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OPTIMIZATION OF OPERATION CHARACTERISTICS FOR ASYNCHRONOUS MOTORS USED IN COAL MILLS

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Key words: Asynchronous motors, Optimal design, Operation characteristics.

Designers aim at finding answers for present questions, as: increasing performances of asynchronous motors, reducing manufacturing and exploitation costs, by adopting optimization solutions. The condition imposed to the asynchronous motor designed is a limited starting current, because it drives a coal mill, where the inertia moment is important, resulting a significant increase in the starting time. The simulations carried out provide some quantitative and qualitative information, necessary in finalizing the optimum constructive solution, where the criterion is minimum exploitation cost.

1. INTRODUCTION

The activity of optimal design electrical machines was well defined many years ago in the speciality literature. At present these methods are re-analyzed and enriched with new elements which are to enable the determinations precision (for example, use of some adequate softwares and performant computers, introducing saturation and the skin effect in the classical models of electrical machines). For this reason, the computation volume is very large and efforts to reduce the working time are made [1–8].

The inertia moment is big in case of a coal mill, resulting a substantial increase in the starting time. In order to avoid an exceeding heating of the rotor cage, the current limitation on this interval and an accessible starting torque are required, because the starting might be made in load and the occurring accelerations must be mechanically beared by the whole system. The maximum necessary torque was imposed, in order to avoid the lock caused by accidental overloads.

Because the consumption of active and reactive electrical energy is high (high exploitation cost), the problem of optimizing this cost is taken into account in this paper.

The asynchronous motor is coupled with the rotor of the mill by means of an adjustable hydraulic gear, where the oil is introduced in semi-couplers, spun to the outside, getting the shape of a toroidal ring which carries out the driving process.

This brief presentation of the coal mill proves difficult operation conditions of the driving asynchronous motor. The advantage of the computer-aided design of these motors is a decrease in the assimilation time of the product, the investments efficiency and gaining the market by the company which manufactures electrical machines.

The simulations and results presented here are based on the modern design methods, using advanced numerical methods and softwares.

2. ASPECTS REGARDING OPTIMAL DESIGN OF ASYNCHRONOUS MOTORS

2.1. OBJECTIVE FUNCTION

The optimal design of high-power asynchronous motors used in coal mills takes into account the *exploitation cost* criterion, $f(\overline{x})=C_e=\min.$ [9–12],

$$C_e = C_{ea} + C_{er} = N_o T_{ri} c_{el.a} \Sigma p + N_o T_{ri} c_{el.r} \Sigma q \,, \qquad (1)$$

where C_{ea}, C_{er} –cost of active and reactive electrical energy, N_o – annual number of operation hours, $c_{el.a}$ –cost of a kWh of active electrical energy, $c_{el.r}$ –cost of a kvarh of reactive electrical energy, T_{ri} –time of the investment recovery, Σp, Σq -total losses of the machine/ reactive power consumption in rated load operation. The study carried out also considers C_f – manufacturing cost of the motor, in order to compare it to the exploitation cost:

$$C_f = k_f C_{ma} \,. \qquad (2)$$

The cost of the active materials C_{ma} is established by having the quantities of active materials used (m_{Fe1}, m_{Fe2}– silicon sheet for the stator and rotor circuit, respectively m_{Cu1}, m_{Cu2} –quantities of copper conductor for windings) and their costs, c_{Fe1}, c_{Fe2}, c_{Cu1}, c_{Cu2}. The costs owed to the manufacturing technological processes and different charges of the company that produces electrical machines are taken into account by means of a factor k_f –established for similar asynchronous motors.

2.2. VARIABLES OF THE OBJECTIVE FUNCTION

The main variables are established relatively to their weight upon the mathematical model and upon the objective function. The main variables include the electromagnetic stresses, because they vary in a narrow range of values for a large range of machines.

For an exact optimization, six main variables have been established, all of them being electromagnetic stresses: A – current load, B –air-gap magnetic induction, J_1, J_2 –current density of the stator/rotor winding, $\beta_{c1}=b_{c1}/t_1$, $\beta_{c2}=h_{c2}/b_{c2}$– form factors for the stator/rotor slot.

