Dynamic State of Low Power Asynchronous Motors in Direct-on-Line Starting

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***Abstract* –The research opportunity is explained by the results obtained in modelling and simulation of asynchronous motors, in the purpose of increasing their technical and economic performances when they operate in dynamic states. The study of the dynamic state is compulsory for low and very low power asynchronous motors which are used for driving industrial robots. In order to have simulation results, which are to be close to reality (those established experimentally), it is necessary to know the main inductance and the leakage inductance of the windings, their dependence upon the machine load, so upon the magnetic saturation. In this paper there are presented results, simulations and experimental tests are carried out in order to establish the errors which occur, for correcting the mathematical model used. With the help of the mathematical model presented in this paper, much complex dynamic states can also be studied, caused by the variation of the voltage, of the resistant torque, of the inertia moment etc. The starting characteristics have been computed considering magnetic saturation and current pressing, the results being: starting current I_p=4.208*I_N, starting time t_p=0.17s. It is considered that this study of asynchronous motor starting is justified, with an eye to obtaining some indications for their optimum construction and operation.**

Cuvinte cheie: *puteri mici, motoare asincrone, regimuri dinamice, simulare.*

Keywords: *low power, asynchronous motors, dynamic states, simulation.*

I. INTRODUCTION

Dynamic state of asynchronous motors has been studied in the speciality literature, but new mathematical models have been emerging where, the machine parameters are considered as being variable quantities in the differential equations. The simplified analytical solution, where the parameters were constant, has been replaced by advanced numerical methods for solving these equations [1-6]. All these aspects aim at increasing the precision of the results obtained by simulations.

At starting, beside the transient mechanical state determined by the speed variation, we also have a transient electromagnetic state conditioned by variations of currents, flux etc. Starting current of an asynchronous motor means the periodical component of the short-circuit current, given by the relation:

$$I_{1p} = \frac{U_1}{Z_{1sc}} \cong \frac{U_1}{\sqrt{(R_1 + R_2^{/})^2 + (X_1 + X_2^{/})^2}} \qquad (1)$$

because, the damping time constant of the current aperiodic component is very low.

At direct-on-line starting of an asynchronous motor, there must be considered: starting current and torque magnitude, starting time, on-time variation curves of current, speed, torque, energy consumed, winding losses, [7-9], etc.

These nonlinearities bring a lot of problems when the system has to be solved, if the solution is given by analytical methods.

It is possible to accept a linearization around the permanent operation point or, in certain conditions, some simplifications can be made and, this way, the equation system can be solved by usual ways.

II. MATHEMATICAL MODEL OF ASYNCHRONOUS MOTOR

Mathematical model of alternating current electrical machine means equations describing dependences between torque and the main electrical and mechanical quantities afferent to it.

Using some very precise mathematical models imposes to consider the influence of the magnetic saturation and the current pressing upon the machine parameters. In this case, the equation system is nonlinear and can only be solved by means of the computer [2-3], [10-19].

As for asynchronous motors, literature records models with distributed parameters and models with concentrated parameters.

The models belonging to the latter category are the most used in practice. In this case the equations are written in function of the machine resistances and inductances.

Using these models [20-22], in the analysis of dynamic processes provides very good input-output results.

From the category of models with concentrated parameters there will be presented below the equations in the two-axis theory, with rotor quantities related to the stator, written in a referential jointed with the stator (ω_B=0), with the following matrix form:

$$\frac{d}{dt}\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr}^{/} \\ i_{qr}^{/} \end{bmatrix} = \frac{1}{L_s L_r^{/} - L_{sh}^2}\begin{bmatrix} -R_s L_r^{/} & \omega L_{sh}^2 & R_r^{/} L_{sh} & \omega L_r^{/} L_{sh} \\ -\omega L_{sh}^2 & -R_s L_r^{/} & -\omega L_r^{/} L_{sh} & R_r^{/} L_{sh} \\ R_s L_{sh} & -\omega L_s L_{sh} & -R_r^{/} L_s & -\omega L_s L_r^{/} \\ \omega L_s L_{sh} & R_s L_{sh} & \omega L_s L_r^{/} & -R_r^{/} L_s \end{bmatrix} \cdot \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr}^{/} \\ i_{qr}^{/} \end{bmatrix}$$

$$+ \frac{1}{L_s L_r^{/} - L_{sh}^2}\begin{bmatrix} L_r^{/} & 0 \\ 0 & L_r^{/} \\ -L_{sh} & 0 \\ 0 & -L_{sh} \end{bmatrix} \cdot \begin{bmatrix} u_{ds} \\ u_{qs} \end{bmatrix} \qquad (2)$$

