ANALELE UNIVERSITĂŢII
"EFTIMIE MURGU" REŞIŢA
ANUL XXI, NR. 2, 2014, ISSN 1453 - 7397

Ion Vlad, Aurel Campeanu, Sorin Enache, Monica Adela Enache

Utility of Numerical Methods in Establishing Performances of Low Power Synchronous Motors

In case of electromechanical equipments driven by alternating current motors, it is possible to reduce the exploitation costs by choosing correctly the driving motor (asynchronous motor or permanent magnet synchronous motor). One of the objectives followed in this paper is the comparative approach from the view point of operation performances and exploitation cost obtained for the two types of motors (asynchronous motor and the permanent magnet one), with the help of some specialized computation soft-wares. The utilization of a permanent magnet synchronous motor, which has an efficiency increased with 11.2% and the power factor better with 10.6%, is a solution for reducing the exploitation cost and for preserving the drive performances.

Keywords: AC machines, modeling, simulation

1. Introduction

In a society that uses intensively computation technique and specialized programs for solving daily problems, the preoccupations regarding the development of new methods and new processes for optimizing driving equipments [2], [9], [11] for different electromechanical systems, is a permanent activity.

The improvement of the motors efficiency [4], [6], [13] can be generally made by reducing the electromagnetic stresses, iron inductions and current densities. In these circumstances, the theme approached in this research is a subject of interest to engineering.

The increase of the electrical machines performances [10], [12] has imposed to use permanent magnets having high specific energies, which influence the performances, as well as the cost and the exploitation price [12]. Nonce, there are not optimum motors from all points of view, different optimization criteria imposing sometimes contradictory conditions.

All the efforts made have not succeeded in elaborating a method having a general character, unanimously accepted, which is to solve the problem of the constructive optimization for electrical machines. The optimization may benefit by all the classical methods known in mathematical programming [1]-[3], [7]-[10], as well as by other specialized methods, elaborated in this purpose [9], [11].

2. Optimal design of low power alternating current motors

2.1. Mathematical model of the motor

Mathematical model [5] means some computation and dimensioning relations, given in the specialty literature and accepted as precision level, tables with standardized values of conductors, magnetization curves etc. The restrictions imposed for certain quantities are checked after computing them and, if they are not accomplished, the mathematical model is resumed for other values assigned to the variables. For low powers and the same rated data it is proposed to do an analysis between the asynchronous motor and the permanent magnet synchronous motor.

For low voltage asynchronous motors rated at low power, by technological considerations, the stator winding is made of round copper conductor (eventually wires in parallel). For the synchronous motor, the adopted constructive solution is that with permanent magnet included in the rotor magnetic circuit, variable air-gap, pole tips with slots and starting cage, outer stator having the same construction as the asynchronous motor. The permanent magnet used here is an alloy having the composition: 9% Al, 26%Co, 4%Cu, 1%Nb, 16% Ni, 44%, Fe, with the following characteristics: Br=1.3 T, Hc=52 kA/m. According to literature, the magnet volume depends on the motor power, on the characteristics of the permanent magnet and on the operation point established on the return line. The design method of the stator is common for the two types of motors; as for the rotors, the computation relations are different and follow the specialty literature.

2.2. Optimization criterion and objective function

Each research regarding the optimization of electrical machines is finalized by an own program, different of the existing other ones, having a personal character. Beside these objective difficulties, which derive from the problem complexity, there are also remarked some controversial aspects (defining the optimum and choosing the objective), which delay the process of finding out some general solutions. The present requirement in the world is to use rationally the electrical energy in exploitation [4], [6], [13]. That is why, for low powers, at the same rated data imposed by the driving system, it is proposed to carry out a comparative study between the asynchronous motor and the permanent magnet synchronous one. This study is carried out considering the criterion minimum exploitation cost and the objective function results:

$$f(\bar{x}) = C_e = C_{ea} + C_{er} = N_{ou} T_{ri} (c_{el.a} \Sigma p + c_{el.r} \Sigma q) \quad (1)$$

where: C_e –exploitation expenses, C_{ea} – cost of the active electrical energy lost in the machine, C_{er} – cost of the reactive electrical energy consumed, N_{ou} number of annual operation hours; $c_{el.a}$, $c_{el.r}$ –costs of a kWh of active electrical energy, respectively reactive electrical energy; T_{ri} -time of the investment recovery; Σp, Σq –total losses of active and reactive power in the machine at rated load operation.

