OPTIMISATION OF LOSSES IN ASYNCHRONOUS MOTORS FOR GENERAL USE

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REZUMAT. Proiectarea optimală a motoarelor asincrone reprezintă un proces de căutare şi selectare a unei maşini electrice care sá corespundá unui criteriu stabilit şi anumitor condiţii restrictive impuse. Simulările, numeroase şi semnificative care se fac, aduc informaţii stric necesare cantitative şi calitative pentru toate categoriile de pierderi care apar la motoarele asincrone, cu scopul diminuării acestora şi definitivarea soluţiilor constructive. Lucrarea are un caracter de noutate, vizează optimizarea pierderilor la funcţionare în sarcină a motoarelor asincrone de uz general.

Cuvinte cheie: motoare asincrone rotative, metode de optimizare.

ABSTRACT. Optimal designing of the asynchronous motor is a process of search and selection of the electrical machine that correspond to a set of criteria and restrictive conditions imposed. The simulations, which are numerous and signifiant, provides informations, strictly quantitative and qualitative for whole range of losses of the asynchronous motors, aimed to decrease them and to define their parameters and their constructive solution. The paper is a novelty, is aimed to optimize the losses of the asynchronous motor for general use at load operation.

Keywords: asynchronous rotating machines, optimization methods.

1. INTRODUCTION

First stage on the designing of a new electrical machine must be the analysis of the impact on the environment. This suppose: to reconsider the quality and to introduce new elements in the design process; to design electrical machines easy to maintain and repairing which use recyclable elements; to simplify the fabrication process; to use standardized components; to consider the whole life cycle of the machine, to reduce the number of technological operations; to maintain the level of performance of the machine; to assure the safety of the customer; to establish the optimal period of life.

In paper is showed that, to obtain well found values for the electromagnetical applications, could be obtained minimal losses in the machine and also good characteristics in functioning. The first mathematical models of designing the asynchronous motor were created long time ago, and now, this models are reanalyzed and permanently improved with new elements. All this allow a much better approximation of the real phenomenas of an electrical machine (for exemple to introduce the saturation and the skin effect), to predetermine more exactly the performance in starting process and operation.

Spectaculous rising of the computers performance allowed a wide restraint of the simplified hypothesis which regulary attend a scientific investigation and make possible the capitalization of the complex models aimed to optimize and which are considering a much more number of variable in the designing activity [1], [2], [4].

2. ASPECTS ON THE OPTIMAL DESIGNING OF THE ASINCHRONOUS MOTORS

A.Mathemathical model and the optimizing criteria

The mathemathical models represent the calculus and dimensioning relations, given by the literature and accepted as level of precision, tables with standardized values of the conductors, magnetization curves, etc.

The imposed restrictions for such parameters are verified after their calculation and, in the case of their overfulfilment, their model is replayed for other values attributed to the variables.

We define the *optimal constructive solution* that in which, the designed machine, is responded to the following requests: respect the technical and economical performance imposed by the customer, in the construction of the machine are used native materials and the technologies are those used in the current fabrication.

It is knowing the fact that the electromagnetical applications are very important in designing of the asynchronous motors, with major effects on the starting and operating characteristics and also on the losses.

B. Objective function and its restrictions

The activity of optimization of the operating characteristics of the asynchronous motors were, for a long period of time, in the attention of the specialists, but now the methodes of designing and construction are replayed and improved with new elements [2], [6], [7], [8]. The final issues is the rising of precision of the determinations by using the numerical calculus, the performant computers, the consideration of the saturation and of the skin effect in the classical models of the electrical machines.

