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Dedicated to the memory of Academician Andrei Țugulea

DYNAMIC STABILITY OF PERMANENT MAGNET SYNCHRONOUS MACHINE VERSUS SYNCHRONOUS MACHINE WITH ELECTROMAGNETIC EXCITATION

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Key words: Permanent magnet, Synchronous motor, Transients, Modeling, Simulation.

There has been followed the effect of the two excitation systems upon the dynamic stability of synchronous machine. The dynamic electromagnetic torques, the electrical angular speeds of the main rotating field, and that of the rotor are simulated in detail; the dynamic magnetic stresses are also specified. By simulation, the currents of all the machine windings can be determined, so on this basis, all the electromagnetic and mechanical stresses are specified. The qualitative and quantitative results are useful both in the design stage of synchronous machine and in the industrial practice.

1. INTRODUCTION

At present by the side of synchronous machines in classical construction, with electromagnetic excitation (SMEE), [1–3] there are also manufactured, in a large range of power, permanent magnet synchronous machines (PMSM), with known advantages and disadvantages and which are the issue of many researches [4–13].

In order to really obtain competitive performances with PMSM, in the design stage it is absolutely necessary to simulate the specific dynamic processes which are to specify the electromagnetic and mechanical stresses; the parameters and constructive solutions are only finalized on this basis.

Generally advanced dynamic mathematical models of synchronous machine (using circuit theory, field models or circuits field) are proved to be a valuable mathematical tool, which provides plausible quantitative results. The simulations are also proved opportune in industrial working for pre-determining the machine behaviour in anticipated dynamic processes.

In this paper there are analyzed comparatively the dynamic performances, by using circuit theory, of a certain synchronous machine, which has the rotor with electromagnetic excitation or with permanent magnets; the same damping windings in D, Q axes are considered. The particularities of the dynamic behaviour of high power synchronous machine are analyzed in [14].

2. DYNAMIC MATHEMATICAL MODELS

Park voltage equations for both excitation systems are of the form [15], (see and [4])

$$A\frac{\mathrm{d}X}{\mathrm{d}t}+BX=U\,. \qquad (1)$$

X is the matrix of the state variables and A, B are matrixes dependent upon the state variables.

For PMSM, the hybrid model is considered with

$$X=\begin{vmatrix} i_d & i_q & \Psi_d & \Psi_q \end{vmatrix}^{\mathrm{T}} \qquad (2)$$

$$U=\begin{vmatrix} u_d & u_q & \dfrac{T_{d0}^{//}}{1-\sigma_D}\psi_p & 0 \end{vmatrix}^{\mathrm{T}}. \qquad (3)$$

Accordingly, the matrices A, B have the form

$$A=\begin{vmatrix} & & 1 & \\ & & & 1 \\ -L_d\dfrac{\sigma_{Dd}}{1-\sigma_D} & & \dfrac{1}{1-\sigma_D} & \\ & -L_q\dfrac{\sigma_{Qq}}{1-\sigma_Q} & & \dfrac{1}{1-\sigma_Q} \end{vmatrix}, \qquad (4)$$

$$B=\begin{vmatrix} R_s & & & -\omega \\ & R_s & \omega & \\ -L_d\dfrac{T_{d0}^{//}}{1-\sigma_D} & & \dfrac{T_{d0}^{//}}{1-\sigma_D} & \\ & -L_q\dfrac{T_{q0}^{//}}{1-\sigma_Q} & & \dfrac{T_{q0}^{//}}{1-\sigma_Q} \end{vmatrix}, \qquad (5)$$

where T''_{d0}, T''_{q0}, – rotor time constants for open stator winding.

For SMEE, the currents of the windings are considered as state variable with

$$X=\begin{vmatrix} i_d & i_q & i_E & i_D & i_Q \end{vmatrix}^{\mathrm{T}}, \qquad (6)$$

$$U=\begin{vmatrix} u_d & u_q & u_E & 0 & 0 \end{vmatrix}^{\mathrm{T}} \qquad (7)$$

and accordingly, the matrices A, B

$$A=\begin{vmatrix} L_d & & L_{md} & L_{md} & \\ & L_q & & & L_{mq} \\ L_{md} & & L_E & L_{DE_\sigma}+L_{md} & \\ L_{md} & & L_{DE_\sigma}+L_{md} & L_D & \\ & L_{mq} & & & L_Q \end{vmatrix}, \qquad (8)$$

$$B=\begin{vmatrix} R_s & -\omega L_q & & & -\omega L_{mq} \\ \omega L_d & R_s & \omega L_{md} & \omega L_{md} & \\ & & R_S & & \\ & & & R_D & \\ & & & & R_Q \end{vmatrix}. \qquad (9)$$

