ISEF 2007 - XIII International Symposium on Electromagnetic Fields
in Mechatronics, Electrical and Electronic Engineering
Prague, Czech Republic, September 13-15, 2007

PARAMETERS INFLUENCE ON THE SYNCHRONIZATION PROCESS OF A PMSM

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Abstract : ***In this paper we apply a two-axis model for accurate representation of the characteristics of permanent magnet synchronous motors of the interior type. We'll analyse the re-synchronization processes of the PMSM and the influence that on transient behaviour of the motor produce different values of some motor parameters. The knowledge of the influence of the different parameters of the PMSM on the synchronization process is crucial for designers.***

1. Introduction

The PM Synchronous motor is a rotating electric machine where the stator is a classic three phase stator like that of an induction motor and the rotor has surface-mounted permanent magnets. In this respect, the PM Synchronous motor is equivalent to an induction motor where the air gap magnetic field is produced by a permanent magnet. The use of a permanent magnet to generate a substantial air gap magnetic flux makes it possible to design highly efficient PM motors

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 decrease. 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 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.

In recent years, compact and high efficiency synchronous motors have been designed using high energy PM in the rotor. Particular interest has been shown in those motors with PM mounted inside the steel rotor core, which is known as interior permanent magnet (IPM) synchronous motor, like the

SIEMOSYN motor with rotor inner magnets. This configuration produces a number of significant effects on the motor's operating characteristics.

2. PMSM two-axis Model

In the two-axis model used the magnet are represented by an equivalent field current and the cage by means of two equivalent coils (Figure 1). The electrical state variables are the flux and the equations are expressed by per unit.

- It is admitted that the magnets do not produce flux linkages in neither of the q-axis circuits, and that these once demagnetized recover themselves along an essentially linear characteristic.
- The hysteresis is do not take in mind and the effect of the saturation is included only in the q-axis.

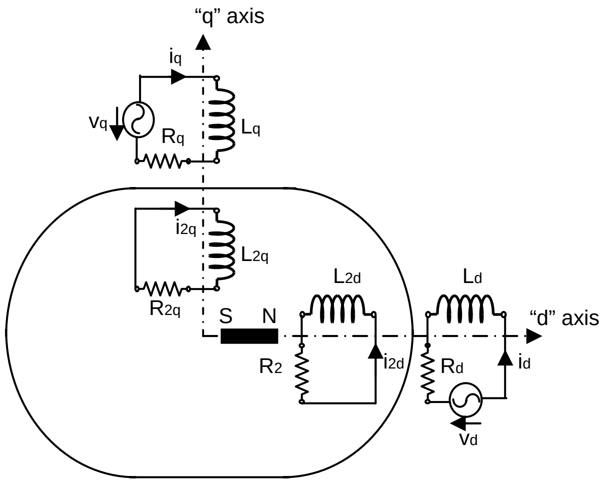

Fig. 1. Electrical circuit representative of a simplified model of two axis

The voltage equations for a balanced operation and for a fixed rotor reference frame, can be expressed in p.u. as follows:

$$v_d = \frac{p \cdot \phi_d}{\varpi_0} + R_1 \cdot i_d - \phi_q \frac{\varpi_r}{\varpi_0} ; \Leftrightarrow V_d = V \sin \delta$$

$$v_q = \frac{p \cdot \phi_q}{\varpi_0} + R_1 \cdot i_q - \phi_d \frac{\varpi_r}{\varpi_0} ; \Leftrightarrow V_q = V \cos \delta$$

$$0 = \frac{p \cdot \phi_{2d}}{\varpi_0} + R_{2d} \cdot i_{2d} \tag{1}$$

$$0 = \frac{p \cdot \phi_{2d}}{\varpi_0} + R_{2d} \cdot i_{2d}$$

The flux-linkage equations (2) as:

$$\begin{bmatrix} \phi_d \\ \phi_{2d} \end{bmatrix} = \begin{bmatrix} X_d & X_{md} \\ X_{md} & X_{2d} \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_{2d} \end{bmatrix} + \begin{bmatrix} X_{md} & X_{md} \end{bmatrix} \cdot \begin{bmatrix} I_{fm} \\ I_{fm} \end{bmatrix}$$

$$\begin{bmatrix} \phi_q \\ \phi_{2q} \end{bmatrix} = \begin{bmatrix} X_q & X_{mq} \\ X_{mq} & X_{2q} \end{bmatrix} \cdot \begin{bmatrix} i_q \\ i_{2q} \end{bmatrix} \tag{2}$$

