Constructive Dimensions Optimization for Asynchronous Motors used in Coal Mills

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***Abstract* - The high operating cost, owed to the large consumption of active and reactive power, led to the optimization of the design and construction of asynchronous motors used in driving the coal mills. The reduction of the operating cost is a difficult problem, because the motor usually lies in a closed enclosure, with provided gauge dimensions, and with specific requirements imposed by the type of drive in use. Using this information, while keeping the existing electromagnetic stresses (for heating reasons), the optimal construction dimensions can be established by design, so as to reduce the operating cost. The optimization is substantiated by the decrease of the operating cost of such a motor with 26100 euros, as compared to the existing version.**

Cuvinte cheie: *motoare asincrone pentru mori de carbune, proiectare optimala, simulare.*

Keywords: *asynchronous motors for coal mills, design optimization, simulations.*

I. Introduction

The preparation of the coal dust is performed with the aid of six combined mills, with hammers and fans, each mill being driven by a high-power asynchronous motor of 500 kW.

The coal grinding mill from Fig.1 performs the crush, grind and transformation of the coal into dust, which is then sprayed into the furnace boiler. The better the quality of the grinding, the higher the efficiency and productivity of the power plant, the costs of electricity production being also reduced.

The coal mill has a high moment of inertia, resulting in a substantial increase of the start-up time. To avoid the overheating of the rotor cage, the current limitation was required over this interval, and an accessible starting torque needed to obtain accelerations mechanically supported by the whole system.

The asynchronous motor is coupled to the rotor of the mill by a regulable hydraulic coupling, to which the oil is introduced in half-couplings, centrifuged toward the outside, thus becoming a toroidal ring that performs the drive.

The concern for the optimization of electric motors has gained a lot of attention lately, considering the huge manufacturing and operating expenses borne by the manufacturer and the beneficiary.

Currently, the optimal design methods of electric motors are reanalyzed and continuously enriched with new elements, in order to increase the accuracy of the experimental measurements (eg use of appropriate software, high-performance computers, introduction of saturation and skin effect in classic models of electric motors). For this reason, the amount of calculations increased a lot, and efforts are being made to reduce the working time [1-6].

The resemblance with an optimal motor can be achieved only by means of a large number of independent variables, which determine a very large number of possible combinations, of around $10^{20} – 10^{24}$. Therefore it is not recommended to try all of the possible combinations.

Fig. 1. Fan coal mill.

In general, the mathematical models that take into account the magnetic saturation and its dynamic variation, as well as the effect of the repression current, accurately provide valuable results in a range of admissible and practical errors.

These models [7-9], are mandatory in the design stage, as well as in anticipating the behavior of a manufactured motor, subjected to a given stationary or dynamic process.

II. The mathematical model used used in the optimal design of asynchronous motors

A.These mathematical models

The models [5] be expressed as:

$$\begin{aligned} h_i(x_1, x_2, \ldots, x_n) = 0, \quad & i = 1,2,\ldots,l \\ g_j(x_1, x_2, \ldots, x_n) \leq 0 \quad & j = 1,2,\ldots,m \end{aligned} \qquad (1)$$

where i = 1, 2, 3, .. n are the optimization variables.

The restrictions imposed for the motor driving the coal mill are checked after their calculation, and in case the mathematical model is not solved, new values are used for the optimization variables.

The literature shows that the electromagnetic stresses are important factors in the design process of asynchronous motors, with major impact over the optimization criteria.

B. The objective function, variables and constraints

In order to establish the optimum constructive dimensions of asynchronous motors used in driving the coal mills, we use of minimum operating cost criterion, $f(\overline{x})=C_e=min.$

It correctly reflects the operating expenses (which are high), necessary during the amortization of the investment:

$$C_e = C_{ea} + C_{er} = N_o T_{ri} c_{el.a} \Sigma p + N_o T_{ri} c_{el.r} \Sigma q \tag{2}$$

N_o - the number of operation hours, during a year, of the motor, $c_{el.a}$ - the cost of one kWh of active power, $c_{el.r}$ – the cost of a kVARh of reactive power, T_{ri} - investment payback time; Σp, Σq - the total motor losses / reactive power consumption at rated load operation.