To obtain the optimum solution involves using an adequate searching method corresponding to the available computation facilities.

The main variables appear in the mathematical model used for design and in the expression of the objective function. For this optimization there have been established ten variables, which are electromagnetic stresses: A –current load; B – air-gap magnetic induction; J_1 –current densities of the stator winding; B_{j1}, B_{j2} – magnetic inductions of the stator and rotor yokes, respectively constructive dimensions: D –machine diameter, δ –air-gap, β_{c1} –shape factor for the stator slot.

2.3. Determining the objective function

In this paper there has been considered the method of successive optimization by each variable (an exploring method) [12], adapted to the restrictive design of electrical machines. Using this method, we aim at minimizing the objective function $f(\bar{x}) = C_e$, dependent upon the following variables:

$$C_c = f(A,B,J_1,B_{j1},B_{j2},D,\delta,\beta_{c1}) \tag{2}$$

The method assumes to establish a searching step for each variable x with a relation as:

$$\Delta x = \frac{x_{max} - x_{min}}{n_x} \tag{3}$$

where, n_x is the number of the intermediary points on the searching direction considered.

The search will be initialized starting from the point of minimum and the optimum value of the variable will be determined in the interval established. Passing to the next variable is made preserving the optimum value of the previous variable. A global minimum of computation is obtained by evaluating the objective function on all the searching directions.

3. Results, simulations and conclusions

We establish the influence of the electromagnetic stresses and constructive dimensions upon the objective function $f(\bar{x}) = C_e$, by analyzing simultaneously two low power motors, an asynchronous one and the other one - a permanent magnet synchronous motor. In order to emphasize the comparison, it has been established that the two motors have the same rated data: P_N= 1.1 kW –rated power, U_N=380 V –rated voltage, n_1=1000 r.p.m –synchronism speed, the same electromagnetic stresses: A_m=200 A/cm; B_m=0.65 T; J_{1m}=4.8 A/mm^2; J_{2bm}=3.4 A/mm^2; B_{j1m}=1.27T,

B_{j2m}=1.36 T and the same main constructive dimensions: D_m=80mm, δ_m=0.25 mm; β_{c1m}=0.488.

Further on, we considered these values as reference quantities (relating to them) and we noted them by index "m".

A usual design of the two motors analyzed (according to the speciality literature), has led to the following results filled in the table 1.

Table 1.

Rated data/ Characteristics	Asynchronous motor	Permanent magnet synchronous motor
P_N [kW] –rated power	1.1	1.1
U_N [V] –rated voltage	380	380
n_1[r.p.m.] –synchronism speed	1500	1500
I_{Nm} [A] –rated current	2.55	1.909
M_{Nm} [Nm] –rated torque	7.45	7.003
M_{maxm} [r.u.] –maximum torque	2.12	1.52
Q_{1Nm} [kVA] –reactive power	1.061	0.295
Σp_m [kW] –total losses	0.252	0.121
η_m -efficiency	0.814	0.901
$\cos\varphi_m$ –power factor	0.803	0.972
C_{tm} [E] –total cost	554	368
C_{fm} [E] –fabrication cost	146	209
C_{em} [E] –exploitation cost	408	159