Finding the currents of equation (3):

$$\begin{bmatrix} i_d \\ i_{2d} \end{bmatrix} = \begin{bmatrix} X_d & X_{md} \\ X_{md} & X_{2d} \end{bmatrix}^{-1} \cdot \begin{bmatrix} \phi_d & -X_{md} \cdot I_{fm} \\ \phi_{2d} & -X_{md} \cdot I_{fm} \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} i_q \\ i_{2q} \end{bmatrix} = \frac{1}{X_q \cdot X_{2q} - X_{mq}^2} \begin{bmatrix} X_{2q} & -X_{mq} \\ -X_{mq} & X_q \end{bmatrix} \cdot \begin{bmatrix} \phi_q \\ \phi_{2q} \end{bmatrix}$$

Once calculated the currents and the flux-linkages we can obtain the torques:

$$T_e = \phi_d \cdot i_q - \phi_q \cdot i_d$$

$$T_j = \phi_{2d} \cdot i_{2q} - \phi_{2q} \cdot i_{2d} \quad (4)$$

In other hand, the swing equation becomes.

$$p\delta = \varpi_0 - \varpi_r$$

$$p\varpi_r = \frac{1}{M}\left(T_e - T_c\right) \quad (5)$$

By transformation with the equations (1) and (3) we can obtain the next system of first order non linear differential equations whose coeffiecients are indicated in the appendix.

$$\begin{aligned} p\phi_d &= A \cdot \phi_d + \varpi_r \cdot \phi_q + B \cdot \phi_{2d} + C \cdot \sin\delta \\ p\phi_{2d} &= D \cdot \phi_d + E \cdot \phi_{2d} + F \\ p\phi_q &= -\varpi_r \cdot \phi_d + G \cdot \phi_q + H \cdot \phi_{2q} + J . \cos\delta \\ p\phi_{2q} &= K \cdot \phi_q + L \cdot \phi_{2q} \\ p\varpi_r &= N \cdot \phi_d \cdot \phi_q - P \cdot \phi_d \cdot \phi_{2q} - Q \cdot \phi_d \cdot \phi_q + R \cdot \phi_q \cdot \phi_{2q} + S \cdot \phi_q + U \\ p\delta &= \varpi_0 - \varpi_r \end{aligned} \quad (6)$$

In order to analyze the effect of sudden changes in load on the torques and speed the set of equations (6) be numerically integrated by means of a fifth order Kutta-Merson algorithm.

3. **Influence of the parameters**

The cage torque disappears when reaching synchronism. This torque depends strongly on the rotor and stator leakage reactances, and more exclusively on the cage resistance and reactance. However it is independent of the magnitudes related to the presence of the magnets. This allows to get for the same set of permanent magnets average torques radically different depending on the design of the rotor cage.

The torque generated by the permanent magnets during asynchronous operation "Tm" is a braking torque, that opposes to the cage torque. Such torque is zero in a standstill position. When accelerating its value reaches a maximum, precisely in the initial place of high slip, to stay later in a very reduced value, during all the speed rate including the synchronous.

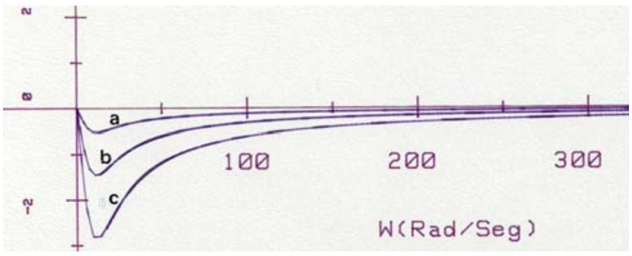

Fig. 2. Braking torque produced by the permanent magnet during the accelerating process for: a) I_{eq}=1,5; b) I_{eq}=2,5; c) I_{eq}=3,5.

