7TH INTERNATIONAL CONFERENCE ON ELECTROMECHANICAL AND POWER SYSTEMS
October 8-9, 2009 - Iaşi, Romania

CONSIDERATIONS REGARDING INFLUENCES OF RELUCTANCE SYNCHRONOUS MOTORS PARAMETERS ON THE ASYNCHRONOUS STARTING

Sorin ENACHE, Aurel CAMPEANU, Ion VLAD and Monica-Adela ENACHE

University of Craiova, Faculty for Electromechanical, Environmental and Industrial Informatics Engineering, senache@em.ucv.ro

***Abstract* – This paper analyzes the reluctance synchronous motors behaviour for a particular regime – the asynchronous starting. There are presented the mathematical model in the two axes d-q theory and an original simulation program, conceived in Matlab-Simulink. The simulations results are confronted with experimental results, obtained with the help of a data acquisition system. The conclusions which are finally presented emphasize the way in which the motor parameters influence the mentioned dynamic regime.**

Keywords: *reluctance synchronous motor, dynamic regime, mathematical model, Matlab-Simulink simulations, test.*

1. INTRODUCTION

The analysis of the dynamic processes from the synchronous machine is quiet difficult because of the magnetic and electric asymmetry of the rotor; this one has symmetry only on two axes, d and q, which are electrically orthogonal. When the stable operation regime is disturbed there occur both alternating components and practically non-periodic components of the machine windings currents, which tend to keep unchanged the windings fluxes (at the moment t=0 the machine windings have a behaviour of superconductor circuits). Owing to the transient currents established through windings, the magnetic field configuration into machine in the subsequent moments is modified and the machine parameters are also modified.

In order to avoid the computation complications, the transient processes study is made in the general case by means of the two axes theory, with enough precision for practice.

2. MATHEMATICAL MODEL OF THE MOTOR

The equations detailed in [2] are the starting point, but the fact that the RSM has not excitation winding is taken into account. The mathematical model written in the reference frame which is fixed relatively to the rotor is such obtained:

$$
\begin{aligned}
&u_d - R_s i_d + \omega L_q i_q + \omega L_{qh} i_Q = L_d \frac{di_d}{dt} + L_{dh}\frac{di_D}{dt}\\
&u_q - R_s i_q - \omega L_d i_d - \omega L_{dh} i_D = L_q \frac{di_q}{dt} + L_{qh}\frac{di_Q}{dt}\\
&-R_D i_D = L_{dh}\frac{di_d}{dt} + L_D \frac{di_D}{dt} \qquad (1)\\
&-R_Q i_Q = L_{qh}\frac{di_q}{dt} + L_Q \frac{di_Q}{dt}
\end{aligned}
$$

The motion equation is added to these relations:

$$\frac{3}{2}p\left(\psi_d i_q - \psi_q i_d\right) - m_r = \frac{J}{p}\frac{d\omega}{dt} \qquad (2)$$

respectively

$$\frac{3}{2}p\left(L_d i_d i_q + L_{dh} i_D i_q - L_q i_q i_d - L_{qh} i_Q i_d\right) - m_r = \frac{J}{p}\frac{d\omega}{dt}$$

(3)

In order to obtain a Matlab – Simulink block scheme which allows to get quickly the answer in the case of the variable frequency command for a MSRV, the equations (1) will be written again as follows.

At the beginning, the following notations will be used:

$$
\begin{aligned}
&a = u_d - R_s i_d + \omega L_q i_q + \omega L_{qh} i_Q\\
&b = u_q - R_s i_q - \omega L_d i_d - \omega L_{dh} i_D \qquad (4)\\
&c = -R_D i_D\\
&d = -R_Q i_Q
\end{aligned}
$$

The obtained system has the equivalent form:

$$
\begin{aligned}
&L_d \cdot \frac{di_d}{dt} + L_{dh} \cdot \frac{di_D}{dt} = a\\
&L_q \cdot \frac{di_q}{dt} + L_{qh} \cdot \frac{di_Q}{dt} = b \qquad (5)
\end{aligned}
$$

$$L_{dh} \cdot \frac{di_d}{dt} + L_D \cdot \frac{di_D}{dt} = c$$

$$L_{qh} \cdot \frac{di_q}{dt} + L_Q \cdot \frac{di_Q}{dt} = d$$

By solving this system relatively to the derivatives one will obtain:

