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SIMULATIONS REGARDING INFLUENCES OF TORQUE DISTURBANCES UPON RELUCTANCE SYNCHRONOUS MOTORS OPERATION

BY

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Abstract. This paper analyzes the dynamic stability of reluctance synchronous motors in case of jump modification of the resistant torque. In order to do this, with the help of a program conceived in Matlab, there have been carried out a series of simulations which emphasize the variations of the characteristic quantities of a motor rated at 1.5 kW in a few concrete dynamic states. The simulations have led to some relevant conclusions regarding the dynamic stability of the system analyzed. The importance of using simulations in the design process of these motors is emphasized. Thus it would be possible to know the parameters which ensure the best dynamic stability of the motor.

Key words: reluctance synchronous motor; mathematical model; simulations; transient states; dynamic stability.

1. Introduction

Owing to the multiple practical applications, reluctance synchronous motors are more and more the object of some extensive researches and this fact is materialized in lots of papers presented in outstanding international scientific manifestations. There are approached problems regarding the motor modelling (Bacco, 2018), simulation (Enache *et al.*, 2016; Bianchi & Mahmoud, 2018), design (Ding *et al.*, 2018; Mahmoud *et al.*, 2018) and its tests (El Refaie *et al.*, 2018).

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One of the specific problems is the study of the motor stability (Diao *et al.*, 2018), knowing that this motor is very unstable.

This paper is in this domain. It aims at emphasizing the dynamic states caused by some shocks of resistant torque and, implicitly, at analyzing the dynamic stability of this system.

In order to analyze the dynamic stability in this case, it is necessary to carry out simulations of those dynamic states. In this purpose, an adequate mathematical model must be used.

2. Mathematical Model of the Motor

In order to complete the research, there has been used the two-axis theory mathematical model of the motor, showed in (Enache, 2015).

Thus the mathematical model written in a reference system fixed relatively to the rotor is considered:

$$\begin{aligned} u_d - R_s i_d &= \frac{\mathrm{d}\psi_d}{\mathrm{d}t} - \omega\psi_q, \\ u_q - R_s i_q &= \omega\psi_d + \frac{\mathrm{d}}{\mathrm{d}t}\psi_q, \\ -R_D i_D &= \frac{\mathrm{d}\psi_D}{\mathrm{d}t}, \\ -R_Q i_Q &= \frac{\mathrm{d}\psi_Q}{\mathrm{d}t}. \end{aligned} \tag{1}$$

The fluxes in these equations have the following expressions:

$$\begin{aligned} \psi_d &= L_d i_d + L_{md} i_D, \\ \psi_q &= L_q i_q + L_{mq} i_Q, \\ \psi_D &= L_{md} i_d + L_D i_D, \\ \psi_Q &= L_{mq} i_q + L_Q i_Q. \end{aligned} \tag{2}$$

The relations (2) are replaced in (1).

It results:

$$\begin{aligned} u_d - R_s i_d + \omega L_q i_q + \omega L_{mq} i_Q &= L_d \frac{\mathrm{di_d}}{\mathrm{dt}} + L_{md}\frac{\mathrm{d}i_D}{\mathrm{d}t}, \\ u_q - R_s i_q - \omega L_d i_d - \omega L_{md} i_D &= L_q \frac{\mathrm{d}i_q}{\mathrm{d}t} + L_{mq}\frac{\mathrm{d}i_Q}{\mathrm{d}t}, \\ -R_D i_D &= L_{md}\frac{\mathrm{d}i_d}{\mathrm{d}t} + L_D \frac{\mathrm{d}i_D}{\mathrm{d}t}, \\ -R_Q i_Q &= L_{mq}\frac{\mathrm{d}i_q}{\mathrm{d}t} + L_Q \frac{\mathrm{d}i_Q}{\mathrm{d}t}. \end{aligned} \tag{3}$$

The motion equation of the system analyzed, according to (Enache *et al.*, 2017), is:

$$\frac{3}{2}p\left(\psi_d i_q - \psi_q i_d\right) - m_r = \frac{J}{p}\cdot\frac{\mathrm{d}\omega}{\mathrm{d}t}. \tag{4}$$

This equation can be written as an equivalent form:

$$\frac{3}{2}p\left(L_d i_d i_q + L_{md} i_D i_q - L_q i_q i_d - L_{mq} i_Q i_d\right) - m_r = \frac{J}{p}\cdot\frac{\mathrm{d}\omega}{dt}. \tag{5}$$

