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DYNAMIC PERFORMANCE OF RELUCTANCE SYNCHRONOUS MACHINES

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Abstract **– In the design stage of synchronous machine and especially of those required by high performance drive systems (for example industrial robots), often is necessary the predetermination of dynamic characteristics, using modelling and simulation. The simulation results and their correlation with reality, essentially depend on the way the synchronous machine is modelled. The general mathematical model [3] is particularized for reluctance synchronous machine. On this basis quantitative data of interest for estimating transient phenomena are obtained.**

Keywords *– synchronous machines, dynamic regime*

1.INTRODUCTION

In many practical applications the position and the speed must be precisely controlled, regardless the existing perturbations (variations of voltage, of resistant torque, etc.).
All these requirements can be achieved using external feedback loops which correct the errors of the system [7], [2].
Another simpler possibility is to utilize the internal feedback loops, part of the operation principle of the driving motor, which allow to get the desired speed or rotor position, without external loops [1], [5]. Such motor is the synchronous motor. It allows in a simple way to get a speed depending only on the frequency of supply voltage.
The motors with electromagnetic excitation are utilized at large power, while the reluctance motors and motors with permanent magnets are the best technical and economical solution for small and medium power.
The reluctance motor presents well known advantages. More, utilization of static converters made possible the speed control with good performances. This is the main reason which allowed the utilization of reluctance motors in industrial applications.
The present paper offer the possibility of predetermination of dynamic performance of reluctance motors, essential in precision drive systems.

2. BASICS OF THE MATHEMATICAL MODEL

Our starting point is given, as usually, by the Park equations of the synchronous machine which are considered together with the equations connecting flux linkage and currents.

$$[u]=[R][i]+[\frac{d}{dt}][\psi]; \quad [\psi]^T=[\psi_d\ \psi_q\ \psi_D\ \psi_Q]$$

where

$$\begin{aligned} \psi_d &= L_{s\sigma}i_d+\psi_{md} & \psi_{md} &= L_{md}i_{md} \\ \psi_q &= L_{s\sigma}i_q+\psi_{mq} & \psi_{mq} &= L_{mq}i_{mq} \\ \psi_D &= L_{D\sigma}i_D+\psi_{md} & i_{md} &= i_d+i_D \\ \psi_Q &= L_{Q\sigma}i_Q+\psi_{mq} & i_{mq} &= i_q+i_Q \end{aligned} \quad (1)$$

The rotor quantities are reported to stator.
The mathematical model of the synchronous machine is considered to have the form:

$$[u]=A\frac{dX_{dq}}{dt}+BX_{dq};[u]=[u_d\ u_q\ 0\,0]^T \quad (2)$$

X_{dq} corresponds to diverse combinations of state variables and A, B are matrices whose form is determined by the choice of the state variables (currents only, flux linkages only or some mixture of currents and flux linkages).
In the following we consider as state variables the currents of the machine windings. In this case, to the state vector $X_{dq}=|i_d\quad i_q\quad i_D\quad i_Q|^T$ correspond to the matrices [3].

$$A=\begin{bmatrix} L_{s\sigma}+L_{md} & 0 & L_{md} & 0 \\ 0 & L_{s\sigma}+L_{mq} & 0 & L_{mq} \\ L_{md} & 0 & L_{D\sigma}+L_{md} & 0 \\ 0 & L_{mq} & 0 & L_{Q\sigma}+L_{mq} \end{bmatrix}$$

$$B = \begin{bmatrix} R_s & -\omega(L_{s\sigma} + L_{mq}) & 0 & -\omega L_{mq} \\ \omega(L_{s\sigma} + L_{md}) & R_s & \omega L_{md} & 0 \\ 0 & 0 & R_D & 0 \\ 0 & 0 & 0 & R_Q \end{bmatrix}$$

At equation (2) we add the movement equation

$$m - M_r = \frac{J}{p}\frac{d\omega}{dt} = \frac{J}{p}\frac{d^2\beta}{dt^2}, \quad (3)$$

where

$$m = \frac{3}{2}p\left[(L_{md} - L_{mq})i_d i_q + L_{md} i_D i_q - L_{mq} i_d i_Q\right]$$

