Design Optimization of an Asynchronous Motor Used in Light Railway Traction

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Abstract – **The appropriateness of this work is provided by highlighting some aspects insufficiently treated in the areas of designing and dimensioning of asynchronous traction motors associated with light traction static converters. The traction system is aimed for the light railway vehicles. Through the usage of asynchronous motors supplied by independent converters, the performances concerning the traction and the electric braking system are improved, while the maintenance expenses are reduced. The newly designed motor is aimed for the traction system of a locomotive driving a multiple unit train, while the parameters necessary for the analysis of the regenerative braking system are also accounted for. An algorithm for the optimal design of the asynchronous motor is developed, considering the main parameters as the electric and magnetic quantities, the manufacturing and operating costs. The motor dimensions are computed starting from the values of the electromagnetic quantities resulted in the optimization process. The optimization algorithm is realized in Mathcad, any parameter modification leading to a new motor model. The main objective of the paper is to optimally design the asynchronous traction motor directly rotating the drive wheel of the electric train. The motor design takes into account the stationary rated regime, with the speed adjustment within wide limits, frequent starts and stops.**

Cuvinte cheie: *motor asincron de tracţiune, proiectare optimală, modelarea asistată de calculator, simularea performanţelor motorului*

Keywords: *asynchronous traction motor; optimal design; computer-aided modeling; motor performances simulation*

I. INTRODUCTION

The design of the railway traction motors represents a continuous concern in electrical engineering research. The design technologies developed nowadays aim to optimize the motor efficiency, the electromagnetic torque, the power quality and other indicators, while meeting the international standards or the demands imposed by the beneficiary [1].

The widespread use of the control with static voltage and frequency converters allowed for a transition to the optimization of the design and functioning of the asynchronous traction motor, special performances being obtained [2], [3].

The idea of obtaining from an asynchronous traction motor used in the railway traction higher maximum torques and minimum manufacturing or operating costs is a global concern, both at the international and national levels. These are requirements in setting precise mathematical models, used both in the design and computation stages of the motor parameters [4].

II. PARTICULAR REQUIREMENTS CONCERNING THE LIGHT RAILWAY TRACTION MOTOR

Thanks to the very strong dynamic regimes, the operation of the traction motor takes place in difficult working conditions [5]. For this reason, the motor must be able to carry an additional load, exceeding in some cases the average power provided by the manufacturer in the datasheet, in order to cope with the traction [6].

Particular requirements must be considered in the design and construction of the traction motor, due to its dimensions, the operation and mounting conditions [7].

The motor characteristics presenting the electromagnetic stresses at startup, at rated speed or for the speed control of the asynchronous motor must meet the high exigencies required by the complex equipment used in light railway vehicles [8]. In order to prevent an eventual motor overheat, cooling should be used [9]. The air flow needed in the cooling process is around 100-200 m^3 of air per minute.

Additional restrictions are imposed if the locomotive is equipped with an electric brake, so the motor must also operate as a generator [10], [11]. From the mechanical point of view, the motor in service is subjected to shocks and vibrations caused by the path misalignment. It may be exposed to external influences caused by the dust, strong cold, rain, snow, excessive heat in the atmosphere or produced by the earthwork [12]. A thermal analysis is also necessary in the motor design stage, as the excessive motor temperature may affect its efficiency and torque density [13]. Furthermore, the insulation of the stator windings may overheat, affecting the reliability of the traction motor. Usually, the thermal characteristics are improved by over sizing the machine. In practice, this may not always be feasible due to constraints related to the motor gauge and the cost of the materials used [14].

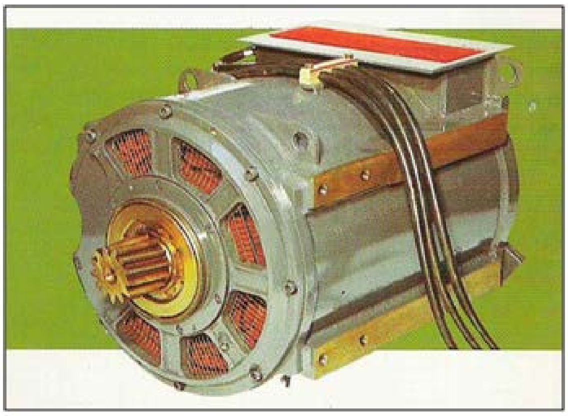


Fig. 1. The traction motor used for the light railway traction.

The solution chosen for transmitting the torque from the motor shaft to the axle's worm gear can influence the motor construction. Therefore, some torque transmission solutions require that the motor shaft should be empty. Other solutions suggest that the motor should possess support claws on the axle [15].

III. ASYNCHRONOUS MOTOR DESIGN OPTIMIZATION

A. General Considerations

Starting from the rated values, imposed by the beneficiary and detailed in Table 1, the design of an asynchronous motor with a squirrel cage rotor was carried out, according to the methodology known from the literature [16]. At this point were computed: the constructive geometrical dimensions, the electromagnetic stresses, the electrical parameters, functioning characteristics, costs, a.s.o. [17].

It is reported that the optimization of an electric motor is essentially a problem of "optimizing" the mathematical model used. So far, in order to simplify the optimization problem, linear mathematical models were used.

The increasing performances of the asynchronous motors and the assertion of new solutions is mainly due to an improvement in the characteristics of the electric materials, specifically in the area of ferromagnetic materials for the magnetic circuits, as well as for the electrical insulating materials, which can withstand high temperatures.

