Transversal Shape Optimization of a Brushless DC Motor for Electric Vehicles

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Abstract – **The opportunity of this research is to emphasize certain approaches related to the design and modeling of low and medium power permanent magnet brushless DC motors for electric vehicles, which are presently poorly treated. The challenge of any manufacturer is to develop electric machines with minimum manufacture and maintenance costs by accomplishing the performance required by the customer. One looks for mathematical models as exact as possible as tools for the design and parameter computation. As a consequence of the progress of control and power electronics, the performances of brushless DC motors have been improved. Therefore, the problems of optimal design and optimal operating mode of such motors are currently reported by the technical literature. By exploiting the available numerical computation tools, we developed the optimized technical design of a brushless DC motor for an electric bicycle. The performed simulations emphasize the technical performances which accomplish the customer requirements as follows: manufacture cost reduction of 27.9%, total cost reduction of 9.11% and a slightly growth of the maintenance cost of 8.01%. It is advisable to do a periodical optimal re-design, which will take into account new performant electrotechnical materials with adequate technologies, in order to decrease the fabrication cost and to increase the energy efficiency of brushless direct current motors. The optimized motor achieves the required overall size.**

Keywords: *brushless DC motors for small electric vehicles, optimization, simulation.*

I. INTRODUCTION

There are many researches in the world concerning the brushless DC motors (BLDCM), and some results are emphasized in the references below. It is investigated their application to electric vehicles – passenger cars and trucks.

The performed studies prove that the permanent magnet direct current motors build according to the technological solution “without brushes” are recommended to drive small vehicles (as scooters, bicycles, wheelchairs for disabled persons, etc.), as well as other passenger cars. A permanent interest is observed in the progress of the CAD tools for electrical engineering, and developing novel optimization methods of electrical machines [1], [3], [5-7].

The technical project is based on the optimization design of the BLDCM used to drive directly the well of the small vehicle, passenger car or truck.

The optimization of electric machines is presently very actual because of the huge expenses involved in the manufacture and maintenance area [3], [7-10], [14].

One recommends the finite element based methods to complete the optimal constructive solution of the PMDCM due to some of advantages, as follows:

- some important quantities as the magnetic flux, magnetic flux density, induced voltages are computed or assessed more precisely;

- the performances of the designed motors are verified prior to the manufacture.

Our research team aims on a continuous improvement of the technical project of BLDCM through:

- upgrading of specific mechanical technologies in the manufacture of electrical machines, as: general metalworking, punching of silicon steel sheets, metalworking of electrical contacts, assembling and quality control;

- identifying of solutions for economy of materials and energy in the manufacture process.

Periodic re-designs based on optimization tools to consider using performance materials and adequate technologies lead towards rising of power density and efficiency of BLDCM.

The characteristics for steady state and dynamic behavior [11], [14], the price, overall dimensions, noise level, reliability must accomplish the restricted requirements specific to the vehicles.

II. DESIGN OF BLDCM

A. Opportunity of the subject: Brushless DC motors for electric vehicles

The manufacture of performance small vehicles for passengers, driven by brushless DC motors, was not possible without laborious research whose main goals were targeted on finding new materials, developing novel modeling principles and using the power and control electronics to improve the efficiency of the power conversion delivered by the battery.

Such motors (fig. 1) are used for the direct drive of the driven wheels of a small electric vehicle: scooter (fig. 1.a) [18], bicycle (fig. 1.b) [19], electric moped (fig. 1.c) [20], electric motorcycle (fig. 1.d) [21], wheelchair for disabled persons, etc.

a)

b)

c) d)

Fig. 1. Two wheel small vehicles for passengers: a) electric scooter; b) electric bicycle; c) electric moped; d) electric motorcycle.

The proposed constructive solution consists in a *bipolar supplied brushless direct current motor*. This means that the three phase floating-neutral star-connected windings are located on the stator, concentrated on teeth and connected in series.

To build such a winding the technology could be simplified and automatically processed using performance winding machines.

The windings concentrated on teeth have many advantages, but they are closely linked with the number of slots and poles. One of the main advantages consists in a significant reduction of winding front ends, with economy at materials and copper losses [7], [11].

For star-connected phase windings, the permanent magnets are located on a circle arc of 180^o, while the winding currents are rectangular for 120^o electric degrees.

Particular for this constructive solution is that two phases always active, while the third remains in no-load, so that the winding copper is exploited very efficient. As consequence, the structure of the control circuit could allow recovering the reactive power.

The adopted ingress protection IP44 allows placing the motor directly in the wheel hub. This confers robustness, shockproof, invulnerability to vibrations and to weather phenomena. The modular case allows an easy and quick disassembly of the motor.

We adopt the constructive solution with the inductor (rotor) placed at exterior, with parallelepiped-shape permanent magnets sealed at the interior surface of a cylinder. The stator is at interior with the winding placed in semi-closed slots. One uses rare earth permanent magnets [4], [16-17], type NeFeB (neodymium, iron, boron) having high values of remanent flux density, coercive magnetic fields and magnetic field energy.