The satisfactory design of the motor allows to keep this braking effect at low speeds within acceptable limits. As it is a generating torque its characteristics remain, although in a very low level when reaching the synchronous speed, without contributing to the motoring action. However, under this condition, the permanent magnets play another basic role becoming, together with the less contribution of the reluctant effect, the main support to the motor synchronous torque.

The sudden application of the load produce an instantaneous decrease of the speed and then appear an positive asynchronous torque 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 figure 3 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.

It is interesting take notice in figure 3 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 factor 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. 4.

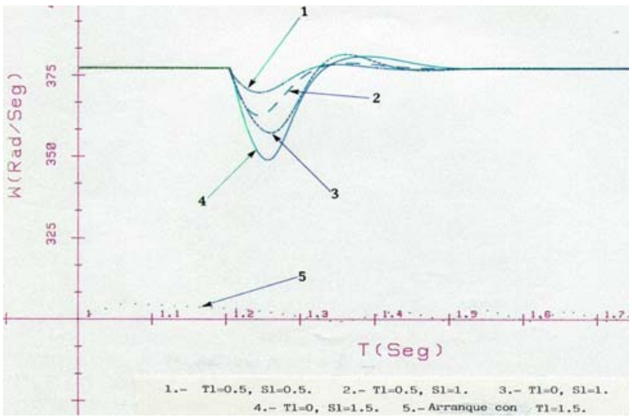

Fig. 3. Graphic representation of speed versus time during a load sudden increase.

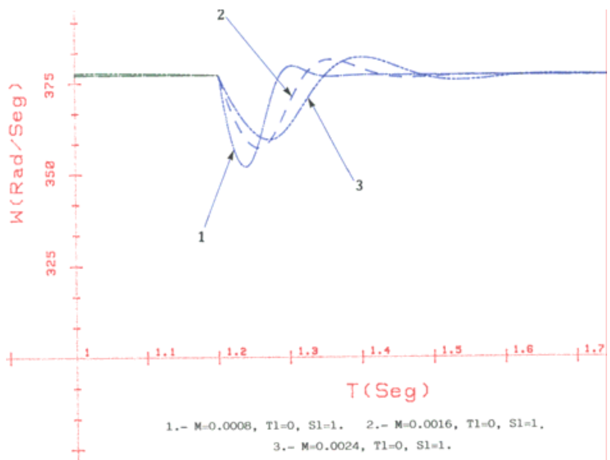

Fig. 4. Graphic representation of speed versus time for different inertia torque (M) with Tl=0 and Sl=1.

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. 5 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 analyze 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. The dynamic equation expressed in the torque-slip plane is, equation (7):

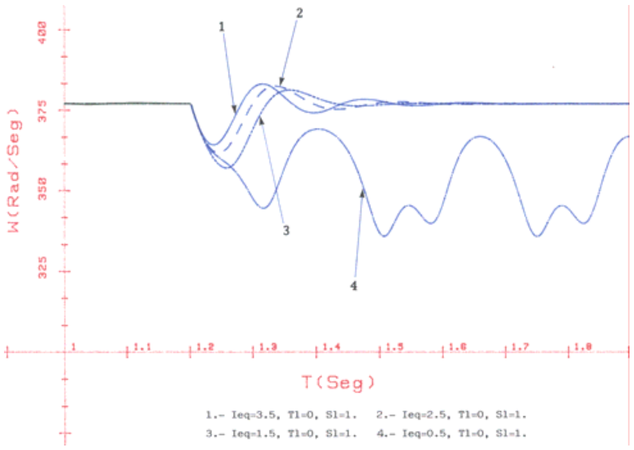

Fig. 5. Graphic representation of speed versus time for different values of the equivalent current of the magnets with Sl=1 and Tl=0.

$$-\frac{1}{p}J.w_0^2 \cdot s\frac{ds}{d\delta} = Ts(\delta) + Ta(s) - Tc(s) \tag{7}$$

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

4. **Conclusions**

The average torque resulting from the cage torque and permanent magnets braking, is what really accelerates the rotor during the asynchronous operation. The pulsating components basically due to the permanent magnets will be the ones that generate the synchronizing torque necessary to make the rotor enter synchronism, near the synchronous speed.