$$\frac{di_d}{dt} = \frac{L_D \cdot a - L_{dh} \cdot c}{L_d L_D - L_{dh}^2}$$

$$\frac{di_q}{dt} = \frac{L_Q \cdot b - L_{qh} \cdot d}{L_q L_Q - L_{qh}^2} \qquad (6)$$

$$\frac{di_D}{dt} = \frac{-L_{dh} \cdot a + L_d \cdot c}{L_d L_D - L_{dh}^2}$$

$$\frac{di_Q}{dt} = \frac{-L_{qh} \cdot b + L_q \cdot d}{L_q L_Q - L_{qh}^2}$$

By replacing a, b, c and d it is obtained:

$$\frac{di_d}{dt} = \frac{1}{L_d L_D - L_{dh}^2}(L_D u_d - R_s L_D i_d + \omega L_q L_D i_q + \\ + \omega L_D L_{qh} i_Q + R_D L_{dh} i_D)$$

$$\frac{di_q}{dt} = \frac{1}{L_q L_Q - L_{qh}^2}(L_Q u_q - R_s L_Q i_q - \omega L_d L_Q i_d - \\ - \omega L_Q L_{dh} i_D + R_Q L_{qh} i_Q)$$

$$\frac{di_D}{dt} = \frac{1}{L_d L_D - L_{dh}^2}(-L_{dh} u_d + R_s L_{dh} i_d - \omega L_q L_{dh} i_q - \\ - \omega L_{dh} L_{qh} i_Q - R_D L_d i_D)$$

$$\frac{di_Q}{dt} = \frac{1}{L_q L_Q - L_{qh}^2}(-L_{qh} u_q + R_s L_{qh} i_q + \omega L_d L_{qh} i_d + \\ + \omega L_{dh} L_{qh} i_D - R_Q L_q i_Q) \qquad (7)$$

These relations can be written in matrix form:

$$\frac{d[i]}{dt} = [A][i] + [B][u], \qquad (8)$$

where:

$$[i] = \begin{vmatrix} i_d \\ i_q \\ i_D \\ i_Q \end{vmatrix}, \ [u] = \begin{vmatrix} u_d \\ u_q \end{vmatrix}$$

$$A = \begin{vmatrix} -\frac{R_s L_D}{L_d L_D - L_{dh}^2} & \frac{\omega L_q L_D}{L_d L_D - L_{dh}^2} & \frac{R_D L_{dh}}{L_d L_D - L_{dh}^2} & \frac{\omega L_D L_{qh}}{L_d L_D - L_{dh}^2} \\ -\frac{\omega L_d L_Q}{L_q L_Q - L_{qh}^2} & -\frac{R_s L_Q}{L_q L_Q - L_{qh}^2} & -\frac{\omega L_Q L_{dh}}{L_q L_Q - L_{qh}^2} & \frac{R_Q L_{qh}}{L_q L_Q - L_{qh}^2} \\ \frac{R_s L_{dh}}{L_d L_D - L_{dh}^2} & -\frac{\omega L_q L_{dh}}{L_d L_D - L_{dh}^2} & -\frac{R_D L_d}{L_d L_D - L_{dh}^2} & -\frac{\omega L_{dh} L_{qh}}{L_d L_D - L_{dh}^2} \\ \frac{\omega L_d L_{qh}}{L_q L_Q - L_{qh}^2} & \frac{R_s L_{qh}}{L_q L_Q - L_{qh}^2} & \frac{\omega L_{dh} L_{qh}}{L_q L_Q - L_{qh}^2} & -\frac{R_Q L_q}{L_q L_Q - L_{qh}^2} \end{vmatrix},$$

$$[B] = \begin{vmatrix} \frac{L_D}{L_d L_D - L_{dh}^2} & 0 \\ 0 & \frac{L_Q}{L_q L_Q - L_{qh}^2} \\ -\frac{L_{dh}}{L_d L_D - L_{dh}^2} & 0 \\ 0 & -\frac{L_{qh}}{L_q L_Q - L_{qh}^2} \end{vmatrix}.$$

to which the motion equation is added, obtained from (3):

$$\frac{d\omega}{dt} = \frac{p}{J}\left[\frac{3}{2}p\left(L_d i_d i_q + L_{dh} i_D i_q - L_q i_q i_d - L_{qh} i_Q i_d\right) - m_r\right] \qquad (9)$$

3. MATLAB-SIMULINK PROGRAM

The following program „parmsrv” has been obtained in Matlab-Simulink [4].