The investment made to buy this type of motor is expressed by the manufacturing cost:

$$C_f = k_f C_{ma} \tag{3}$$

The cost of the active materials C_{ma}, is simply determined by knowing m_{Fe1}, m_{Fe2}–the consumption of silicon sheet for the stator and rotor magnetic circuit, respectively; m_{Cu1}, m_{Cu2} –the quantities of copper conductor for windings, and the prices of these materials.

The factor k_f –determined for asynchronous similar motors, takes into account the efficiency of the technological process in the power plant.

The variables of the objective function are established depending on their weight over the established optimization criterion.

This optimization uses eight variables, these being the main constructive dimensions: D, δ -diameter and air gap of the machine, $\beta_{c1}=b_{c1}/t_1$, b_{01}, h_{01}, - dimensions related to the stator slot and $\beta_{c2}=h_{c2}/b_{c2}$, b_{02}, h_{02} - dimensions related to the rotor slot.

The lower and superior limits are established to limit the search domain, thus reducing the working time.

$$\begin{gathered} x_{\min_i} \le x_i \le x_{\max_i} \\ x_i = \{D,\delta,\beta_{c1},b_{01},h_{01},\beta_{c2},b_{02},h_{02}\} \end{gathered} \tag{4}$$

There are also restrictions imposed by the specific of the coal mills drive system:

$$m_p \ge m_{p.i}\,; \qquad i_p \le i_{p.i}\,; \qquad m_m \ge m_{m.i} \tag{5}$$

m_p, m_m, i_p - starting and maximum torque; starting current.

C. Computing the minimum of the objective function

The direct search methods [10-14], of the optimum for multi-variable problems, with restrictions, are the most appropriate, because they do not use the derivatives of the objective function and are based on the idea of advancing to the optimal through improvements made along the way.

Determination of the optimum using Rosenbrock method with constraints

It is proposed the minimization the objective function depending on the following variables:

$$C_e = f(D,\delta,\beta_{c1},b_{01},h_{01},\beta_{c2},b_{02},h_{02}) \tag{6}$$

The Rosenbrock optimization methods involve a search after each variable, until convergence is reached or an area limited by the vicinity of the constraints is reached. The limit areas are determined as follows:

-the lower area

$$x_{\min_i} \le x_i \le x_{\min_i} + (x_{\max_i} - x_{\min_i}) \cdot 10^{-4} \tag{7}$$

-the superior area

$$x_{\max_i} - (x_{\max_i} - x_{\min_i}) \cdot 10^{-4} \le x_i \le x_{\max_i} \tag{8}$$

The search begins with an arbitrary point $\overline{x}^{(0)}=(D^{(0)}, \delta^{(0)}, \beta_{c1}^{(0)}, b_{c1}^{(0)}, h_{c1}^{(0)}, \beta_{c2}^{(0)}, b_{c2}^{(0)}, h_{c2}^{(0)})$ placed in the admissible domain of restrictions, without being part of the limit areas. The main stages are:

- the function $f(\overline{x}^{(0)})=C^{(0)}=C^*$ is evaluated
- from the chosen point, the initial search directions parallel to the coordinate system are established and the next steps are determined;
- for each point where the constraints are met, the function $f(\overline{x})$ is evaluated;
- the obtained value is compared with the previous one, the lowest value is kept and it is denoted by C *.
- Rosenbrock sequential movements are carried out for each direction and the value of the function $f(\overline{x})$ is evaluated.

If the value at the current point is weaker than C *, or the restrictions are violated, the search procedure is continued without restrictions, by using new movement reference frames, obtained with the Gramm - Schmidt procedure.

The search continues until the chosen convergence criterion is met.

III. Simulations and Results

The results of the construction optimization of the asynchronous motor used to drive a coal mill can be noted in the presented analysis. The considered parameters are P_N=500 kW – rated power; U_N=6 kV – rated voltage; I_{1N}=62.6 A – rated current; n_1=500 rpm - synchronism speed.

The operation of the mill requires the following starting and operating characteristics: $M_p \ge 1.05*M_N$ – starting torque; $I_p \le 5.5*I_N$ – starting current; $M_m \ge 2.1*M_N$ – maximum torque.

The manufacturing, operation costs and the costs with the active / reactive power were calculated starting from known data: N_{ore}=330*24=7920 hours / year - the number of operaton hours per year; T_{ri}= 6 years - time to recover the investment; c_{Cu} =12 €/kg - the cost of one kilogram of copper; c_{Fe}=0.95 €/kg -the cost of one kilogram of iron (silicon sheet); $c_{el.a}$=0.131 €/kWh - the cost of one kWh of active power, $c_{el.r}$ =0.013 €/kVARh - the cost of one kVARh of reactive power.

