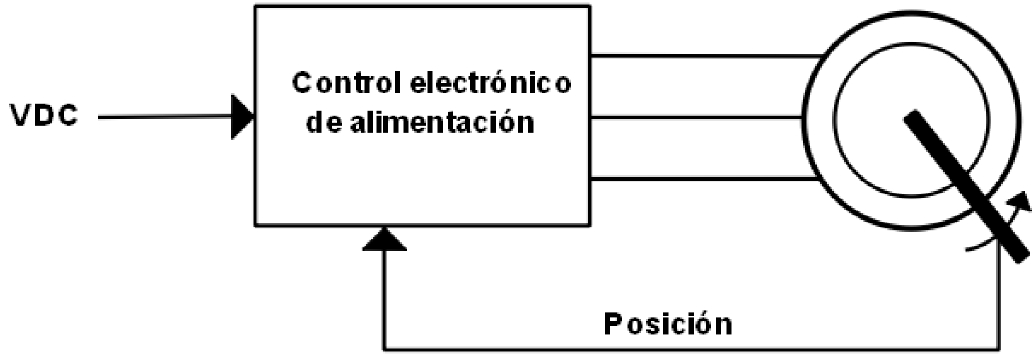

Figure 4 Position control loop

The unit receives electrical power supply from the DC storage batteries. Therefore, an active inverter is used to apply the correct voltage to each phase at any given time.

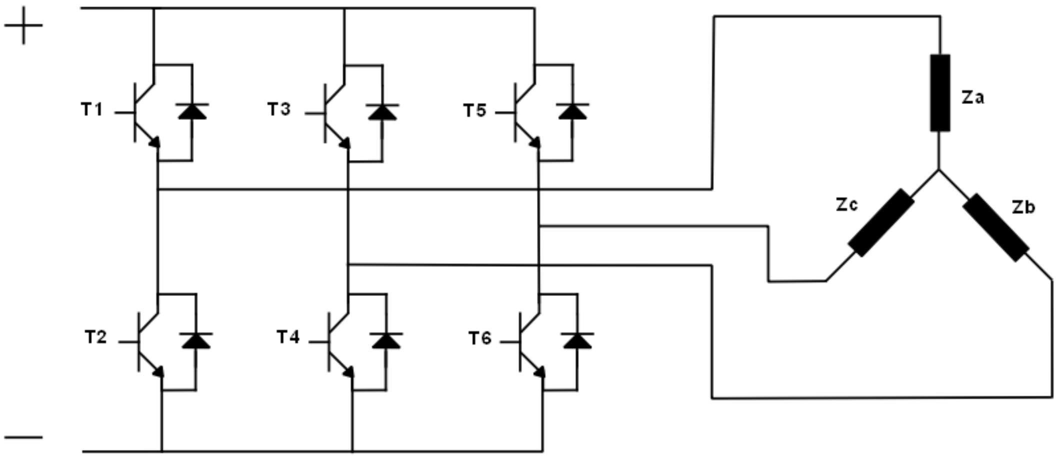

Figure 5 System electrical diagram

Trapezoidal control involves the application of current to two phases, while the other one remains in an open circuit. The inverter diodes allow current return whenever necessary, while the transistors allow direct power supply to be controlled.

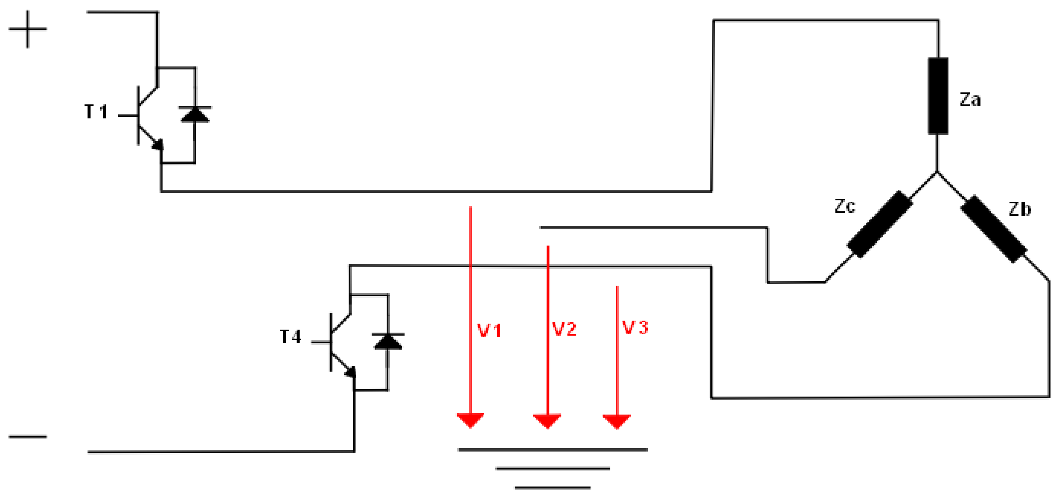

Figure 6 Trapezoidal control electrical diagram.

In order to carry out this type of control, the permanent magnet motors normally include three HALL effect sensors that digitally codify the rotor position by means of three bits that transmit to the outside. This information is interpreted by preprogrammed integrated circuits to apply the pulses calculated by the control algorithm to the inverter. This control algorithm is normally known as trapezoidal current control (not to be confused with the trapezoidal flux generated by the grooved rotor motors: trapezoidal control can be applied to both grooved or wound rotor motors). For instance, device UCC2626 by Texas Instruments, implements this type of control by introducing a 60º overlap angle between the three bits. The graph below shows the steady-state phase currents for a 100% useful cycle (no PWM pulses are applied to the transistors) and for a 50% useful cycle applying PWM to the active transistors.