The PMSM can support sudden variations of load of higher value than those that it can synchronized during the starting process.

The speed variations produced on applying these overloads can be minimized with an adequate choice of the more characteristics parameters of the motor.

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APPENDIX

$$A=\frac{-\varpi_0\cdot R_1\cdot X_{2d}}{X_d\cdot X_{2d}-X_{md}^2};\ B=\frac{\varpi_0\cdot R_1\cdot X_{md}}{X_d\cdot X_{2d}-X_{md}^2};\ C=\frac{-\varpi_0\cdot R_1\cdot X_{md}^2\cdot I_{eq}+\varpi_0\cdot R_1\cdot X_{md}\cdot I_{eq}\cdot X_{2d}}{X_d\cdot X_{2d}-\varpi_{md}^2}-\varpi_0\cdot V$$

$$D=\frac{\varpi_0\cdot R_{2d}\cdot X_{md}}{X_d\cdot X_{2d}-X_{md}^2};\ E=\frac{\varpi_0\cdot R_{2d}\cdot X_d}{X_d\cdot X_{2d}-X_{md}^2};\ F=-\frac{\varpi_0\cdot R_{2d}\cdot X_{md}^2\cdot I_{eq}}{X_d\cdot X_{2d}-X_{md}^2}+\frac{\varpi_0\cdot R_{2d}\cdot X_{md}\cdot X_d\cdot I_{eq}}{X_d\cdot X_{2d}-X_{md}^2}$$

$$G=-\frac{\varpi_0\cdot R_1\cdot X_{2q}}{X_q\cdot X_{2q}-X_{mq}^2};\ H=\frac{\varpi_0\cdot R_1\cdot X_{mq}}{X_q\cdot X_{2q}-X_{mq}^2};\ J=\varpi_0\cdot V;\ K=\frac{\varpi_0\cdot R_{2q}\cdot X_{mq}}{X_q\cdot X_{2q}-X_{mq}^2};\ L=-\frac{\varpi_0\cdot R_{2q}\cdot X_q}{X_q\cdot X_{2q}-X_{mq}^2}$$

$$N=\frac{X_{2q}}{M\left(X_q\cdot X_{2q}-X_{mq}^2\right)};\ P=\frac{X_{mq}}{M\left(X_q\cdot X_{2q}-X_{mq}^2\right)};\ Q=\frac{X_{2d}}{M\left(X_d\cdot X_{2d}-X_{md}^2\right)};\ R=\frac{X_{md}}{M\left(X_d\cdot X_{2d}-X_{md}^2\right)}$$

$$S=-\frac{X_{md}^2\cdot I_{eq}}{M\left(X_d\cdot X_{2d}-X_{md}^2\right)}-\frac{X_{md}\cdot I_{eq}\cdot X_{2d}}{M\left(X_d\cdot X_{2d}-X_{md}^2\right)};\ U=-\frac{P_c}{M}$$

PMSM Parameters	
I_{eq}: Equivalent rotor field current	w_r/w: Rotor angular speed
M: Rotor inertia constant=0.0016	w_0: Angular synchronous speed
R_1: Stator winding resistance=0.0173	X_d: d-axis reactance=0.543
R_{2d}: d-axis rotor cage resistance=0.054	X_q: q-axis reactance=1.086
R_{2q}: q-axis rotor cage resistance=0.108	X_{2d}: d-axis rotor cage reactance=0.608
S_l: Sudden load applied	X_{2q}: q-axis rotor cage reactance=1.151
T: Torque	X_{md}: d-axis magnetizing reactance=0.478
T_c: Cage torque	X_{mq}: q-axis magnetizing reactance= 1.021
T_e : Motor torque	X_1: Stator leakage reactance= 0.0652
T: Time	X_2: Rotor leakage reactance= 0.132
V: Supply voltage	$\varnothing$: flux linkages