A609 Modeling of AC Servomotor Using Genetic Algorithm and Tests for Control of a Robotic Joint

J. G. Batista, T. S. Santiago, E. A. Ribeiro, G. A. P. Thé

***Abstract*—**This work deals with parameter identification of permanent magnet motors, a class of ac motor which is particularly important in industrial automation due to characteristics like applications high performance, are very attractive for applications with limited space and reducing the need to eliminate because they have reduced size and volume and can operate in a wide speed range, without independent ventilation. By using experimental data and genetic algorithm we have been able to extract values for both the motor inductance and the electromechanical coupling constant, which are then compared to measure and/or expected values.

***Keywords*—**Modeling, AC servomotor, Permanent Magnet Synchronous Motor-PMSM, Genetic Algorithm, Vector Control, Robotic Manipulator, Control.

I. Introduction

POSITION control is essential for a wide range of industrial applications as, for instance, robotic manipulation, transportation in conveyor belts, etc., allowing for quality of products and processes as well as security. Typical choices for accomplishing motion in industrial application relied on the use of DC motors, a scenario which has changed due to the progresses carried out by power electronics in the development of frequency converters, thus opening the way for AC driving. Particularly important in this context was the advance of microelectronics, which provided frequency converters with increasingly complex functions [1].

Indeed, the use of electric motors with AC drives has increased significantly in recent years; main reasons for choosing motor/frequency converter assembly are speed adjustment, energy saving, position control and soft start, as well as adaptability to different motor technologies (synchronous, permanent magnet synchronous, switched reluctance, etc.) [2].

A. The Permanent Magnet Synchronous Motors

The Permanent Magnet Synchronous Motors – PMSM, also called by the manufacturers of AC servo motor. "Booster" because this motor run with feedback monitoring system of the motor shaft due to a position sensor. The MSIPs fed by a frequency inverter can be used in industry where the speed variation with constant torque and high performance are required [3]-[5].

The PMSM are also being used in applications where reliability, smooth torque, low vibration and noise are key [6].

The PMSM, generally used in applications where high performance is required, are very attractive for applications with limited space and reducing the need to eliminate because they have reduced size and volume and can operate in a wide speed range, without independent ventilation [7].

Following the market trends, the use of synchronous motors with permanent magnet is in wide expansion, also in the industry, because the motor has extra-high-yield, low volume and weight, smooth torque, low vibration and noise, wide band rotation with constant torque and with the advent from the 80s, Magnets Neodymium Iron Boron (NdFeB), high energy, there was an increase in the number of applications, which uses this technology [8].

B. The Permanent Magnet Synchronous Motors AC

There are two main types of PMSM: DC and AC. The PMSM has the similar function with the DC motor with brushes. DC motor in the fixed magnetic field is formed by permanent magnets or coils that are in the stator. In the rotor are coils of armor where voltage and supply current to control speed and torque are applied. PMSM happens in reverse manner, we have a permanent magnet for generating the fixed field in the rotor and stator coils in which voltage to control speed and torque are applied.

In DC motor, torque control is realized by armature current. In PMSM, the torque control is accomplished through the vector or field oriented control. In this research we will use an AC PMSM drive for joint of a robotic manipulator SCARA (Selective Compliant Assembly Robot Arm) 4 degrees of freedom.

The aim of this paper is the identification of garments from PMSM for the lifting of transfer function, allowing subsequently control the motor using vector control for the movement of joints of the robotic manipulator mentioned above, since the robotic manipulator lies unused by problems the controller. The main idea in this moment would be the reuse of MSIPs that it is in perfect working order. For the motor drive a frequency inverter with vector control will be used.

The main justification for the application of this motor would be the high performance resulting in lower power

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consumption compared to other types of motors as well as other advantages mentioned above.

II. Vector Control

The vector control (also called Field Orientation Control - FOC) is a method used in variable speed drive for AC PMSM to control the torque, and hence, the speed, through a control loop that monitors the current sent to the machine.

Vector control allows achieving a high degree of accuracy and speed in the torque and speed control.