The system of restrictions of variables

$$\begin{aligned} & x_{\min_i} \le x_i \le x_{\max_i} \\ & x_i = \{A, B, J_1, J_2, \beta_{c1}, \beta_{c2}\} \end{aligned} \,, \qquad (3)$$

respectively, restrictions imposed by customer:

$$m_p \ge m_{p.i}\,; \qquad i_p \le i_{p.i}\,; \qquad m_m \ge m_{m.i} \qquad (4)$$

are applied to the mathematical model, where m_p, m_m, i_p starting/maximum torque, starting current.

The values ranges of these variables are established on the basis of the indications known in the speciality literature. The upper limit of each range results by the condition of limiting

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the maximum temperatures allowed according the insulation class. As for the lower limit, the searching area (working time), has to be reasonable.

The paper aims at carrying out a larger study, in order to establish the optimum values of the electromagnetic stresses, considering the criterion stated before: minimum exploitation cost of the motor.

3. COMPUTATION OF THE OBJECTIVE FUNCTION MINIMUM

Methods of direct searching of the optimum are the most suitable for multi-variables problems, with restrictions, because they do not use the derivatives of the objective function and are based on the idea of advancing towards the optimum by ongoing improvements.

Establishing the optimum by using the COMPLEX algorithm, for the minimization of the objective function is proposed, $f(\bar{x})=C_e$ dependent upon the following variables:

$$C_e = f(A, B, J_1, J_2, \beta_{c1}, \beta_{c2}) \ . \tag{5}$$

Further on, there are briefly presented the stages of this algorithm adapted to the optimal design of asynchronous motors for solving the minimization of the function $f(\bar{x})=C_e$.

The method involves computing the objective function in the vertexes of an irregular polyhedron with $p = 2n$ vertexes and removing successively the vertexes in which the function gets the maximum value.

The main stages of the algorithm, Fig.1, are:

1) Establishing the p points –vertexes of the irregular polyhedron, by using the relation

$$V_k(\bar{x}) = V_k(A_k, B_k, J_{1k}, J_{2k}, \beta_{c1k}, \beta_{c2k}) \ , \tag{6}$$

where k=1, 2, 3,…, p, and each variable A_k, B_k, J_{1k}, J_{2k}, β_{c1k}, β_{c2k}, is computed this way:

$$x_k = x_{k\,\min} + r_k(x_{k\,\max} - x_{k\,\min}). \tag{7}$$

In the relation (10), r_k are pseudorandom numbers, within the range [0, 1), constituted by means of a special sub-program.

The necessity of obtaining random variables r, uniformly distributed in a variation range, unrepeatable, occurred with the development of numerical computation methods. The numbers must be fast generated and the generating program must need a small quantity of computer memory.

The generating sub-program used is based on the multiplicative method for which the values a_o = 3125 P = 67108864 are indicated and:

$$M_o = 101 n_o + 42758321 \ \text{with} \quad n_o < 24350542 \quad , \quad M_o \text{ - odd} \ . \tag{8}$$

In order to extablish M_o the literature indicates n_o=29 and in the relation generating numbers, M_i is:

$$M_i = a_o M_{i-1} = 3125 M_{i-1} \quad N_i = (M_i)_{(\bmod P)} \tag{9}$$

and the pseudorandom numbers from the range [0, 1) will be:

$$r_i = \frac{N_i}{P} \ . \tag{10}$$

2) Computing the value of the objective function in the polyhedron vertexes with the relation (4), filling in the Table no. 1, establishing then the points corresponding to the extreme values of the function $f(\bar{x})$ for the k-th step of iteration:

$$f(\bar{x}_M^{(k)}) = \max[f(\bar{x}_1^{(k)}), f(\bar{x}_2^{(k)}), ..., f(\bar{x}_p^{(k)})] \tag{11}$$

$$f(\bar{x}_m^{(k)}) = \min[f(\bar{x}_1^{(k)}), f(\bar{x}_2^{(k)}), ..., f(\bar{x}_p^{(k)})] \ . \tag{12}$$

Table 1

$\bar{x}_1$	$\bar{x}_2$		$\bar{x}_M$		$\bar{x}_m$		$\bar{x}_p$
A_1	A_2		A_M		A_m		A_p
B_1	B_2		B_M		B_m		B_p
$J_{1.1}$	$J_{1.2}$		$J_{1.M}$		$J_{1.m}$		$J_{1.p}$
$J_{2.1}$	$J_{2.2}$		$J_{2.M}$		$J_{2.m}$		$J_{2.p}$
$f(\bar{x}_1)$	$f(\bar{x}_2)$		$f(\bar{x}_M)$		$f(\bar{x}_m)$		$f(\bar{x}_p)$