The equation of motion is added to the voltage eqs. (1),

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$$m - M_r = \frac{J}{p}\frac{\mathrm{d}\omega}{\mathrm{d}t}, \tag{10}$$

where for PMSM

$$m = \frac{3}{2}p\left(\Psi_d i_q - \Psi_q i_d\right), \tag{11}$$

and for SMEE

$$m = \frac{3}{2}p\left[L_{md}\left(i_d + i_E + i_D\right)i_q - L_{mq}\left(i_q + i_Q\right)i_d\right]. \tag{12}$$

In equations (1–10) u_i, i_i, ψ_i, R_i, L_i are voltages, currents, flux linkages, resistances and inductances. The indices $i=d$, q and $i=D$, Q, E refer to the stator and rotor; ψ_p – the permanent magnetic flux linkage. The index σ is attached to the leakage inductances and the subscript m to the cyclic magnetization inductances. J is the rotor inertia and m, M_r are the electromagnetic and load torques.

The speed ω_ψ of the main magnetic field $\underline{\psi}_m$, during the dynamic processes will be [4]

$$\omega_\psi = \frac{\mathrm{d}\varphi}{\mathrm{d}t} + \omega, \tag{13}$$

where ω is the electrical speed of the rotor, and

$$\frac{\mathrm{d}\varphi}{\mathrm{d}t} = \frac{1}{\psi_m}\left(\frac{\mathrm{d}\psi_{mq}}{\mathrm{d}t}\cos\varphi - \frac{\mathrm{d}\psi_{md}}{\mathrm{d}t}\sin\varphi\right), \tag{14}$$

φ specifies the position of $\underline{\psi}_m$ in the (d, q) reference frame.

The system of equations (1–14) is generally valid, irrespective of the dynamic state considered.

3. SIMULATION RESULTS

There is considered a synchronous motor, with given parameters of the stator and damping windings. The main excitation flux is ensured: a) by a permanent magnet, b) by an excitation winding, E. The parameters used for simulations are given in the appendix. Sudden application of a load torque is considered. The effects of the excitation systems upon the dynamic performances of the synchronous machine are compared, where there have been plotted representative characteristics regarding electromagnetic torques the main magnetic field, the electrical transient speeds of the main magnetic field and of the rotor and. The figures affected by indices a, b refer to PMSM and SMEE respectively. In points **1** the load torque is applied, in points **2** the dynamic process ends; for electromagnetic excitation the dynamic excitation process is also plotted (zone (0, 1)].

Let us consider M_r=10 Nm.

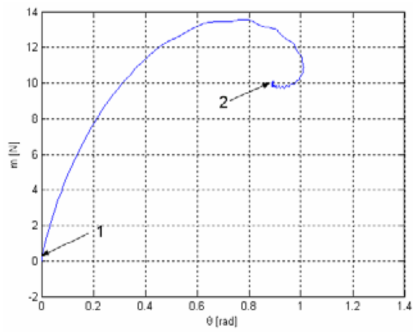

Fig. 1a

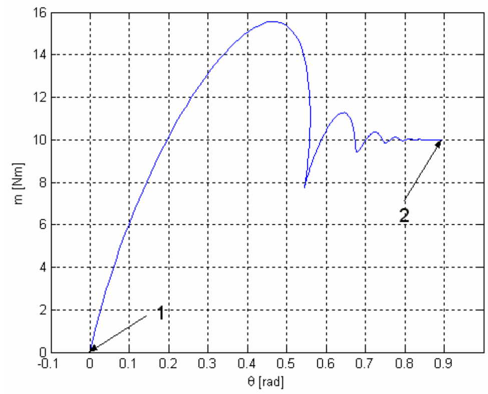

Fig. 1b

Fig. 1 – Characteristics $m(\theta)$.