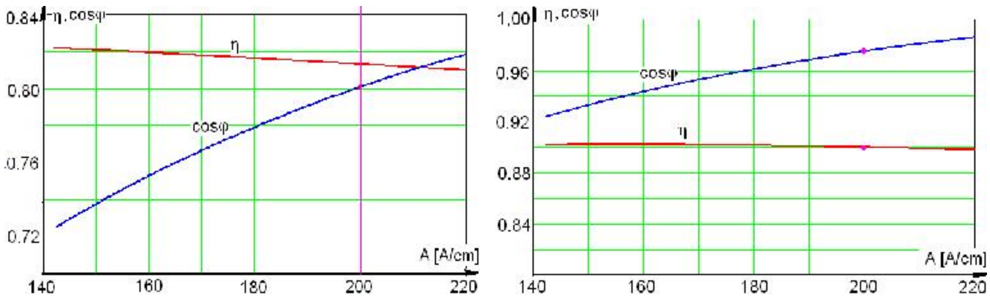
3.1. Analysis of the exploitation cost

The study aims at identifying the quantities that condition the exploitation cost (consumption of active and reactive electrical energy) and at establishing the ways to diminish them. The power factor allows to establish the consumption of reactive power, so its cost and the reactive component which conditions the current received from the supply network ($\underline{I} = \underline{I}_a + \underline{I}_r$). A high reactive component means the increase of the winding losses, so a higher consumption of active power.

We aim at establishing the importance of a variable (electromagnetic stress or constructive dimension) upon the optimization criterion established (minimum exploitation expenses). The researches carried out and presented here have considered the rated load operation and emphasize the variation curves for: η -efficiency (red colour) and $\cos\varphi$ -power factor (blue colour). We consider the electromagnetic stresses as variables between the limits -30%, respectively +10% relatively to the reference values known for the motor given.

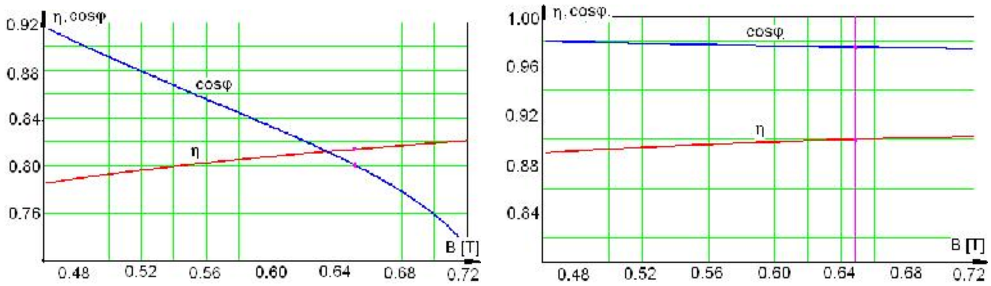
The operation characteristics presented further on are based on analytical relations known in literature. From the analysis of the figures we may establish which motor (asynchronous motor or permanent magnet synchronous motor) is more performant, how the motor should be correctly dimensioned, for reducing the cost of the active and reactive electrical energy, therefore for accomplishing the criterion proposed, C_e=minimum. There are presented simultaneously the curves for the two types of motors analyzed: asynchronous motor and permanent magnet synchronous motor.

From the analysis of the figures depicted below (fig.1., fig.4), we notice that the permanent magnet synchronous motor has a much better efficiency and a much better power factor. At the asynchronous motor, the power factor is much dependent upon the value of the electromagnetic stresses, respectively upon the constructive dimensions.



a) b)

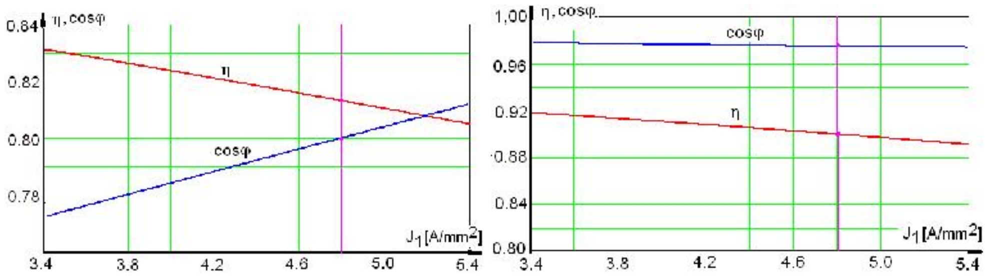
Figure 1. Variation curves relatively to the variable A (current load), for efficiency and power factor at: a) asynchronous motor, b) synchronous motor.