In the referential system *d*, *q* we consider

$$u_d = \sqrt{2}U\cos(\omega_1 t - \beta), \quad u_q = \sqrt{2}U\sin(\omega_1 t - \beta)$$

where

$$\beta = \int \omega \, dt + \beta_0.$$

The speed of the main magnetic field ψ_m during the dynamic processes will be

$$\omega_\psi = \frac{d\varphi}{dt} + \omega, \quad (4)$$

where

$$\frac{d\varphi}{dt} = \frac{1}{\psi_m}\left(\frac{d\psi_{mq}}{dt}\cos\varphi - \frac{d\psi_{md}}{dt}\sin\varphi\right), \quad \sin\varphi = \frac{\psi_{mq}}{\psi_m}$$

$$, \quad \cos\varphi = \frac{\psi_{md}}{\psi_m}, \quad \psi_m = \sqrt{\psi_{md}^2 + \psi_{mq}^2}$$

The fluxes are simply obtained, depending on the considered state variables, see (1).
The above notations are those of [3] and used by some authors.

3. SIMULATION RESULTS

In the sequel we study the dynamic performances of a reluctance synchronous machine with star winding and rated voltage U_n=220V. We take into account the particular case of starting and synchronization. The effects of leakage inductance of stator winding, of resistances of *D, Q* damping windings and also of mechanical inertia J, are especially analysed. The proposed model is used. The simulations were performed in Matlab using a fifth-order Runge-Kutta with variable step method. The motor parameters are: R_s =2.5Ω, $L_{s\sigma}$ =0.01H, $L_{D\sigma}$ =0.008H, $L_{Q\sigma}$ =0.006H, L_d =0.71H, L_q =0.06H, $R_D = 1{,}5\Omega$, $R_Q = 3\Omega$, p=2, *J*=0.004kgm^2.

The curves $\omega(t)$, $\omega_\psi(t)$, $m(\omega)$, $\psi_{md}(\psi_{mq})$ were simulated considering the rated torque M_n=9.5Nm and various $L_{s\sigma}$, R_D, R_Q, *J*, which significantly affect the dynamic and stationary performances.
Figs. 1 presents the characteristics considering the rated parameters. The dynamic electromagnetic torque is important in the first moments of starting. (Fig. 1b) and, consequently, the starting and synchronization process is short (Fig. 1a). In Fig.1a one can observe too the clear connection between the mechanical and electromagnetic transient processes, in fact one electromechanical process. As we can see from Fig. 1b, the synchronization process is good, the *steady state point* of synchronism being reached practically in the absence of torque oscillations. Like the electromagnetic torque the characteristic $\psi_{md}(\psi_{mq})$ in the case of a firm synchronization finalizes in a *well defined synchronous operation point* (see Fig. 1c). The simulations presented suggest that the considered motor has good dynamic and stationary performances. Figs. 2-6 present the characteristics for different values of R_D, R_Q, $L_{s\sigma}$, *J.* Figs. 2a and 2b correspond to $R_D = 3\Omega$. One can observe that an increase in R_D affects, the motor performances. The starting process is longer, the electromechanical oscillations are larger and the synchronous operation is reached after relatively important oscillations of the electromagnetic torque.
Figs. 3, 4 consider $R_Q = 5\Omega$ and $R_Q = 1.5\Omega$ respectively.
Compared to Fig. 1b as a reference, one can see firmly damped oscillations of electromagnetic torque around the synchronous speed (Fig. 3) and a prolonged process of damped oscillations (Figs. 4) of the electromagnetic torque in the neighborhood of the synchronous speed which can affect the motor performances. Fig. 4b details these oscillations.
Figs. 5 considers $L_{s\sigma} = 0.015H$. All characteristics show an asynchronous operation. In the Fig. 5b (and details in Fig. 5c) the *closed limit cycle* indicates the limits in which *m(t)* and $\omega(t)$ oscillate permanently at asynchronous operation. Like the electromagnetic torque, the characteristics $\psi_{md}(\psi_{mq})$ remain closed in a limit cycle (Fig. 5d).
Fig. 6 considers J=0.01 kgm^2. Compared with the reference characteristics of Fig. 1, one can see an increase of duration of dynamical regime (Fig. 6a), and as consequence of the number of electromechanical oscillations.
The dynamical process finalizes as above, with a synchronous operation but with a number of oscillations of larger amplitude, around the

synchronous operation (Fig. 6b). The detailed Fig. 6c, confirms the absence of a limit cycle, and a final synchronous operation. The same conclusion results also from the Fig. 6d, in which the limit cycle is not present.