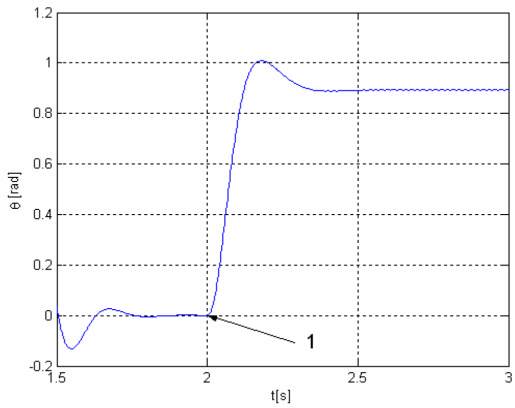

Fig. 2a

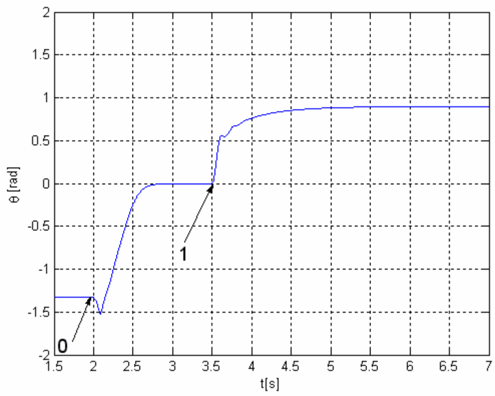

Fig. 2b

Fig. 2 – Characteristics $\theta(t)$.

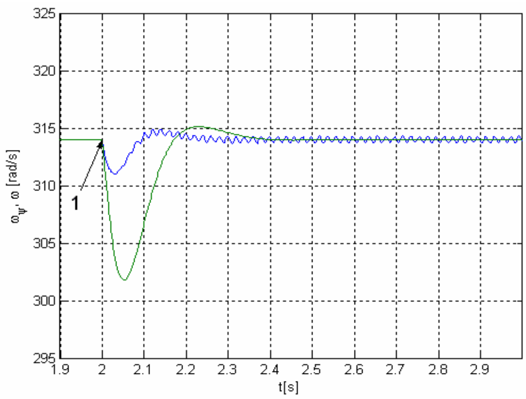

Fig. 3a

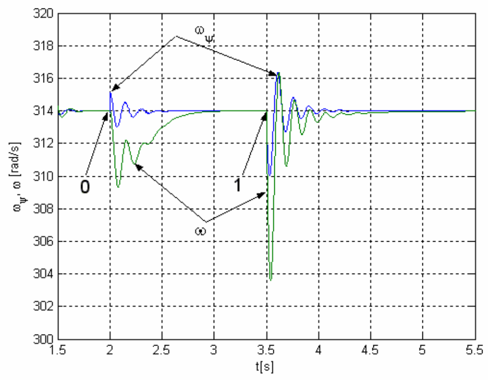

Fig. 3b

Fig. 3 – Characteristics $\omega_\psi(t)$, ω (t).

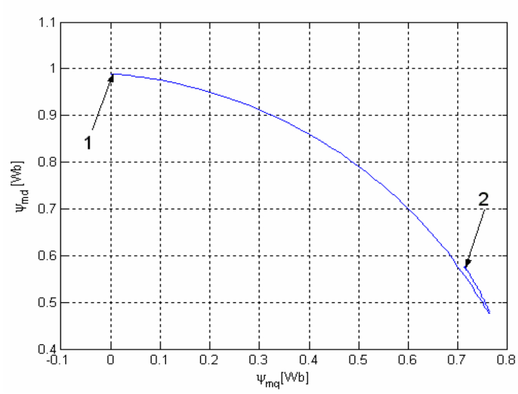

Fig. 4 – Characteristic (ψ_{md}, ψ_{mq}).

The dynamic starting process analyzed in [4] is not considered. The zone (**1**, **2**) is analyzed preferentially.

In Figs. 1a, 1b there are plotted *angular characteristics* $m(\theta)$. It is noticed that finally the synchronous operation is preserved, as expected, with the same internal angle.

By comparing the characteristics, it results that there is a transition **1**→**2** sensitively oscillating and with higher dynamic torques in case of electromagnetic excitation. The *characteristics* $\theta(t)$ given in Figs. 2a, 2b are sensitively different, but there is no oscillating character as before; a longer duration of the dynamic process is noticed in case of electromagnetic excitation.

Figure 3 emphasizes a tight connection between the *angular speeds* ω (t), $\omega_\psi(t)$. In case of permanent magnet, the dynamic process, with oscillations including over-synchronous oscillations, is quickly damped; in case of electromagnetic excitation these oscillations are larger. In Fig. 3b, the whole dynamic process (including the zone (**0–1**) is detailed. In Fig. 4, there is plotted *dynamic characteristic* (ψ_{md}, ψ_{mq}), by passing 1→2 for estimating the magnetic stresses. In case of electromagnetic excitation, there results a characteristic having practically the same evolution, with the same coordinates of the points **1**, **2**.

Let us consider M_r= 15 Nm. The same characteristics are plotted. At the end of the dynamic process, the synchronous machine loses the synchronism in both excitation systems and enters an oscillating asynchronous quasi-steady state operation. In case of electromagnetic excitation, the dynamic process of the excitation voltage increase to u_E = 6 V is also analyzed.