In order to carry out simulations in Matlab, it is necessary to write the equations (3) and (5) in the following matrix form:

$$\begin{bmatrix} L_d & 0 & L_{md} & 0 & 0 \\ 0 & L_q & 0 & L_{mq} & 0 \\ L_{md} & 0 & L_D & 0 & 0 \\ 0 & L_{mq} & 0 & L_Q & 0 \\ 0 & 0 & 0 & 0 & \dfrac{J}{p} \end{bmatrix} \cdot \frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} i_d \\ i_q \\ i_D \\ i_Q \\ \omega \end{bmatrix} = \tag{6}$$

$$= \begin{bmatrix} u_d - R_s i_d + \omega L_q i_q + \omega L_{mq} i_Q \\ u_q - R_s i_q - \omega L_d i_d - \omega L_{md} i_D \\ -R_D i_D \\ -R_Q i_Q \\ \dfrac{3}{2}p\left(L_d i_d i_q + L_{md} i_D i_q - L_q i_q i_d - L_{mq} i_Q i_d\right) - m_r \end{bmatrix}.$$

3. Simulation Program

Starting from the mathematical model detailed before, a simulation program has been conceived in Matlab. It contains a main program and two functions (for integrating the model and for plotting variations of the quantities analyzed).

A detail of the integration function is presented in the Fig. 1.

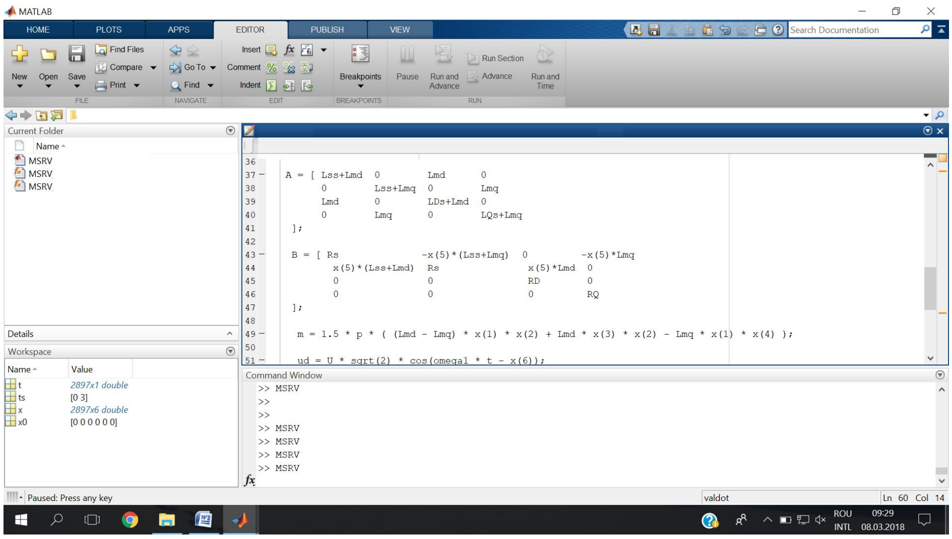


Fig. 1 – Print screen of the working screen.

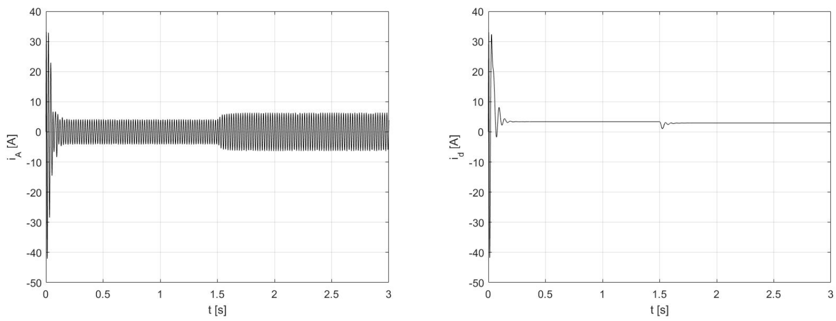
4. Simulations

A few dynamic states have been simulated with the help of the program presented before. In this paper there is presented the case of the dynamic states caused by some shocks of resistant torque.

The cases of some shocks of 10 Nm (Fig. 2), respectively of 17 Nm (Fig. 3) are detailed. These were applied at 1.5 seconds after motor starting (at a resistant torque of 5 Nm).