The motors vector control can be further divided into two types: normal and "sensorless" (without sensors). Recently, many researches are conducted for the control of PMSM using vector control. The idea is to estimate the rotor position through angle estimation, where the stator voltages and currents signals are used to estimate the instantaneous flow. The position value is obtained through the phase angle of the stator current which can be controlled to keep it perpendicular to the rotor magnetic field vector for excellent range of torque and speed [9].

With the advent of permanent materials (PM) with high coactivity of residual flow, it has been possible for the PMSM are higher than the induction of general use in power density, ratio of torque to inertia, and efficiency of motors. Therefore, PMSM are most interest in many industrial applications as substitutes for induction motors. Furthermore, the vector control MSIPs is much simpler than that the induction motor because there is no need to consider the slip frequency as in the induction motor [6]. However, a vector control of PMSM requires a position sensor, to correctly orient the current vector orthogonal to the flow, since the rotor flux is obtained from permanent magnets. Thus, we can directly control the torque simply acting on the amplitude of stator current. Thus, one can achieve a high degree of torque control of wide speed range, including motor braking, which can be instantly [7].

Fig. 1 illustrates the representation of the electrical equivalent circuit of the PMSM per phase. We can observe that the DC motor is similar, except that the values of current and voltage are sinusoidal [3], [4].

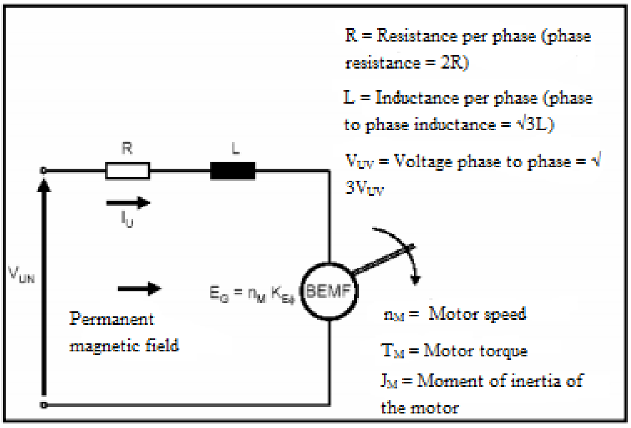

Fig. 1 Electrical equivalent circuit of the PMSM

The vector control of PMSM allows current phase remains in phase with the electromotive force against (BEMF) all the time and controlling the amplitude of the phase current can adjust the motor torque.

Fig. 2 shows the relationship of voltage vectors of the electric circuit shown in Fig. 1.

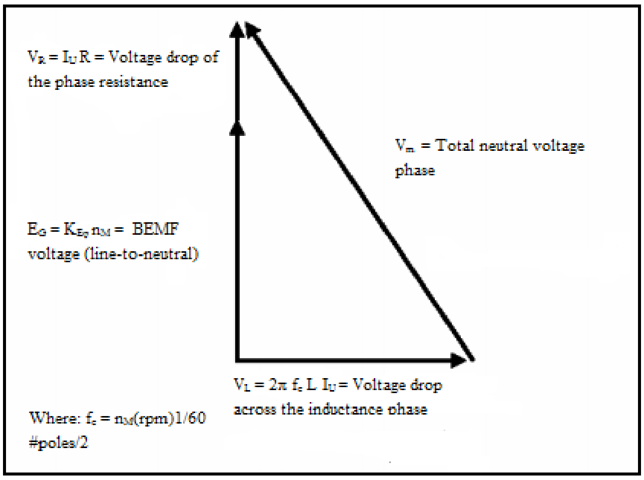

Fig. 2 Voltage Vectors of the PMSM.

Since the voltage vectors can be concluded:

$$V_{un} = \sqrt{(V_L)^2 + (E_G + V_R)^2} \quad (1)$$

$$V_{un} = \sqrt{(2\pi f_e L I_U)^2 + (k_{E\varphi} n_M + I_U R)^2} \quad (2)$$

where: n_M is the rotation speed of the motor, f_e is the frequency of the rotating field of rotor, R is the coil resistance per phase, L is coil inductance per phase, IU is current phase and$k_{e\varphi}$is a constant that depends on the constructive characteristics of motor.