Figures 5a, 5b1 represent the *characteristics* $m(\theta)$. Figure 5a shows how it passes from the point **1** to an oscillating asynchronous operation on a *limit cycle*; the oscillation limits of the electromagnetic torque clearly result.

The moment when u_E = 6 V is applied, can determine synchronization or deepening the asynchronous operation of the machine.

Figure 5b1 represents the whole evolution from the moment when the machine is excited until it passes on a limit cycle, determined by applying M_r = 15 Nm in **1**. Figures 5b11 and 5b12 are plotted for clarity. In Fig. 5b12 the limit cycle is exclusively plotted. Applying u_E = 6 V and leaving the limit cycle at different moments, end with synchronization in Figs. 5b2, 5b2det or 5b3 which emphasizes the unstable operation. To be noted the major difference between the limit cycles from Figs. 5a and 5b12 caused by the excitation systems.

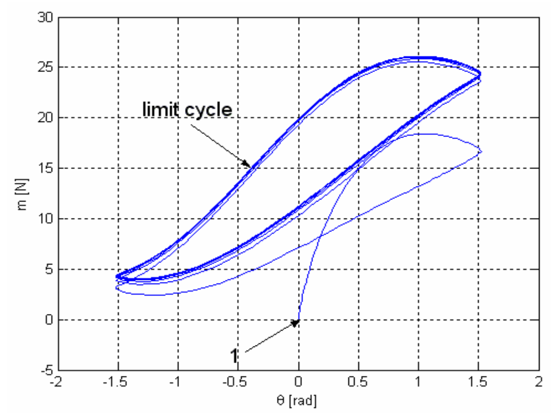

Fig. 5a

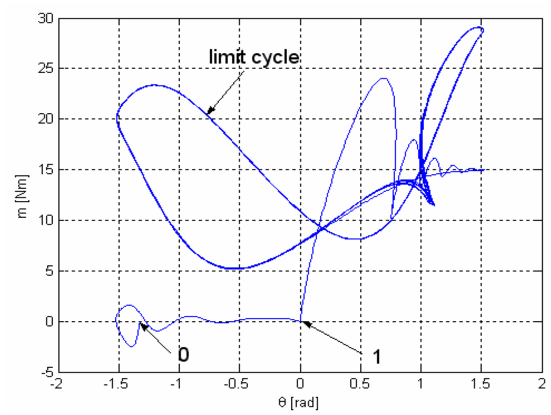

Fig. 5b1

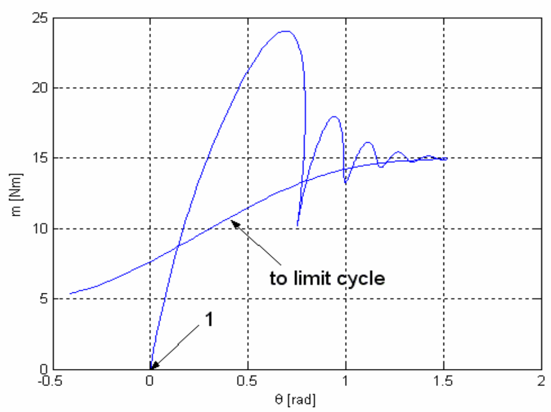

Fig. 5b11

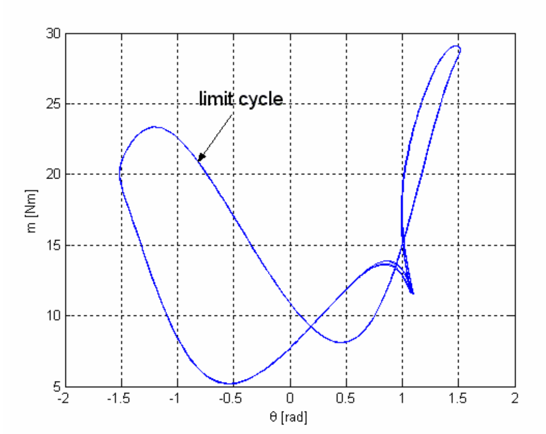

Fig. 5b12

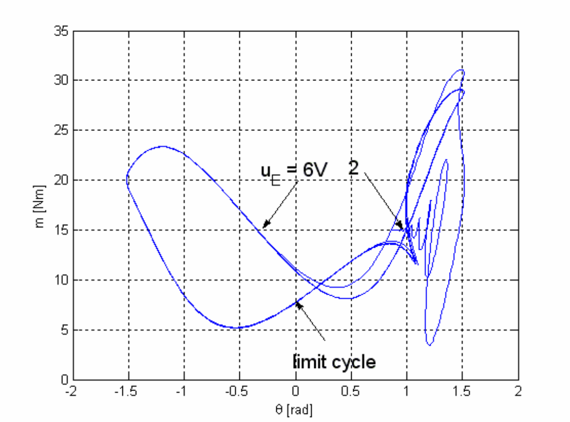

Fig. 5b2

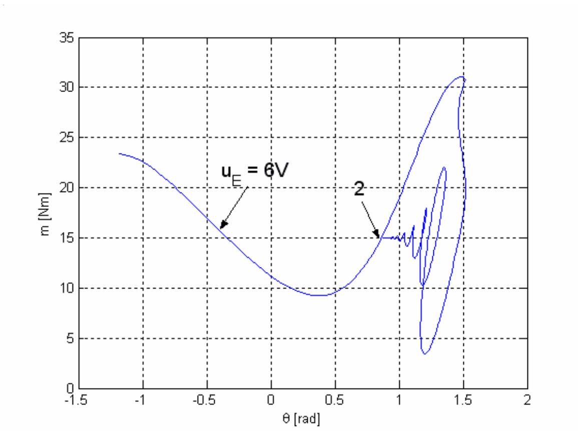