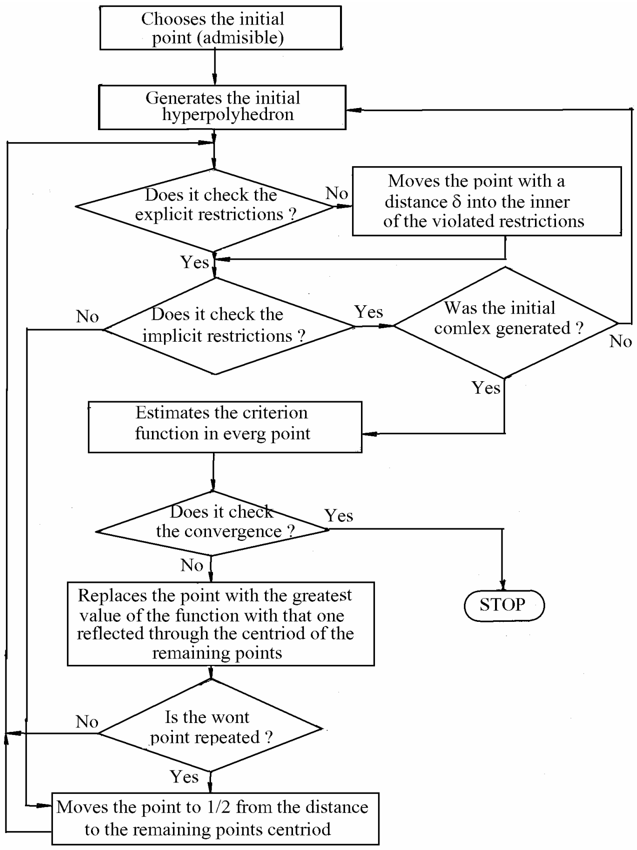


Fig.1 – Logical scheme of the COMPLEX algorithm.

3) The speed of convergence to the optimum can be increased, if the values of the objective function are used in the computation of the coordinates of the polyhedron weight center:

$$\bar{x}_w^{(k)} = \sum_{j=1}^{p}\left[f\left(\bar{x}_j^{(k)}\right)\right]^{\beta} \cdot \bar{x}_j^{(k)} \Bigg/ \sum_{j=1}^{p}\left[f\left(\bar{x}_j^{(k)}\right)\right]^{\beta} \ . \tag{13}$$

4) If $\bar{x}_W^{(k)}$ are the coordinates of the centroid, the unfavourable point $\bar{x}_M^{(k)}$ is projected through the centroid, obtaining a new point

$$\bar{x}_{p+1}^{(k)} = \bar{x}_W^{(k)} + \alpha(\bar{x}_W^{(k)} - \bar{x}_M^{(k)}) \,, \qquad (14)$$

where the projection coefficient $\alpha \geq 1$.

5) If $f(\bar{x}_{p+1}^{(k)}) \leq f(\bar{x}_m^{(k)})$ the direction where the point moves is good and, consequently, an ***extension*** of the reflection is tried:

$$\bar{x}_q^{(k)} = \bar{x}_{p+1}^{(k)} + \gamma(\bar{x}_{p+1}^{(k)} - \bar{x}_W^{(k)}). \qquad (15)$$

6) But if $f(\bar{x}_{p+1}^{(k)}) \geq f(\bar{x}_j^{(k)})$ for any j except for the unfavourable point $\bar{x}_M^{(k)}$), then a "*contraction*" is carried out,

$$\bar{x}_q^{(k)} = \bar{x}_W^{(k)} + \beta(\bar{x}_M^{(k)} - \bar{x}_W^{(k)}) \,, \qquad (16)$$

where $\beta \in (0 \div 1)$.

7) The optimum solution is obtained when the following conditions are fulfilled:

$$\left| \frac{f(\bar{x}_M^{(k)}) - f(\bar{x}_m^{(k)})}{f(\bar{x}_M^{(k)})} \right| \leq \xi_1 \qquad \left| \frac{\bar{x}_M^{(k)} - \bar{x}_m^{(k)}}{\bar{x}_M^{(k)}} \right| \leq \xi_2 \,, \qquad (17)$$

where $\xi_1, \xi_2 = (10^{-3} \div 10^{-6})$ established according the imposed precision. The simplified logical scheme of the COMPLEX algorithm is depicted in Fig. 1.