Actual request of rational using of the energy in exploitation imposed the optimisation of losses in the operation of asynchronous motors for general use. In this conditions are established criteria of minimum total losses and resulted the *objective function:*

$$f(\bar{x}) = \Sigma p = p_{Fep} + p_{Fes} + p_{Cu1} + p_{Cu2} + p_{m+v} \quad (1)$$

The restrictions imposed are: $C_f \leq C_{f.mot}$ fabrication price lower than the those existent, the characteristics of starting imposed a minimum: $m_p \geq 1{,}0$ –minimum starting torque because usual, the starting is no load or with small load, $i_p \leq 6{,}5$ –starting current is limited. To calculate the fabrication price we use the relation:

$$C_t = k_f C_{ma} \quad (2)$$

C_{ma} – active materials costs established reported to the quantities of the active materials used (m_{Fe1}, m_{Fe2}– silicious iron plate for the magnetic circuit for stator and rotor, respectively m_{Cu1}, m_{Cu2} – copper conductor for the windings) and their costs c_{Fe1}, c_{Fe2}, c_{Cu1}, c_{Cu2}. Without a big mistake, it's proposed the estimation of the fabrication costs through a factor, k_f, determinated for similar motors, because the cost of manual labor, energetical consumption, different specifics overhead for the production process are hard to calculated.

Optimization on the total losses (minimal value), for stationary regime and rated load, could be in divergence with the imposed restrictions, but could be solved. If the critical torque is a very important characteristics for an asynchronous motor taking account on its destination, in this case it could be modified easily the imposed restrictions. Once with this study are pursued the effects on the criteria costs (C_t – total costs, C_f – fabrication cost, C_e – energy losses cost in use).

To obtain an optimal solution means to use an appropriate methode of search, adequated to the facilities offered by the computer calculus.

Main variables appear in the mathemathical model used to design and in the expression of objective function. Reported to this variables are made the optimization, and their number is established according with the condition to obtain a more exactly mathematical model and to reduce at maximum the working time. For a more exact optimization were established 7 main variables, this being electromagnetical applications: A – surface current density; B –magnetic induction in airgap; J_1, J_{2b}, J_{2i} – current density in stator, rotor and shortcircuit belt ; B_{j1}, B_{j2} – magnetics inductions in stator and rotor yoke. Others variables used in the mathematical model and to the calculus of objective function are established according with the literature and represents the class of the *auxiliary variables*.

The aim of this paper is a more ample study to establish the optimal values of the electromagnetical applications, taking account the criteria: minimum total losses (maximum efficiency), and imposed values for the starting characteristics.

C. Calculus of the minimum of the objective function

To optimize multi variables problems, with and without restrictions, are used *exploratory methods* when the analythical method couldn't be applied [1], [2], [7]. In paper was used *Rosenbrock method with restrictions*. This method is a version of the Rosenbrock procedure for problems with restrictions and has the advantages to accelerate the process of search on the established direction. Using this method we aimed to minimize the objective function $f(\bar{x}) = \Sigma p$, depending on the following variables:

$$\Sigma p = f(A, B, J_1, J_{2b}, J_{2i}, B_{j1}, B_{j2}) \quad (3)$$

In relation (6) the symbols are those used in literature. The objective function is conformed to the system with restrictions on variables:

$$x_{\min i} \leq x_i \leq x_{\max i}$$
$$x_i = \{A, B, J_1, J_2, J_i, B_{j1}, B_{j2}\} \quad (4)$$

And to the restrictions imposed by the customer:

$$C_f \leq C_{f.mot} \quad m_p \geq 1{,}0 \quad i_p \leq 6{,}5 \quad (5)$$

Procedure is advanced toward optimal through a search without restrictions, until attendance of the convergence, or arrived in a area bounded by the restrictions neighbourhood. Bounded areas are defined as:

lower area:

$$x_{\min_i} \leq x_i \leq x_{\min_i} + (x_{\max_i} - x_{\min_i}) \cdot 10^{-4} \quad (6)$$

uper area:

$$x_{\max_i} - (x_{\max_i} - x_{\min_i}) \cdot 10^{-4} \leq x_i \leq x_{\max_i} \quad (7)$$

Search start in a point $\bar{x}^{(0)} = (A^{(0)}, B^{(0)}, J_1^{(0)}, J_{2b}^{(0)}, J_{2i}^{(0)}, B_{j1}^{(0)}, B_{j2}^{(0)})$ placed in the admited area of the restriction without belong to the bounded areas.

Main stages literatures are:

1. Are choosed arbitrarily the start point $\overline{x}^{(0)}$, are established the initial search directions, parallel with the coordinate axis and are determined the advancement steps s_i (i = 1,2,…,n). Are evaluated function $f(\overline{x}^{(0)}) = \Sigma p^{(0)}$ and make $f(\overline{x}^{(0)}) = \Sigma p^{(0)} = \Sigma p^{*}$, where:

- $\Sigma p^{(0)}$ – best current values of the function $f(\overline{x})$ in a point in which the restrictions are satisfied.