a) b)

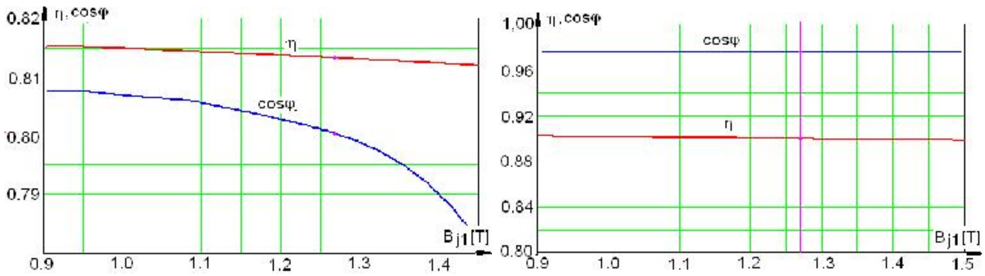
Figure 2. Variation curves relatively to the variable B (air-gap magnetic induction), for efficiency and power factor at: a) asynchronous motor, b) synchronous motor.

A high power factor means the increase of the electrical stresses and the decrease of the magnetic stresses. The electromagnetic stresses and the constructive dimensions modify the power factor of the permanent magnet synchronous motor in small limits.



a) b)

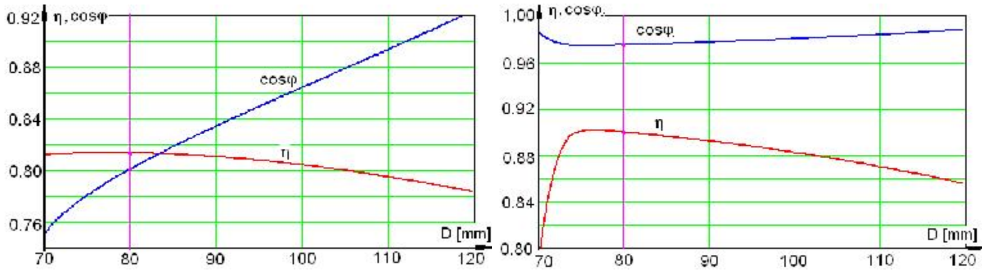
Figure 3. Variation curves relatively to the variable J_1 (stator current density), for efficiency and power factor at: a) asynchronous motor, b) synchronous motor.



a) b)

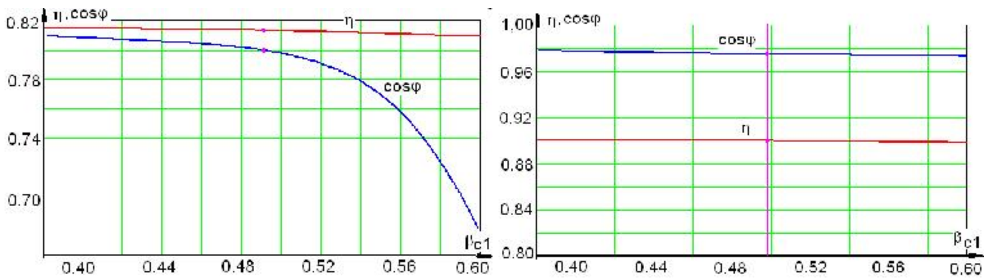
Figure 4. Variation curves relatively to the variable B_{j1} (stator yoke magnetic induction), for efficiency and power factor at: a) asynchronous motor, b) synchronous motor.

In the second part of the study we consider the important constructive dimensions as variable: D –machine diameter, δ –air-gap, β_{c1} –shape factor of the stator slot. The searching domain for all the variables is of -40%, respectively +40% relatively to the reference values. More important results are given in figures 5-figures 7.