4. SIMULATIONS AND RESULTS

In order to see concretely the advantages of the optimal design, there has been considered as an example even the high-voltage three phase squirrel cage asynchronous motor driving a coal mill, rated as follows: P_N =500 kW –rated power; U_N=6 kV –rated voltage; I_{1N}=63.5 A –rated current; n_1=600 rpm –synchronism speed. The starting and operation characteristics imposed by the customer are: $M_p \geq 1.1 \cdot M_N$ –starting torque; $I_p \leq 5.5 \cdot I_N$ –starting current; $M_m \geq 2.0 \cdot M_N$ –maximum torque.

The costs (manufacturing, exploitation and total) have been computed on the basis of the known documentation: N_{ore}=330·24=7920 hours/year –annual number of operation hours; T_{ri}= 5 years –time of the investment recovery; c_{Cu} =12 €/kg –cost of a kg of copper; c_{Fe}=0.95 €/kg –cost of a kg of iron (silicon sheet); $c_{el.a}$= 0.131 €/kWh –cost of a kWh of active electrical energy, $c_{el.r}$ =0.013 €/kvarh –cost of a kvarh of reactive electrical energy. The follwing costs have resulted for the motor we analyzed:

$C_{f.m}$=58620 €; C_{em}=374700 €; $C_{t.m}$=433300 €.

All the quatities regarding the motor analyzed, resulted by a traditional design (known according to the speciality literature) are considered as reference quantities below.

The study carried out and presented below has taken into account for each variable analyzed (A, B, J_1, J_2, β_{c1}, β_{c2}) a variation within the limits – 35 %, respectively + 15 % as against the known reference value. For example, for the current load we have:

$A \in [A_{min} \div A_{max}]$=[0.65 ÷ 1.15]·$A_m$=[250 ÷ 450] A/cm

The optimal design of the asynchronous motor used in the coal mill takes into account the optimization (minimization) of the function exploitation cost, $C_e = f(\bar{x})$, following the weight of the two components, C_{ea}, C_{er} – cost of the active/reactive electrical energy, in order to have a rational exploitation.

During the optimization there are taken into account restrictive conditions imposed by the customer and the evolution of some important indicators (less weight criteria): costs (C_f, C_t –manufacturing cost and total cost); starting and operation characteristics (m_p, i_p, m_m –starting torque and current, maximum torque).

In order to follow the influence of each variable upon the optimization and upon the criteria presented above, the graphics are plotted in per unit values. These values are computed, for the torques, as follows:

$$m_p = \frac{M_{p\,var\,mot}}{M_{pm}} \qquad m_m = \frac{M_{m\,var\,mot}}{M_{max.m}} \,, \qquad (18)$$

$M_{p.var.mot}$, $M_{m.var.mot}$ –starting torque (maximum torque) for the variant of motor we analyzed;

$M_{p.m}$, $M_{max.m}$ – staryting torque (maximum torque) for the variant of motor considered as a reference.

For costs, the relations are:

$$c_e = \frac{C_{e\,var\,m}}{C_{e\,m}} \quad c_f = \frac{C_{f\,var\,m}}{C_{f\,m}}, \ldots \,, \qquad (19)$$

$C_{e.var.m}$, $C_{f.var.m}$,–exploitation/manufacturing cost for the variant of motor we analyzed;

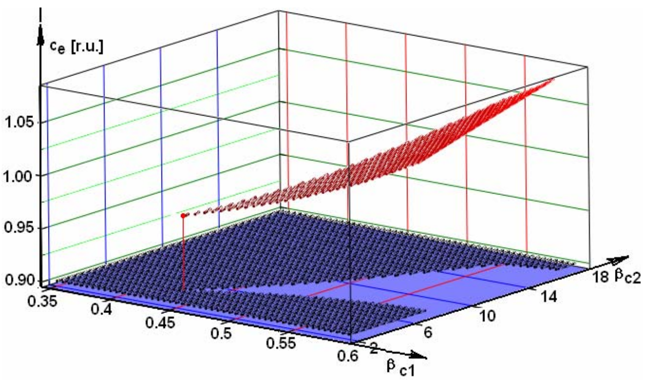
$C_{e.m}$, $C_{f.m}$ – exploitation/manufacturing cost for the variant of motor considered as a reference etc.