- Σp^{*} - best value of the function $f(\overline{x})$ in a point in which the restrictions are satisfied, and the bounded areas are not breaking.

2. Are made Rosenbrock sequential movements on each direction and are evaluated the values of function $f(\overline{x})$. The movements are accelerated according with the successes or failures of the searching process.

The process of acceleration is continued until one of the successes and one failure are obtained on all n directions simultaneously.

3. Are determined $\Sigma p^{(0)}$ şi Σp^{*} for each searching stage.

4. If the value in current point is lower than $\Sigma p^{(0)}$, or the restrictions are breaking, the procedure is continued without restrictions, using new directions of movement in quadrature, obtained with Gramm-Schmidt procedure, considering this point as a failure. ,

5. If the current point is in bounded areas, objective function is modified:

$$f\left(\overline{x}^{**}\right) = \Sigma p^{**} = f\left(\overline{x}^{(k-1)}\right) - \left[f\left(\overline{x}^{(k)}\right) - f\left(\overline{x}^{(k-1)}\right)\right]\cdot\left(3\lambda - 4\lambda^2 + 2\lambda^3\right) \quad (8)$$

where:

$f\left(\overline{x}^{(k)}\right) = \Sigma p^{(k)}$ - the new value of the function accordind with (k) step;

$f\left(\overline{x}^{(k-1)}\right) = \Sigma p^{(k-1)}$ - the old value of the function in the last step (k-1);

$\lambda =$ [distance to the bound of the area]/[width of bounded area], that is the lower area,

$$\lambda = \frac{\left[x_{\min_i} + \left(x_{\max_i} - x_{\min_i}\right)\cdot 10^{-4}\right] - x_i}{\left(x_{\max_i} - x_{\min_i}\right)\cdot 10^{-4}} \quad (9)$$

Respectively for the upper area.

$$\lambda = \frac{x_i - \left[x_{\max_i} - \left(x_{\max_i} - x_{\min_i}\right)\cdot 10^{-4}\right]}{\left(x_{\max_i} - x_{\min_i}\right)\cdot 10^{-4}} \quad (10)$$

It is observed that for λ = 0, $\Sigma p^{**} = f\left(\overline{x}^{(k-1)}\right)$ also the current point is inside the bounded area, and for λ = 1, $\Sigma p^{**} = \Sigma p^{*}$ and the current point is in the area of restrictions.

For the functions which are improved itself when the current point come closer with a restriction, the modified function Σp^{**} has an optim in bounded area.

6. If it is obtained an improvement of the criteria function in the current point, without the breaking of bounded area or of the restrictions it could be considering the step as a success, $\Sigma p^{*} = \Sigma p^{(k)}$ and the search is continued.

7. The procedure is continued until the convergence criteria are satisfied.

3. RESULTS AND CONCLUSIONS

To distinguish the influence of the electromanetic applications on objective function $f(\overline{x}) = \Sigma p$, was analised particularly an asynchronous motor for general use. The ideas of this analyse are the base for the optimization process of the losses in this machine.

To exemplify it was considering a three phase asynchronous motor of low voltage with the rotor in cage with rated values: P_N= 30 kW – rated power, U_N=380 V – rated voltage, I_{1N}=64 A, n_1=1000 rpm – synchronous speed. To find the costs, based on the existing documentation were considered: N_{ore}=190*8=1520 hours/year – number of hours of operation in one year; T_{ri} =4 years – time of recovering of the investition; c_{Cu} =11 E/kg – cost of one kilo of copper; c_{Fe}= 4,8 E/kg - cost of one kilo of iron plate of silicious; $c_{el.a}$ =0,098 E/kWh – cost of a kWh of active energy, $c_{el.r}$ =0,024 E/kVARh – cost of a kVARh of reactive energy.