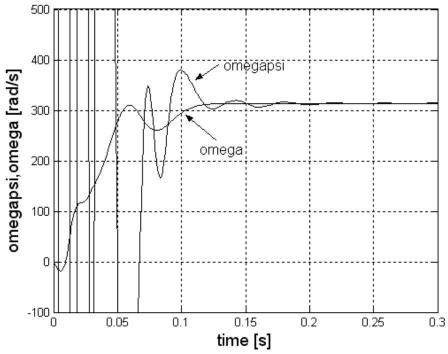

Figure 1.a: Characteristic $\omega(t)$, $\omega_{\psi}(t)$.

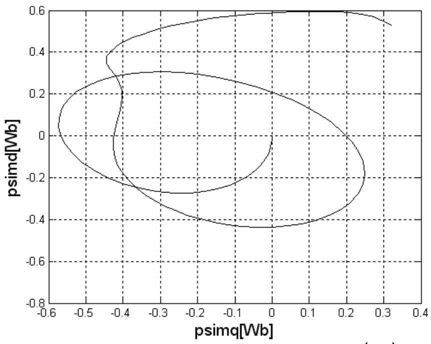

Figure 1.b: Characteristic $m(\omega)$.

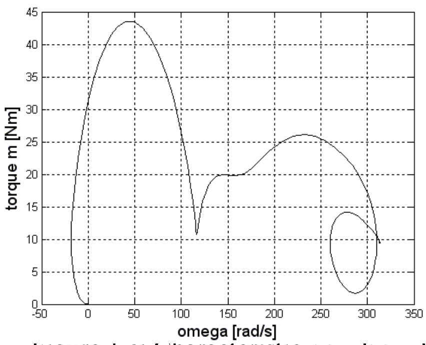

Figure 1.c: Characteristic $\psi_{md}(\psi_{mq})$.

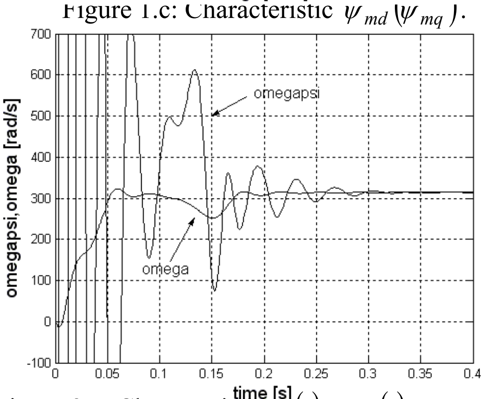

Figure 2.a: Characteristic $\omega(t)$, $\omega_{\psi}(t)$, $R_D = 3\Omega$.

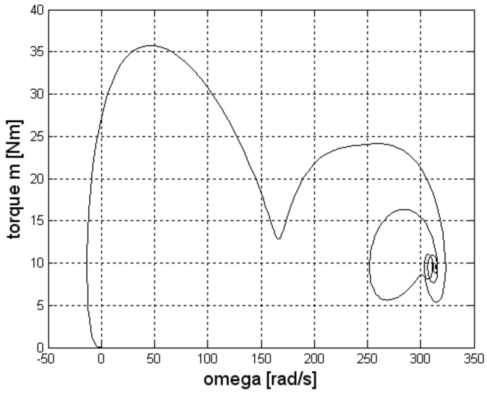

Figure 2.b: Characteristic $m(\omega)$, $R_D = 3\Omega$.