The current cannot be isolated, because it has a non-linear dependence parameters:

$$I_u = \mathrm{f}(V_{un}, n_M) \quad (3)$$

We also have that:

$$\tau = \mathrm{k_T} . \mathrm{I_U} \quad (4)$$

Fig. 3 shows the block diagram of the PMSM.

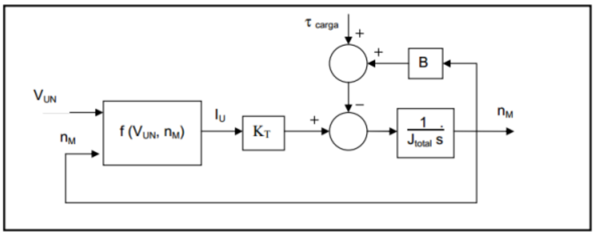

Fig. 3 Block diagram of the PMSM where J_{total} is the moment of inertia of the mechanical system: the motor shaft more load; B is the viscous friction; $K_T$is the torque constant

III. Experiments

The experiment was conducted in the laboratory using a brushless motor whose characteristics are shown in Table I.

TABLE I
BRUSHLESS MOTOR DATA

Number of poles	2
Resistance (R) per phase	10 Ω
Potency (P)	160 W
Voltage (V)	220Vca
Frequency (f)	60 Hz
Rated Torque(T_{nom})	$9.55*(P_n/N_n) = 9.55*(160/3000) = 0.5094$ Nm

For identifying the parameters, the experiment illustrated in Fig. 4 was performed; data were collected and are shown in Table II.

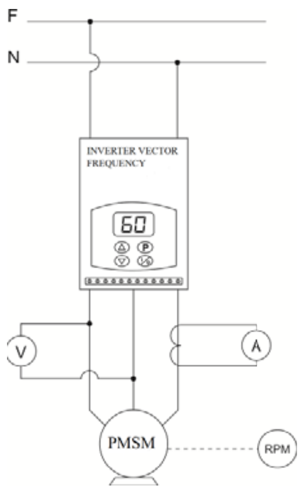

Fig. 4 Scheme of the experiment to identify the parameters

In this experiment, we used an AC-DC-AC converter (variable frequency drive) applying modulated PWM voltage.

This inverter has the option to open-loop vector control, sensor less. Fig.5 shows the diagram of the frequency inverter used in PMSM drive.

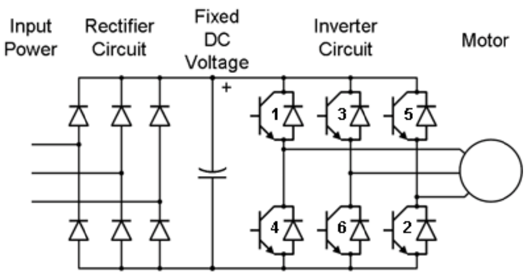

Fig. 5 Diagram of the frequency inverter used in the PMSM drive

Fifteen tests conducted by varying the frequency at 5 Hz, the current values corresponding to a phase were measured using a current clamp ammeter. Phase voltage was obtained by measuring the inverter output were measured.

The values of rotations were obtained using a tachometer with laser optical measurement.

TABLE II
VALUES OBTAINED IN THE TEST WITH PMSM

Test	I (A)	U(V)	f (Hz)	Rotation(rpm)
01	0.6	15	5	150
02	0.8	18	10	300
03	0.9	24	15	450
04	1.1	31	20	630
05	1.0	36	25	770
06	0.9	40	30	910
07	0.8	45	35	1060
08	0.8	50	40	1210
09	0.7	55	45	1360
10	0.6	60	50	1509
11	0.6	64	55	1659
12	0.5	68	60	1809
13	0.3	69	65	1960
14	0.8	70	70	2135
15	0.8	72	75	2276

IV. Genetic Algorithm – GA

Genetic algorithms are especially used to find solution of problems with a large search space, with many restrictions and problems with several parameters with a high possibility of combinations [10]. This applies to the problem in question, because there must be a pair (K, L) such that, if applied to (2) provides solution for all test data presented in Table II.