Fig. 5b2det

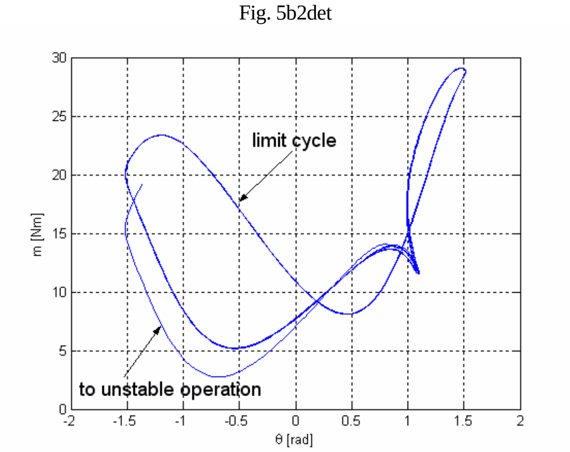

Fig. 5.b.3

Fig. 5 – Characteristics $m(\theta)$.

In Figs. 6 there are plotted the *characteristics* $\theta(t)$. Figures 6a, 6b1, 6b2, 6b3 correspond to the dynamic processes detailed respectively in Figs. 5a, 5b1, 5b2, 5b3.

Figure 7 corresponds to the *characteristics* $\omega_\psi(t)$, $\omega(t)$. Figure 7a details the transition to the asynchronous operation with practically sinusoidal oscillations. Figures 7b1, 7b2, 7b3 are the correspondents of the Figs. 5bi and 6bi (i = 1, 2, 3).

In Fig. 7b1 the whole dynamic process (including the zone (**0–1**) is detailed, for an overview image. Applying of M_r = 15 Nm causes a first group of oscillations, practically damped, round the synchronism speed, followed by an oscillating asynchronous operation (corresponding to the limit cycles from Fig. 5b1), with important correspondent oscillations, which suggest a major distorting state. Applying u_E = 6 V at different moments is followed, in Figs. 7b2, 7b3 by the synchronization process, respectively by an unstable operation, with important oscillations and by ever larger pulsations of ω_ψ as the rotor speed decreases.