The mathematical model starts with an application of standard analytical design formulas, with precision levels confirmed by the literature [18]. Some particular features like the optimal thickness and shape of the conductors or the silicone sheet are selected from tables with standard values.

With dedicated tools and packages available nowadays, the solving of electrical engineering problems has become possible. New methods and algorithms for optimizing the construction of the electric motors can be developed through computer-aided engineering. The advantage of the design with Mathcad is that, after the equations are implemented, any parameter modification leads to a new motor version, with a minimum computational effort.

The restrictions imposed for certain variables in the design stage are checked after their computation, and if the restrictions are not being met, the mathematical model is redone for different values of the electromagnetic stresses and of the main geometrical dimensions. If the tolerances are exceeded for the given variables, measures must be taken [19].

The asynchronous motor construction must have in view some of the following aspects related to the traction system it is connected to [19], [20]:

- the manner it is connected to the bogie – a single motor or two motors connected in parallel;
- the insulation class of the stator windings (e.g. for class H, the maximum admissible temperature is 160 °C);
- the value of the inverter's output voltage, different by the value of the fundamental harmonic component, with a sinusoidal shape;
- the value of the overheat allowed for heavy starts, with highly variable loads, or the long starting times on ramps with high slopes;
- the value of the maximum allowed current corresponding to the maximum power in the case of two motors connected in parallel to the bogie determine a decrease of around 20% in the traction power, due to the difference in adhesion;
- the reduced weight, along with the vehicle's high speed for a given load and a high output inverter frequency lead to the utilization of a four pole motor.

TABLE I
DESIGN PARAMETERS OF THE TRACTION MOTOR

Parameter	Value
Rated Power P_N [kW]	430
Rated Voltage U_N [V]	1,016
Rated Current I_N [A]	239
Rated Speed n_N [r.p.m]	2,691
Rated Frequency f_1 [Hz]	91
Rated Efficiency η_N [%]	0.948

B. Objective Function Setting

In practice, a motor with a given power, operating under required conditions, can be manufactured in different ways, different in the dimensions of the active parts, in the values of the electromagnetic stresses, through the consumption of the active materials a.s.o. [21] The purpose of the optimization is to choose, from the set of proposed solutions, the best one with respect to a well defined criterion.

The criterion established in the design stage for the optimum asynchronous traction motor, used in driving a light train for transporting passengers, is m_m – the maximum torque, established as the objective function:

$$m_m = \frac{1}{2 \times c_1} \frac{m_1 \times p}{2 \times \pi \times f_1} \frac{U_1^2}{R_1 + \sqrt{R_1^2 + \left(X_1 + c_1 \times X_2'\right)^2}} \qquad (1)$$

where m_1 is the starting torque; p is the number of pole pairs; U_1 is the supply voltage; f_1 is the synchronous frequency; R_1, X_1, are the stator resistance and reactance, respectively; X_2' is the rotor resistance with respect to the stator and c_1 is a complex coefficient with the absolute value slightly higher than one.

The determination of the optimum solution is reduced to computing the maximum value of the objective function [22], [23].

The restrictions of the objective function are determined by the conditions imposed to the asynchronous traction motor, by the equipment on which it is mounted on and by the conditions specific to their design, respectively [24].

An important quantity for the construction and operation of the electric motors is their total cost, defined as:

$$c_t = c_f + c_e \qquad (2)$$

where c_f is the manufacturing cost and c_e is the energy losses cost for the motor in service.

The cost of the energy losses, c_e, is determined with:

$$c_e = n_{hours} \cdot c_{el} \cdot t_{ri} \cdot \sum p \qquad (3)$$

where: n_{hours} - number of motor operating hours / year;

c_{el} - the cost of a kWh of electric energy;

t_{ri} - the time for recovering the investment;

Σp - the total losses experienced by the motor.

The manufacturing and operating costs were calculated having as landmark the costs of the used materials.

The independent variables are having a greater weight in the motor design process and in the objective function expression, and their limits are set with respect to the guidelines provided by the standards [25]. As main (independent) variables are considered the electric and magnetic quantities, varying in a narrow range of values for a wide range of motors [26].

Restrictions on the variables are determined by the gauge dimensions imposed to the motor, by the manufacturing and operation cost, and also by limitations concerning the losses that may occur in the motor due to electromagnetic stresses, in order to not exceed the maximum admissible temperatures corresponding to the insulation class:

$$x_{p\,min} \le x_p \le x_{p\,max} \qquad (4)$$

IV. Simulations and Graphical Representations

The main objective of the computer-aided design is to optimally provide the model of an asynchronous motor rotating the drive wheel of the locomotive. The motor volume is constrained by the small space available inside the vehicle and should operate at high speeds, resulting in the choice of a motor with few magnetic pole pairs.

In order to highlight the aspects corresponding to the plots presented below, with complex shapes and harder to explain analytically, the particular case of the designed asynchronous motor was considered. All of these preconditions represent the starting point for the optimal design that follows.

The designed motor must present superior power efficiency, as the electric braking might be regenerative until the train stops and the energy dissipation over the braking resistances might be small. The asynchronous motor should exhibit insignificant losses and no thermal problems. The higher efficiency can also be obtained from overall system improvements, such as intense utilization of an energy management system and the implementation of adjustable speed drives.

