COUPLED MODEL FOR THE INTERIOR TYPE PERMANENT MAGNET SYNCHRONOUS MOTORS AT DIFFERENT SPEEDS

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1. INTRODUCTION

Permanent Magnet Synchronous Motors (PMSM) are widely applied in industrial and robotic applications due to their high efficiency, low inertia and high torque-to-volume ratio. Concerning with the design one of the greatest advantages of PMSM is that it can be designed directly for low speeds without any weakening in efficiency or power factor. An induction motor with a mechanical gearbox can often be replaced with a direct PMSM drive. Both space and cost will be saved, because the efficiency increases and the cost of maintenance decreases. A PMSM and a frequency converter form together a simple and effective choice in variable speed drives, because the total efficiency remains high even at lower speeds and the control of the whole system is very accurate. Since a low speed motor requires often a large amount of poles the number of stator slots per pole and phase is typically low. Thus the stator magneto motive force contains a lot of large harmonic components. Especially the fifth and the seventh stator harmonics are very harmful and tend to produce torque ripple at a frequency six times the supply frequency. At the lowest speed this might be extremely harmful.

The classical d-q model, uncoupled, linear and with constant parameter, applied to salient pole synchronous machines may be inadequate for accurate modelling and characteristics prediction of permanent magnet synchronous motors of interior type. It leads to important errors when evaluating machine performance or calculating the control circuits.

The lack of excitation control is one of the most important features of permanent magnet motors, as a consequence, the internal voltage of the motor rises proportionally to the rotor speed, and when the motor is working at constant horsepower mode its power factor becomes leading.

The behaviour of permanent magnet machines of the interior type can be rather different than expected form the conventional two axis theory. For this reason, it is necessary to establish new models to take into account the magnetic flux redistribution phenomena along the rotor iron placed between the magnets and the air-gap.

On the other side due to the presence of permanent magnet excitation, the conventional methods of testing for determination of synchronous machine parameters can not be applied in the case of permanent magnet machines, then it is necessary use tests procedures that differ from the classical methods applicable to wound field synchronous machines.

In order to observe the cross coupling phenomenon, we can measure and plot the curves of the interior voltage of the motor, "Vqi" versus "Id", for the machine under study, Fig. 1.

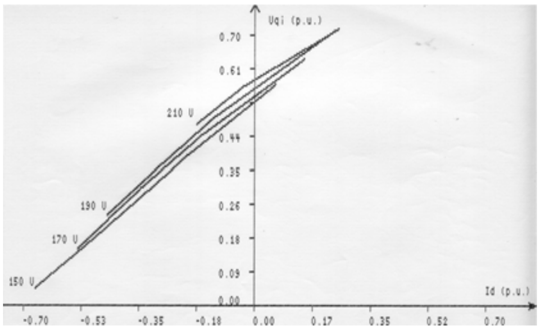

Figure 1.- Graphic representation of Vqi versus Id

The voltage steady state equations will be:

$$Vqi = \alpha \cdot Vq - R_1 \cdot Iq = \alpha \cdot Eo + \alpha \cdot Xd \cdot Id \qquad (1)$$
$$Vdi = \alpha \cdot Vd - R_1 \cdot Id = \alpha \cdot Xq \cdot Iq$$

Where "R_1" is the stator resistance, "E" is the induced voltage by the magnets and α is a coefficient for take into account the operation at different speeds.

If the cross coupling effect didn't exist and considering constant excitation all curves Vqi=f(Id) should cross at the same point for Id=0. However they intersect in different points. We can see , Fig. 1, that for Id=0 the distance between two curves Vqi is proportional to Iq, then we can think it is due to the magnetic coupling between d-q axis circuits, or in other words, the magnetic effects on the d-axis flux caused by q-axis current, of course we can consider the influence on the q-axis flux motivated by d-axis current. A possible solution for take into account this effect consist in the addition of a coupling term between the direct and the quadrature axis, then the model becomes:

$$Vqi = \alpha \cdot Eo + \alpha \cdot Xd \cdot Id + \alpha \cdot Xqd \cdot Iq \qquad (2)$$
$$Vdi = \alpha \cdot Xq \cdot Iq + \alpha \cdot Xdq \cdot Id$$

The effect of the term $\alpha \cdot Xdq \cdot Id$ depends of the configuration and dimensions of the PMSM and for the SIEMOSYN motors, Fig. 2, we have observed that it is practically negligible.