The idea to use Genetic Algorithm (GA) is that it is able to evolve a population of candidate solutions to a given problem, so that an operator inspired by natural genetic variation and natural selection will find best solution [10]. Fig. 6 summarizes the process, and chooses the best solution. We used the GA in this work because it was the method that is currently available faster.

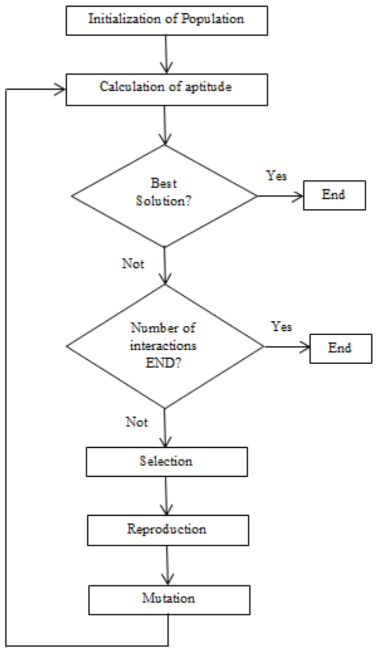

Fig. 6 Steps to implement the GA

Each individual in the population, which is randomly initialized, has 24bits as shown in Fig. 7 and this figure consists of the input parameters.

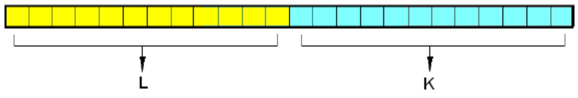

Fig. 7 Individual or chromosome formed by 24 bits

Each individual generates a solution of voltage according to (2) that seeks to satisfy the measurement of voltage tests. From this it will be reported as the best individual evolves along the search, the term best guy who has lower cost (fitness). Individuals with the best reviews will be selected to generate new individuals, thus formed a new generation of solutions [11].

When generating a set of (population) solutions using genetic algorithm, these results are evaluated individually, receiving a score according to the need and constraints imposed by the project. To make this assessment, the Genetic Algorithm (GA) uses an equation fitness (5), calculated for the entire range of frequencies tested, and associates a note. The evolution of the evaluation of best individual is shown in Fig. 8.

$$Rating = SUM \mid (Test\ Result - Result\ AG) \mid \tag{5}$$

In this research, several trials, we was observed that after generation 500 there are almost no change in the best individual, in this way, the problem in question, the stopping criterion was chosen number of generations equal to 1000. We can be seen in Fig. 8 that this generation number meets the needs of search.

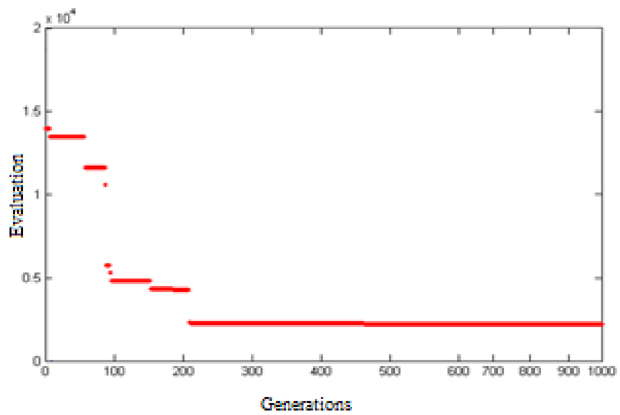

Fig. 8 Evaluation of the Evolution of Best Individual (solution) using GA

Another consideration in the algorithm is that there is elitism, in other words the best individual always remains in the next generation, this is a way not to lose the best solution if it has already been found [10].

V. Analysis of Results of Identification with GA

Simulating the algorithm using GA for multiple tests with different voltages and frequencies, we found as the best solution values as Table III.

TABLE III
BEST PARAMETERS FOUND BY THE GA

Parameter Searched	Best results found
L (Inductance)	26.50 mH
K (Motor constant)	0.149 V/rad/s

The value found for the inductance is compatible with the same type motors and with equivalent specifications. For comparison, the CMP40S motor manufacturer SEW EURODRIVE [12] presents rated speed equal to 3000 rpm (same as indicated on the motor nameplate in research), rated torque of 0.5 Nm (comparable to the calculation of Table I) , per phase resistance of about 10 ohms (also comparable to the motor test), equal to inductance and 23.0 mH.