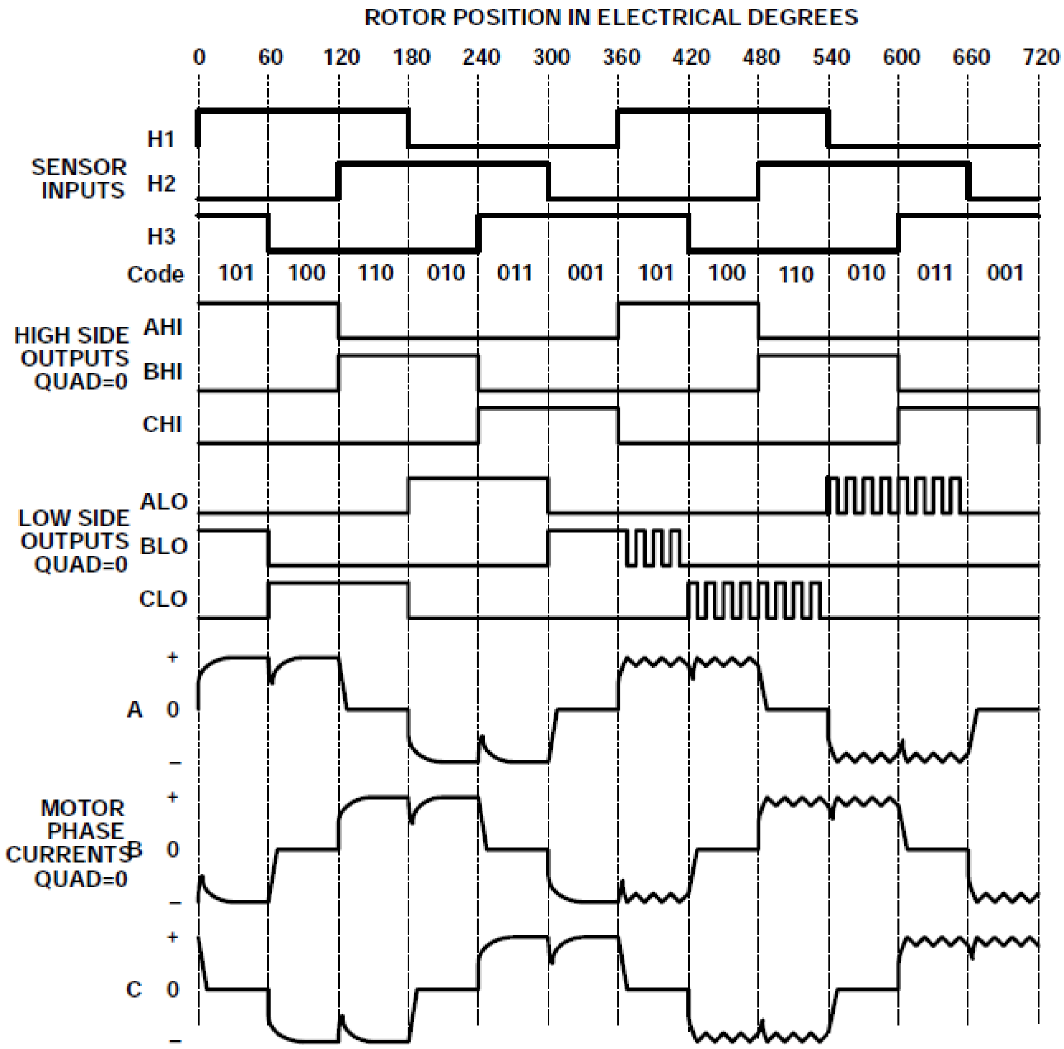

Figure 7 Evolution of the main variables of a trapezoidal control system.

4. MODEL DEVELOPED IN ECOSIMPRO

After the above concepts have been introduced, the model developed in EcosimPro [1] can be analysed. The system shall have a dual purpose: Firstly, it shall be used as motive power during the startup of the main motors. To do this, the unit shall be fed from a DC power source (batteries) until the assembly reaches enough velocity for the main motor to reach the compression required to operate by itself. In addition, the main motors shall be in charge of rotating the assembly once they are in operation. Under these circumstances, the operation of the unit shall be inverted and shall operate as a generator feeding the electrical system of the aircraft.