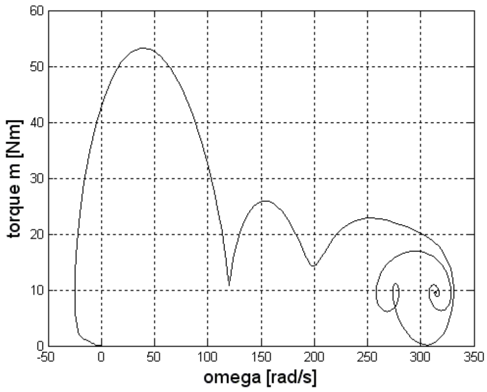

Figure 3: Characteristic $m(\omega)$, $R_Q = 5\Omega$.

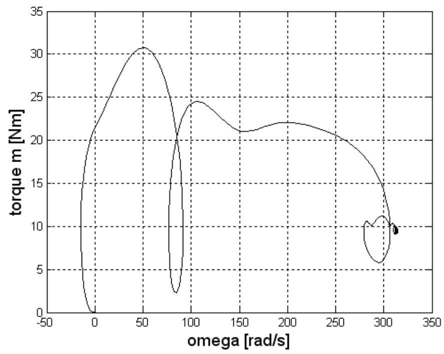

Figure 4.a: Characteristic $m(\omega)$, $R_Q = 1.5\Omega$.

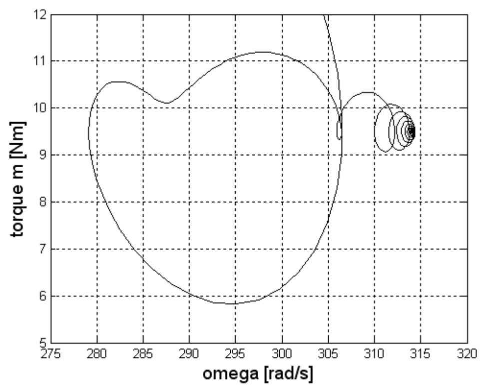

Figure 4.b: Characteristic $m(\omega)$, $R_Q = 1.5\Omega$, detail.

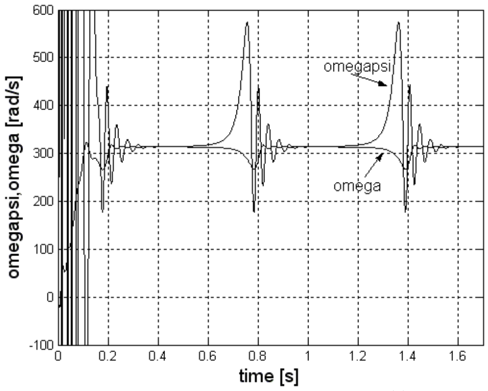

Figure 5a. Characteristic $\omega(t)$, $\omega_{\psi}(t)$, $L_{s\sigma} = 0.015H$.

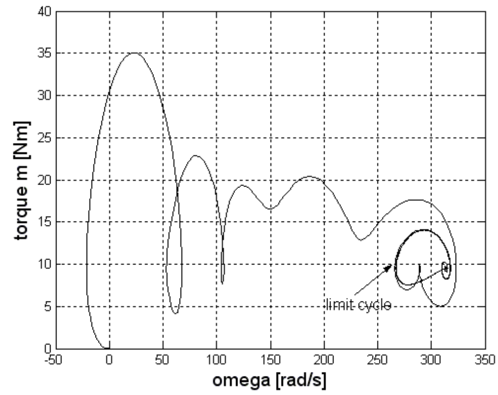

Figure 5b: Characteristic $m(\omega)$, $L_{s\sigma} = 0.015H$.

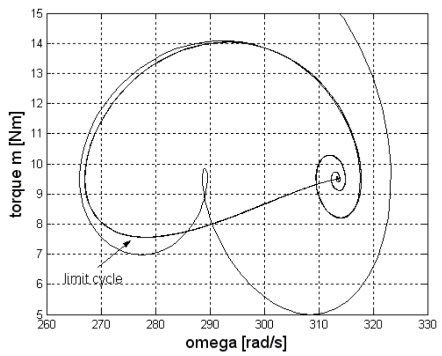

Figure5c:Characteristic $m(\omega)$, $L_{s\sigma} = 0.015H$, detail.