4.1. OPTIMIZATION RELATIVELY TO THE VARIABLES β_{C1}, β_{C2} (THE FORM FACTORS OF THE STATOR/ROTOR SLOT)

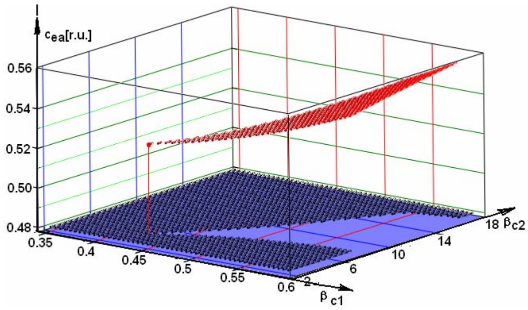
The research results for the optimization by these variables are presented below. The response quantities are surfaces in the three-dimensional space.

The surfaces of evolution in space for the optimization criterion established, c_e –minimum exploitation cost, is depicted in Fig. 2a, when the imposed restrictions occur.

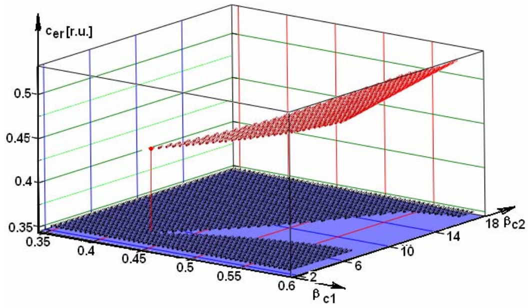
We notice that these restrictions limit the variation range of the variables. In Figs. 2b and 2c we see the surfaces corresponding to the costs of active/reactive electrical energy, with restrictions. Figure 3 emphasizes the evolution of the manufacturing cost (Fig. 3a), respectively the total cost (Fig. 3b).



a)

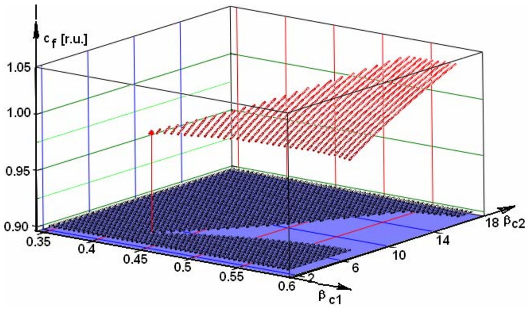


b)

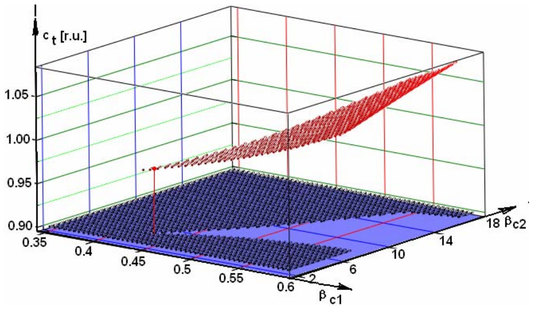


c)

Fig. 2 – Response surfaces for the pair of variables β_{c1}, β_{c2}: a) c_e–exploitation cost; b) and c) costs of the active/reactive electrical energy.



a)



b)

Fig. 3 – Response surfaces for c_f, c_t–manufacturing costs/ total cost when β_{c1}, β_{c2} are the variables.

The results of the optimization by the pair of variables analized (β_{c1}, β_{c2}), are filled in the *Table 2*, where the most important characteristics are presented. The point of optimum resulted for: β_{c1}=0.43/β_{c2}=3.93 –form factors of the stator/rotor slot and a decrease by Δc_e=3.02 % in the exploitation cost has resulted by optimization.