The following costs resulted for the analyzed motor: $C_{f.m}$=68590 €; C_{em}=403400 €; $C_{e.a}$=217000 €, $C_{e.r}$=186400 €.

These results will be further considered as reference (reported) quantities.

In order to easily track the weight of each optimization variable, the plots are provided in per unit values. The costs are reported with equations of type (9):

$$c_e = \frac{C_{e\,\mathrm{var}\,m}}{C_{e\,m}} \quad c_{ea} = \frac{C_{ea\,\mathrm{var}\,m}}{C_{ea\,m}}, \quad c_{er} = \frac{C_{er\,\mathrm{var}\,m}}{C_{er\,m}}, \tag{9}$$

$C_{e.var.m}$, $C_{ea.var.m}$, $C_{er.var.m}$–costs with the operation / active energy/ reactive energy for the analyzed motor version;

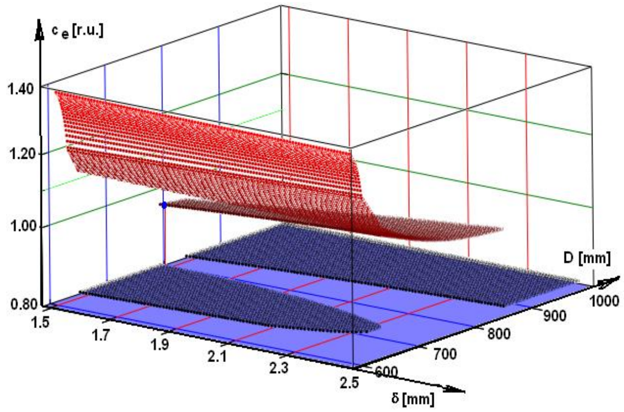
$C_{e.m}$, $C_{ea.m}$, $C_{er.m}$ – the same costs, but for the motor version considered as reference.

A.The optimization with respect to the variables D, δ (motor and air gap diameter)

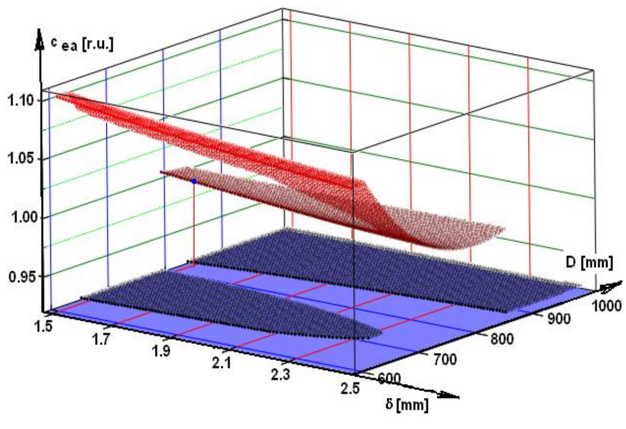
The research conducted with respect to these variables (constructive dimensions) led to much better results: a decrease of c_t by approximately 4.54%, Fig.2.a.

There is a great limitation of the search field due to the restrictive conditions imposed. The areas of $c_{e.a}$,c_{er} - the total active / reactive power costs, as components of the operating cost, can be noticed in Fig.2.b and Fig.2.c.

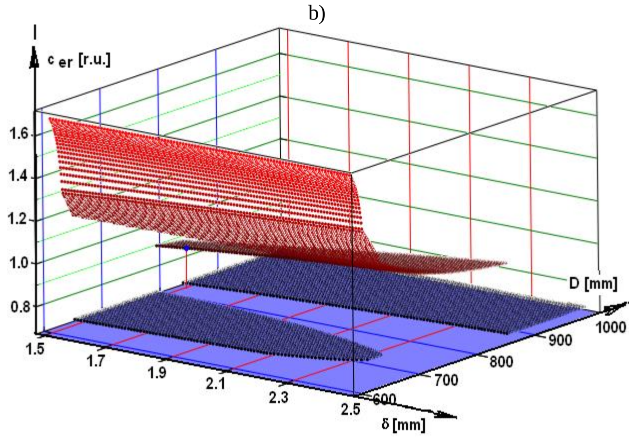
The results of the optimization with respect to the analyzed pair of variables (D, δ) can be observed in table no.1, where the most important characteristics are presented.



a)



b)



c)

Fig. 2. The response areas for the pair of variables D, δ: a) c_e - the operating cost; b) c_{ea} - the active power cost; c) c_{er} -the reactive power cost.