In order to carry out the simulations, a reluctance synchronous motor rated at 1.5 kW has been considered; the motor parameters are:

R_s = 3.77 Ω;	R_D = 1.5 Ω;	R_Q = 4.5 Ω;
L_d = 0.281 H;	L_q = 0.081 H;	$L_{s\sigma}$ = 0.0081 H;
$L_{D\sigma}$ = 0.0059 H;	$L_{Q\sigma}$ = 0.0067 H;	p = 2.



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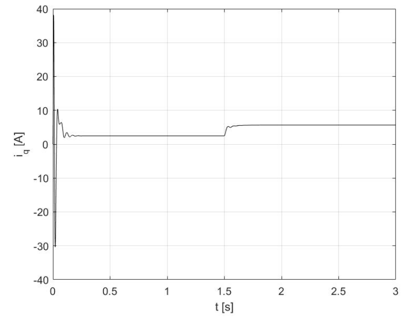
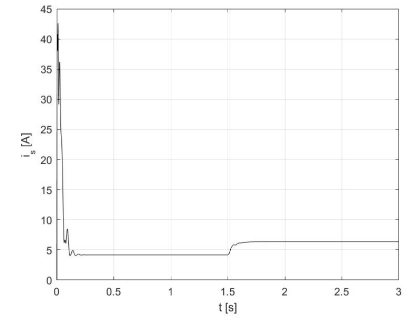
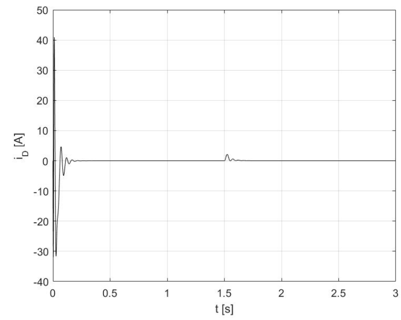
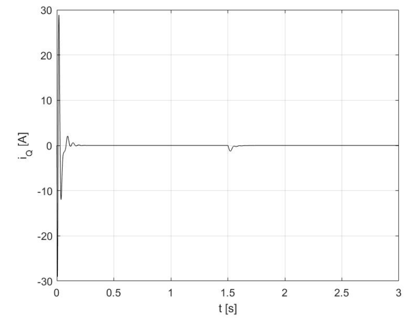
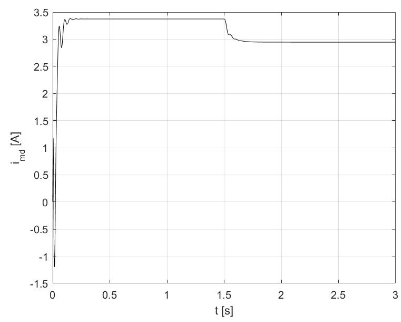
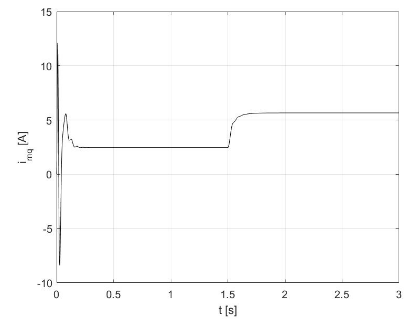

i_q [A]
40 30 20 10 0 -10 -20 -30 -40
0 0.5 1 1.5 2 2.5 3
t [s]
c)

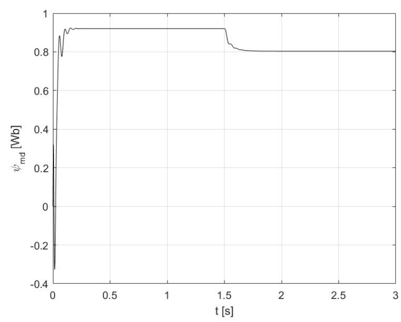

i_s [A]
45 40 35 30 25 20 15 10 5 0
0 0.5 1 1.5 2 2.5 3
t [s]
d)

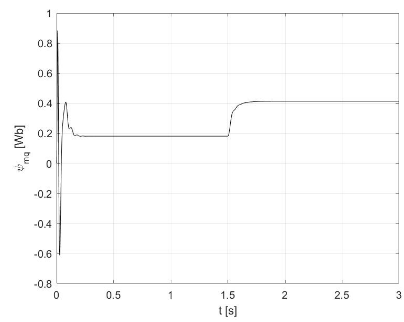

i_D [A]
50 40 30 20 10 0 -10 -20 -30 -40
0 0.5 1 1.5 2 2.5 3
t [s]
e)