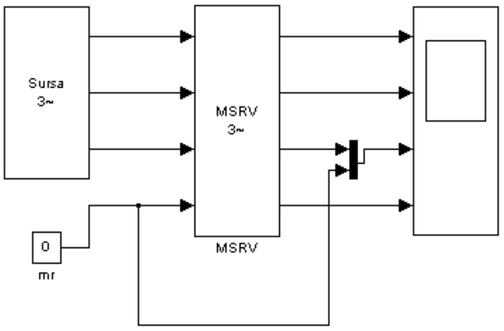


Fig. 1 – Mask of the simulation program

Block „Sursa” simulates the three-phase supply network. It has the following content.

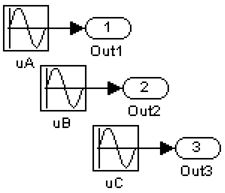


Fig. 2 – Structure of the block „Sursa”

The Simulink model of the motor has been obtained with the help of the equations (8), model depicted in the following figure.

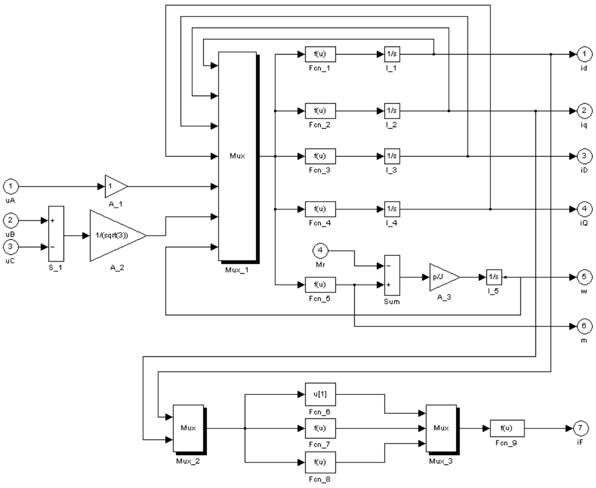


Fig. 3 - Simulink model of the motor

The functions Fcn_1, Fcn_2, Fcn_3, Fcn_4, Fcn_5 have the following forms:

(-Rs*LD*u[1]+u[7]*Lq*LD*u[2]+RD*Ldh*u[3]+u[7]*LD*Lqh*u[4]+LD*u[5])/(Ld*LD-Ldh^2)

(-u[7]*Ld*LQ*u[1]-Rs*LQ*u[2]-u[7]*LQ*Ldh*u[3]+RQ*Lqh*u[4]+LQ*u[6])/(Lq*LQ-Lqh^2)

(Rs*Ldh*u[1]-u[7]*Lq*Ldh*u[2]-RD*Ld*u[3]-u[7]*Ldh*Lqh*u[4]-Ldh*u[5])/(Ld*LD-Ldh^2)

(u[7]*Ld*Lqh*u[1]+Rs*Lqh*u[2]+u[7]*Ldh*Lqh*u[3]-RQ*Lq*u[4]-Lqh*u[6])/(Lq*LQ-Lqh^2)

3/2*p*(Ld*u[1]*u[2]+Ldh*u[3]*u[2]-Lq*u[2]*u[1]-Lqh*u[4]*u[1])

A few blocks necessary for the inverter input current, i_F, computation have been added in order to make possible the model utilization in the frame of the driving systems.

In order to obtain it, the currents i_A, i_B and i_C have been computed, they being then multiplexed and passed through the block Fcn_9.
The structures of the blocks Fcn_6, Fcn_7, Fcn_8 and Fcn_9 are, in order:

u[1]

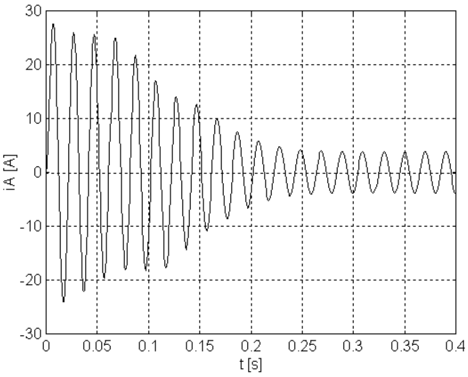
(-u[1]+sqrt(3)*u[2])/2

(-u[1]-sqrt(3)*u[2])/2

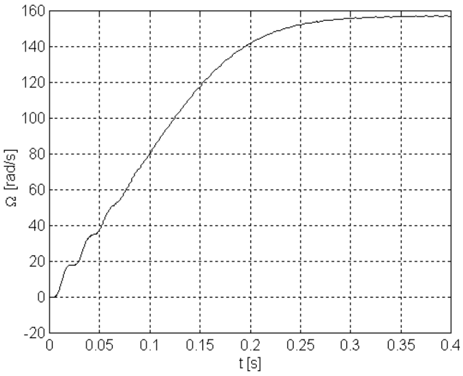
(u[1]*(u[1]>0))+(u[2]*(u[2]>0))+(u[3]*(u[3]>0))