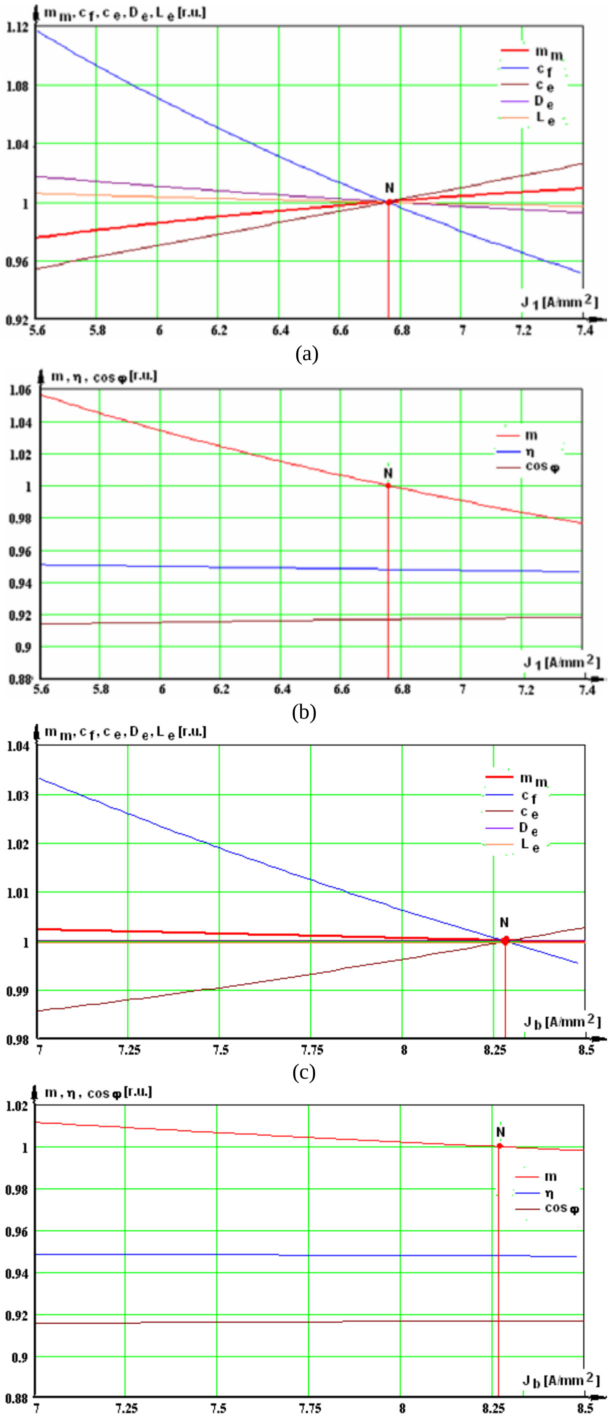
An analysis of the motor's optimal design is done, depending on the independent variables, and some plots are drawn in the following figures. These are: the electrical quantities: the current densities in the stator/rotor windings $J_{1/b}$ [A/m^2] (Fig. 2); the magnetic quantities: the magnetic field density in the air gap B [T]; the magnetic field densities in the stator/rotor yokes $B_{j1/2}$ [T] (Fig. 3); the geometrical dimensions: the motor air gap δ [mm]; the isthmus dimensions for the stator slot b_{01}, h_{01} [m]; the form factor of the stator slot β_{c1}, the isthmus dimensions for the rotor slot b_{02}, h_{02} [m].

The study performed and further presented considered for each analyzed variable a variation between -30% and +15%, respectively, as compared to the known reference value.

In the next graphical representations one may observe the variation plots for the maximum torque (the optimization criteria considers the maximum torque) and other important quantities for the manufacturing and operation, considering the imposed restrictions. These are provided as per unit quantities, because they can be easier compared with the reference values of the motor in service at present.

The considered quantities are: m_m – the maximum torque (thick red line), c_f – the manufacturing cost (blue), c_e – the operation cost (brown), D_e – the outer diameter (magenta), L_e – the total length (light brown), m – the total weight (red), η – the efficiency (blue), cos φ – the power factor (brown).

A. *The main variables: the electrical stresses*



(a)