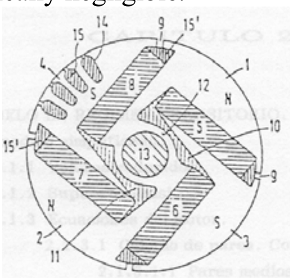

Figure 2.- Rotor configuration of a SIEMOSYN interior type PMSM

Then we can consider that the definition equations, Vqi and Vdi, for a SIEMOSYN PMSM, are:

$$Vqi = \alpha \cdot Eo + \alpha \cdot Xd \cdot Id + \alpha \cdot Xqd \cdot Iq \qquad (3)$$
$$Vdi = \alpha \cdot Xq \cdot Iq$$

and in Fig. 3 we can see the phasor diagram

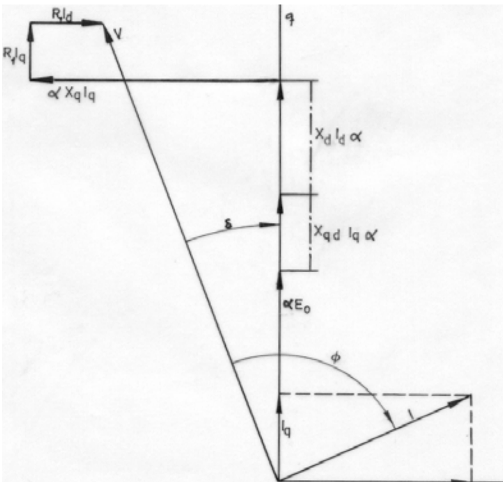

Figure 3. Phasor diagram for the SIEMOSYN interior type PMSM

II SYNCHRONOUS REACTANCES

Due to the presence of permanent excitation, the conventional methods of testing for determination of synchronous machine parameters can not be applied in the case of a permanent magnet machine. Measurement of its electrical parameters requires test procedures that differ from the classical methods applicable to wound field synchronous machines.

LOAD-ANGLE METHOD.

In this method, the MSIP operate like a generator, at synchronous speed, over a balanced three phase load. First we text the machine without load, we take the measurement of the Eo voltage and establish the position of the q-axis. After that we apply at synchronous machine different loads and we obtain the load angle in each case. In Fig.4 we can see the text scheme for this method.

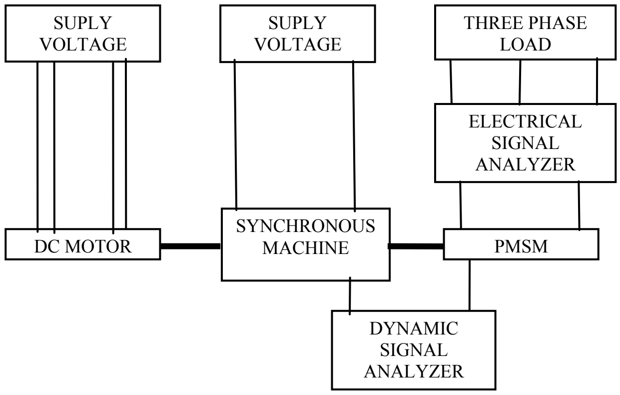

Figure 4.- Text scheme load-angle method.

Taking into account the classical model and for different speeds (different frequencies), the phasor diagram is represented in Fig. 5.

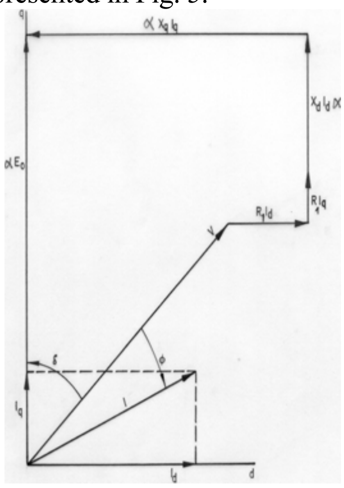

Figure 5. Phasor diagram model for a synchronous generator of salient poles at different speeds.