The optimum point resulted for: D=826.1 mm, δ =1.502 mm, and the optimization resulted in a decrease of the total cost Δc_t=4.536%.=18300 €.

TABLE 1

Criterion / Variant	C_e (€)	$C_{e.a}$ (€)	$C_{e.r}$ (€)	$C_{e.a}/C_{er}$ (r.u.)	m_p (r.u.)	i_p (r.u.)	m_m (r.u.)
Values imposed	-	-			≥1.05	≤5.5	≥ 2.1
V_m –Real var.	**403400**	**217000**	**186400**	**1.164**	**1.184**	**5.455**	**2.627**
V_o.– Opt. var.	385100	218200	166900	1.307	1.050	5.346	2.504

B.Study on the optimization of the main dimensions

For the pair of variables D and δ (diameter and air gap), possessing the largest weights in the optimization process, a supplementary analysis was performed considering a single variable. Due to the restrictions imposed by the design theme, taking into account the proposed variation domain for the studied variable, only one area of the domain is allowed. This may be also noticed while performing the simulations for the optimization and previously presented.

In Fig. 3 are presented the per unit plots for the analyzed criterion and the associated costs c_e -operation cost and c_{ea}, c_{er} -active and reactive power costs. The two variables greatly change the reactive power consumption, which has an important weight in the optimization, $c_{er} \approx 0.46 * c_e$. It results that, in order to reduce the operating cost, the most important aspect is to reduce the air gap and to increase the diameter of the machine as much as the imposed restrictions allow.

In Fig. 4 are analyzed the variation curves for m_m, m_p, i_p – the maximum / strating torque and the start current, and important variations may be noticed for these quantities.

The lower limit of the variable δ - the air gap is determined by the increase of the start current over the imposed limit. All of the starting current limits the variable D – the diameter on a certain area, D =(650÷750) mm, and the superior limit is imposed by the decrease of the starting torque.

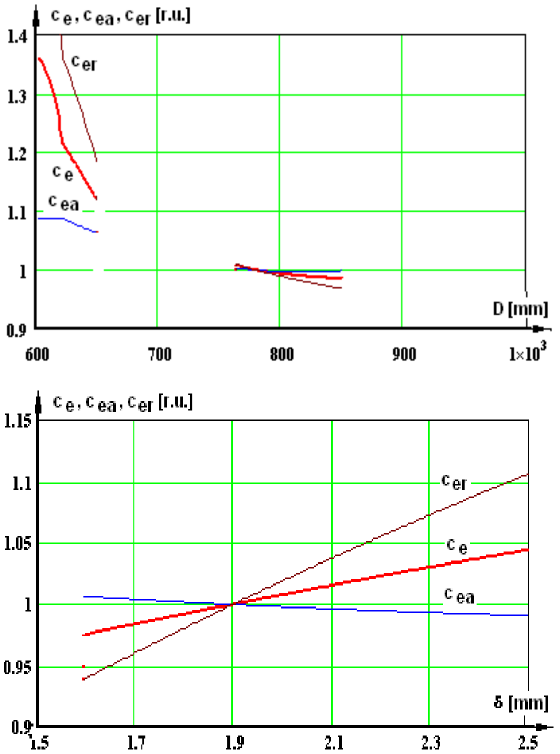
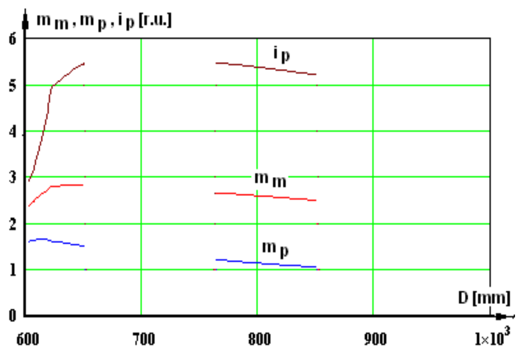
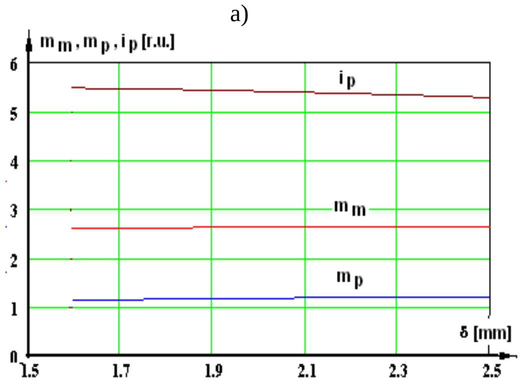