An usually designing of the motors (according with the literature) was established the following values: $\cos\varphi_m$=0,782; η_m=0,884; $M_{max.m}$=2,113*M_N; $M_{p.m}$=1,047*M_N; $I_{p.m}$=4,274*I_N; A_m=347 A/cm; B_m=0,76 T; $J_{1.m}$=5,7 A/mm^2; $J_{2b.m}$=4,3 A/mm^2; $J_{2i.m}$=3,3 A/mm^2; B_{j1}=1,4 T, B_{j2}=1,33 T, $C_{f.m}$=2695 E, $C_{e.m}$=2979 E, $C_{t.m}$=5674 E.

These values are considered as references (values for reported).

It is known that the electromagnetic applications are influencing the size of losses in a electric machine. In paper is shown that also some constructive dimensions of the machine (D – machine diameter, ….) could influencing some kind of losses.

This study taken account for every variable analysed (A, B, J_1, J_2, J_i, B_{j1}, B_{j2}), a variation with -30%, respectively +10% (upper values were restricted because of heating reasons), regarding references values. față de valorile de referință date mai sus.

In the optimal design of the asynchronous motor was considered also the evolution of others parameters, equal as importance : maximal torque, costs criteria (C_f, C_e, C_t - cost of fabrication, of use and total cost), etc.

To avoid the gravity of each variable on the principal criteria, the graphical representations are given in relative units and in each characteristic are seven curves: one for each kind of losses meet to the asynchronous motor. When we report this values we meet the following relations:

$$\Sigma p = \frac{\Sigma p_{\mathrm{var}\,m}}{\Sigma p_m} \quad p_{Fe} = \frac{p_{Fe\,\mathrm{var}\,m}}{p_{Fe\,m}} \quad p_{Cu1} = \frac{p_{Cu1\,\mathrm{var}\,m}}{p_{Cu1\,m}}, \quad (11)$$

$\Sigma p_{var.m}$, $p_{Fe.var.m}$, $p_{Cu1.var.m}$ – total losses, in iron and in stator winding for the analysed motor; $\Sigma p_{.m}$, $p_{Fe.m}$, $p_{Cu1.m}$ –total losses, in iron and in stator winding for the real motor, etc.

A. Analysis of the machine losses

Through the research realised after each variable it was highlighted the importance of a set of variables on the optimize established criteria (minimal total losses).

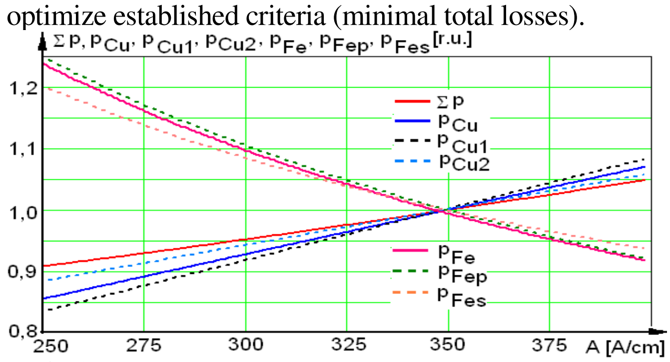

Fig. 1. Curves of variation of motor losses reported to A – surface density of current.

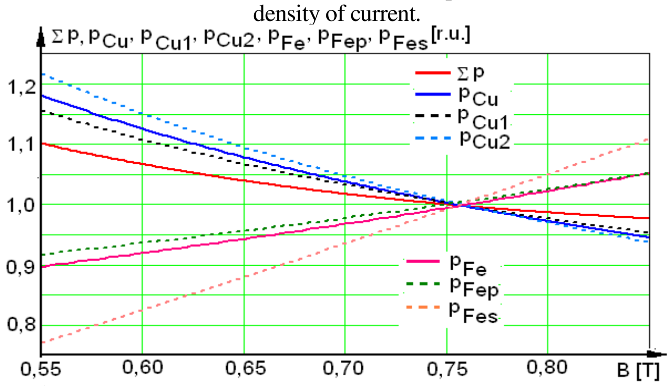

Fig. 2. Curves of variation of motor losses reported to B –magnetic induction in airgap.