And then the equations of the voltages over the d and q axis, are:

$$\begin{aligned} V \cdot Sin(-\delta) &= \alpha \cdot Xq \cdot Iq - R_1 \cdot Id \\ V \cdot Cos(-\delta) &= \alpha \cdot Eo - \alpha \cdot Xd \cdot Id - R_1 \cdot Iq \end{aligned} \qquad (4)$$

For currents:

$$\begin{aligned} Id &= I_1 \cdot Sin(\phi - \delta) \\ Iq &= I_1 \cdot Cos(\phi - \delta) \end{aligned} \qquad (5)$$

Replacing the d-q currents, into voltage equations, allows solution to direct and quadrature axis reactances, for α=1:

$$Xd = \left[Eo - V \cdot Cos(-\delta) - R_1 \cdot I_1 \cdot Cos(\phi - \delta)\right] / $$
$$/ \, I_1 \cdot Sin(\phi - \delta)$$
$$Xq = \left[V \cdot Sin(-\delta) - R_1 \cdot I_1 \cdot Sin(\phi - \delta)\right] / $$
$$/ \, I_1 \cdot Cos(\phi - \delta) \qquad (6)$$

Where: α= actual frequency/base frequency, δ=load angle and Φ=power factor angle.

Using the expressions (6) we can calculate the reactances taken measurements for obtain the values of V, I_1, P, $Cos\phi$ and also the load-angle (δ). Without load this angle is δ_0, Fig. 6. The load angle along the successive load test is calculated comparing the waveforms of the voltage supply and the reference signal.

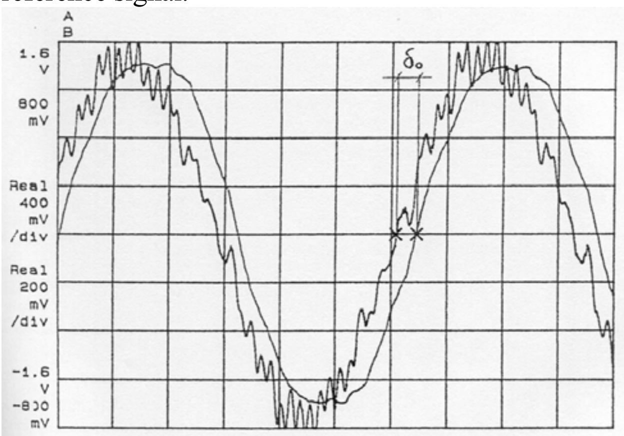

Figure 6.- Charts for determination of the reference angle δ_0 .

In Fig. 7 we have represented the results obtained for the quadrature reactance Xq. Like we can see that the results are not constant if the Iq current change. We also have obtained this values by other procedure (current method) and we can conclude that both procedures are in a good agreement. This results are also in concordance with the obtained by other authors for PMSM of the interior type but with different geometries. Then we can say that this phenomena is common for all the interior type PMSM.

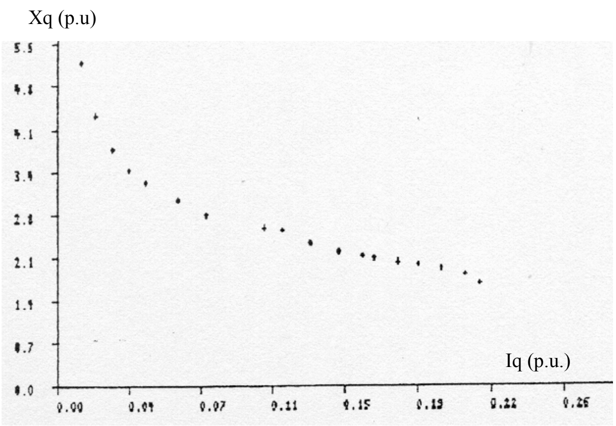

Figure 7. Graphic representation of Xq versus Iq.

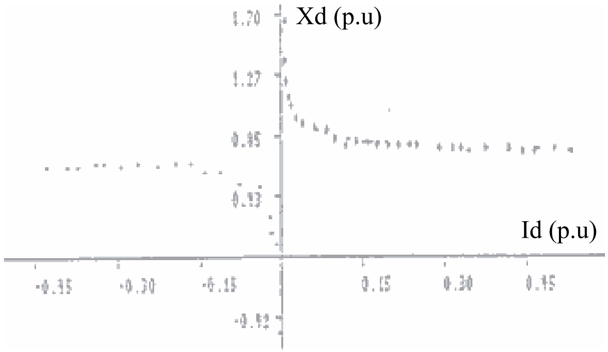

Figure 7. Graphic representation of Xd versus Id.