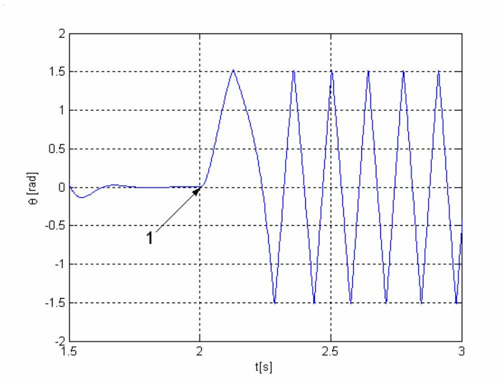

Fig. 6a

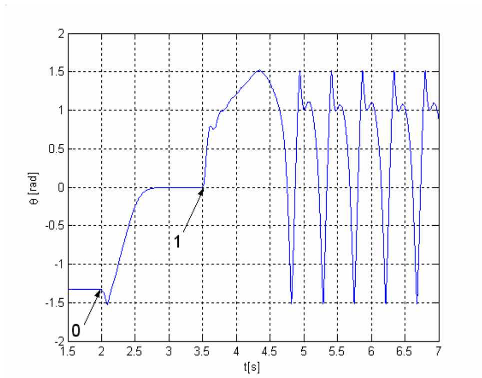

Fig . 6b1

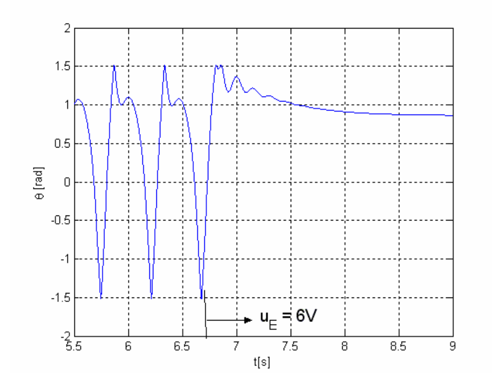

Fig. 6b2

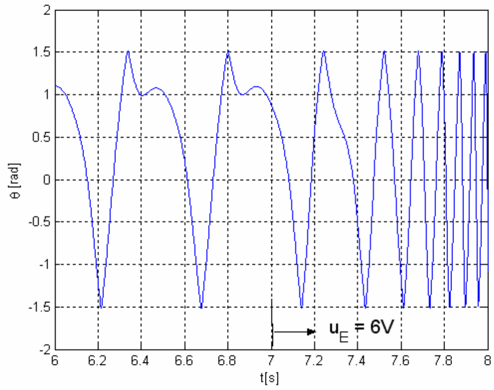

Fig. 6b3

Figs. 6 – Charateristics θ(*t*).

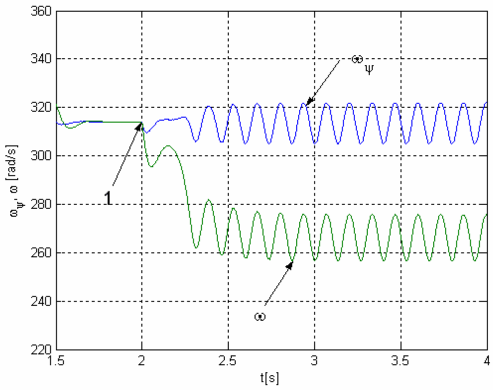

Fig. 7a

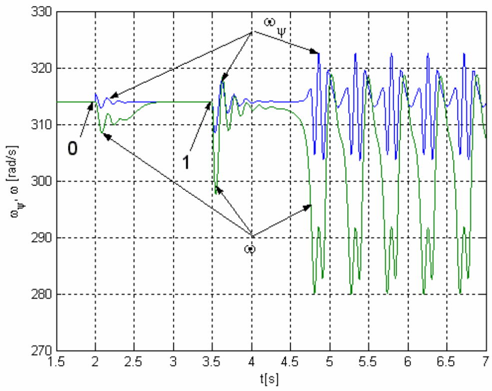

Fig. 7b1

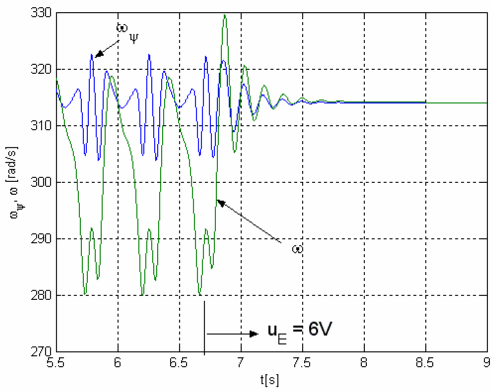

Fig. 7b2.

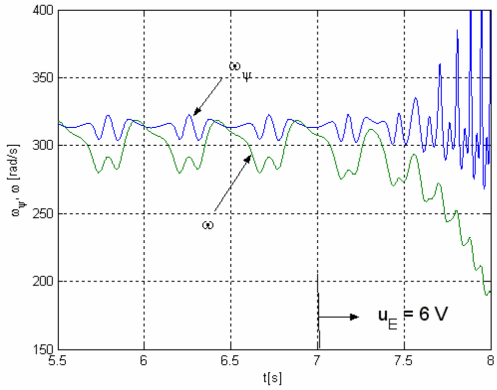

Fig. 7b3

Figs. 7 – Characteristics $\omega_\psi(t)$, $\omega(t)$.