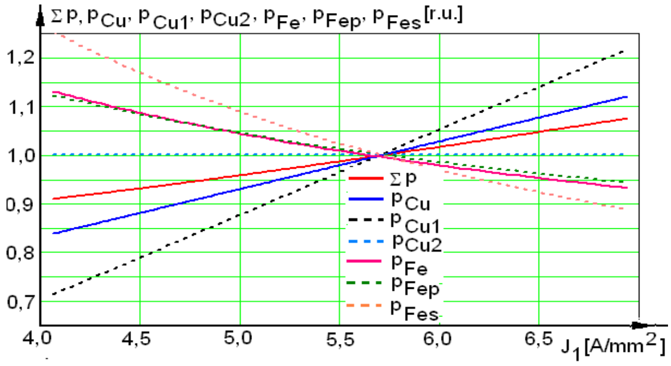

Fig. 3. Curves of variation of motor losses reported to J_1 – current density of stator winding.

In fig.1., …, fig.10 are shown the curves of variation for all kind of losses in motor, in relative units reported to rated load: Σp – total losses (red color), p_{Cu} – windings losses (blue color), p_{Cu1}, p_{Cu2} – windings losses of the stator and rotor (black and light blue), p_{Fe} – iron losses (pink color), p_{Fep}, p_{Fes}- principal and secondaire losses in iron (green and orange).

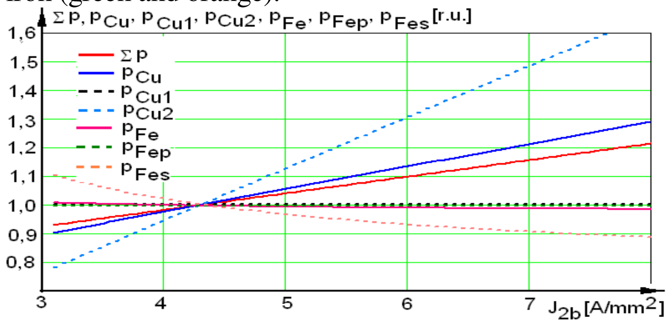

Fig. 4. Curves of variation of motor losses reported to J_{2b} – current density of rotor winding.

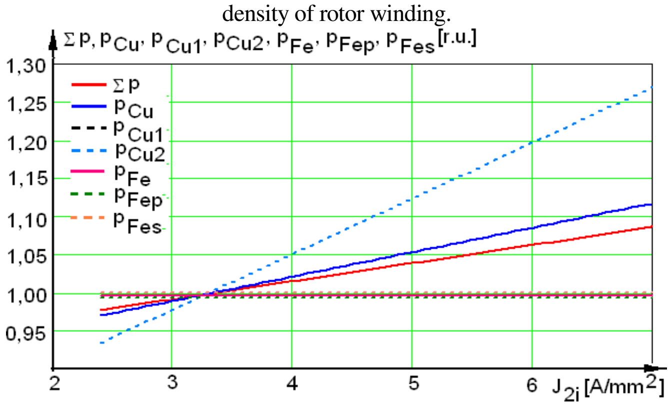

Fig. 5. Curves of variation of motor losses reported to J_{2i} – current density of shortcircuit belt.

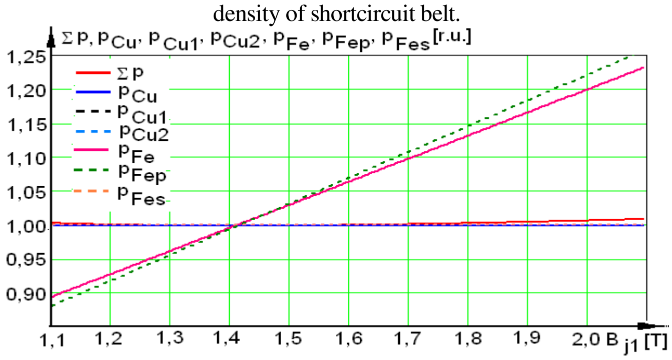

Fig. 6. Curves of variation of motor losses reported to B_{j1} – magnetic induction of stator yoke.