The model developed on this occasion focuses on the modelling of the startup phase and its trapezoidal current control. The purpose is to reach a speed of approximately 9000 rpm. To do this, the useful cycle required for the PWM of the poles shall be established with prior experiments. Modulation by pulse width allows additional control. The position of the rotor determines what transistors are active, while the PWM control makes those active transistors remain open during part of their activity and closed the rest of the time. This control may be applied to the top part of the inverter, the bottom one or both. It has only been applied to the top part in the developed model. Thus, the model of the battery startup system by means of permanent magnet synchronous motor developed by EcosimPro is as shown in the following figure:

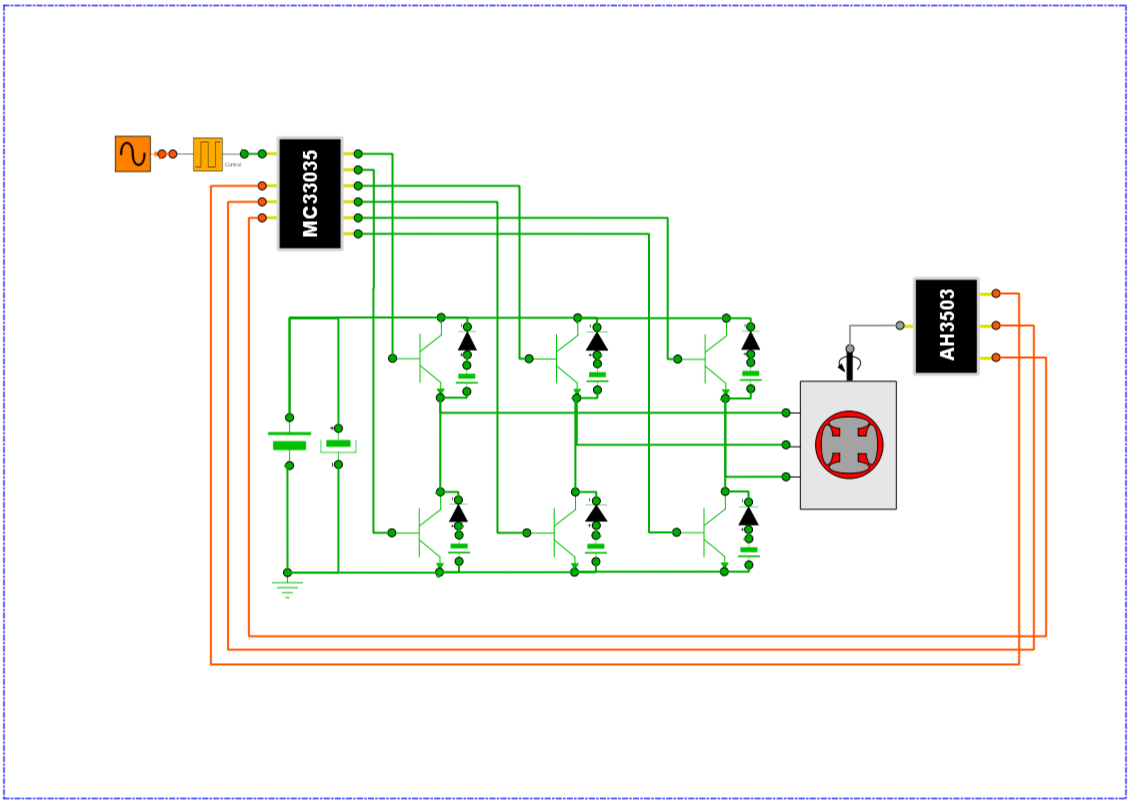

Figure 8 Model developed in EcosimPro [1] / Proosis [2]

The inverter has been modelled with ideal transistors and ideal diodes. However, the data for the conductor resistance and locking of both, and for the direct voltage of the diode, are available. Using these parameters it is possible to model poles with a behaviour that is much closer to reality.

In addition, component AH3503 is the integrated circuit of the same name, and it provides the angular position of the rotor as the digital output with three bits. Integrated component MC33035, as set out above, applies the trapezoidal current control depending on the rotor position and on the PWM modulation indicated by the controller that is shown in the figure. The synchronous unit follows the model presented above: permanent magnet with wound rotor configured with the following parameters:

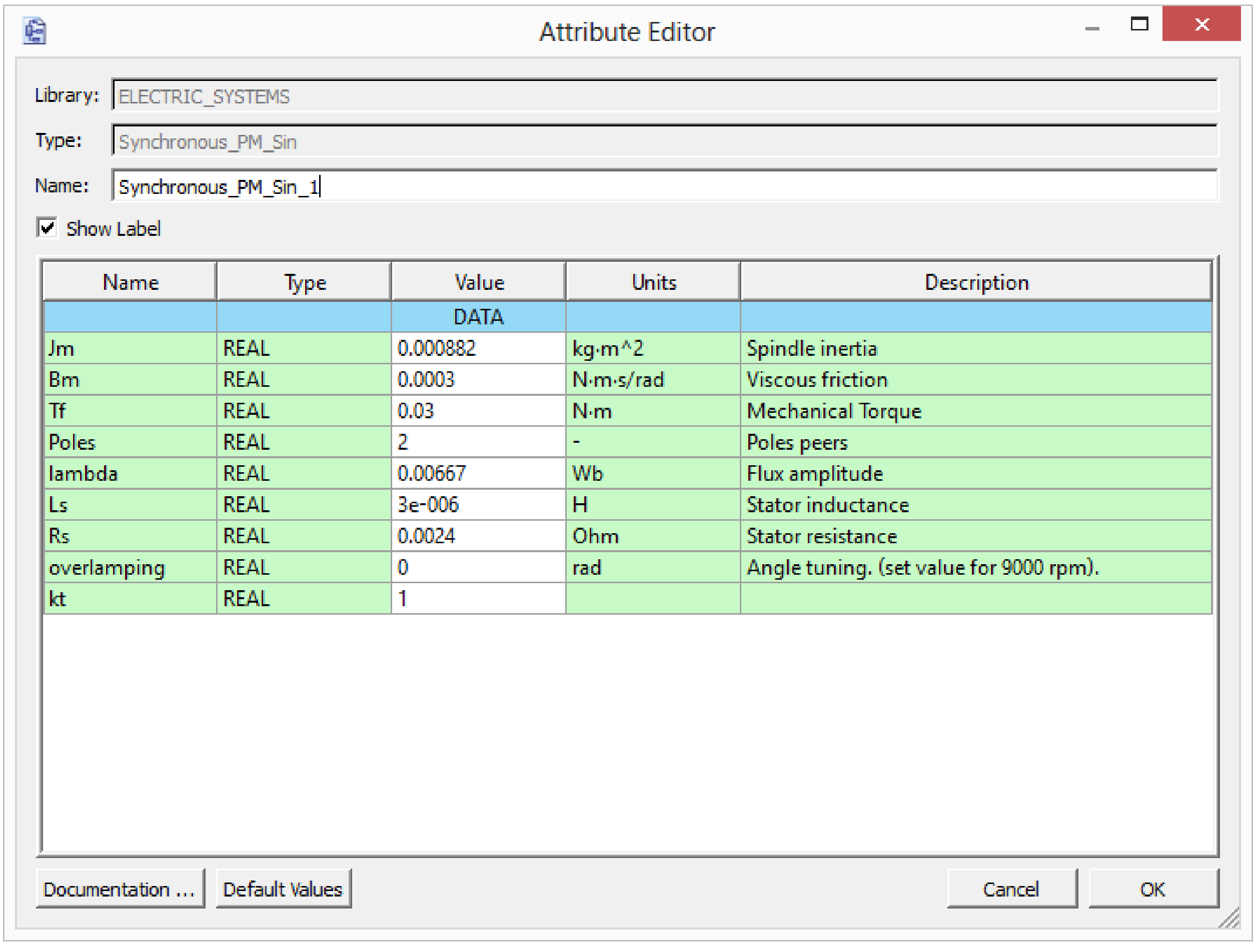

Figure 9 Configuration menu of the permanent magnet unit

5. SIMULATION AND RESULT ANALYSIS

The results obtained can be analysed after the model has been described. Firstly, the evolution of the speed during startup is analysed. As anticipated, it reaches a steady-state value of around 9000 rpm. The useful cycle allows the power provided by the motor and, therefore, its steady-state speed with a given load, to be modified. The final value has been set at 65%.

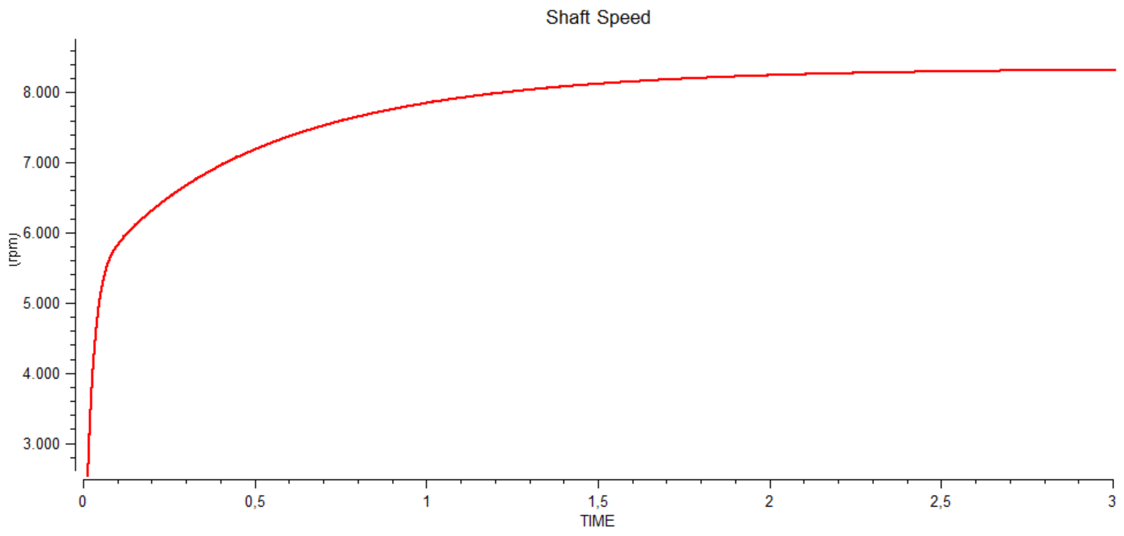

Figure 10 Evolution of the shaft speed.

The following chart shows how current drops as the unit gains speed and the induced electromotive forces increase. In addition, the shape of the domes bounded by flat areas of zero current coincides with the expected values set out in the manufacturer's data sheet. It can be seen that each section is formed by six different sections that correspond to each of the six poles of the inverter.