The values of the direct axis reactance, Xd, calculated by the equation 6 are not in agreement with the expected values of this reactance. We think this is because the d-axis flux consist of the combine action of magnets, d-axis current and q-axis current. The effect of Iq can be magnetizing or demagnetizing depending of the rotor geometry and it is not possible to separate by test the individual contributions of the magnet and the Id current to the total d-axis flux.

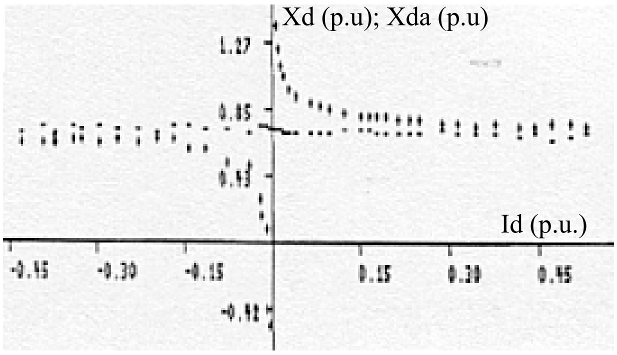

Figure 8. Graphic representation of Xd versus Id.
+ Values of Xd according with the classical model
- Values of Xd take into account the cross coupling

In Fig. 8 we can see Xd values versus Id applied the classical model and calculated by the following equation (coupled model):

$$Xda = \left[Vd - Eo - R_1 \cdot Iq - Xdq \cdot Iq\right] / \, Id \qquad (7)$$

In Fig. 8 we can observe that the values of Xd with cross coupling are practically constant, which implies that, in this case, the most of the flux path on the d-axis is produced by the magnets.

In reference [4] we have developed the Xqd reactance determination and we have compared, in different cases, the simulation results using the classical model and the coupled model with the real measurements and we concluded that the values calculated using the coupled model are in better agreement with those obtained by text.

III PMSM BEHAVIOR

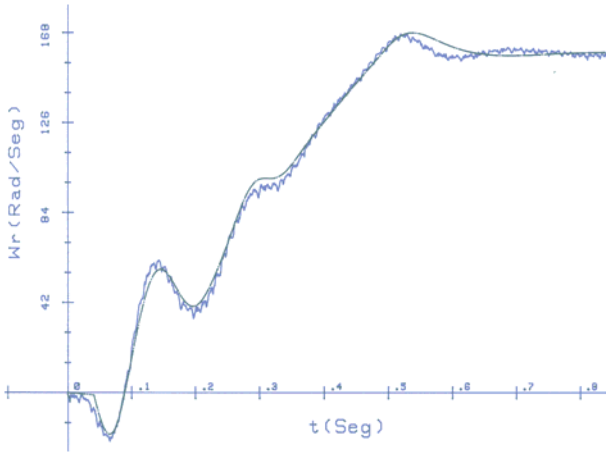

Figure 8. Graphic representation of speed versus time during the started process, obtained by: -.- Applied the model (simulation) and taken measurements (continuous line).

Now we have developed new texts and simulations for analyse other cases of the real operation of the PMSM. Then Fig. 8 show the good concordance between the curves speed-time obtained by simulation and by text. In this case we have used an acceleration ramp of 0 to 50 Hz during 0.45 seconds take into account a friction and ventilation torque of 0.011 p.u. and without load. It is curious observe the initial negative interval of the speed which depend on the initial angle between one of the motor phases and the direct axis. The effect of the saturation on the q-axis is take into account using the variation of the q-reactance with the q-axis current obtained by text.

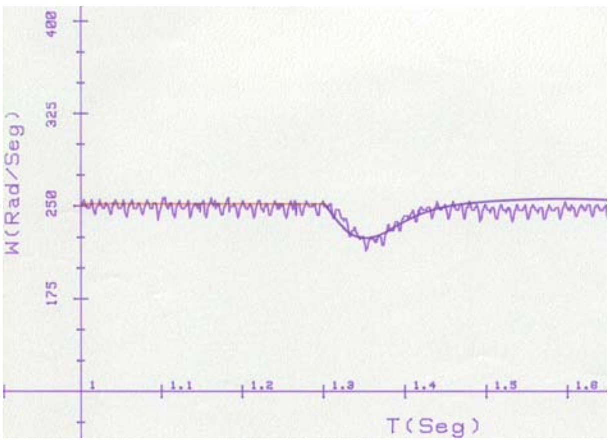

Figure 9. Graphic representation of speed versus time during a load sudden increase, obtained by: -.- Applied the model (simulation) and taken measurements (continuous line).