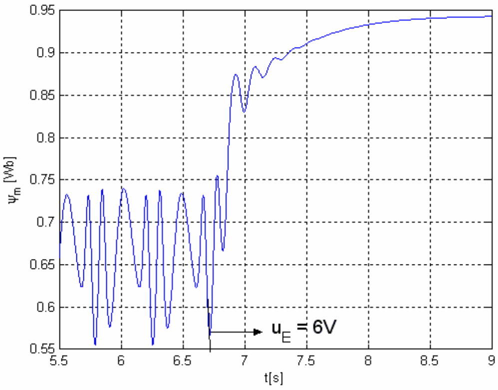

Fig. 8b2

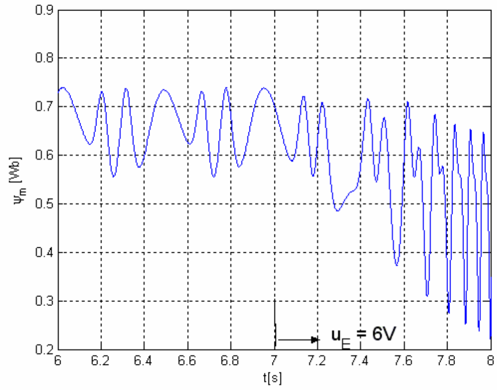

Fig. 8b3

Fig. 8 – Characteristics $\psi_m(t)$.

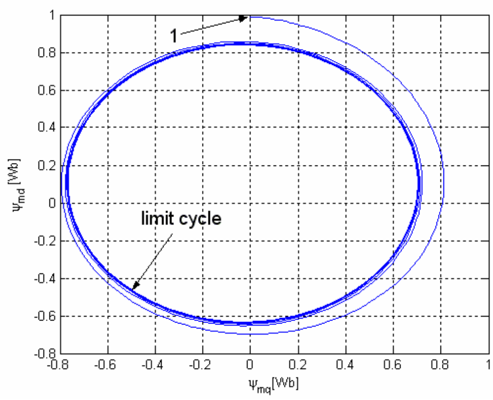

Fig. 9a

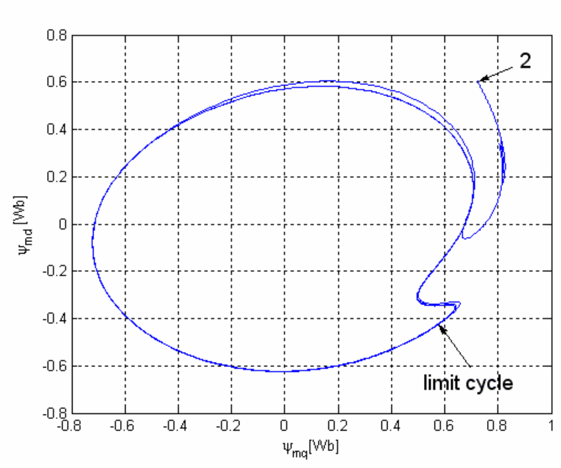

Fig. 9b2

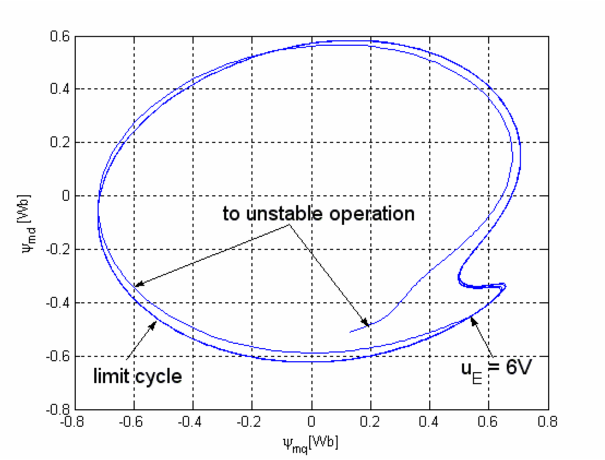

Fig. 9b3

Fig. 9 – Characteristics (ψ_{md}, ψ_{mq}).

Figures 8 and 9 emphasize the level of the *dynamic magnetic stresses*, when the limit cycles are present and different moment when u_E = 6 V is applied.

Only representative characteristics are plotted. Figures 8b2, 8b3 represent the characteristics in zones of oscillating quasi-steady state asynchronous operation and in those corresponding to u_E = 6 V, at passing to synchronous, respectively asynchronous operation.

Figure 9a presents the limit cycle afferent to PMSM. Figures 9b2, 9b3 also use the coordinates (d, q) and they are correspondent to Figs. 8b2, 8b3. In Fig. 9b2 the limit cycle and the point **2** of synchronism define the dimensions of the magnetic stresses. Figure 9b3 represents passing to unstable operation.

4. CONCLUSIONS

In this paper the dynamic behaviour of PMSM and SMEE is comparatively analyzed in details. The mechanical stresses (electromagnetic torques) and the magnetic stresses are mainly followed.