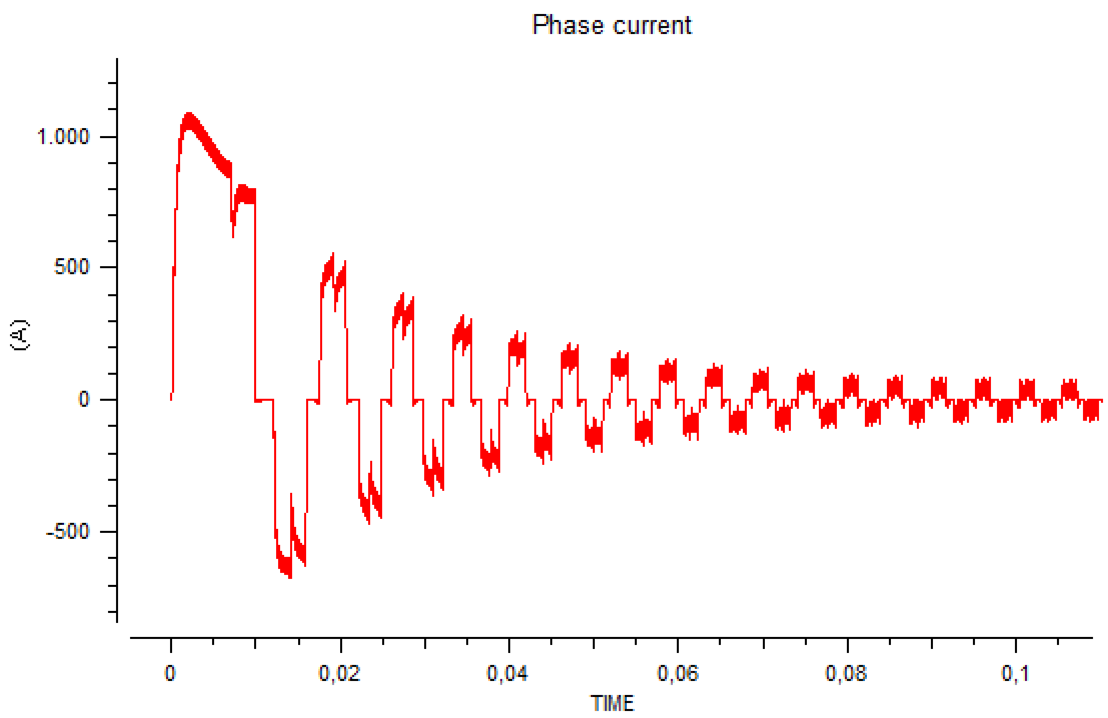

Figure 11 Phase current.

The following image shows the high-frequency PWM switching and the six switching states of a complete cycle that correspond to each of the six poles of the inverter:

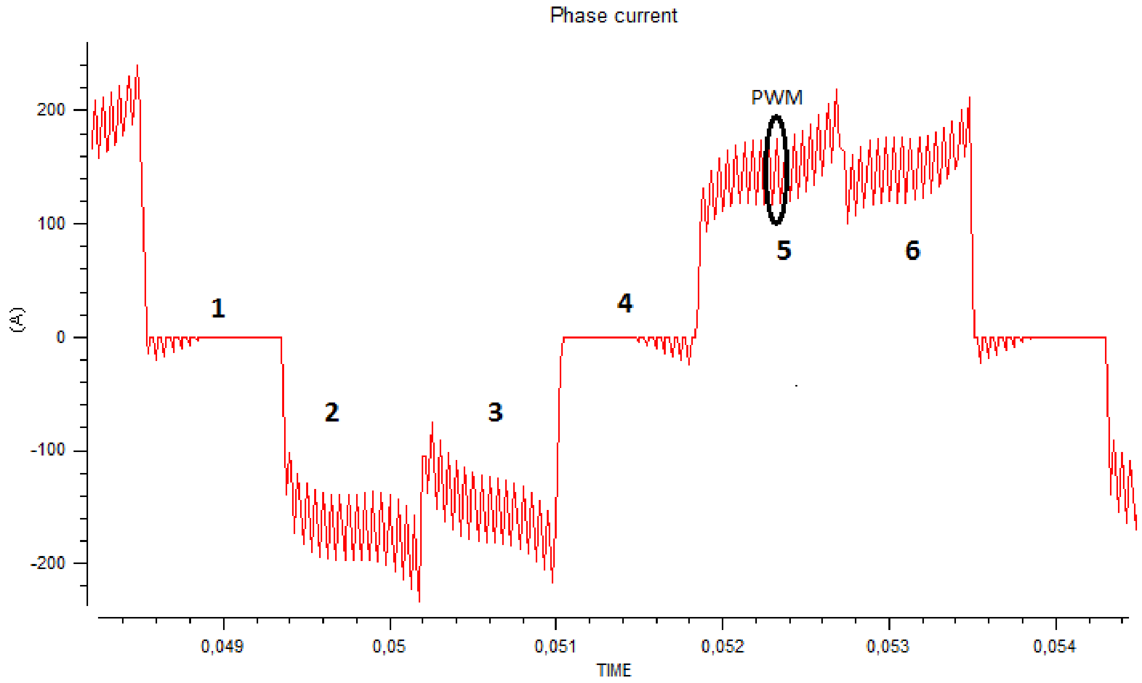

Figure 12 PWM detail in the phase current.

The EcosimPro monitor allows an in-depth study of the operation of the model and its control. The following graph shows the control of the top part of the inverter with a 100% useful cycle and the next one shows the control of the bottom part with PWM and a 65% useful cycle. Both are shown overlapping a turn of the rotor (2pi radians).