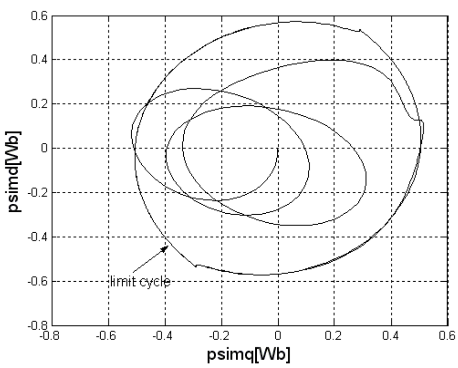

Figure 5d: Characteristic $\psi_{md}(\psi_{mq})$, $L_{s\sigma} = 0.015H$.

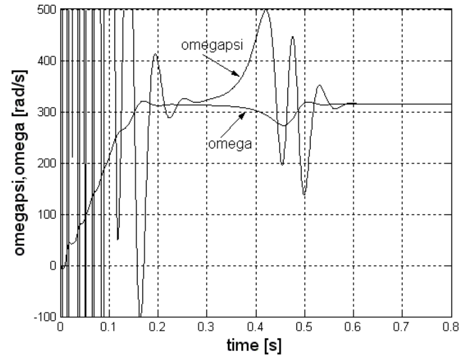

Figure 6a: Characteristic $\omega(t)$, $\omega_{\psi}(t)$, J=0.01 kgm^2

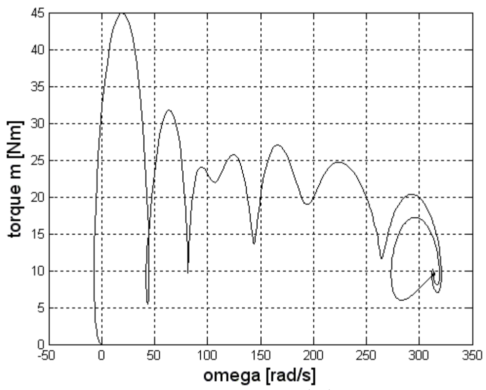

Figure 6b: Characteristic $m(\omega)$, J=0.01 kgm^2.

An increase of mechanical inertia of the machine, compared with the reference one in Fig. 1, does not improve the dynamical characteristics. Changing the stator resistance R_s does not modify significantly the dynamical characteristics compared with those of Fig. 1; the simulation results are not presented.

4. CONCLUSIONS

The paper presents the particular dynamic model of the reluctance synchronous machine, considering the winding currents as state variables.

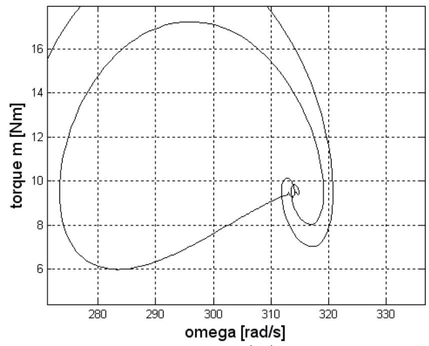

Figure 6c. Characteristic $m(\omega)$, J=0.01 kgm^2, detail

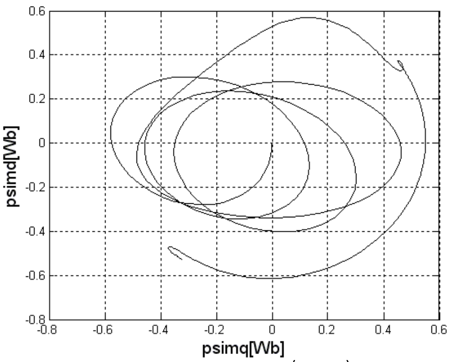

Figure 6d. Characteristic $\psi_{md}(\psi_{mq})$, *J*=0.01 kgm^2

Many simulations allow the following general conclusion: a variation even in tight limits of the considered parameters, can undergo structural modifications in the dynamic characteristics.

The equation (4) contains valuable information about the velocity $\omega_{\psi}(t)$ of the main rotating magnetic field during the transient processes. A close connection between $\omega_{\psi}(t)$ and $\omega(t)$ is observed in all simulations shown above. The considered model allows valuable predeterminations, absolutely necessary, for convenient design of synchronous reluctance motors intended to operate in a required dynamical regime.

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