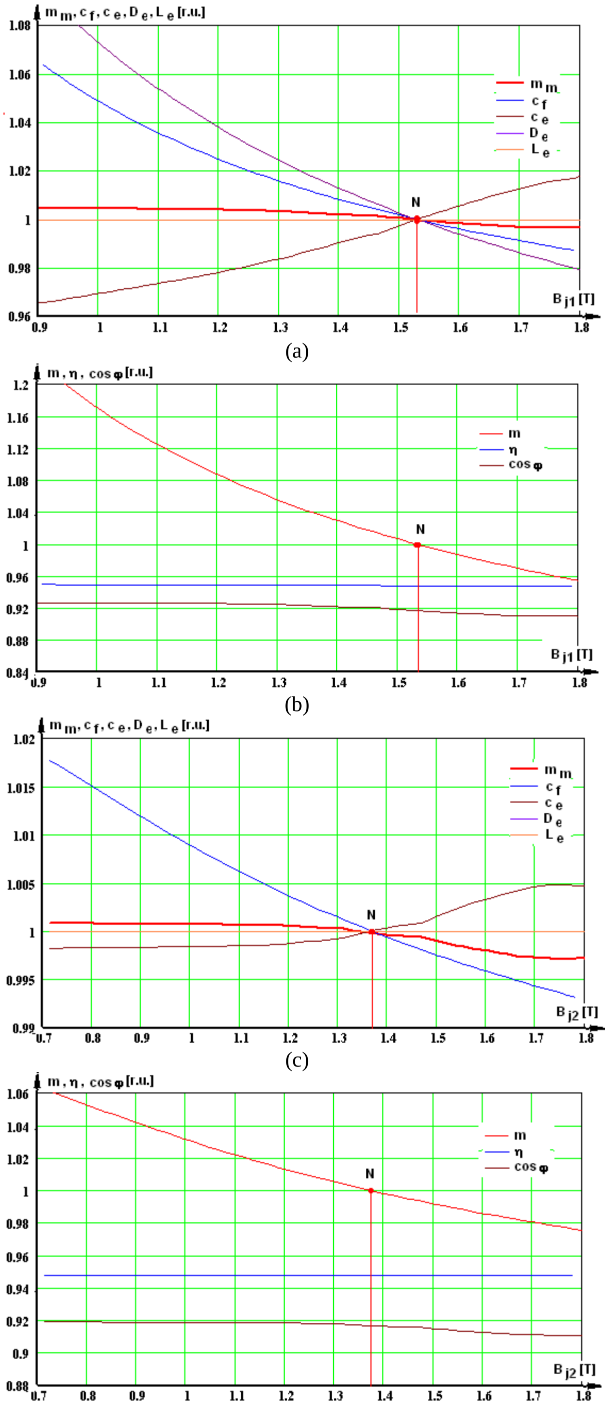
(b)

(c)

(d)

Fig. 2. The variation curves with respect to the main variable J_1 – the stator current density (a, b) and the main variable J_b - the current density in the rotor bar (c, d) for: m_m – the maximum torque, c_f – the manufacturing cost, c_e – the operating cost, D_e, L_e – the gauge dimensions; m–the motor weight, η efficiency, cosφ- the power factor.

B. The main variables: the magnetic stresses



(a)

(b)

(c)

(d)

Fig. 3. The variation curves with respect to the main variable B_{j1} – the magnetic field density in the stator yoke (a,b) and the main variable B_{j2} – the magnetic field density in the rotor yoke (c,d) for: m_m – the maximum torque, c_f – the manufacturing cost, c_e – the operation cost, D_e, L_e – the gague dimensions; m – the motor weight, η - the efficiency, cosφ - the power factor.

The motor is supplied by a static converter and is operating in the constant magnetic flux region with a constant voltage / frequency ratio from $U \approx 0/f_1 \approx 0$ up to U_1=1200V/f_1=91Hz. Afterwards, the motor has to operate in the flux weakening region, with U_1=1200 V and f_1= (91÷143) Hz.

In general, in order to obtain the per unit values, the equations are written as follows:

$$C_f = \frac{C_{f.var.mot}}{C_{f.m}} \tag{5}$$

where: $C_{f.var.mot}$ is the manufacturing cost for the analyzed motor version and $C_{f.\,m}$ is the manufacturing cost for the motor considered as reference.

In Fig. 4 are plotted the other main variables with respect to the magnetic field density in the air gap, B. Fig. 5 depicts the evolution of the other variables with the motor’s air gap, δ.

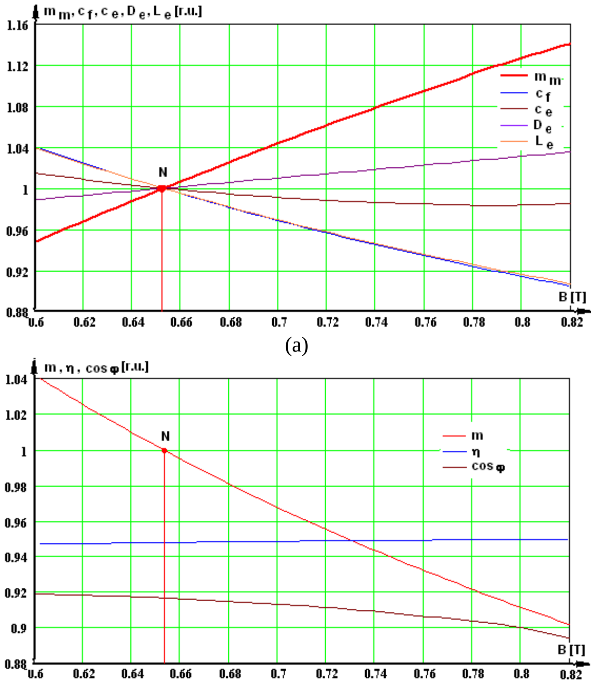
In Fig. 6 are depicted the variation curves with respect to the form factor of the stator slot, β_{c1}.

Fig. 7 and Fig. 8 depict the variation of the main variables with the isthmus height at the stator and rotor slots: h_{01} and h_{02}.

In Fig. 9 is presented the variation of the main variables with the isthmus width at the rotor slot, b_{02}.

Through the analysis of these plots were identified the important variables that can lead to an increase in the maximum torque. This condition was imposed by the optimization and is analytically given by the objective function. The restrictive conditions imposed are the motor’s gauge dimensions.

The simulation results presented below consider the optimized asynchronous traction motor, with the following rated values: power P_N= 430 kW, voltage U_N= 1,016 V, frequency f_1 = 91 Hz, speed n_1= 2,691 rpm, per unit torque m_{mi} =M_m/M_N> 2.1, overload capability.