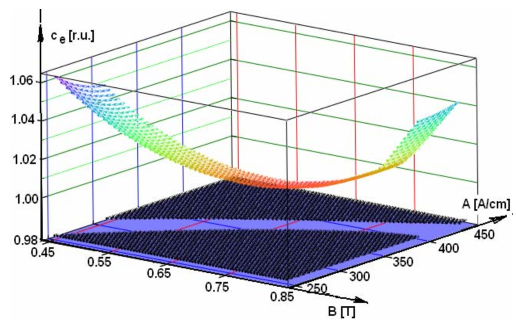
Table 2

Criterion / Variant	C_f (€)	C_e (€)	$C_{e.a}$ (€)	$C_{e.r}$ (€)	m_p (r.u.)	i_p (r.u.)	m_m (r.u.)
Values imposed	-	-	-	-	≥1.1	≤5.5	≥2.0
V_m –Real var.	58620	374700	199600	175100	1.145	5.128	2.473
V_o.– Opt. var.	57980	363500	196900	166700	1.10	5.485	2.59

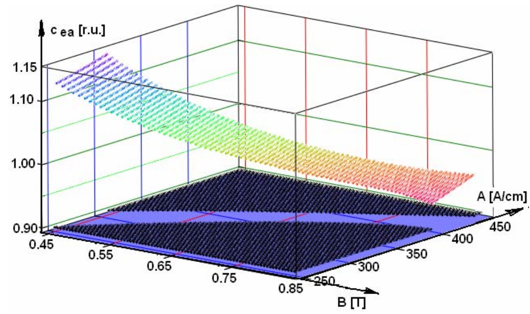
4.2. OPTIMIZATION RELATIVELY TO THE VARIABLES *A*, *B* (THE CURRENT LOAD AND THE AIR-GAP MAGNETIC INDUCTION)

The study was repeated for the following pairs of variables taken into account in optimization (electromagnetic stresses).

Similarly, we have surfaces for c_e –exploitation cost established with restrictions imposed, Fig. 4a. The electromagnetic stresses are very important in an asynchronous motor design; however, because of these restrictions imposed by the customer, the result is not the expected one (a very small decrease in c_e). The surfaces for the manufacturing cost and the total cost are depicted in Fig. 5.



a)



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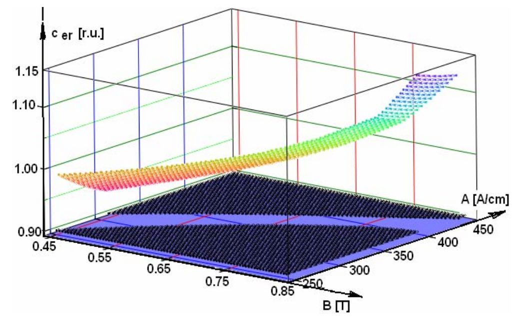
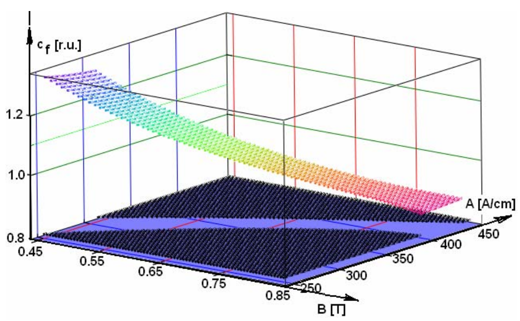
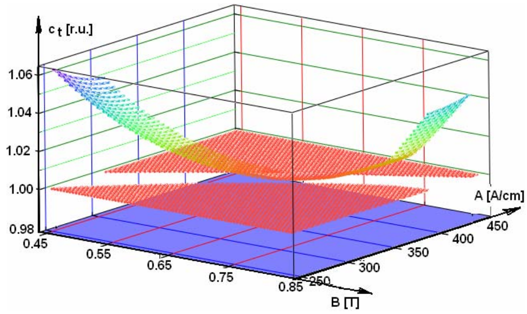


c)

Fig. 4 – Response surfaces for the pair of variables *A*, *B*: a) c_e–exploitation cost; b) and c) costs of the active/reactive electrical energy.



a)



b)

Fig. 5 – Response surfaces for c_f, c_t–manufacturing/total cost when *A*, *B* are the variables.