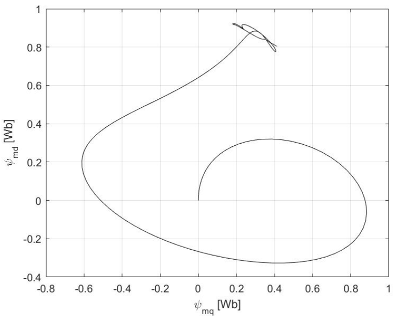

i_Q [A]
30 20 10 0 -10 -20 -30
0 0.5 1 1.5 2 2.5 3
t [s]
f)


i_md [A]
3.5 3 2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5
0 0.5 1 1.5 2 2.5 3
t [s]
g)


i_mq [A]
15 10 5 0 -5 -10
0 0.5 1 1.5 2 2.5 3
t [s]
h)


ψ_md [Wb]
1 0.8 0.6 0.4 0.2 0 -0.2 -0.4
0 0.5 1 1.5 2 2.5 3
t [s]
i)


ψ_mq [Wb]
1 0.8 0.6 0.4 0.2 0 -0.2 -0.4 -0.6 -0.8
0 0.5 1 1.5 2 2.5 3
t [s]
j)



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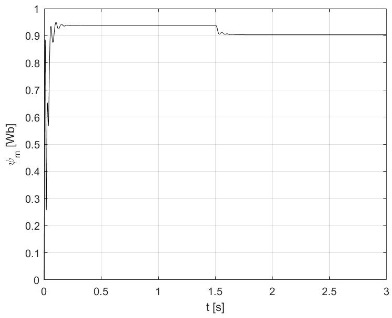

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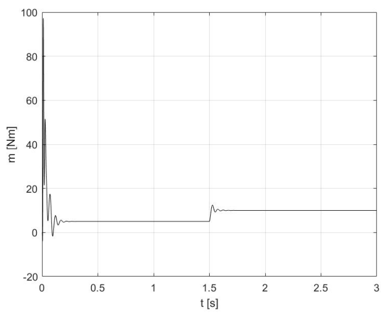

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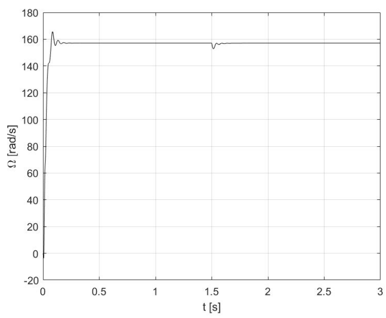

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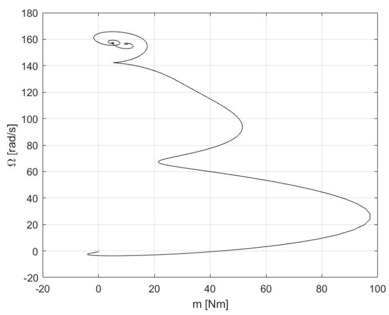
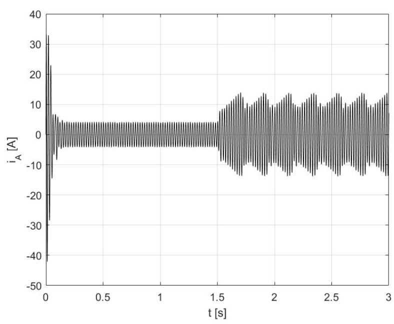


o)

Fig. 2 – Characteristics corresponding to the case: U = 220 V, J = 0.01, Mr = 10 Nm.



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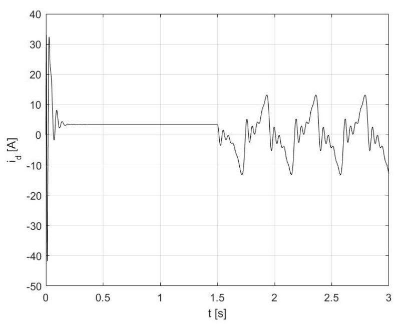
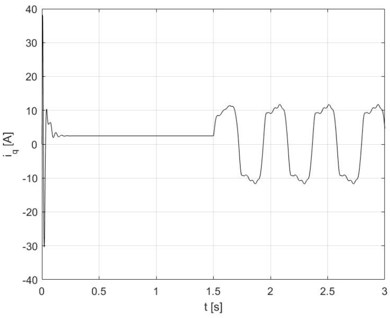


b)