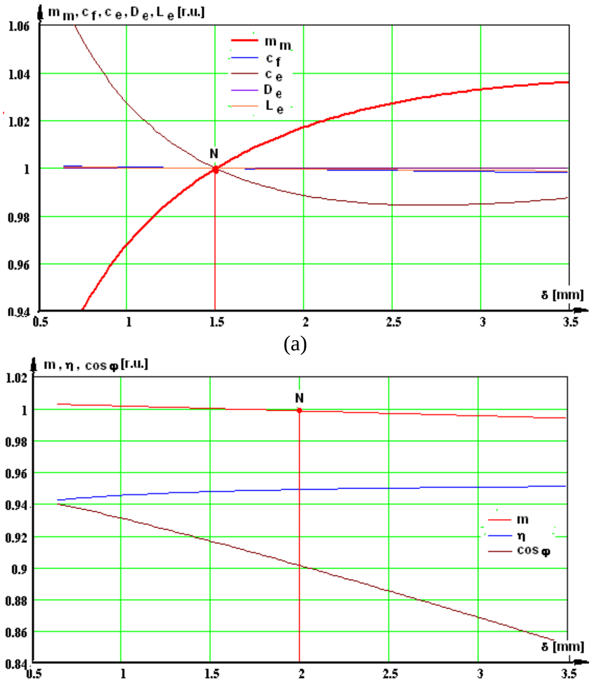


(a)

(b)

Fig. 4. The variation curves with respect to the main variable B (the magnetic field density in the air gap) for: a) m_m – the maximum torque, c_f – the manufacturing cost, c_e – the operation cost, D_e, L_e – the gauge dimensions; b) m –the motor weight, η - the efficiency, cosφ - the power factor.

C. The main variables: the constructive dimensions

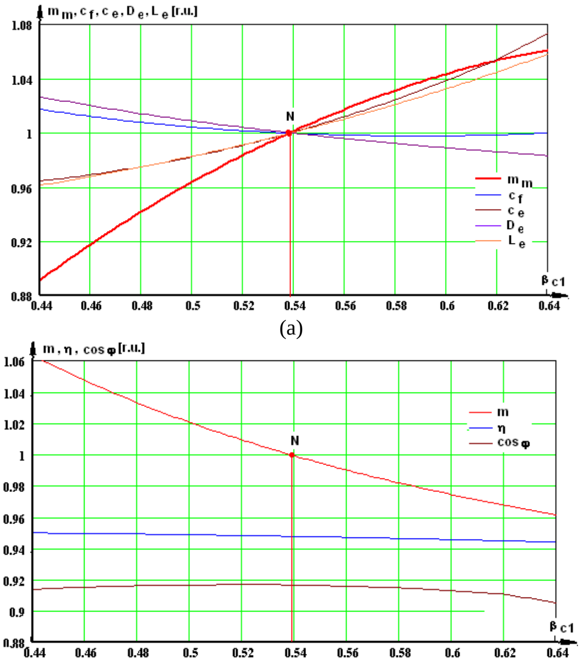


(b)

Fig. 5. The variation curves with respect to the main variable δ – the motor’s air gap for: a) mm – the maximum torque, cf – the manufacturing cost, ce the operating cost, De, Le - gauge dimensions; b) m – the motor’s weight, η - the efficiency, cosφ - the power factor

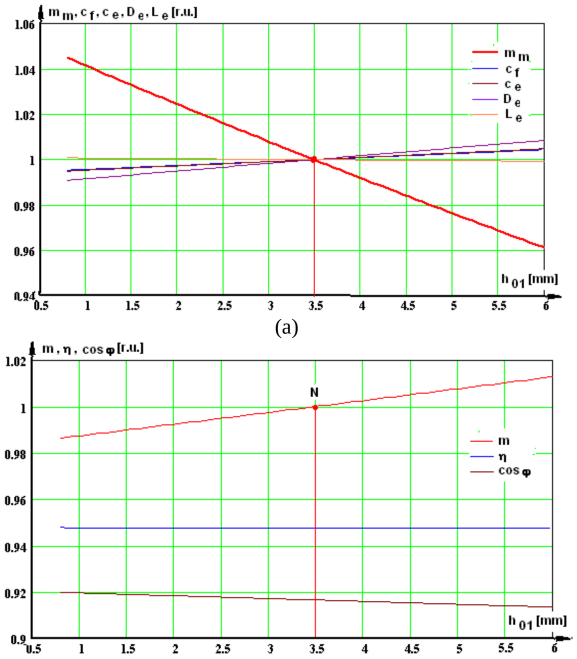
All of the subsequent graphical representations are provided as per unit (p.u.) quantities. The per unit quantities plotted in Figs. 8÷13 are:

D. Constructive data of the stator slot



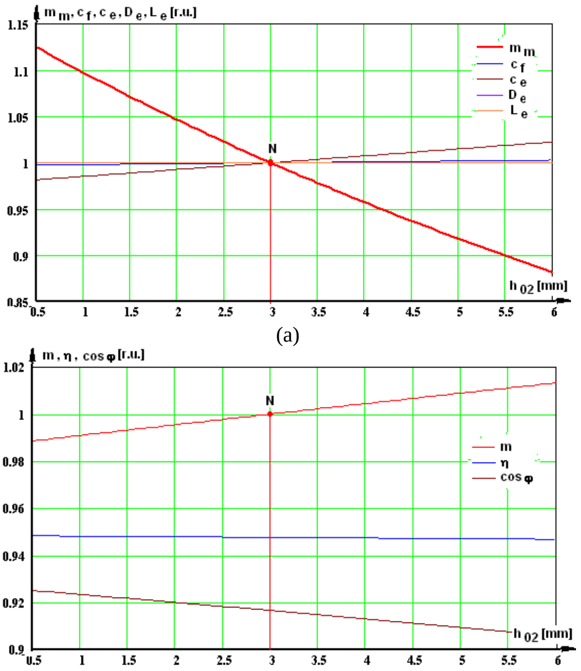
(b)

Fig. 6. The variation curves with respect to the main variable β_{c1} – the form factor of the stator slot for: m_m – the maximum torque, c_f – the manufacturing cost, c_e – the operation cost, D_e, L_e – gauge dimensions; m – the motor weight, η - the efficiency, cosφ - power factor.



(b)

Fig. 7. The variation curves with respect to the main variable h_{01} – the height of the isthmus at the stator slot for: m_m – the maximum torque, c_f – the manufacturing cost, c_e – the operation cost, D_e, L_e – gauge dimensions; m – the motor weight, η - the efficiency, cosφ - power factor



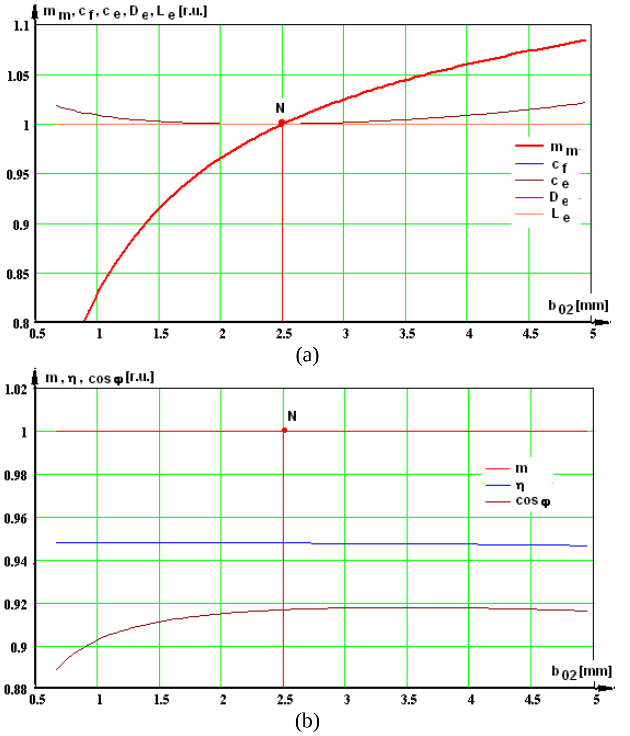
(b)

Fig. 8. The variation curves with respect to the main variable h_{02} – the height of the isthmus at the rotor slot for: m_m – the maximum torque, c_f – the manufacturing cost, c_e – the operations cost, D_e, L_e –gauge dimensions; m –motor weight, η - the efficiency, cosφ - power factor.

- s - rotor slip;
- $r_{2\zeta}=R_{2\zeta}/R_2$ – per unit value of the rotor winding resistance; $R_{2\zeta}$, R_2 – resistance values with and without the repression influence;

- $x_{2\zeta}=X_{2\zeta}/X_2$ – per unit value of the rotor winding reactance and $x_{1s}=X_{1s}/X_1$ - per unit value of the stator winding reactance when the magnetic saturation is consider;

E. Constructive data of the rotor slot



(a)

(b)

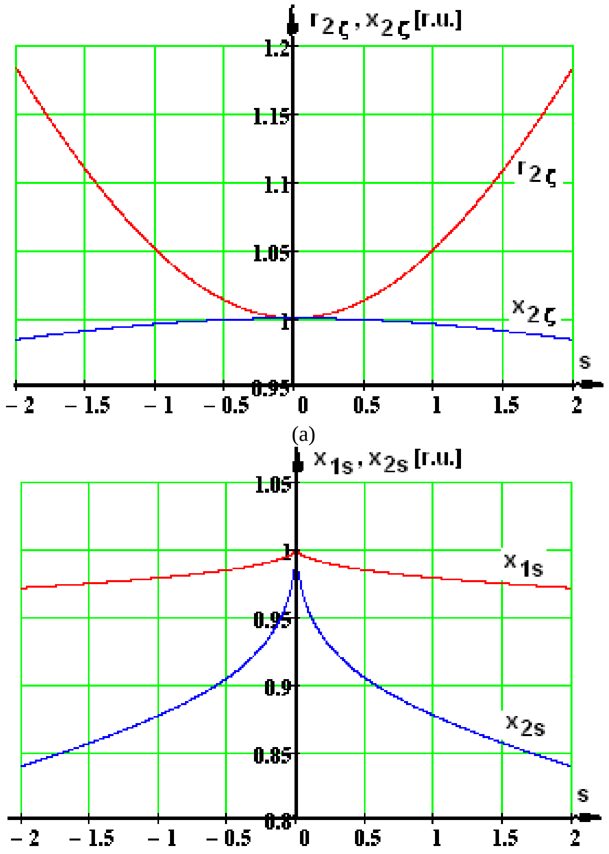
Fig. 9. The variation curves with respect to the main variable b_{02} – the width of the isthmus at the rotor slot for: m_m – the maximum torque, c_f – the manufacturing cost, c_e – the operations cost, D_e, L_e – the gauge dimensions; m – the motor weight, η - the efficiency, cosφ - power factor.