Fig. 3. Variation curves for c_e, c_{ea}, c_{er} - operating costs of active / reactive power for: a) variable D - machine diameter; b) the variable δ – the size of the air gap



a)



b)

Fig. 4. Variation curves for m_m, m_p, i_p – the maximum / starting torques and the starting current for: a) variable D - machine diameter; b) variable δ - the size of the air gap.

C.Optimization of the stator slot geometry

A study was performed for optimizing the geometry of the stator slot, with respect to the established criterion, C_e=minimum.

The variables considered are: $\beta_{c1} = b_{c1}/t_1$ - the slot shape factor (b_{c1}, t_1 - the width of the slot and the tooth pitch), b_{01}, h_{01} - the dimensions of the isthmus. With respect to the most important variables β_{c1} and h_{01}, a simulation was performed, the results being presented in Fig.5.

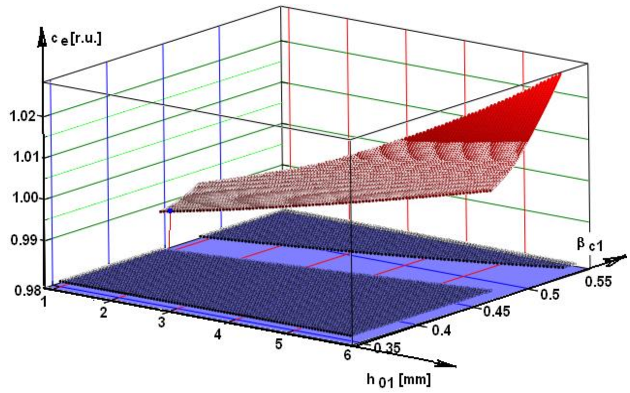


Fig. 5. Response areas for c_t - the operating cost when the pair of variables β_{c1} and h_{01} is considered.

The optimum solution resulted for the following variable values: β_{c1} =0.451, b_{01} =10.23 mm, h_{01}=1.53 mm.

The number of analyzed versions was N_t=747900 motors, and in this case resulted a decrease of the operating cost by Δc_e=0.967%.=3900 €.

TABLE 2

Criterion / Version	C_e (€)	$C_{e.a}$ (€)	$C_{e.r}$ (€)	$C_{e.a}/C_{e.r}$ (r.u.)	m_p (r.u.)	i_p (r.u.)	m_m (r.u.)
Values imposed	-	-			≥1.05	≤5.5	≥2.1
V_m –Real ver.	**403400**	**217000**	**186400**	**1.164**	**1.184**	**5.455**	**2.627**
V_o.– Opt. ver.	399500	218500	183600	1.175	1.067	5.207	2.507

D.Optimization of rotor slot geometry

A study was performed for optimizing the geometry of the rotor slot, considering the established criterion C_e=minim. The variables are: $\beta_{c2} = h_{c2}/b_{c2}$ - the shape factor of the slot (b_{c2}, h_{c2} the width and height of the slot), b_{02}, h_{02} - the dimensions of the isthmus.

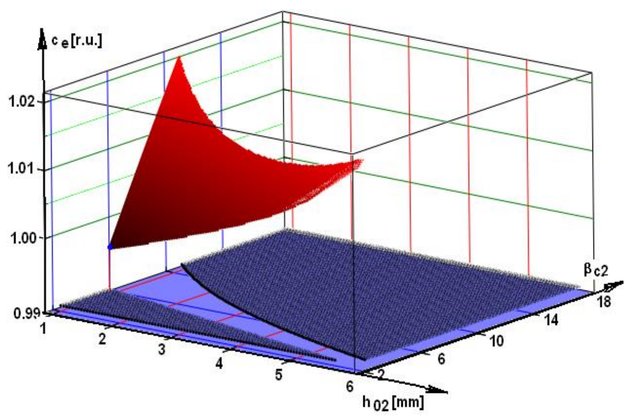


Fig. 6. The response areas for c_t - the operating cost when the pair of variables β_{c2} and h_{02} is cosidered.