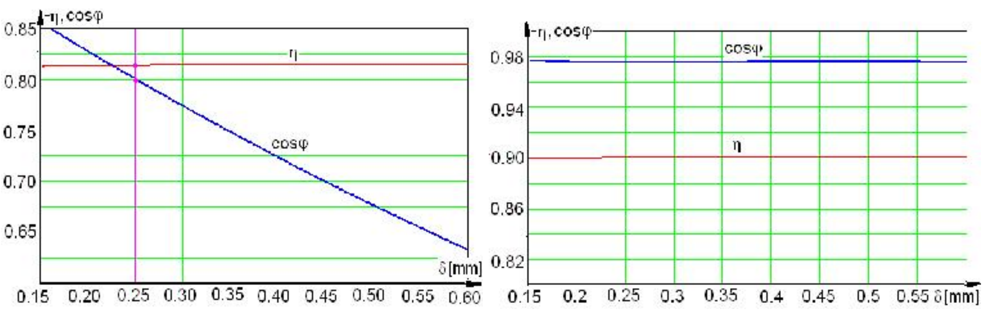
a) b)

Figure 5. Variation curves relatively to the variable D (machine diameter), for efficiency and power factor at: a) asynchronous motor, b) synchronous motor.



a) b)

Figure 6. Variation curves relatively to the variable β_{c1} (shape factor of the stator slot), for efficiency and power factor at: a) asynchronous motor, b) synchronous motor.



a) b)

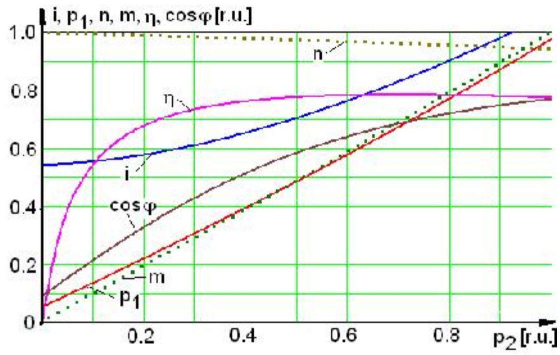
Figure 7. Variation curves relatively to the variable δ (machine air-gap), for efficiency and power factor at: a) asynchronous motor, b) synchronous motor.

3.2. Operation characteristics

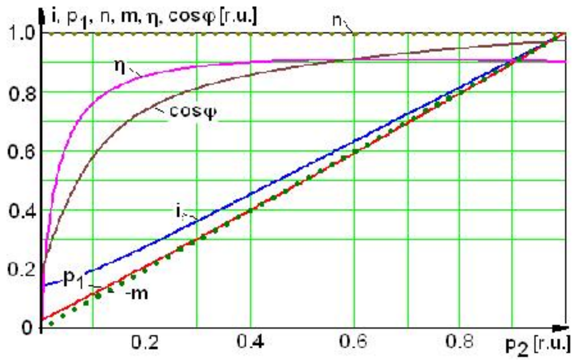
In order to emphasize the comparison between the two types of motors (asynchronous motor and permanent magnet synchronous motor), which have the same rated data, the same electromagnetic stresses and the same constructive dimensions, the operation characteristics will be analyzed further on.

In figure 8 there are presented these characteristics in per unit, when the load does not exceed the rated value for the two motors: a) asynchronous motor and b) permanent magnet synchronous motor. The notations mean: p_1 –power received (red colour), i –current (blue colour), n –speed (green colour and dotted line), m –torque (green colour, dotted line), η -efficiency (pink colour), $\cos\varphi$ -power factor (brown colour). The characteristics m, $p_1=f(p_2)$ for the two types of motors have the same aspect (linear) and approximately the same values.

Owing to the high consumption of reactive power, the current curve of the asynchronous motor is much above the synchronous motor. At the same time, in case of permanent magnet synchronous motor, we see that the curves of the efficiency and power factor are almost constant all over the operation domain and the values are much higher than in case of asynchronous motor. As a consequence, the current received from the supply network is much reduced in case of permanent magnet synchronous motor. In conclusion, the operation characteristics presented show that the permanent magnet synchronous motor is superior to the asynchronous motor.



a)



b)

Figure 8. Load operation characteristics for: a) asynchronous motor, b) permanent magnet synchronous motor.