The motion equation is added to these equations:

$$\frac{d\omega}{dt} = \frac{p}{J}\left[\frac{3}{2} pL_{sh}(i_{qs}i'_{dr} - i_{ds}i'_{qr}) - m_r\right], \qquad (3)$$

where, the bracket is the electromagnetic torque:

$$m = \frac{3}{2} pL_{sh}(i_{qs}i'_{dr} - i_{ds}i'_{qr}) . \qquad (4)$$

The analysis of the dynamic behaviour of an asynchronous motor, where the rated data, parameters and resistant torque are known, results by solving numerically the equations presented before.

A. Computation program

A computation program has been carried out by using the mathematical model presented before, the fourth order Runge Kuta method of numerical computation, specific to differential equations [2-5], [15], [20].

With the help of the program, a lot of studies can be carried out, in order to emphasize the dynamic behaviour of asynchronous motor, the causes being as follows: variation of the supply voltage, variation of the rotor resistance or inductance, variation of the resistant torque.

For high currents, the motor inductances (stator, rotor and main) are quantities variable with the load factor ($k_s=I_1/I_{1N}$), due to the magnetic saturation, fact that modifies the dynamic behaviour. Solving this system becomes complicated because of all these situations; the system turns into a strongly nonlinear one and it only can be solved by numerical methods.

The values of the input quantities (voltage, resistant torque etc.), during the transient state can be modified by step, linear variation or by a certain law. These variations are given by points or as a matrix.

III. RESULTS OBTAINED BY SIMULATION

MATHCAD programming language has been used for numerical simulation of the asynchronous motor. It is a complex programming and simulation mathematical environment which can be used for modelling and analyzing dynamic systems.

The mathematical model presented was at the basis of a program and of many simulations, for establishing final conclusions.

The theoretical researches and experimental tests have been carried out with a squirrel-cage asynchronous motor rated as follows: $P_N=1,1$ kW –rated power; $U_N=380$ V –rated voltage; $I_{1N}=2.545$ A –rated current; $n_1=1500$ r.p.m. –synchronism speed; $s_N=3.8\%$ -rated slip and parameters $R_s=1.16$ Ω, $R'_r=3.515$ Ω, $L_{s\sigma}=0.024$ H, $L'_{r\sigma}=0.0034$ H, $L_{sh}=0.2986$ H, J=0.048 kgm^2.

The operation characteristics are: $cos\varphi=0.782$; $\eta=0.818$; $M_{max}=2.22{\cdot}M_N$; $M_p=1.74{\cdot}M_N$; $I_p=4.25{\cdot}I_N$.

A. Asynchronous motor starting

There are presented forwards the results obtained by solving the presented equations with numerical methods, regarding the electromechanical transient process of asynchronous motor direct-on-line starting for:

-no-load starting: J=0.048 kgm^2, $M_{st}=0.055{\cdot}M_N=0.395$ Nm..

-on-load starting: J=0.085 kgm^2, $M_{st}=1.0{\cdot}M_N=7.63$ Nm..

The analysis from Fig. 1 shows that in the first moments of the starting, the maximum momentary torques are high but few.