The simulation was carried out with respect to the most important variables β_{c2} and h_{02}, the result of which being presented in Fig. 6.

The optimal solution resulted for the following values of the variables: β_{c2} =5.436, b_{02} =1.648 mm, h_{02}=1.102 mm.

The number of analyzed versions was N_t=375800 motors, and in this case a small decrease of the operating cost resulted, by Δc_e=0.396%.=1600 €.

TABLE 3

Criterion / Version	C_e (€)	$C_{e.a}$ (€)	$C_{e.r}$ (€)	$C_{e.a}/C_{e.r}$ (r.u.)	m_p (r.u.)	i_p (r.u.)	m_m (r.u.)
Values imposed	-	-			≥1.05	≤5.5	≥2.1
V_m –Real ver.	**403400**	**217000**	**186400**	**1.164**	**1.184**	**5.455**	**2.627**
V_o– Opt. ver.	401800	216900	184900	1.173	1.217	5.500	2.693

E.Total optimization

The optimization study is further performed with respect to all of the analyzed variables (D, δ, β_{c1}, b_{01}, h_{01}, β_{c2}, b_{02}, h_{02}). No graphical representations can be provided for this case, but the results are listed in table no. 4.

The optimal solution resulted for the following values of the variables: D=867.1 mm, δ=1.484 mm, β_{c1}=0.483, b_{01}=10.9 mm, h_{01}=1.053 mm, β_{c2}=4.494, b_{02}=1.60 mm, h_{02}=1.02 mm.

In order to solve the problem, a number of N_t=22450000 motor versions was considered, and the optimal solution resulted was obtained with a decrease of the operating cost by Δc_e=9.075%.=26100 €.

TABLE 4

Criterion / Version	C_e (€)	$C_{e.a}$ (€)	$C_{e.r}$ (€)	$C_{e.a}/C_{e.r}$ (r.u.)	m_p (r.u.)	i_p (r.u.)	m_m (r.u.)
Values imposed	-	-			≥1.05	≤5.5	≥2.1
V_m –Real ver.	**403400**	**217000**	**186400**	**1.164**	**1.184**	**5.455**	**2.627**
V_o– Opt. ver.	377300	218000	159200	1.369	1.060	5.489	2.604
Variation in %	9.075% ↘	0.461% ↗	14.59% ↘	17.61% ↗	10.50% ↘	0.623% ↗	0.875% ↘

Table no. 5 collects the results of the analyzed optimizations (by groups of variables and the end result), in order to establish which variables are most relevant. In this way, the variables with low weights are droped, the volume of computations decreases and, consequently, the computation time is reduced.

Table no. 5

Criterion / Optimization	C_e (€)	$C_{e.a}$ (€)	$C_{e.r}$ (€)	$C_{e.a}/C_{e.r}$ (r.u.)	m_p (r.u.)	i_p (r.u.)	m_m (r.u.)
Values imposed	-	-			≥1.05	≤5.5	≥2.1
The real version	**403400**	**217000**	**186400**	**1.164**	**1.184**	**5.455**	**2.627**
Main dimensions	385100	218200	166900	1.307	1.050	5.346	2.504
Stator slot dimensions	399500	218500	183600	1.175	1.067	5.207	2.507
Rotor slot dimensions	401800	216900	184900	1.173	1.217	5.500	2.693
Optimization for all variables	377300	218000	159200	1.369	1.060	5.489	2.604

IV.CHARACTERISTICS OF THE OPTIMIZED MOTOR

In order to meet the imposed requirements, the resulted solution is a motor with a cage made of high crossing bars, with slightly variable parameters (affected by the current repression and the magnetic saturation).

For the optimal asynchronous motor solution, which fulfills all the conditions required by the operation of the coal mill, the operating characteristics were depicted in Fig.7, while the current diagram was plotted in Fig.8.

In Fig.7.c is depicted the evolution of the partial and total losses with respect to the motor load. Considering the operating characteristics presented in Fig.7, an increase of cosφ=0.878 and η=0.923 may be noticed, leading to a low operating cost.