The quantitative and qualitative differences in the dynamic zones of the characteristics are notable. In dynamic processes, electromagnetic excitation generally lengthens their duration.

Moreover, in these zones, electromagnetic excitation determines an important distorting state, with increased electromagnetic and mechanical stresses.

The mathematical models used take into consideration fundamental processes in the machine and, consequently, the quantitative results obtained are realistic and useful in the design stage, as well as in industrial practice.

To be noted that at this detailed level of analysis, some of them, can be obtained only this way.

APPENDIX

The synchronous motor parameters used for simulation are $R_s = 2\Omega$, $R_D = R_Q = 4.5\ \Omega$, $L_{md} = L_{mq} = 0.21$ H, $L_{D\sigma} = L_{Q\sigma} = 0.034$ H, $L_{s\sigma} = 0.032$ H, $p = 2$, $J = 0.048$ kgm^2, for:

a) PMSM, ψ_p= 0.98 Wb;
b) SMEE the winding E, with $L_{E\sigma}$=0.038H, L_{DE} = 0.015H, R_E = 0.86 Ω, u_E = 4 V, $\psi_{Ed}=\psi_p$ is introduced.

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REFERENCES

1. A. Campeanu, *Nonlinear dynamical models of saturated salient pole synchronous machine*, Rev.Roum. Sci. Techn. – Electrotechn. et Energ., **47**, *3*, pp. 307–317, 2002.
2. T. Dordea, *Beitrag zur Zweiachsentheorie der Elektrischen Maschinen*, Archiv fur Elektrotechnik, **50**, *6*, pp. 362–371, 1966.
3. E Levi, *Saturation modeling in D-Q axis models of salient pole synchronous machines*, IEEE Trans. on Energ. Conversion, **14**, pp. 44–50, 1999.
4. A. Campeanu, S.Enache, I. Vlad, M.A. Enache, I. Cautil, *Asynchronous starting of permanent-magnet synchronous motor. Modelling and simulation*, Rev. Roum. Sci Techn. – Electrotechn. et Energ., **61**, *4*, pp. 313–318, 2016.
5. A. Campeanu, I. Vlad, S. Enache, *Effect of parameters and resistant torque upon dynamic performances of permanent-magnet synchronous machine*, The 10th International Symposium on Advanced topics in Electrical Engineering, Bucharest, 2017.
6. A. Takahashi, S. Kikuchi, *et al. Transient torque analysis of line-starting permanent-magnet synchronous motor*, International Conference on Electrical Machine, ICEM, Villamoura, Portugal, 2008.
7. A. Hassanpour Isfahani, S.Vaez-Zadeh, *Effects of Magnetizing Inductance on Start-Up and Synchronization of Line-Start Permanent Magnet Synchronous Motors*, IEEE Trans. on Magnet., **47**, *4*, 2011.
8. H. Behtahanifard, A. Sadoughi, *Line Start Permanent Magnet Synchronous Motors Performance and Desing*; *a Reviev*, I World Elect. Tech., **4**, *2*, pp 58–66, 2015.
9. X. Lu ,K. Lakshmi et al, *Development of a Novel Magnetic Circuit Model for Desing of Premium Efficiency Three-Phase Line Start Permanent Magnet Machines Whit Improved Starting Performance.* IEEE on Magnet., **49**, *7* , 2013.
10. M. D. Bogomolov, *Concept of study of 20 MW high speed PMSM for marine propulsion*, University of Technol., Eindhoven, 2013.
11. T. Ding, N. Takorabet, F.M. Sargos, *et al. Desing and Analysis of Different Line-Start PM Synchronous Motors for Oil-Pump Applications*, IEEE Trans. on Magn.,**45**, *3*, 2009.
12. R.T. Ugale, B.N. Chaudhari, *A New Rotor Structure for Line Start Permanent Magnet Synchronous Motor*,.IEEE International Conference on Electrical Machines & Drives IEMDC, 2013.
13. G. Yang, J-X Shen, *et al*., *Optimal Desing and experimental Verification of a Line Start Permanent Magnet Syncronous Motor.International* Conference on Electrical Machines and System ICEMS, 2008.
14. A. Campeanu, R.Munteanu, V. Iancu, *About dynamic stability of high power synchronous machine*. A review, Rev. Roum. Sci Techn.- Electrotechn. et Energ., **62**, *1*, pp. 8–13, 2017.
15. A. Campeanu, I. Cautil, I. Vlad, S. Enache, *Modeling and simulation of AC electrical machines* (in Romanian), Edit. Academiei Române, Bucharest, 2012.