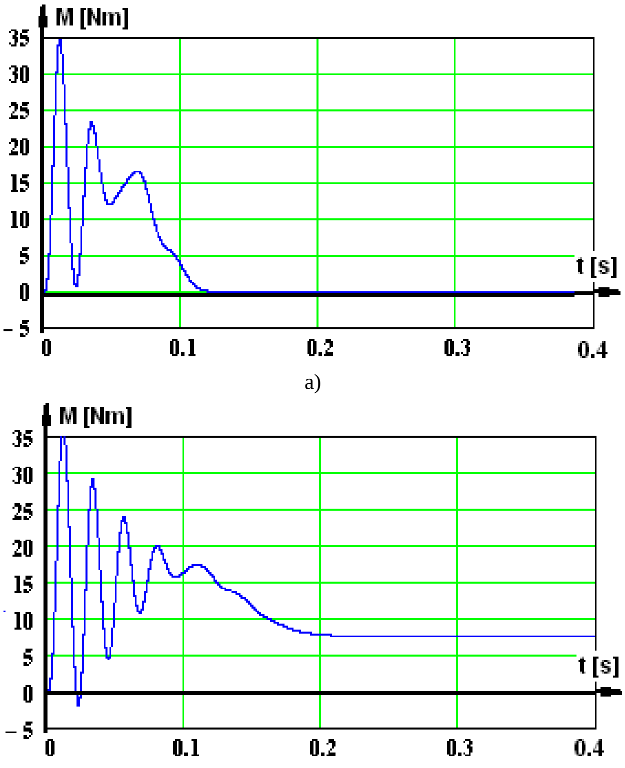


Fig.1. Variation curves for electromagnetic torque: a) no-load starting; b) on-load starting.

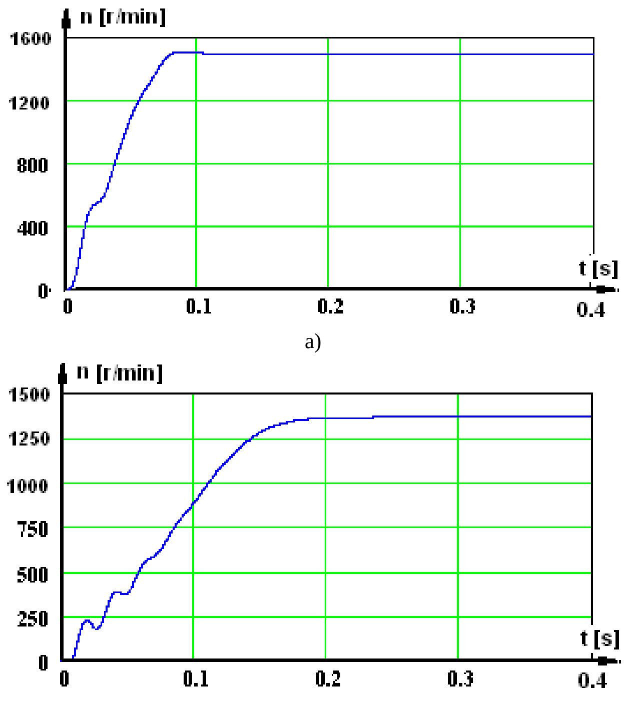


Fig.2. Variation curves for speed: a) no-load starting; b) on-load starting.

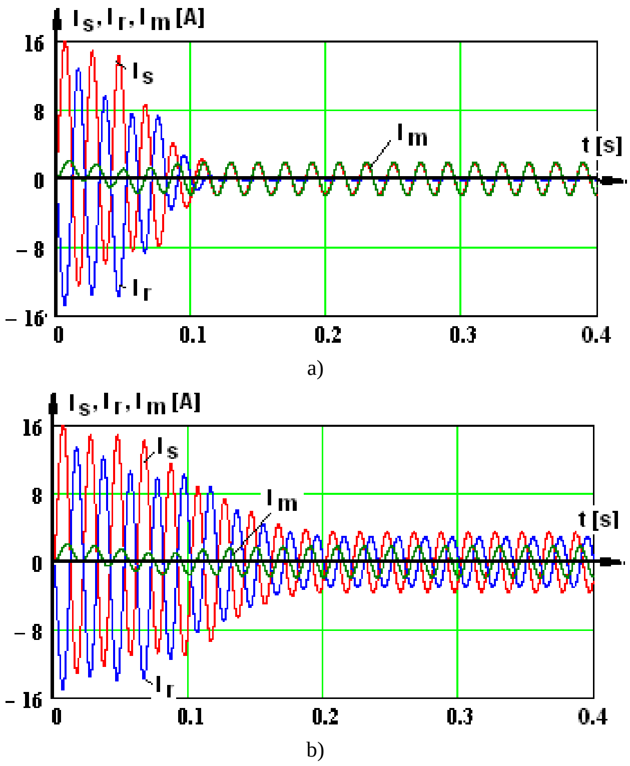


Fig.3. Variation curves for currents I_s – stator, I_r –rotor, I_m – magnetization: a) no-load starting; b) on-load starting.