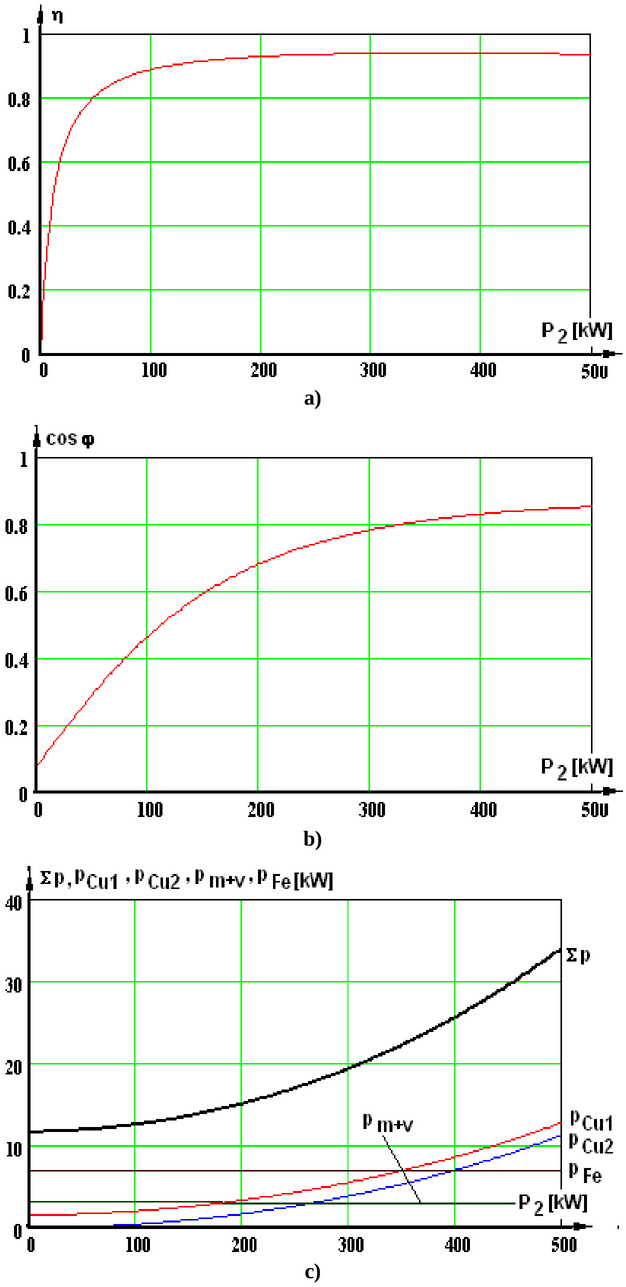


Fig. 7. Operating characteristics of the optimized motor: a) efficiency curve; b) power factor curve; e) variation curves for the motor losses: p_{Cu1}, p_{Cu2} - losses in stator / rotor windings, p_{Fe} - iron losses, p_{m+v} - mechanical losses, Σp - total losses.

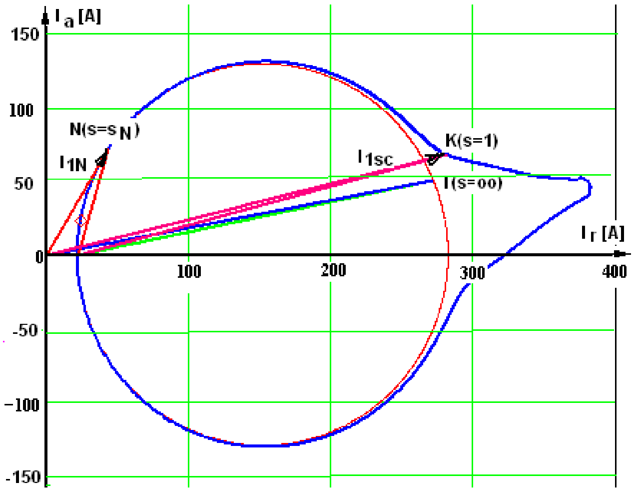


Fig. 8. Current locus for the optimized asynchronous motor.