3.3. Establishing of optimum solution

For the searching domain considered, relatively to the variables established, from the analysis of the figures presented, the table 2 has been filled in, where we see how much η and $\cos\varphi$ modify, quantities which have important weight in the exploitation cost. For instance, when the variable A increases in the established searching range, from figure 1.a for the asynchronous motor it results $\Delta\cos\varphi$ =0.82-0.72=0.10, $\Delta\eta$=0.810-0.822=-0.012.

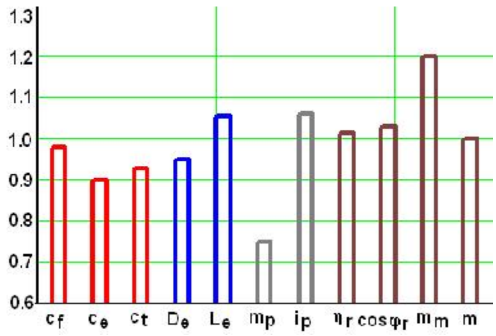
Table 2.

Criterion \ Variable		A (A/cm)	B (T)	J_1 (A/mm^2)	B_{j1} (T)	D (mm)	β_{c1}	δ (mm)
Asynchronous motor	$\Delta\cos\varphi$	0.100	-0.180	0.042	-0.028	0.170	-0.130	-0.115
	$\Delta\eta$	-0.012	0.047	-0.027	-0.003	-0.034	-0.004	-0.001
Permanent magnet synchronous motor	$\Delta\cos\varphi$	0.062	-0.005	-0.005	-0.002	0.012	-0.003	-0.003
	$\Delta\eta$	-0.004	0.011	-0.030	-0.003	-0.044	-0.002	-0.001

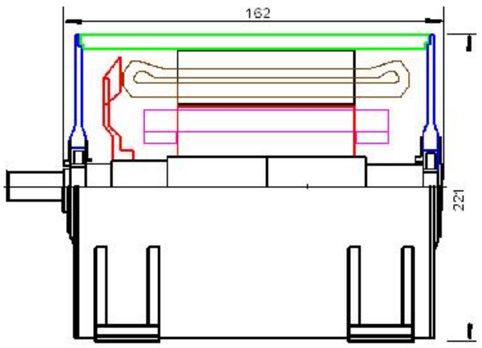
On the occasion of the study carried out, other important quantities imposed by the customer have been emphasized: m_{max}, –maximum torque; D_e, L_e –gauge dimensions.

At the optimized permanent magnet synchronous motor, the performances are shown in figure 9.a; they are obtained for variables: A_o=175.7 A/cm; B_o=0.681 T; J_{1o}=4.80 A/mm^2; B_{j1o}=1.28 T, B_{j2o}=1.36 T, D_o=77 mm, δ_o=0.40 mm; β_{c1o}=0.551, C_{to}=292.4 E.

For the optimized asynchronous motor, figure 9.b shows the longitudinal section and the gauge dimensions.



a)



b)

Figure 9. a) Per unit values of the quantities analyzed at the optimized permanent magnet synchronous motor relatively to all the variables b) longitudinal section.

For the optimized variants of the two motors obtained by research, are given the afferent costs, efficiency and power factor.

Table 3.

Rated data/ Characteristics	Asynchronous motor	Permanent magnet synchronous motor
P_N [kW] –rated power	1.1	1.1
U_N [V] –rated voltage	380	380
n_1[r.p.m.] –synchronism speed	1500	1500
η -efficiency	0.811	0.910
cosφ –power factor	0.940	0.994
C_t [E] –total cost	486	306
C_f [E] –fabrication cost	154	196
C_e [E] –exploitation cost	332	110

4. Conclusions

By the research carried out, there have been identified the important variables in case of optimization $f(x)=C_e$=minimum. This way, the number of variables and the computation effort are substantially reduced and the designer can offer customer the optimum solution in a short time.