The explanation is the inertia moment and the low power of the motor. In case of on-load starting, more torque oscillations occur, oscillations occur even in the speed curve and the starting time increases, Fig.2.

During the starting, the stator and rotor currents have high oscillations Fig.3, and the magnetization current remains almost constant. All the information necessary for no-load/on-load starting and those corresponding to the steady state can be obtained by simulation (Table I). At no-load operation Fig.3.a a low rotor current can be noticed, which causes an important magnetization current and so a very low power factor.

TABLE I. Starting results

			Results obtained by simulation	
Quantity analyzed	Symbol	MU	No-load operation	On-load operation
Inertia moment	J	kgm^2	0.048	0.0851
Resistant torque	M_r	Nm	0.395	7.63
Phase stator current	I_1	A	1.242	2.504
Related phase rotor current	I_{2r}	A	0.160	2.101
Magnetization current	I_{1m}	A	1.084	1.31
Speed	n_0	r/min	1496	1367

B. Dynamic state for a high inertia moment

The simulations presented below take into consideration the analyzed asynchronous motor rated at: $P_N=1,1$ kW –rated power; $U_N=380$ V –rated voltage; $I_{1N}=2.545$ A –rated current; $n_1=1500$ r.p.m. – synchronism speed.

All the graphic representations are plotted in per unit, with the following meaning of the quantities used:

s -slip;

R_{2r} - rotor winding resistance with pressing influence;

L_{1s}, L_{2sr} – per unit stator and rotor inductances, when magnetic saturation is considered;

L_{1m} – cyclic main inductance, when magnetic saturation is considered.

$m_{=}M(R_{2\zeta}, X_{1s}, X2_s)/M_N$ –per unit value of the torque;

$M(R_{2\zeta}, X_{1s}, X2_s$, M –real electromagnetic torque computed with the influence of the pressing and saturation, respectively the torque obtained without these two effects;

$n_{r=}n/n_1$ -per unit value of the speed;

$i_{p=}I_p/I_{1N}$ -per unit value of the starting current.

Forwards there will be carried out a detailed analysis of these two factors (pressing and magnetic saturation) upon the motor paramaters, respectively upon the mechanical and starting characteristics.

Fig. 4 shows the effect of current pressing in the rotor bar and Fig. 5 shows the effects of magnetic saturation upon the stator, rotor and magnetization inductances.