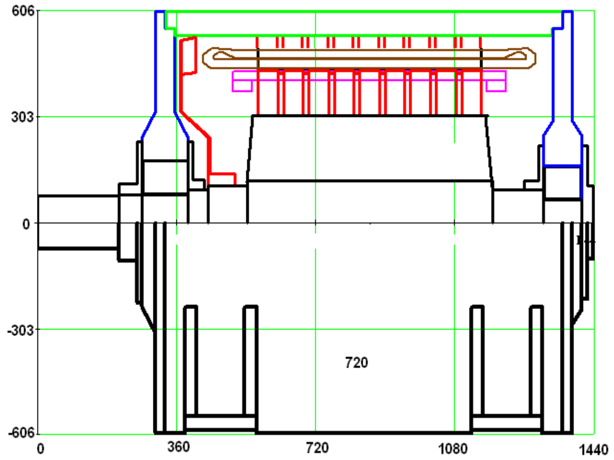


Fig. 9. Longitudinal section and view through the optimized motor.

CONCLUSIONS

The study and the simulations performed had as main objective the identification of the important variables involved in the optimization for obtaining $C_e = f(\bar{x})$=minimum, in order to substantially reduce the number of variables, and finally the computation effort necessary for the optimization.

For constant electromagnetic stresses, by modifying the main constructive dimensions and the stator and rotor slots, a significant decrease of the operating cost with Δc_e=9.075%.=26100 € resulted, as compared to the existing motor version, while keeping the restrictions imposed by the specifics of the drive system.

The presented simulations and results prove that the geometries of the stator and rotor slots affect the operating cost.

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First co-author – 20%
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The third co-author – 15%

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REFERENCES

[1] J. L. Besnerais, V. Lanfranchi, M. Hecquet, and P. Brochet, “Multi-objective optimization of induction machines including mixed variables and noise minimization”, *IEEE Trans. on Mag.*, vol. 44, no. 4, Apr. 2008.

[2] M. Centner, U. Schäfer, “Machine design software for induction machines,” in *Proc. ICEM*, Vilamoura, Portugal, 2008, pp. 1–4.

[3] C.U. Brunner, "International Standar/ds for Electric Motors", Standards for En.Efficiency of Electric Motor Systems (SEEEM), 2007, pp. 6-10.

[4] D. Necula, N. Vasile, M.F. Stan, “The Electrical Machines Impact on the Environment and Solution to reduce its”, *Scientific Bulletin of the Electrical Engineering Faculty,* no.3(17)/2011, Bibliotheca Publishing House, Târgovişte, 2011, pp. 37 – 42.

[5] I. Vlad, A. Campeanu, S. Enache, *Computer-aided design of asynchronous motors. Optimization problems*. Universitaria Publishing House, Craiova, 2011 (in Romanian).

[6] *** CEI 60034-2-1 Standard: "Rotating electrical machines-Part 2-1. Standard methods for determining losses and efficiency from tests", Edition 1.0, 2007.

[7] A. Câmpeanu, “Nonlinear dynamical models for the saturated induction machine”, *Revue Roum. Sci. Techn-Electrotech. et Energ.,* Vol 46, No. 1, pp 89-99, January-March 2001.

[8] A. Boukhelifa, M. Kherbouch, A. Cheriti, R. Ibtiouen, O. Touhami, R. Tahmi, “Stator current minimization by field optimization in induction machine”, *International Conference on Electrical, Electronic and Computer Engineering, ICEEC’04*, 2004.

[9] W. N. Fu, S. L.Ho, and H.C. Wong, “Design and analysis of practical induction motors”, *IEEE Trans. on Magnetics*, vol. 37, no. 5, pp. 3663-3667, 2001.

[10] S. Curteanu, *Numerical computation and symbols in MATHCAD,* Matrix Rom Publishing House, Bucharest, 2004 (in Romanian).

[11] G. Liuzzi, S. Lucidi, F. Parasiliti, M. Villani, “Multiobjective optimization techniques for the design of induction motors”, *IEEE Trans. on Magnetics*, vol. 39, no. 3, May 2003.

[12] D. Samarkanov, F. Gillon, P. Brochet, D. Laloy, “Techno-economic Optimization of Induction Machines: an Industrial Application”, *ACEMP - Electromotion 2011,* Istanbul –Turkey, 2011, pp. 825-830.

[13] I. Vlad, A. Campeanu, S. Enache, G. Petropol, “Operation Characteristics Optimization of Low Power Three-Phase Asynchronous Motors”, *AECE Journal*, Volume 14, Issue 1, Year 2014, pp. 87-92.

[14] J.P. Wieczorek, Ö. Göl, Z. Michalewicz, “An evolutionary algorithm for the optimal design of induction motors”, *IEEE Trans. on Magnetics,* Vol. 34 No.6, 1998, pp. 3882-3887.