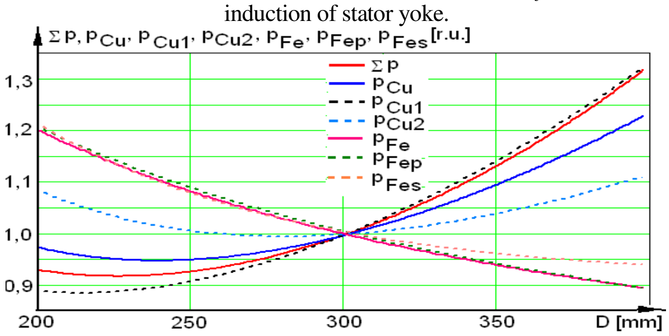

Fig. 7. Curves of variation of motor losses reported to D –machine diameter.

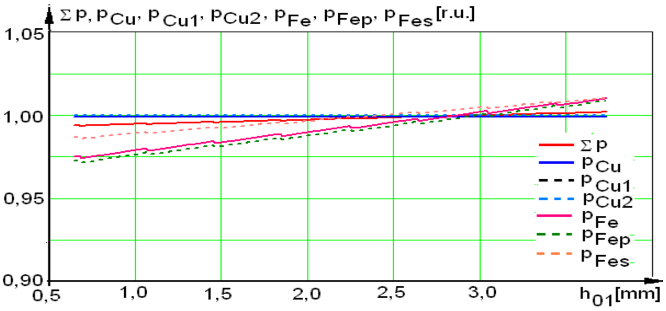

Fig. 8. Curves of variation of motor losses reported to h_{01} – isthmus height stator slot.

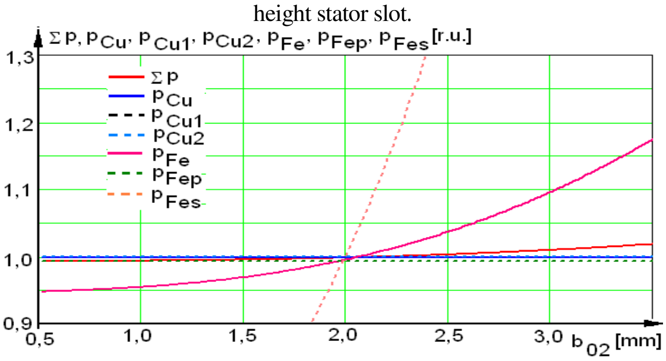

Fig. 9. Curves of variation of motor losses reported to b_{02} – isthmus width rotor slot.

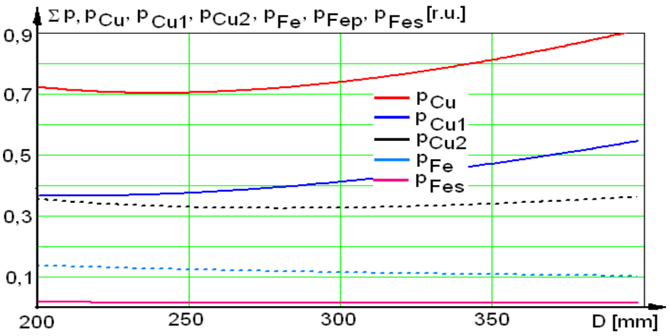

Fig. 10. Curves of variation of motor losses reported to D – machine diameter.

For all analyzed variables, researched areas were bounded to -30%, respective +10% reported to references values of the studied motor.

Analyze of the shown figures (fig.1, fig.2, fig.3, fig.5) we can see that through the modification of the values of electromagnetic solicitation A, B, J_1, J_{2i} results for the analyzed criteria Σp – for total losses a variation about 15%, and could be see what kind of losses is more influenced, reported to each variable.

The most important solicitation is J_{2b} – current density in the rotor bar, where Σp is varying with 19,8% (fig.4), and those with the minimum effect is B_{j1} – magnetic induction in the stator yoke (fig.6).

Follow up a study which is considering as variable the most important constructive dimensions: D – machine diameter, δ – airgap, β_{c1}, β_{c2}, – form factors for the stator and rotor slot, b_0, h_0 –isthmus dimensions for the stator and rotor slot. The most important results are given in fig.7-fig.9.

Analyzing fig.7 and fig.10 could be observed that for a diameter of the machine, correctly established, total losses are reduced with 21%. In fig.10 all kind of losses were reported at Σp_m – total losses of the references motor, and could be observed that the most important are those in windings (≈70%). The others constructive dimensions (fig.8-fig.9), have an minimal influences on the total losses criteria Σp.