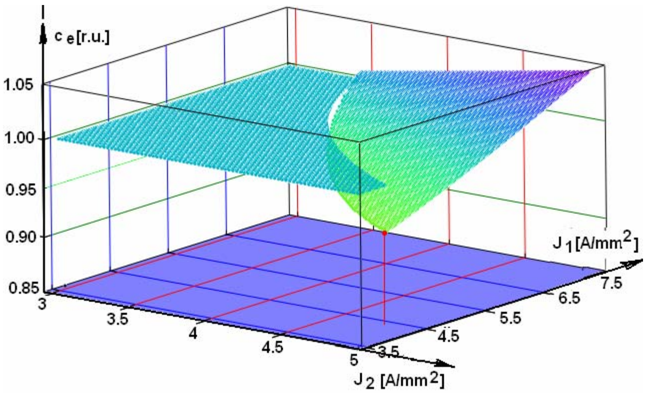
The results of the optimization by the pair of variables analyzed (*A*, *B*) are filled in the *Table 3*, where the most important characteristics are presented. The point of optimum resulted for: *A* = 330.4 A/cm, *B* = 0.763 T and a decrease by Δc_e=0.031 % in the exploitation cost resulted by optimization.

Table 3

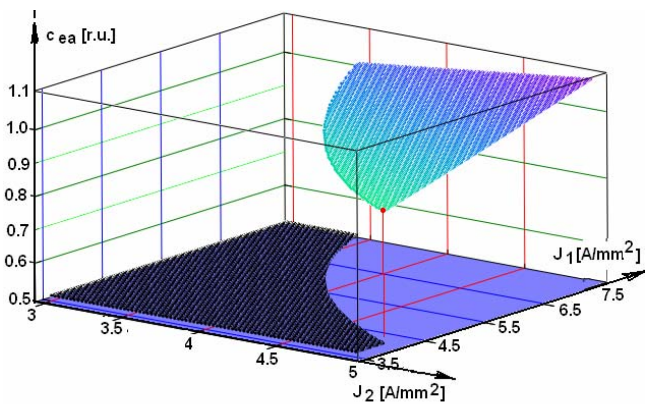
Criterion / Variant	C_f (€)	C_e (€)	$C_{e.a}$ (€)	$C_{e.r}$ (€)	m_p (r.u.)	i_p (r.u.)	m_m (r.u.)
Values imposed	-	-	-	-	≥1.1	≤5.5	≥2.0
V_m–Real var.	58620	374700	199600	175100	1.145	5.128	2.473
V_o– Opt. var.	58700	374600	200700	173900	1.103	5.007	2.394

4.3. OPTIMIZATION RELATIVELY TO THE VARIABLES J_1, J_2 (THE CURRENT DENSITY OF THE STATOR/ROTOR WINDING)

The research by these variables (electrical stresses) provided much better results (a decrease in c_e by round 5 %).



a)



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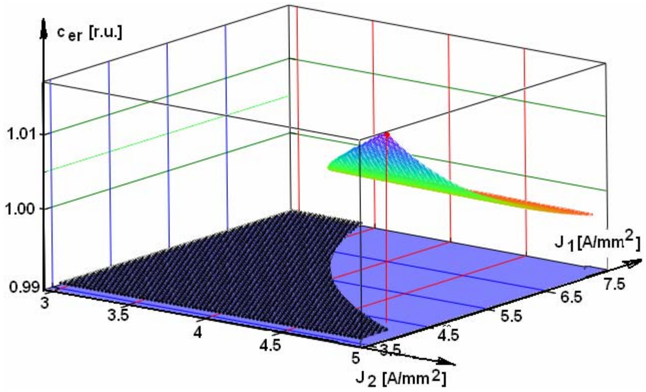
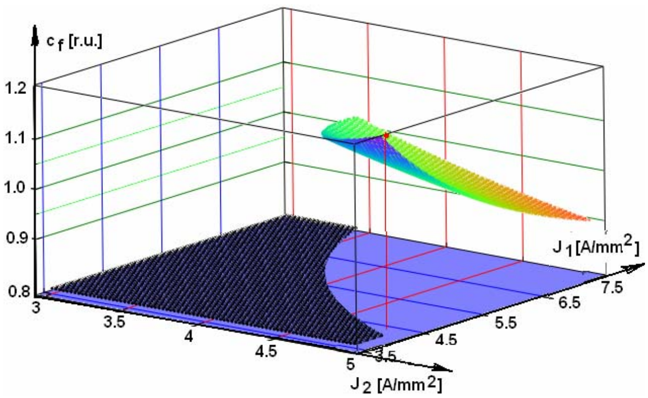
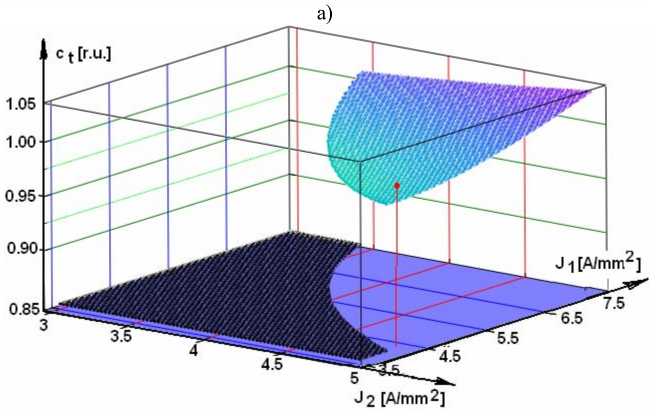


c)