- $x_{2s}=X_{2s}/X_2$ – per unit value of the rotor winding reactance when both the repression and magnetic saturation are considered;
- $m=M(R_{2\zeta}, X_{1s}, X_{2s})/M_N$ – per unit torque;
- $M(R_{2\zeta}, X_{1s}, X_{2s})$, M - the real electromagnetic torque calculated considering the influence of the repression and magnetic saturation, and the torque obtained without considering the two influences, respectively;
- $n_r=n/n_1$ – per unit speed;
- $i_1=I_1/I_{1N}$ – per unit value of the stator current.

A detailed analysis is realized, considering the influence of the two factors (the repression and the magnetic saturation) over the motor parameters, and also over the mechanical characteristics.

In Fig. 10, the cumulated effects of the repression and the magnetic saturation over the stator and rotor reactances may be noticed.

In Fig. 11 are presented the known operating characteristics, required for simulating the asynchronous motor in service: the speed n, the active power received from the supply network p_1, the stator current i_1, the efficiency η, the power factor cosφ. The characteristics are calculated as per unit values for the rated voltage and frequency. One may notice that, in the working area, in the frequency range (0.5 – 1)*P_N, the motor has a very high efficiency and power factor, a good aspect in the design process. Fig. 12 depicts the current locus for the analyzed synchronous motor, the plots considering variable parameters, when the repression and magnetic saturation are taken into account (the blue curve) and when the parameters are constant, respectively (the red curve).



(a)

(b)

Fig. 10. The variation curves of the asynchronous motor parameters: a) with current repression; b) with magnetic saturation.

Analyzing these figures, a starting current of I_p=1,108 A resulted, and in per unit $i_p=I_p/I_N$=1108/243=4.55.

In Fig. 13 is presented the mechanical characteristic computed correctly (1st curve) and the simplified one (2nd curve, without repression and magnetic saturation).

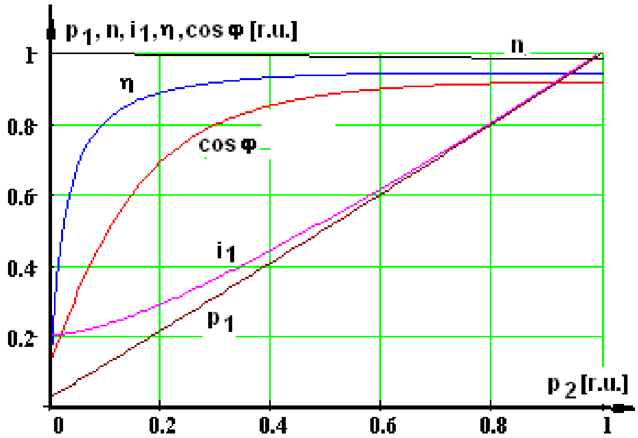


Fig.11. Operating characteristics of the optimized asynchronous motor with respect to the load: p_1–received active power; i_1- current; n –speed; cosφ – power factor; η - efficiency.

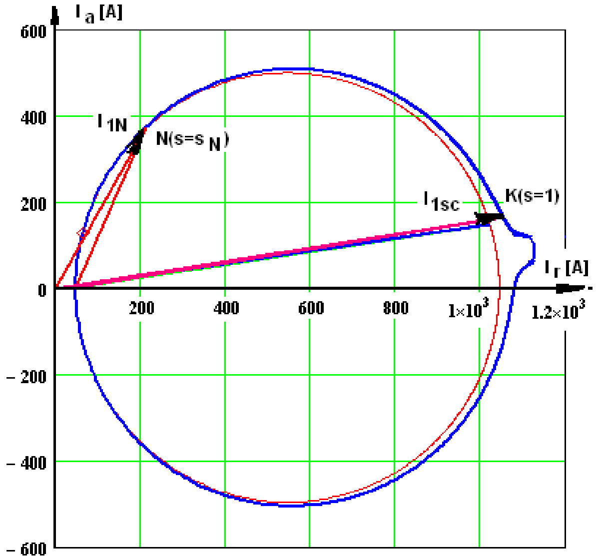


Fig.12. Current diagram for the optimized asynchronous motor.

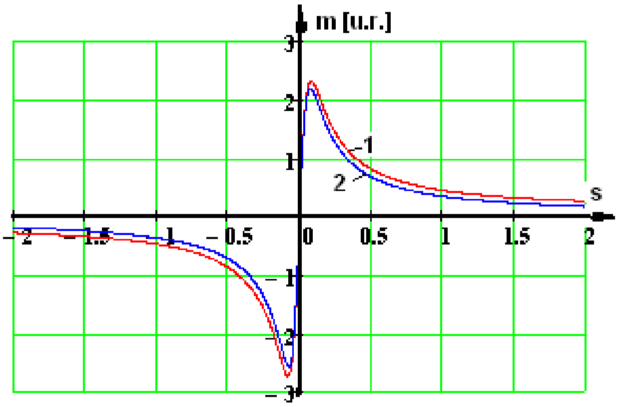


Fig. 13. Mechanical characteristics: 1-the real one; 2- simplified calculation without repression and magnetic saturation.