The second part of this study speaks about the optimization regarding the two most important variables with the established criteria: J_1 – current density in stator winding and D –machine diameter.

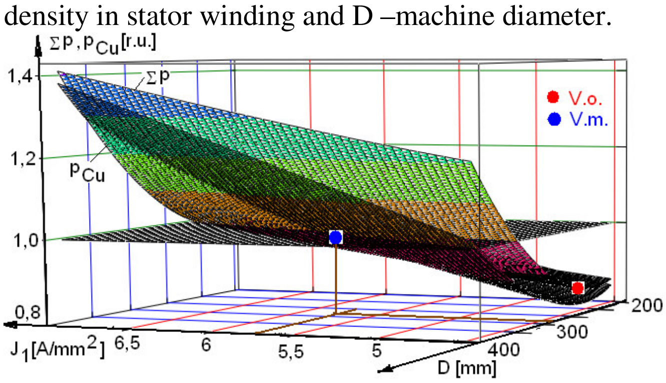

Fig. 11. Answer surfaces, in space, for the criteria: total losses and copper losses, considering as variables: diameter of the machine and current density in stator winding.

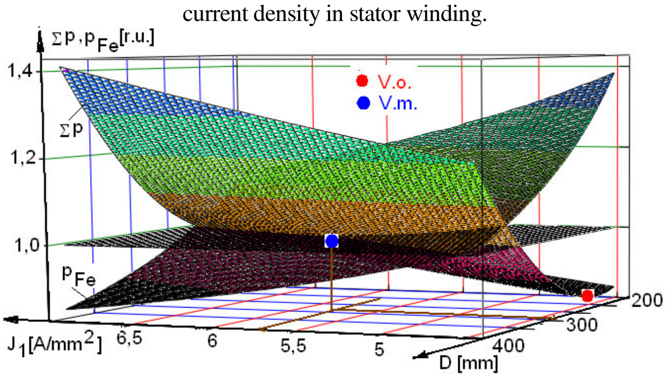

Fig. 12. Answer surfaces, in space, for the criteria: total losses and iron losses, considering as variables: diameter of the machine and current density in stator winding.

The parameters which are the answer represent the surfaces in 3D and could be observed that the final results are different according with the overlapping of each optimization shown separated. For a good delimitation of the optimal and unfavorable areas was plotted the surface corresponding with Σp_r=1 (grey color).

Fig.11 show in same axis, the surfaces: Σp – total losses and p_{Cu} – losses in copper reported to the variables D and J_1. In fig.12 are shown the surfaces: Σp –total losses and p_{Fe} – total losses in iron. On the figures we make the following abbreviations: V_o – optimal variant of motor (red bullet), V_m – real variant (blue bullet).

In table no.1 is shown the comparison between V_m – real variant of motor and V_o – optimized variant.

Table no. 1

Criteria / Obtained values	Σp (W)	m_p (r.u.)	i_p (r.u.)	m_m (r.u.)	cosφ	C_f (E)	C_e (E)
V_o optimal variant	3146	1,155	4,01	2,253	0,632	2684	2505
V_m real variant of motor	3940	1,05	4,27	2,113	0,782	2695	2979

In this context were distinguished also other important quantities of the design process: m_p, i_p –starting current and torque; m_m, cosφ – maximal torque and power factor; C_f , C_e – fabrication costs and operation cost. Optimal machine was resulted for the following variables: A_o=385 A/cm; B_o=0,823 T; $J_{1.o}$=5,368 A/mm^2; $J_{2b.o}$=3,053 A/mm^2; $J_{2i.o}$=2,343 A/mm^2; B_{j1o}=1,36 T, B_{j2o}=1,42 T, D_o=230 mm.

B. Conclusions regarding the optimization process

This study was a proposal to identify the most important variables in optimization situation $f(\bar{x})=\Sigma p=\min.$, to reduce substantial the number of variables, and also the effort of calculation. In this way, the designer knows and could offer to the costumer the optimal solution in a short time. Taken account that the problem of reducing the energetically consumptions in operation is so actual, this study, which shows the possibility of losses reducing, is justified.

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