In Fig. 9 we can observe the incidence that over the speed has a 0.25 p.u. sudden increase of the load and in Fig. 10 the influence that produce a sudden decrease of load, when previously the machine has obtained the permanent regimen.

The Fig. 11 represent the temporal evolution of the speed just after has take place a overload Sc, for different values of the permanent load torque before

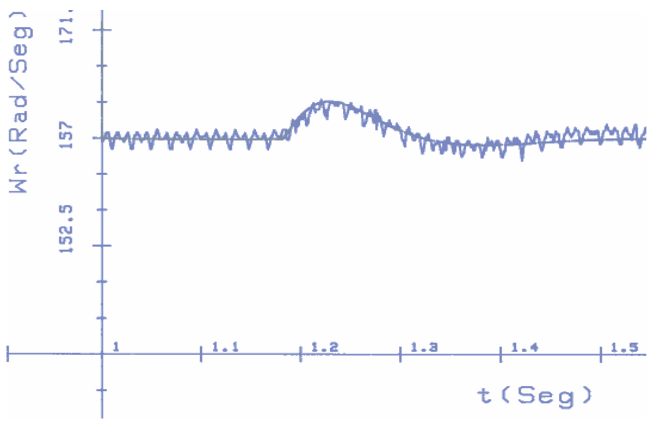

Figure 10. Graphic representation of speed versus time during a load sudden decrease, obtained by: -.- Applied the model (simulation) and taken measurements (continuous line).

the disturbance. The sudden application of the load produce an instantaneous decrease of the speed and then appear an positive asynchronous torque (Fig.14) that helps to the rotor obtain one time more the synchronism. This asynchronous torque disappear just in the moment that the rotor obtain the synchronization. Like one can observe in Fig. 11 with the same value of the overload, the maximum slip obtained is lower for the higher level of the stationary initial load torque. At the same time this slip is so higher as so higher is the overload value and in consequence, for the same final load, so higher is the overload as higher is the maximum slip obtained. At the same time we can also observe that the time for which the maximum slip is obtained is practically the same in all cases.

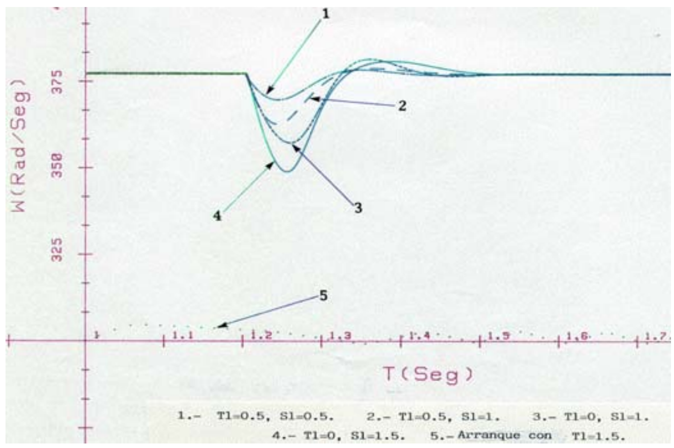

Figure 11 Graphic representation of speed versus time during a load sudden increase.

It is interesting take notice in Fig. 11 that, one time that the motor obtain the synchronization, it can permit the application of sudden loads higher than it can synchronise when it start for the same inertia.

Then one of the most important factors that has influence about the transient behaviour of the PMSM in front of a sudden increase/decrease of the load is the rotor inertia. A high value of the rotor inertia produce a large number of oscillations and if the value of the inertia is lower the response is more quicker, because the ratio torque/inertia is higher, but with the maximum slip more higher, Fig. 12.

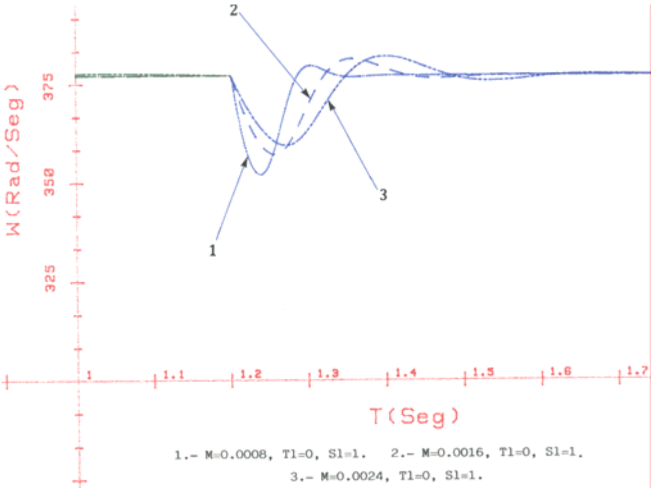

Figure 12. Graphic representation of speed versus time for different inertia torque (M) with Tl=0 and Sl=1.