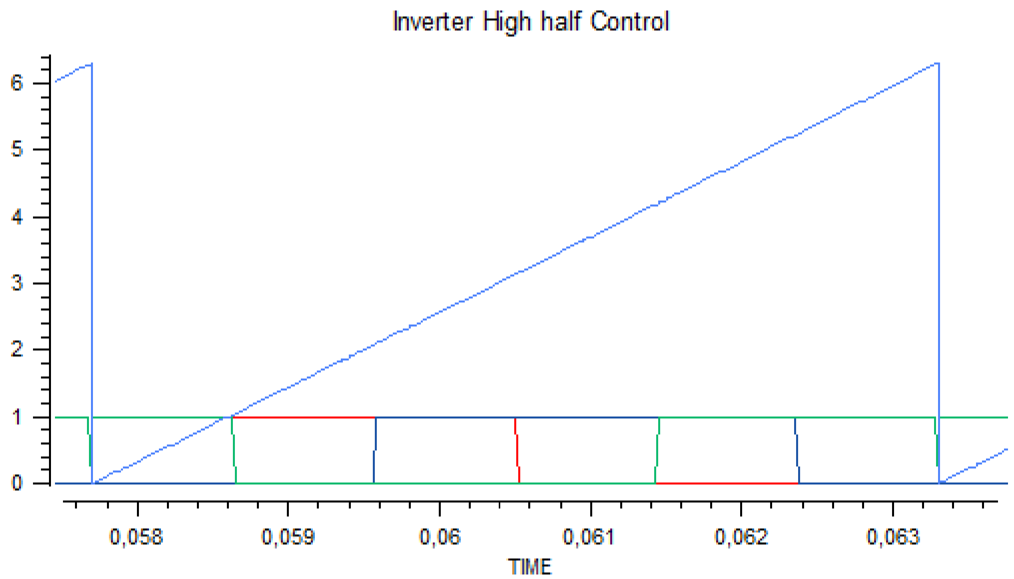

Figure 13 Follow-up of the rotor position.

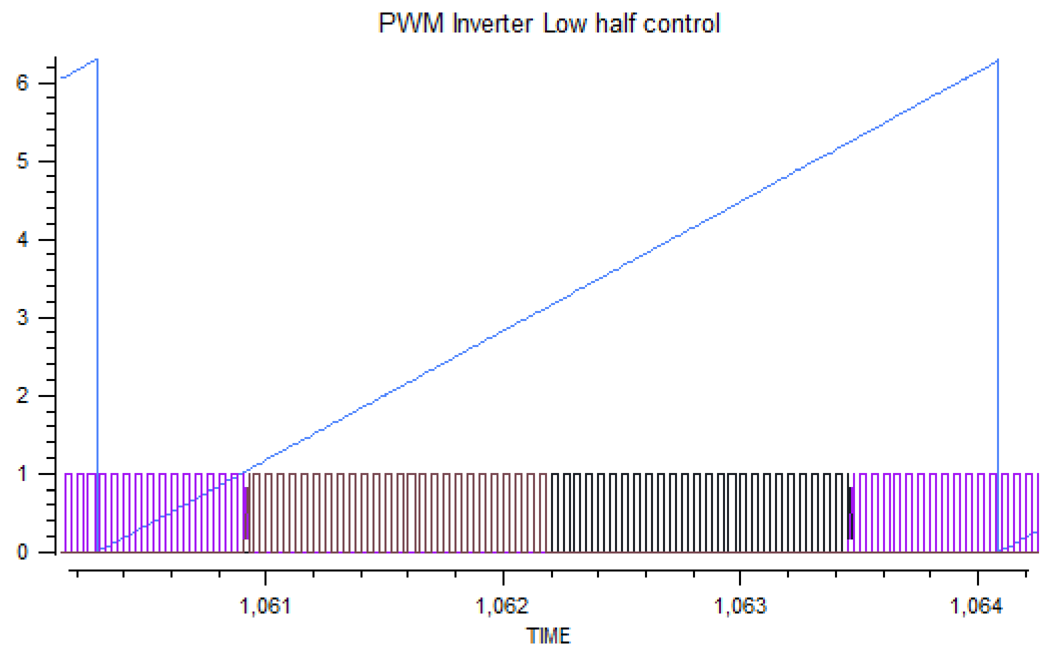

Figure 14 PWM modulation

Below is an analysis of the system response upon different modifications. Firstly, the useful cycle of the PWM signal is reduced from 60% to 50%.

The shaft speed response is shown below:

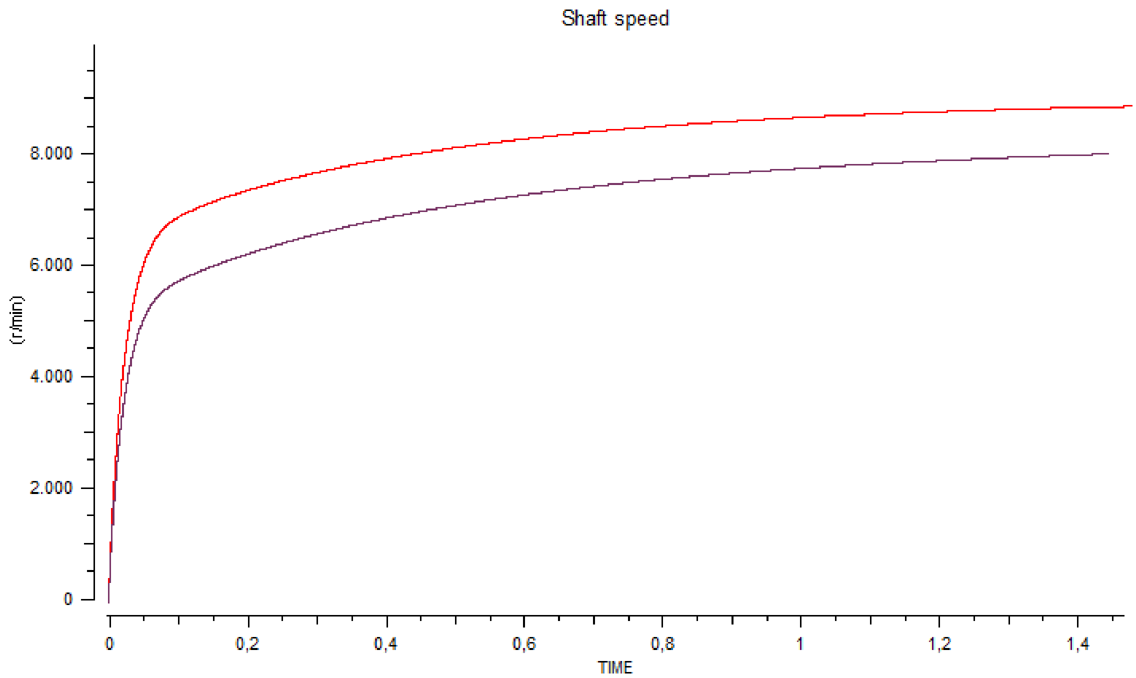

Figure 15 Shaft speed for PWM of different useful cycles.

The figure shows that the motor accelerates slower when the torque is lower and, in turn, the steady-state speed is lower.

Furthermore, the amplitude of the phase current is also reduced. It is also clear that the change in shaft speed slows down the change in position and this, in turn, reduces the frequency of the supply current and introduces a delay in the waveforms with respect to those generated during the no load startup.

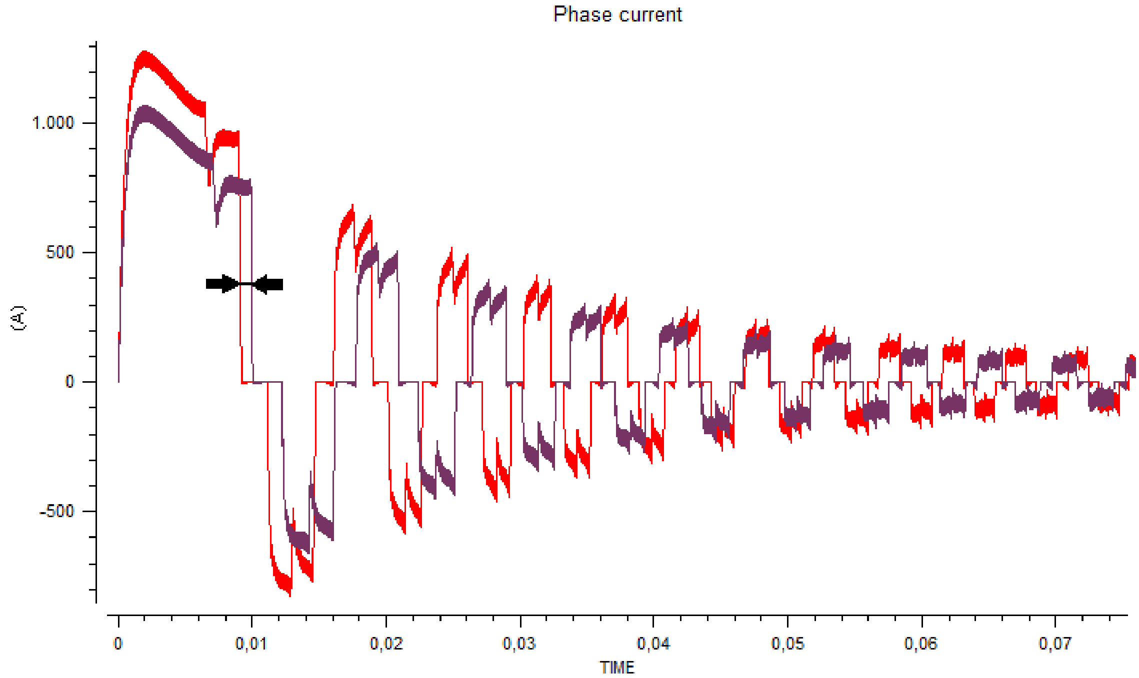

Figure 16 PWM phase current with different useful cycles.

The influence of the mechanical load applied on the shaft is also studied, by increasing its value up to 10 Nm:

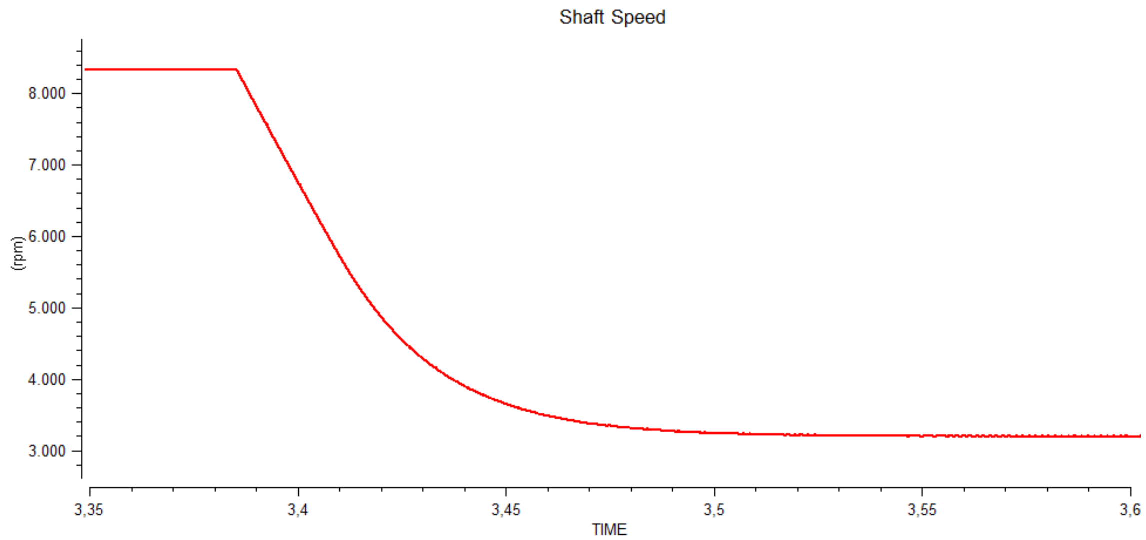

Figure 17 Shaft speed upon a load increase.

The motor specifications indicate that 10 Nm are a significant mechanical load. The motor speed is thus seen to drop by more than 50%, bellow 4000 rpm.

The value of the current needs to increase to generate a higher torque and make up for this load. The phase current increases significantly from the value close to no load where the startup occurred:

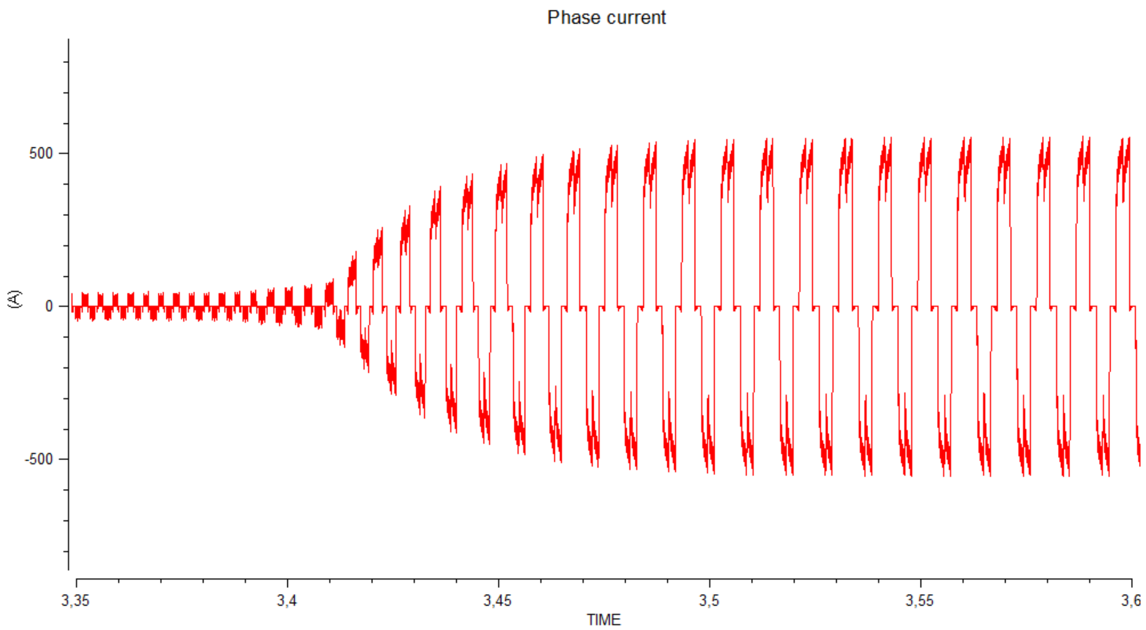

Figure 18 Phase current upon a load increase.

It is also important to note how, once again, the synchronism between supply currents and the shaft position means that the current frequency is lower when the shaft speed drops.

6. CONCLUSIONS

After completing the system model and analysing the results, it can be ascertained that EcosimPro [1] / Proosis [2] and the ELECTRIC SYSTEMS [3] library constitute an adequate environment to develop and model this type of system. The components are flexible enough to allow easy adaptation to the specific characteristics of every motor, inverter or mechanical load.

The waveforms obtained for the electrical variables were as expected, and their behaviour is very similar to the behaviour measured with the instrumentation applied to real systems. On the other hand, the shaft speed was the same as the one measured in real motors with similar configurations.

In addition, the model may be extended to cater for additional needs. The following goal would be to implement the measurement of active and reactive power in axes d and q in the unit model. Following up on these variables allows the comparison of the capability of reversibility of the model, which would change from operating as a starter motor to operating as an electrical power generator moved by the main motors.

Several alternative versions with concentric control loops on the motor have been developed. In particular, in many applications it is useful to maintain a certain control over the shaft speed. Under these conditions, the shaft position would dictate what poles are active, while its speed would establish the useful cycle of the PWM signal.

7. REFERENCES

- [1] PROOSIS: Propulsion Object Oriented Simulation Software, Empresarios Agrupados Internacional (EAI).

- [2] TURBO: Gas Turbine Performance Simulation Library, Empresarios Agrupados Internacional (EAI).

- [3] ELECTRIC_SYSTEMS: Electric, Electronic and Power Systems Simulation Library, Empresarios Agrupados Internacional (EAI).