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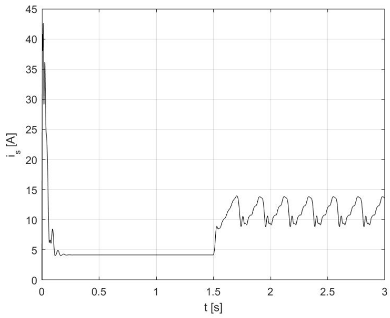

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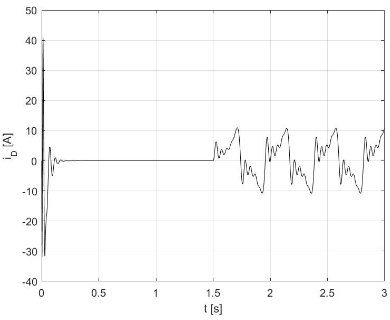

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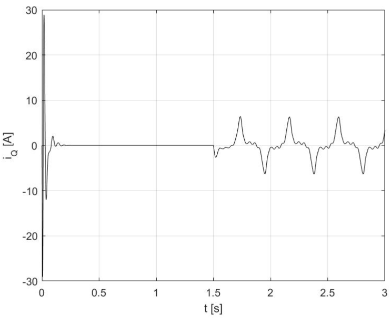

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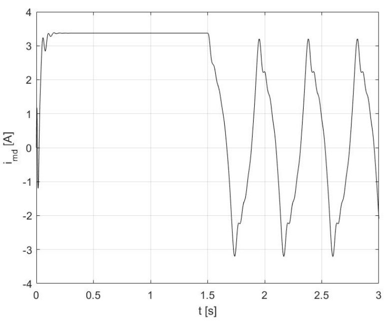
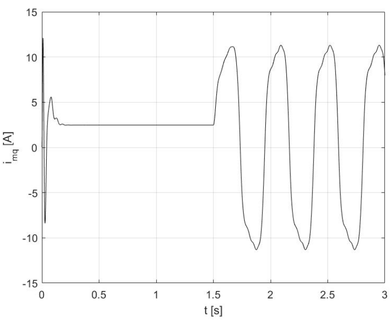
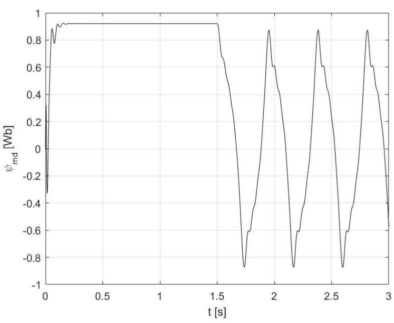


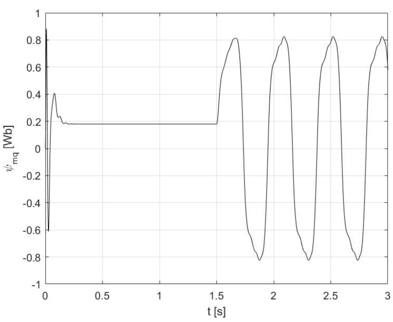
g)



h)



i)



j)