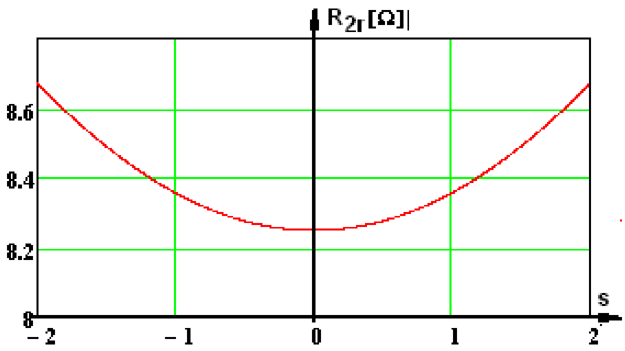
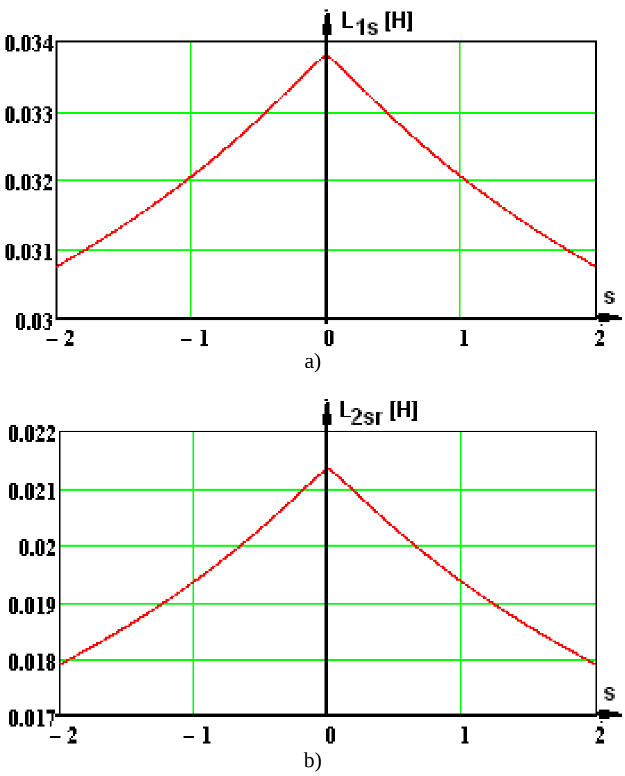
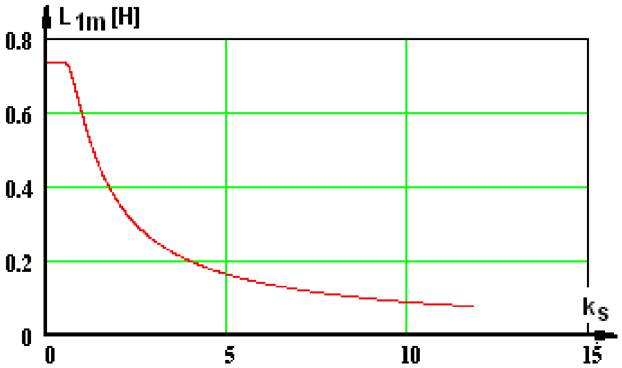


Fig. 4. Variation curve of the rotor winding resistance with current pressing.





c)

Fig. 5. Variation curves of the asynchronous machine parameters with magnetic saturation for a) stator winding inductance; b) rotor inductance; c) cyclic main inductance.

A thorough analysis of the no-load starting electromechanical transient process of asynchronous motor is carried out by means of the mathematical model presented in (2 -5).

The case when a mechanism having a very high inertia moment is coupled to the shaft is studied forwards (J_2=60*J=60*0.048= 2.88 kgm^2 and M_{st}=0.55*M_N=0.395 Nm).

This research also allows to establish the torque characteristics, respectively the current characteristic for steady state, by computing the average values for a period.

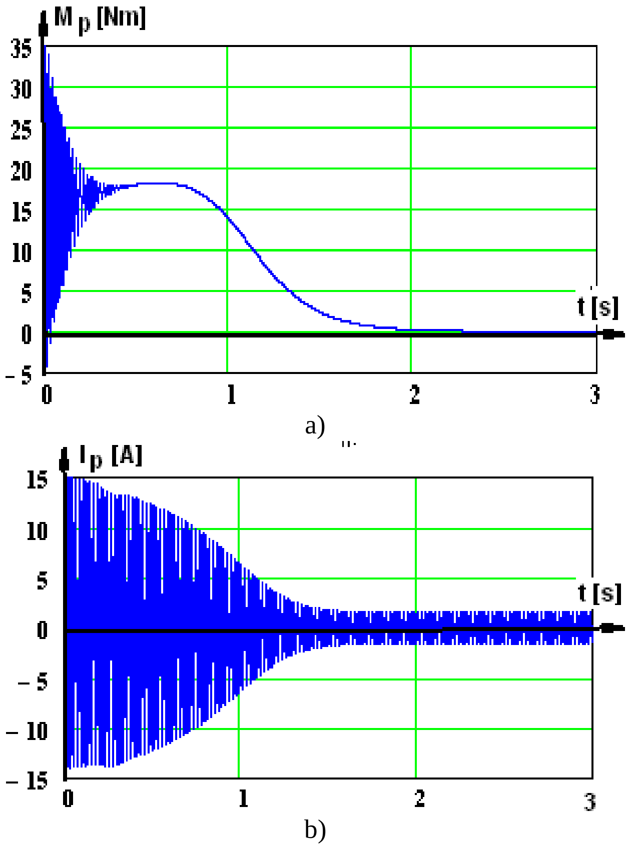


Fig.6. Variation curves during the starting period for: a) electromagnetic torque; b) current.