Fig. 6 – Reponse surfaces for the pair of variables J_1, J_2: a) c_e–exploitation cost; b) and c) costs of the active/reactive electrical energy.



a)



b)

Fig. 7 – Response surfaces for c_f, c_t–manufacturing/total cost when J_1, J_2 are the variables.

An important limitation of the searching range is noticed. The surfaces for c_e –exploitation cost and its components are depicted in Fig. 6, where the criterion c_e and its component is plotted. The surfaces for the manufacturing cost and the total cost are depicted in Fig. 7.

The results of the optimization by the pair of variables analyzed (J_1, J_2), are filled in the Table 4. The point of optimum resulted for: J_1=4.208 A/mm^2, J_2=4.843 A/mm^2 and a decrease by Δc_e = 4.81 % in the exploitation cost resulted by optimization.

Table 4

Criterion / Variant	C_f (€)	C_e (€)	$C_{e.a}$ (€)	$C_{e.r}$ (€)	m_p (r.u.)	i_p (r.u.)	m_m (r.u.)
Values imposed	-	-	-	-	≥1.1	≤5.5	≥2.0
V_m–Real var.	58620	374700	199600	175100	1.145	5.128	2.473
V_o– Opt. var.	68930	356700	179100	177600	1.101	4.865	2.428

Table 5

Criterion / Variant	C_f (€)	C_e (€)	$C_{e.a}$ (€)	$C_{e.r}$ (€)	m_p (r.u.)	i_p (r.u.)	m_m (r.u.)
Values imposed	-	-	-	-	≥1.1	≤5.5	≥2.0
V_m –Real var.	58620	374700	199600	175100	1.145	5.128	2.473
V_o – Opt. var.	84230	331400	176700	154700	1.112	5.463	2.581
Variation in %	41.3% ↗	11.6% ↘	11.5% ↘	11.7% ↘	2.91% ↘	6.50% ↗	4.39% ↗

4.5. TOTAL OPTIMIZATION

The results of the study regarding the optimization by all the six variables analyzed are presented below. In this case, no graphic representation can be given, but the results are filled in the *Table 5*.

The optimization aspects can be also analyzed by percentage increases/decreases of the important characteristics taken into account as against the reference motor.

The optimum solution resulted for the following values of the variables: A_o=410.9 A/cm, B_o=0.77 T, β_{c1o}=0.513, β_{c2o}=2.01, J_{1o}=3.517 A/mm^2, J_{2o}=3.663 A/mm^2 and the exploitation cost decreased by Δc_e=11.6 % or Δc_e=38440 €.

5. **CONCLUSIONS**

The study and the simulations carried out aimed mainly at identifying the important variables in case of optimization C_e= f($\bar{x}$)=minimum, in order to reduce considerably the number of variables and finally the computation effort necessary for optimization.

It is noticeable that in the final optimum variant, by choosing correctly the electromagnetic stresses and the constructive dimensions, an important decrease by 11.6 % in the exoloitation cost resulted (ΔC_e=38440 €.) as against the variant of reference motor, preserving the restrictive conditions imposed by the customer.

The coal dust, carried out by means of six mills, is powdered in the firebox of the 1035 t cauldron of the power plant for being burnt. In this case, the exploitation expenses necessary for only one cauldron are reduced with ($\Delta C_{e.cauldron}$= =6·38440 € = 230640 €).

If we take into account the fact that there are a lot of such motors in the existing thermo-electric plants, important savings might be obtained.

The simulations fully justify their utility in the optimal design stage, for manufacturing such a motor which works in difficult conditions.

An optimum solution, with lower electromagnetic stresses against the known variant of motor, has resulted, which is very favourable because the machine losses are reduced and, being a closed construction motor, the ventilation problem is solved easily.

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