For reducing the exploitation cost, it can be recommended to design the motor with high electrical stresses and low magnetic stresses, with a big diameter and a small air-gap.

Analyzing the optimized variants for the two types of motors, the permanent magnet synchronous motor is recommended instead of the asynchronous motor, because it has an efficiency better with $\Delta\eta=11.2\%$, and a power factor better with $\Delta\cos\varphi=10.6\%$, therefore low exploitation expenses.

These results are spectacular and, correlated with the big number of such motors, an important decrease of the electrical energy consumption results.

Acknowledgment

This work was partially supported by the grant number 30C/27.01.2014, awarded in the internal grant competition of the University of Craiova.

References

[1] Ancau M., Nistor I., Tehnici numerice de optimizare în proiectarea asistatá de calculator, Editura Tehnicá, Bucuresti, 1996.
[2] Abbaszadeh K., Rezaee Alam F., Teshnehlab M., Slot opening optimization of surface mounted permanent magnet motor for cogging torque reduction, Energy Conversion and Management 55, 2012, pp.108–115.
[3] Aydin M., Magnet Skew in Cogging Torque Minimization of Axial Gap Permanent Magnet Motors, Proceedings of the 2008 International Conference on Electrical Machines, 2008.
[4] Brunner C.U., International Standar/ds for Electric Motors, Standards for En.Efficiency of Electric Motor Systems (SEEEM), 2007, pp. 6-10.
[5] Campeanu A., Vlad I., Enache S., Numerical Analysis of the Dynamic Behavior of a High Power Salient Pole Synchronous Machine by using a Corrected Model, AECE Journal, Vol.12, Issue 1, 2012, pp.97-102.
[6] Centner M., Schäfer U., Machine design software for induction machines, Proc. ICEM, Vilamoura, Portugal, 2008, pp. 1–4.
[7] Daniel I., Munteanu I., s.a., Metode numerice in ingineria electrica, Editura Matrix Rom, Bucuresti, 1998.

[8] A EL-Refaie, Fractional-Slot Concentrated-Windings Synchronous Permanent Magnet Machines: Opportunities and Challenges, IEEE Trans. on Industrial Electronics, vol. 57, no. 1, 2010.
[9] Faiz J., Sharifian M.B.B., Optimal design of three-phase Induction Motors and their comparison with a typical industrial motor, Computers and Electrical Engineering, vol. 27, 2001, pp. 133-144.
[10] Guemes J.A., Iraolagoitia A.M., Del Hoyo J.I., Fernandez P., Torque Analysis in Permanent-Magnet Synchronous Motors: A Comparative Study, IEEE Trans on Energy Conversion, vol. 26, no. 1, 2011.
[11] Liuzzi G., Lucidi S., Parasiliti F., Villani M., Multiobjective optimization techniques for the design of induction motors, IEEE Trans. on Magnetics, vol. 39, no. 3, May 2003.
[12] Vlad I., Campeanu A., Enache S., Enache M., Aspects regarding design of squirrel cage asynchronous motors for mining excavators, Anals of the University of Craiova, Series Electrical Engineering", Year 36, No. 36, 2012, pp. 57-62.
[13] ***** CEI 60034-2-1 Standard: Rotating electrical machines-Part 2-1, "Standard methods for determining losses and efficiency from tests".

Addresses:

- Prof. Dr. Eng. Ion Vlad, University of Craiova, Faculty of Electrical Engineering, 107 Decebal Stret, 200440, Craiova, ivlad@em.ucv.ro
- Prof. Dr. Eng. Aurel Campeanu, University of Craiova, Faculty of Electrical Engineering, 107 Decebal Stret, 200440, Craiova, acampeanu@em.ucv.ro
- Prof. Dr. Eng. Sorin Enache, University of Craiova, Faculty of Electrical Engineering, 107 Decebal Stret, 200440, Craiova, senache@em.ucv.ro
- S.l. Dr. Eng. Monica Adela Enache, University of Craiova, Faculty of Electrical Engineering, 107 Decebal Stret, 200440, Craiova, menache@em.ucv.ro