It is worth mentioning that, during the analysis of the results of Genetic Algorithm, we supposed that the inductance has less influence in obtaining lower of cost function of the constant K. The values presented in Table III correspond to approach the order of 1.2 V between the measured voltage value (Table II) and the theoretical value of convergence voltage obtained via the genetic algorithm. This is in the range from 2.0 to 4.0% for intermediate values of frequency, which is acceptable if the measurement process uncertainties are taken into account.

Although the inductance could be measured with equipment such as FLUKE - AM 6304 - PROGRAMMABLE AUTOMATIC METER RLC, the absence of such equipment in the laboratory and a procedure for estimating K justify, in the opinion of the authors, the adoption of the method used.

VI. Moment of Inertia

The moment of inertia or inertia moment is a parameter which defines the strength of a body opposed to the variations in speed relative to a given axis. We observed that the moment of inertia of a body depends on the axis around which it is rotating, the body shape and the way that its mass is distributed and is defined as the product of the rotating mass of gyration radius square, expressed in kgm² [13].

It is essential to know the moment of inertia of the load to be triggered to determine the "acceleration time" of a motor, that is, whether the motor will be able to drive the load under normal conditions and without causing damage to the motor [13].

We noted that the total moment of inertia of system is the sum of the moments of inertia of load and motor:

$$J_t = J_m + J_c \tag{6}$$

If the load is rotating at a speed different from the motor, its inertial movement must be converted to motor speed before being added to this inertia.

$$J_{cr} = J_c \left(\frac{nc}{n}\right)^2 [kgm^2] \quad (7)$$

where:
J_t = total moment of inertia;
J_{cr}= moment of inertia of the load referred to the motor shaft;
J_m = moment of inertia of the motor;
J_c = moment of inertia of the load;
n_c= load speed;
n= rated motor speed.

The NBR 17094 sets the maximum values of moment of inertia of load (Table IV) for which the motor must be able to meet the conditions of the drive load.

TABLE IV
MOMENT OF INERTIA EXTERNAL (J) TO THE NORMALIZED POWERS (VALUES GIVEN IN TERMS OF MR², WHERE M IS THE MASS AND R IS THE MEAN RADIUS OF GYRATION)

Rated Power		Number of poles			
kW	cv	2 J [kgm²]	4 J [kgm²]	6 J [kgm²]	8 J [kgm²]
0.37	0.50	0.016	0.092	0.255	0.523
0.55	0.75	0.023	0.132	0.364	0.747
0.75	1.0	0.031	0.175	0.481	0.988
1.1	1.5	0.044	0.247	0.679	1.390
1.5	2.0	0.058	0.326	0.898	1.840
2.2	3.0	0.081	0.460	1.270	2.600
3.0	4.0	0.108	0.608	1.680	3.440
3.7	5.0	0.130	0.735	2.020	4.160
5.5	7.5	0.186	1.050	2.890	5.940
7.5	10	0.242	1.370	3.780	7.750
11	15	0.346	1.960	5.400	11.10
15	20	0.458	2.590	7.130	14.60
18.5	25	0.553	3.130	8.620	17.70
22	30	0.646	3.650	10.10	20.70
30	40	0.854	4.830	13.30	27.30

The values in Table IV are given in terms of mass-radius squared. They were calculated from (8):

$$J_m = 0{,}04 Pn^{0{,}9} p^{2{,}5} [kgm^2] \quad (8)$$

where:
Pn = Nominal power in kW;
p= number of pairs of poles.

For intermediate values of rated power, the moment of inertia must be calculated outside the above equation.