4. SIMULATIONS

A series of graphic representations have been obtained by running the program, but only a few of them, corresponding to the dynamic regime of the asynchronous starting, are depicted further on.



a) Characteristic i_A=f(t)

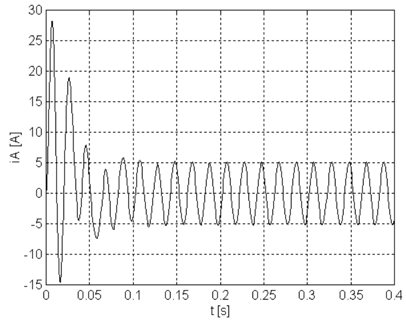


b) Speed characteristic Ω =f(t)

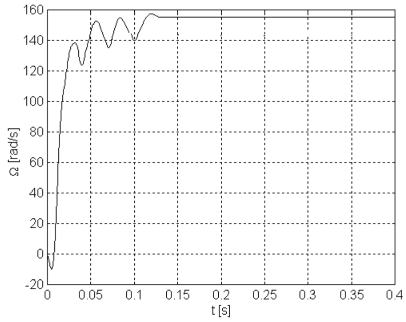
Fig. 4 - Starting characteristics obtained for the case J=10 J_m

5. TEST BENCH

The following experimental scheme has been used (figure 8) for obtaining the steady state characteristics of RSM [5].

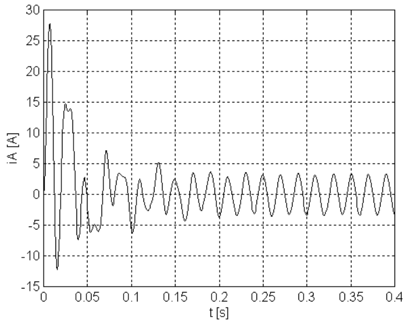


a) Characteristic i_A=f(t)

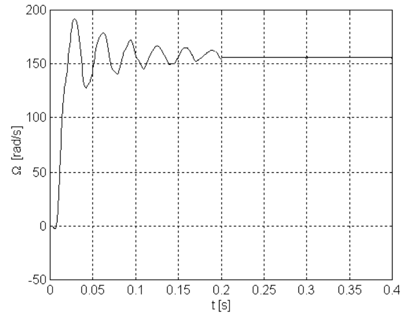


b) Speed characteristic Ω =f(t)

Fig. 5 - Starting characteristics obtained for the case M_r=10 Nm

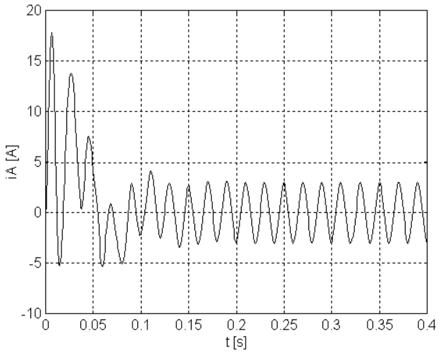


a) Characteristic i_A=f(t)

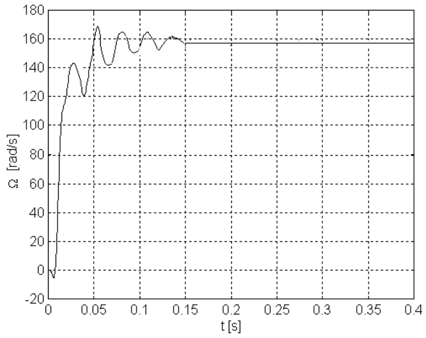


b) Speed characteristic Ω =f(t)

Fig. 6 - Starting characteristics obtained for the case R_Q=0,5 R_{Qm}



a) Characteristic i_A=f(t)



b) Speed characteristic Ω =f(t)

Fig. 7 - Starting characteristics obtained for the case R_D=2,5 R_{Dm}

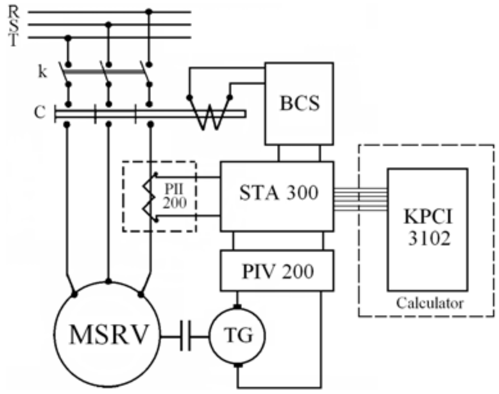


Fig. 8 - Experimental scheme

6. EXPERIMENTAL DETERMINATIONS AND CONCLUSIONS

The phase current and the speed dependence during the transient regime of asynchronous starting are depicted in the figures 9 and 10.