In Fig. 6 there are presented the variation curves for torque and current and in Fig. 7 we have the average value of the torque, of the speed, respectively the root-mean-square of the current. The notations are: 1 –curves for constant parameters and 2 – variable parameters.

It is notices that, if we consider variable parameters, then the simulation provides a higher maximum torque and a faster starting, which reflects in practice.

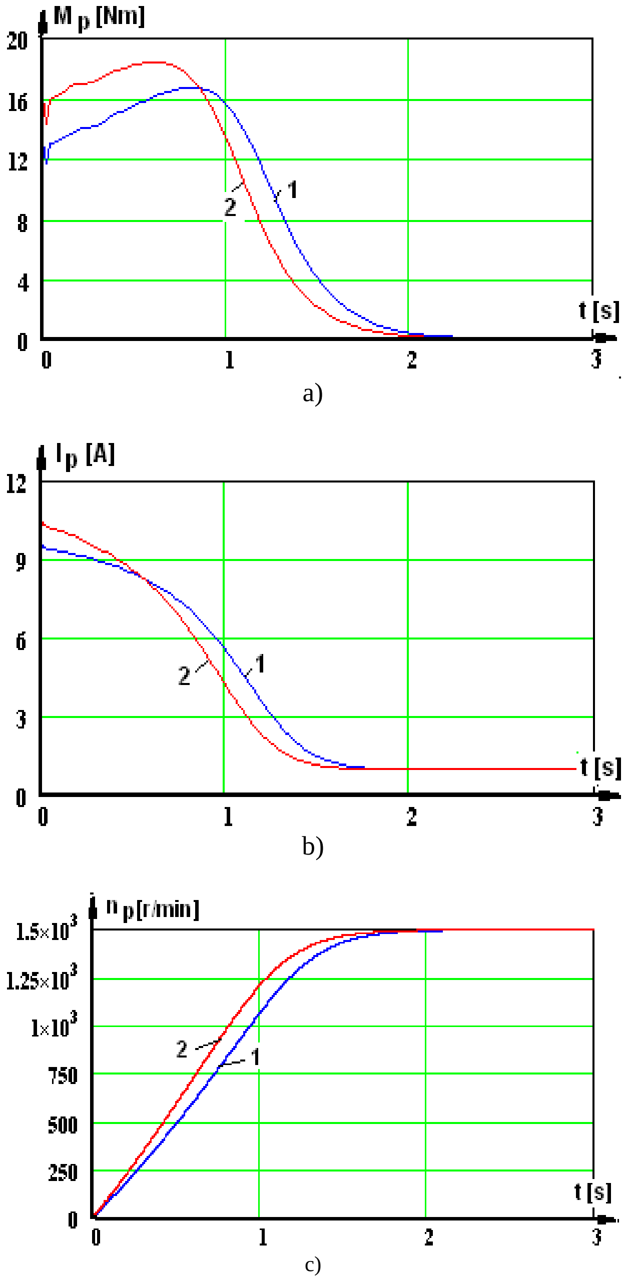
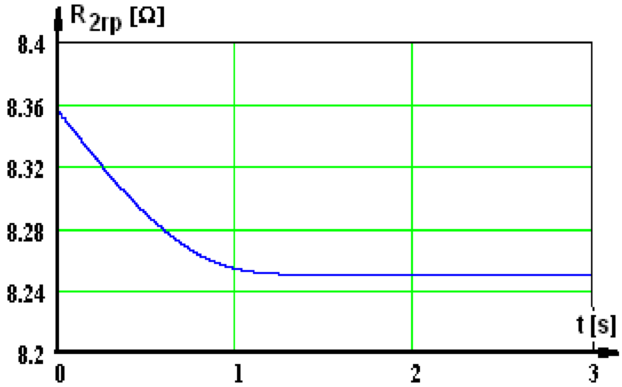