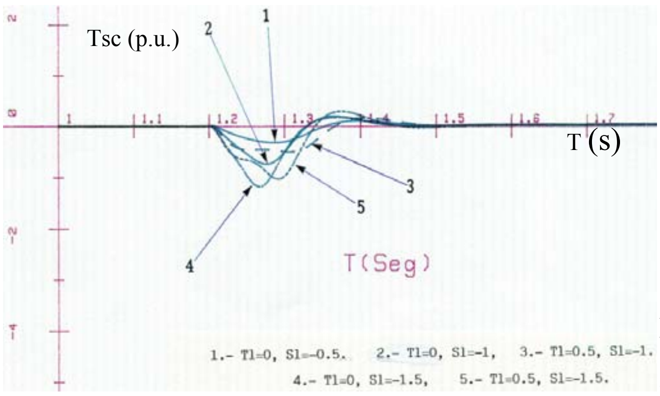

Figure 13. Graphic representation of the torque of the squirrel cage versus time for a sudden decrease of the load.

In Fig. 13 we have represented the squirrel cage torque when take place a sudden decrease of the load and in Fig. 14 when the load increase. In both cases for the same values of the load torque (Tl) and over-load (Sl).

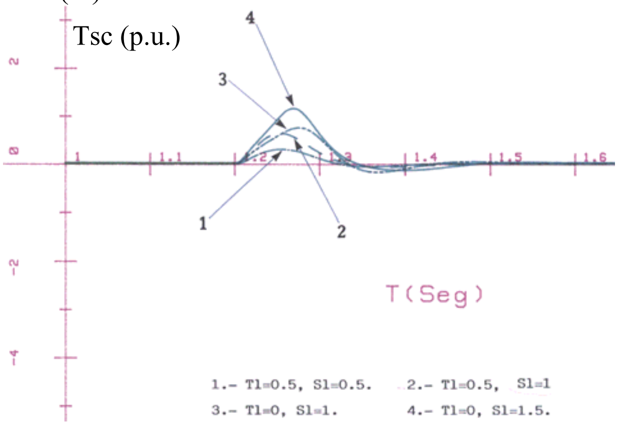

Figure 14. Graphic representation of the torque of the squirrel cage versus time for a sudden increase of the load.

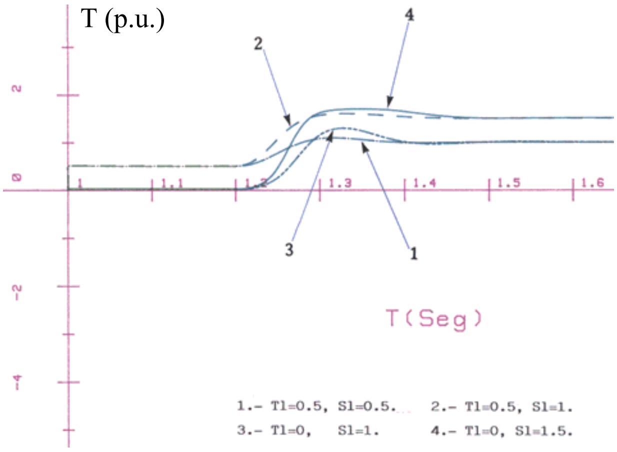

Figure 15. Graphic representation of the magnets and reluctance torques versus time during a sudden increase of the load.