In Fig. 14 is depicted the natural mechanical characteristic used for the electric traction, also presenting the area where the motor is operating as a generator (the area with regenerative braking).

The neglecting of the repression and magnetic saturation effects determines errors in establishing the maximum torque (the optimization criterion aimed).

The real maximum torque (variable parameters are considered) is higher then the one usually computed with:

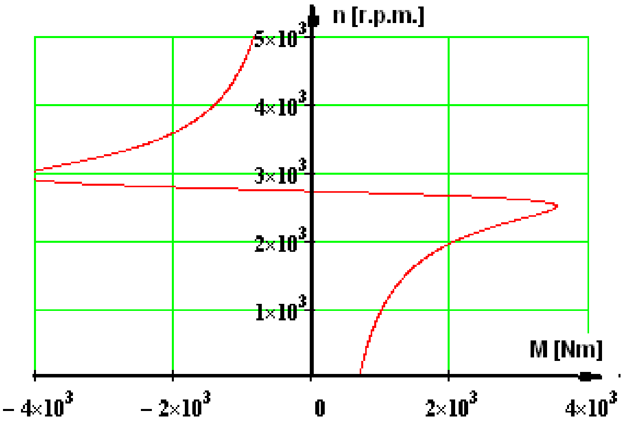


Fig. 14. Natural mechanical characteristic of the optimized motor.

$$\Delta m_m=100*(M_{m.1}-M_{m.2})/M_N=(3542-3357)/1527=12.1\%$$

In Fig. 15, one may notice the evolution of the losses in the motor operating region in per unit values, where:

- $p_{Cu1}=P_{Cu1}/\Sigma P_N$ - per unit value of the stator lossses;
- $p_{Fe}=P_{Fe}/\Sigma P_N$ - per unit value of iron losses;
- $\Sigma p=\Sigma P/\Sigma P_N$ - per unit value of the total losses.

A visible increase in the copper losses is visible when the motor load increases.

In Table II are summarized different optimization options, starting from the existent motor, and imposing the condition that the least number of constructive modifications is done. The following possibilities were identified:

- only the geometry of the stator slot is modified, resulting in an increase of the maximum reported torque, up to m_m=2.337 N·m;
- only the geometry of the rotor slot is modified, resulting in an increase of the maximum reported torque, up to m_m=2.423 N·m;
- both the rotor and stator geometries are modified, resulting a maximum torque of 2.526 N·m;

TABLE II
MOTOR OPTIMIZATION ALTERNATIVES

	Real motor version	The optimized motor version with respect to the geometry of the stator slot	The optimized motor version with respect to the geometry of the rotor slot	The optimized motor version with respect to the geometries of stator and rotor slots
m_m (u.r.)	2.196	2.337	2.423	2.526
C_f (€)	22010	21940	21920	21570
C_e (€)	78130	81600	77860	76510
m (kg)	890.8	861.1	875.8	878.6
η	0.948	0.945	0.948	0.950
cosφ	0.917	0.913	0.921	0.910
Variables used for the optimization		**β_{c1}=0.61, b_{01}=10.5 mm h_{01}= 2.5 mm**	**β_{c2}=2.1, b_{02}=3.5 mm, h_{02}= 2.0 mm**	**β_{c1}=0.615, b_{01}=10.5 mm, h_{01}= 2.35 mm β_{c2}=2.23, b_{02}=3.25 mm, h_{02}= 2.24 mm**

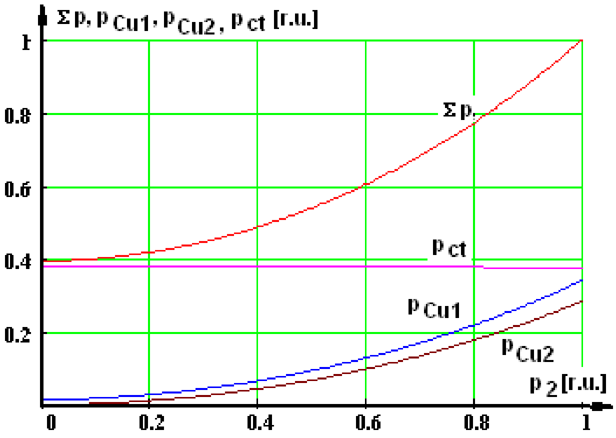


Fig.15. The variation curves of the motor losses while carrying a load: Σp- total losses, p_{Cu1}, p_{Cu2} - losses in the stator and rotor windings, p_{Fe} - iron losses.

CONCLUSIONS

The importance of this research is proven by highlighting some aspects insufficiently treated in the areas of modeling and simulation of light traction asynchronous traction motors, used in railway applications.

The work presented in the paper provides an optimization of the design of a squirrel cage asynchronous motor, aimed for rotating the worm gear of the driving wheel of a locomotive.

The optimization criteria considered for the optimum motor version may vary from one design stage to the other, depending on several factors related to the manufacturing process, to the characteristics of the electrotechnic materials used, the working conditions a.s.o.

Through the optimization, one at a time, of the stator and rotor geometries, each time a cheaper and smaller motor resulted. Optimizing both the stator and rotor geometries, an even better motor version resulted, fully validating the proposed algorithm.

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Contribution of authors:

First author – 40%

First coauthor – 30%

Second coauthor –25%

Third coauthor –5%

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