VII. Mechanical Parameters of PMSM

A. Moment of Inertia, J_m

From (8), applying data from the PMSM can find the moment of inertia:

$$\mathbf{J_m = 0,0435\ [\,kgm^2]}$$

B. Equivalent Viscous Friction Coefficient of the Motor, B

A simplified method is performed by measuring the power absorbed by the electric motor, spinning the empty and steady speed. However, neglecting the resistive and magnetic losses, it can be stated that the electrical power, P_{el}, absorbed is equal to the mechanical power, P_{mec}, developed by the motor:

$$P_{el} = P_{mec} = \Omega C_L = \Omega C_m \quad (9)$$

Turning the motor without load and constant speed, we can write:

$$C_m = B\Omega \quad (10)$$

$$B = \frac{C_m}{\Omega} \quad (11)$$

From (10) and (11) we find B, the motor using**Ω** = 150 rpm (15.7 rad/s) and Cm = 0.5094 Nm, hence we have:

B = 0.032446 Nm/rad/s.

C. Motor Torque Constant, Km

Using (11) we conclude that:

$$C_m = K_m I = B\Omega \quad (12)$$

$$K_m = \frac{B\Omega}{I} = \frac{C_m}{I} \quad (13)$$

With the values of Cm = 0.5094 and I = 0.6 A, have:

$$\mathbf{K_m = 0.849\ Nm/A}$$

The determination of Km is done by measuring the current I absorbed at a given speed Ω and knowing the coefficient of equivalent viscous friction of motor at that speed, and then measuring the Cm conjunction with a dynamometer, and the corresponding current I.

VIII. PMSM Parameters and Transfer Function

From the tests and identifications shown above, we have all of the PMSM parameters shown in Table V.

TABLE V
PMSM PARAMETERS OBTAINED THROUGH THE IDENTIFICATION AND TESTS

Parameters	Value
Resistance (R) per phase	10 Ω
Inductance (L)	26.50 mH
Constant fcem (Kb)	0.149 V/rad/s
Moment of inertia of the motor(Jm)	0.0435 kgm²
Constant Torque(Km)	0.849 Nm/A
Coefficient of Friction(B)	0.032446 Nm/rad/s

As previously mentioned, the similarity between the electric permanent magnet synchronous servo motors and DC servo motors allows us to write the transfer function of the PMSM from the transfer function of DC motor.

With the parameters of Table V and the block diagram shown in Fig. 9 we can write the transfer function of the PMSM.

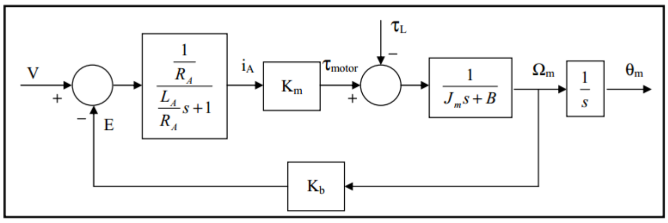

Fig. 9 Block diagram of the DC motor

$$F(s) = \frac{\Omega_m}{V} = \frac{K_m}{(J_m s+B)(Ls+R)+K_m K_b} \quad (14)$$

Substituting the values from Table V, we have:

$$F(s) = \frac{\Omega_m}{V} = \frac{736.5}{s^2+386.5s+400} \quad (15)$$

The transfer function show in (15) relating the input voltage with the speed of the PMSM and discarding the touch load τ_l.

For the motor position we have:

$$F(s) = \frac{\theta_m}{V} = \frac{736.5}{s^3+386.5s^2+400s} \quad (16)$$

IX. Simulation Results

With the transfer function identified, however, the first step is to perform the simulation of motor in open loop. The simulation was performed in a software environment that provides good resources. The block diagram of the motor is shown in Fig.10.

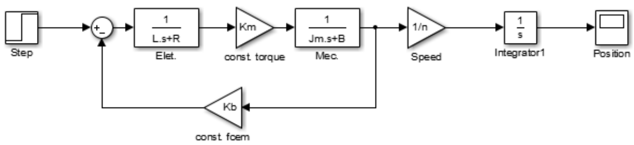

Fig. 10 Block diagram for simulation of PMSM

Using the functional units and the structure presented above presented simulation and applying a value of input voltage equal to 75 V, we can obtain the value of speed in motor output equal to 188 rad/s (1795,25 min^{-1}).The value of motor speed can be obtained from the simulation shown in Fig. 11.