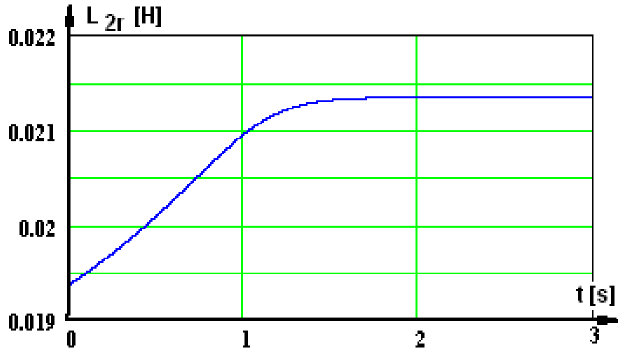
Fig.7. Variation curves during the starting period: a) average value of the torque; b) root-mean-square value of the current, (1- constant parameters, 2-variable parameters).

In the torque curve it is noticeable that we have minimum value immediately after starting, after that the torque increases to the maximum value and in the end it sets to the value of the resistant torque.

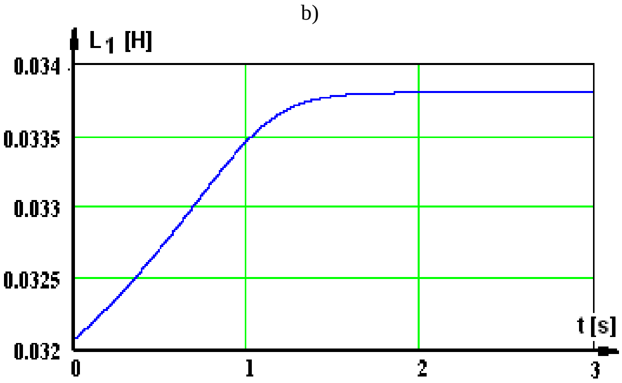
In the real case of the machine with variable parameters (with pressing and magnetic saturation), $R_{2rp}(n)$, $L_{2r}(n,I_p)$, $L_1(I_p)$, $L_{sh}(I_p)$, then their variation during the starting process can be seen, Fig. 8.



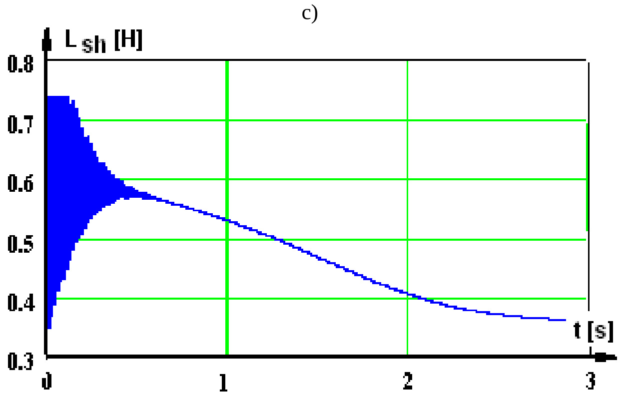
a)



b)



c)



d)

Fig. 8. Variation curves of the asynchronous machine parameters during the starting process: a) b) rotor winding resistance and inductance; c) stator inductance; d) cyclic main inductance.

IV. SIMULATIONS AND EXPERIMENTAL TESTS

In Fig. 9 there are presented curves for current, during the no-load starting, simulated curves, respectively experimentally established curves.

The comparison of the curves obtained by modelling (simulation Fig.9.a) to the curves obtained experimentally Fig.9.b, shows that insignificant differences occur, justified by the fact that the machine inductances have been considered variable –dependent upon the saturation with the motor load and the losses torque at no-load starting M_r =constant.