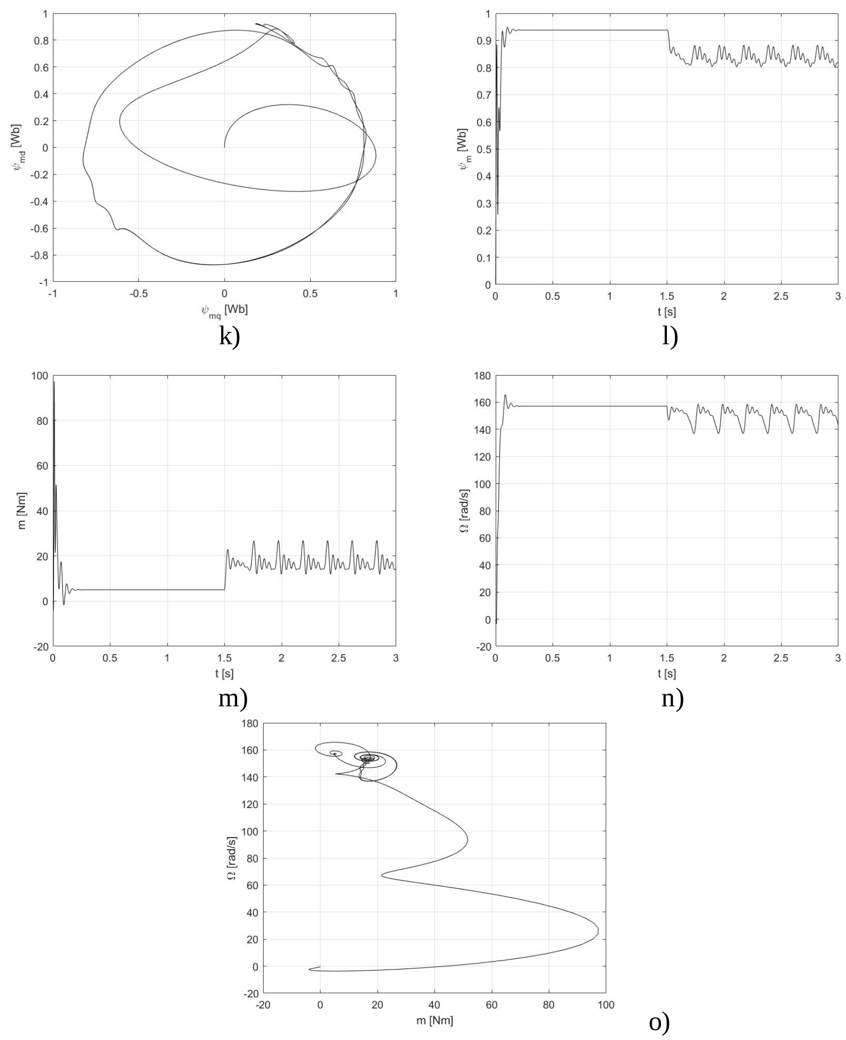


Fig. 3 – Characteristics corresponding to the case: U = 220 V, J = 0.01, Mr = 17 Nm.

5. Conclusions

A few relevant conclusions have been obtained by completing the study presented before:

– by simulations it is possible to view the evolutions of some quantities which cannot be measured in other way (*e.g.* fluxes and magnetization currents);

– the motor behaviour after applying a torque shock is conditioned by the value of this torque shock; over a certain value the motor loses its stability;

– according to Fig. 2, for a low torque shock, the motor does not lose its stability (it passes in another steady state);

– if the torque shock is high, the motor loses its stability; as noticed in Fig. 3, once entered oscillation, the rotor cannot get the synchronism speed. Moreover, large variations of the currents and fluxes occur;

– finally the operation point, in coordinates $\Omega = f(m)$, goes on a limit cycle.

It is possible to establish, by simulations, the value of the resistant torque for which the RSM becomes unstable (it exceeds the stability limit). Consequently, the values range of the resistant torque which must be avoided will be known.

The stability limit depends upon the motor parameters, too (for the same values of the disturbances). By an adequate design, motors having a large limit of stability can be obtained. Consequently, in design, it is absolutely necessary to take into account simulations of the motor behaviour for different parameters. So, the simulations contribute to a useful pre-determination of the parameters. The parameters that will ensure the best stability of the motor will be known.

Appendix

The notations used have the following meanings:
R_s – the phase of stator winding;
R_D – resistance of winding equivalent to starting cage by d-axis;
R_Q – resistance of winding equivalent to starting cage by q-axis;
L_d – longitudinal synchronous inductance;
L_q – cross synchronous inductance;
$L_{s\sigma}$ – stator leakage cyclic inductance;
$L_{D\sigma}$ – leakage inductance of winding equivalent to starting cage by d-axis;
$L_{Q\sigma}$ – leakage inductance of winding equivalent to starting cage by q-axis.

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SIMULĂRI PRIVIND INFLUENȚA PERTURBAȚIILOR DE CUPLU ASUPRA FUNCȚIONĂRII MOTOARELOR SINCRONE CU RELUCTANȚĂ

(Rezumat)

În lucrare se analizează stabilitatea dinamică a motoarelor sincrone cu reluctanță în cazul modificării bruşte a cuplului rezistent. Pentru aceasta, cu ajutorul unui program realizat în Matlab, s-au realizat o serie de simulări care evidențiază variația caracteristicilor unui motor de 1,5 kW în câteva stări dinamice. Simulările au dus la concluzii relevante cu privire la stabilitatea dinamică a sistemului analizat. Se accentuează importanța utilizării simulărilor în procesul de proiectare a acestor motoare. Astfel este posibil să se cunoască parametrii care asigură cea mai bună stabilitatea dinamică a motorului.