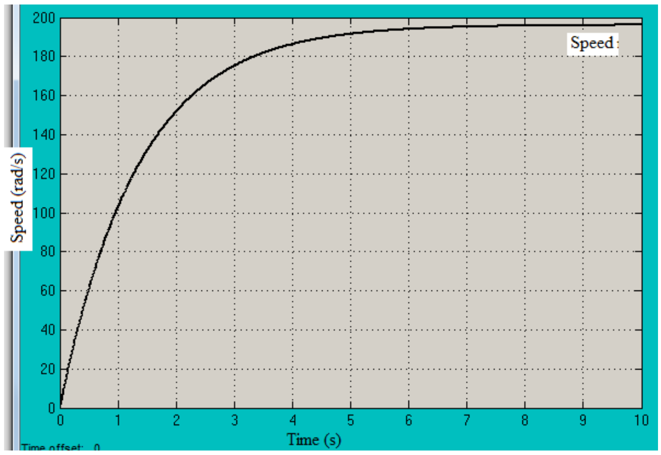

Fig. 11 Value of motor speed obtained in the simulation

The value of the applied voltage to the motor in the experiment was 75 V and measuring the output speed of the motor can show the values of velocity in Fig. 12. The value of the scheme was 1850 rpm, a value close to the simulation value with a small difference of only 3% of the value found in the simulation.

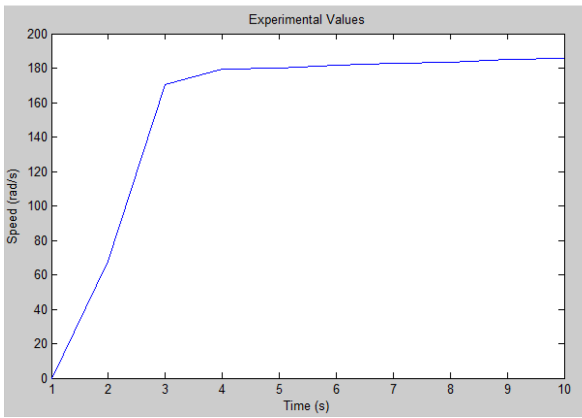

Fig. 12 Value of motor speed obtained in practical experiment

Fig. 13 shows a comparison of the values found in the experiment and the simulation values. With this we have a better view of the results found.

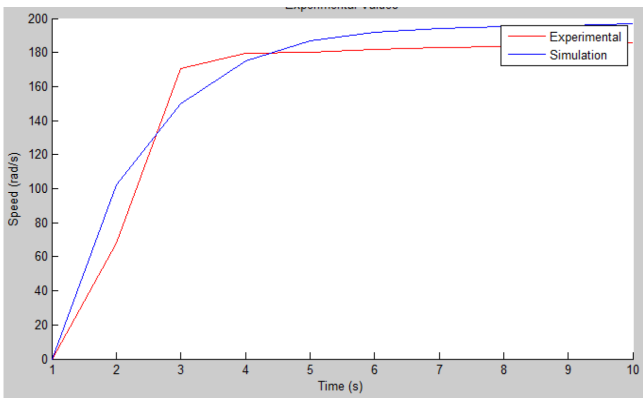

Fig. 13 Assimilation between experimental and simulated values

X. Conclusions

The adoption of the electrical equivalent circuit of the PMSM reveals a mesh equation (2), which relates the physical parameters of motor (U, K, R, number of pair of poles, etc.) with the excitation parameters (voltage and current). Through the tests we were able to find the mechanical parameters of motor. From the viewpoint of the dynamic model of said motor has been possible to construct the transfer function.

In this study, the approach of genetic algorithms to find a solution for the unknowns L (inductance) and K (electromechanical coupling) showed a method of rapid convergence (only 500 generations) were extracted by means of which L = 26, 5 mM and K = 0.149 V / rad / s for the frequency range of 75 Hz is not to say that the method used was the best because there are several methods that could be used. Particularly, the inductance value obtained is comparable to similar motors as well as parameters related to the mechanics. To tests performed to found here the transfer function of the motor researched. The main idea of this work is to find the transfer function of the motor control to perform this motor.

As future research, the motor control to drive a robotic SCARA manipulator that uses this motor in the joints, the dynamic model of the manipulator and finally the development of the controller will be held.

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