The following conclusions result from the analysis of these graphics:

- a similar phenomenon also occurs in the case of the starting with a great resistant torque (when the resistant torque increases very much it is possible for the motor not to synchronize anymore);

-the increase of the inertia moment value determines the increase of the analyzed transient process duration, the synchronization being made after a great number of oscillations;
- the increase of the resistance R_D value has a non-stabilizing effect;
- a small value of the resistance R_Q, even at null resistant torque, and a small inertia moment, can lead to an unstable operation.

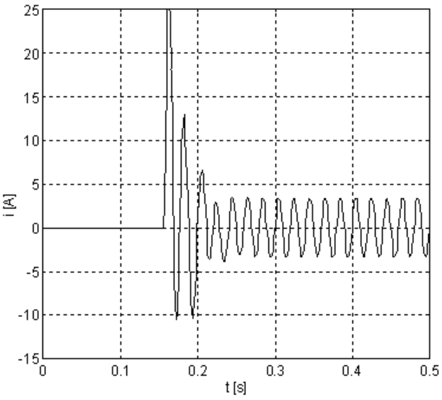


Fig. 9 - Current variation

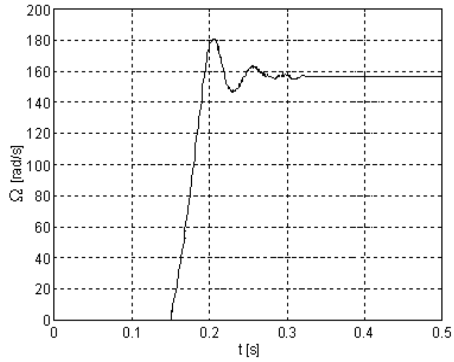


Fig. 10 - Speed variation

References

1. R.E. Betz, R. Lagerquist, M. Jovanovic, T.J.E. Miller, R.H. Middleton, *Control of Synchronous Reluctance Machines*, IEEE Transactions on Industry Applications, Vol. 29, No. 6, November/December 1993.
2. A. Campeanu, *Introducere in dinamica masinilor de curent alternativ*, Ed. Academiei, Bucuresti, 1995.
3. A. Staton, T.J.E. Miller, S.E. Wood, *Optimization of the synchronous reluctance motor geometry*, IEE Electrical Machines and Drives Conf., London, (UK), Sept. 1991.
4. M.A. Enache, C. Nica, S. Ivanov, *Aspects Regarding Modelling of Reluctance Synchronous Motors*, Analele Universității din Craiova, Seria: Inginerie electrică, Anul 31, nr.31, Vol.II, 2007, ISSN 1842-4805.
5. S. Enache, I. Vlad, M.A. Enache, *Test Bench for Reluctance Synchronous Motors*, Analele Universității din Craiova, Seria: Inginerie electrică, Anul 31, nr.31, Vol.II, 2007, ISSN 1842-4805, pp. 122-125.
6. T.A. Lipo, *Synchronous Reluctance Machines – a Viable Alternative for a.c, Drives*, Electric Machines and Power Systems, vol. 19, Nov./Dec., 1991, No. 6, pp. 659-671.
7. T.J.E. Miller, D.A. Staton, S.E. Wood, *Maximing the Saliency Ratio of the Synchronous Reluctance Motor*, Internal Report, Speed Consortium, 1992.
8. A. Vagati, M. Pastorelli, G. Franceschiuni, St. Petrache, *Design of Low-Torque-Riple Synchronous Reluctance Motors*, IEEE Transaction on Industry Applications, vol. 34, no. 4, 1998, pp. 758-765.
9. L. Xu, F. Liao, *Design of the Doubly-Fed Reluctance Motor for Adjustable Speed Drives*, IEEE-IAS Annual Meeting Proceedings, Denver, 1994.
10. ***, *KPCI 3102 - Operating Manual, Keithley Metrabyte*, 2007.