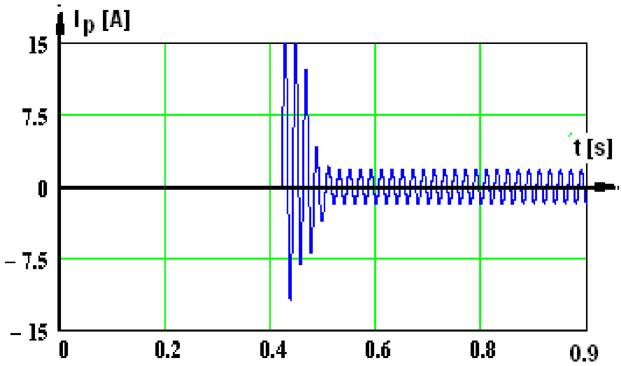
For the starting we analyzed, the experimental results shows a no-load current I_{10}=1.395 A, the shock current I_{1max}=15.1 A or, in per unit

$i_{1max0}=I_{1max}/I_{10}$= 15.1/(1.41*1.395)=7.677,

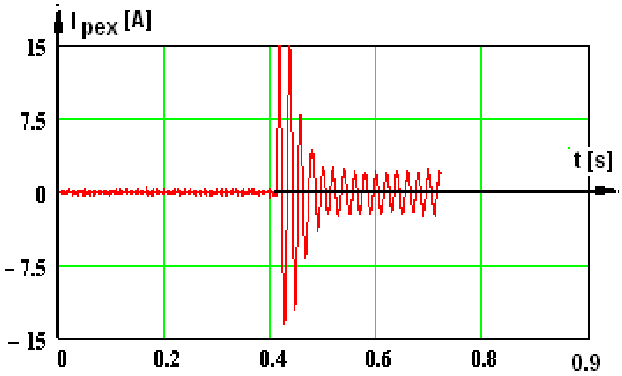
respectively,

$i_{1maxN}=I_{1max}/I_{1N}$= 15.1/(1.41*2.545)=4.208.

Experimentally, by using a data acquisition system [22-24], there have been established the starting curves of the stator voltages, currents and of the speed. These curves are presented in per unit in Fig.10.



a)



b)

Fig.9. Phase currents curves during the starting period: a) curves established by simulation b) curve experimentally established.

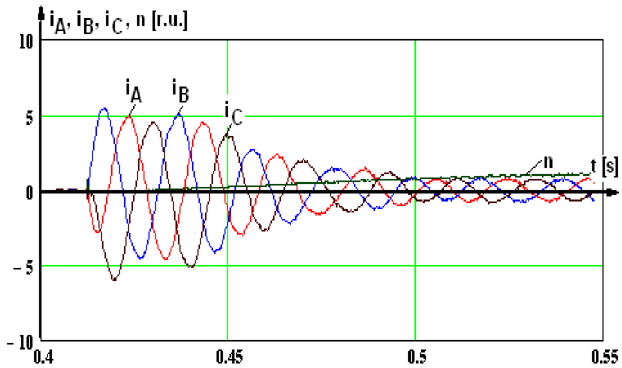


Fig.10. Curves of the phase currents and of the speed during the dynamic state of direct-on-line starting.

The experimental tests have been carried out in the laboratory of the faculty and the power supply network was the three-phase network U=400 V.

V. CONCLUSIONS

The mathematical model used allows more complex simulations, which take into account the rapid on-time evolution of the input quantities, situations which are frequently encountered in robots.

The results obtained by simulation are compared to the results obtained experimentally in order to notice the errors which occur, their cause and in order to correct this way the mathematical model proposed.

The current shock is within normal limits I_{1max}= 4.208*I_{1N} and it does not influence the voltage source. The starting time was of 0,17s and the speed has low damped oscillations.

In the design of present asynchronous machines which operate in complex dynamic states, modelling and simulation must be compulsory stages.

This is the only way to finalize the electromagnetic parameters and the constructive solutions, so that the machine corresponds to requirements imposed by a given dynamic state.

ACKNOWLEDGMENT

This paper was realized under the frame of the grant POC 59/05.09.2016, ID: P_40_401, SMIS 106021.

Contribution of authors:
First author – 40%
First coauthor – 20%
Second coauthor – 20%
Third coauthor – 20%

Received on April 11,2017
Editorial Approval on November 4, 2017

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