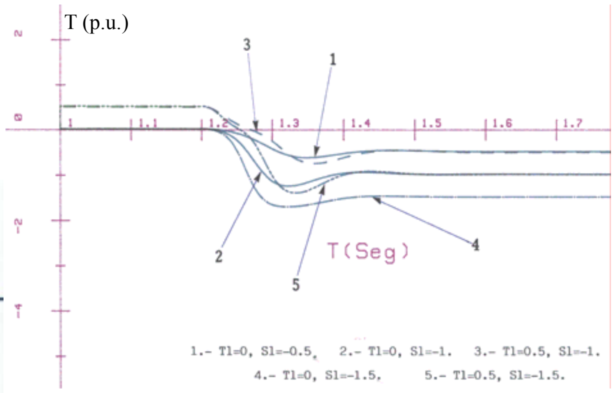

Figure 16. Graphic representation of the magnets and reluctance torques versus time during a sudden decrease of the load.

In Fig. 15 we have represented the torque of the magnets and reluctance when take place a sudden increase of the load and in Fig. 16 when the load decrease. In both cases for the same values of the load torque (Tl) and over-load (Sl). Logically the synchronous torques of permanent magnets and reluctance permit maintain the rotor in synchronism.

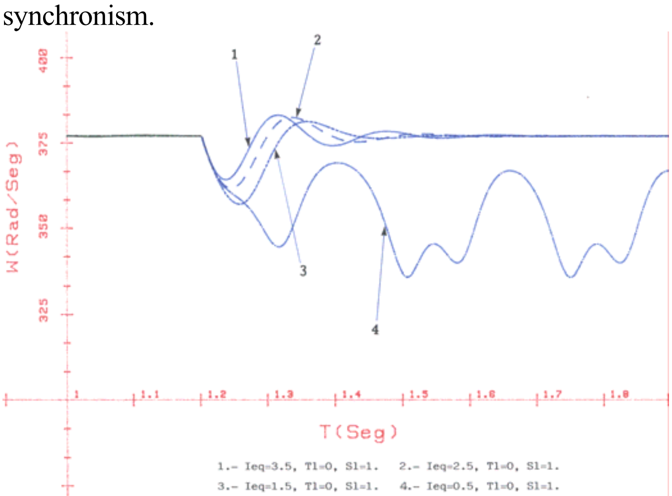

Figure 17. Graphic representation of speed versus time for different values of the equivalent current of the magnets with Sl=1 and Tl=0.

The permanent magnets influence about the transient behaviour of the PMSM is very important. As higher are the equivalent currents of the magnets as lower are the slips of the transient response. In Fig. 17 we can observe that if the current of the magnet decrease below a certain value the motor is not capable of take up the overload and the motor lost the synchronism. The optimum value of this current depends, amount other factors, of the magnets braking torque at the synchronous speed proximity. If this value is overcome they will appear higher oscillations during the transient operation.

The rotor geometry and in consequence the relationship between the d-axis and q-axis reactances, also modify the PMSM behaviour, as in the same way that for the equivalent current we must obtain an optimum value for the relation Xd/Xq and also it is important to obtain the most appropriate squirrel cage resistance value.

Really the number of variables that have influence about the starting and synchronization processes of a PMSM, take into account the motor and also the load, is very higher and then it is very difficult know in advance a set of necessary conditions for the correct synchronization of the PMSM. Then for develop an analyse of this type it is necessary take into account the parametric variation of the main magnitudes that have influence about the synchronization process.

In this particular case we have analyzed this process in term of his synchronization energy, specially we have considered the property "capacity of synchronization" of the motor, that we can defined it like a set of critical combinations of inertia and load torque in which the PMSM is capable to obtain the synchronization.

For obtain the synchronization energy we use a set of simple expressions that permit determine this magnitude in the last stage of the synchronous operation of the motor just when the machine describe a limit circle.

The dynamic equation expressed in the torque-slip plane is, (8):

$$-\frac{1}{p} J . w_0^2 \cdot s \frac{ds}{d\delta} = Ts(\delta) + Ta(s) - Tc(s) \quad (8)$$

Where: J is the combination inertia of the motor and the load, Ts is the sum of all the synchronization torques, Ta include all the asynchronous average torques and Tc is the sum of the load, slip and ventilation torques.

The equation (8) describe the critical trajectories of the polar slips on the load angle-slip plane.

IV CONCLUSIONS

We have developed along this paper a coupled model for accurate representation of the characteristics of permanent magnet synchronous motors and we have proposed the determination of the direct axis reactance, "Xd", and the quadrature axis reactance, "Xq", by calculus and texts with the permanent magnet synchronous machine under generator duty.

We also have analysed the starting and synchronization processes of the PMSM and the influence that on transient behaviour of the motor produce different values of the main motor parameters.

V. REFERENCES.

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