B. Optimization criterion

The optimal design targets mainly the criterion C_t – total cost (manufacturing and maintenance). This criterion depends, from one stage to another, on many aspects linked to the manufacturing and operating processes, on characteristics and costs of materials, etc.

As consequence, we used for optimization the *target function:*

$$f(\bar{x}) = C_t = C_f + C_e \tag{1}$$

where: C_f – is the manufacturing cost, and C_e – is the operating (maintenance) cost.

C. Establishing the optimal point

Optimizing means choosing a target, and then establishing a mathematical numerical method that allows finding the combination of variables to reach the proposed target. Therefore, one obtains the "optimal motor" which accomplishes the rated parameters and the restrictions required by the customer.

This combination of variables is the solution of the optimization problem, i.e. the optimal motor accomplishes the requirements related to the operation in steady state and dynamic conditions.

The simplest optimization method (explorative method), involves searching the optimum for each variable of interest [2], [4], [11], [13-14]. With this method the minimization of the target function $f(x)=C_t$, depends by the following variables:

$$C_t = f(A, J_a, B, B_d, B_{ja}, D, \delta) \tag{2}$$

Seven variables were chosen for optimization: A – current load, J_a – current density of armature winding, B – magnetic flux density in the airgap, B_d, B_{ja} – magnetic flux densities in the tooth / induced core yoke, D – motor diameter, δ – airgap length.

To reduce the searching area, and the power losses one has the restrictions:

$$x_{\min_i} \le x_i \le x_{\max_i}$$
$$x_i = \{A, J_a, B, B_d, B_{ja}, D, \delta\} \tag{3}$$

The searching step for each variable x_i will be computed with:

$$\Delta x = \frac{x_{\max} - x_{\min}}{n_x} \tag{4}$$

where n_x is the number of points on the assumed searching way.

III. Results, Simulations and Conclusions

One performs a technical and economic analysis of the BLDCM used to drive an electric bicycle. The rated parameters are power P_N = 800 W, voltage U_N = 30 V, current I_N=28.3 A, speed n_N = 350 r.p.m.

Using the known design procedure, the main dimension were found: D_e = 208.2 mm – exterior diameter, L_e = 79.6 mm – total length, D = 180 mm – motor diameter, l_{Fe} = 40.2 mm – ferromagnetic core length, δ = 0.25 mm – airgap length, N_c = 27 cr. – number of slots of the induced circuit, cylindrical iron case, $2p$ = 30 poles (permanent magnets) sealed at the inner side, m = 7.57 kg – motor weight, η = 0.828 - efficiency, $C_{f.}$ = 182.2 € – manufacturing cost, C_e = 149.3 € – maintenance cost, C_t = 331.5 € – total cost.

The manufacture and maintenance costs were computed using the available documentation [11-13].

A. Transversal shape optimization

This method leads to reduce the total cost for an imposed or existing gauge [13-14]. The extensive method, which means oversizing the motor to increase the efficiency, does not lead always to satisfactory results. Any combination of parameters that leads to efficiency increasing without additional costs comes closer to the optimal transversal shape.

The transversal shape of the motor results by pairing, the geometrical dimensions of a stator core sheet with those of a rotor core sheet. The pair for which the total cost C_t is minimum represents the chosen optimal solution. There is an opposite pair for which the total cost is maximum, this being the most unfavorable solution.

The optimal design software tool could provide both extreme solutions, useful for a complete analysis.

The optimization was performed by considering:

- the main variables: A, J_a, B, B_d, B_{ja}, D, δ;
- the rated parameters and overall dimensions of the example motor $D_e = 210$ mm, $L_e = 85.0$ mm.

The optimization of the transversal shape related to the defined variables could involve changes which harm the rated parameters of the motor.

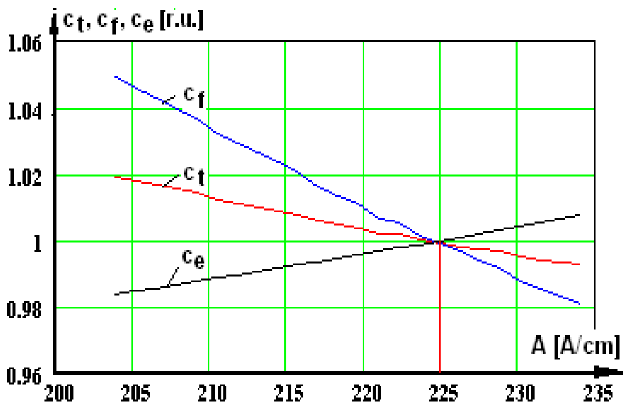
Therefore, to preserve the rated input parameters (power, voltage, speed), the mathematical model has the possibilities as follows:

- to modify the length of the magnetic core (so that the total length does not exceed the imposed limit value), to preserve the main flux;
- to modify the magnetic flux density in the rotor yoke to keep the imposed exterior diameter;
- to modify the thickness of the permanent magnet related to the computed magnetic force;
- to modify the number of conductors in one slot;
- to modify the dimensions of the slot of stator (induced circuit);
- to modify the inner diameter of the motor.

In fig. 2.a,.., fig.2.g the main costs targeted by the optimization of the transversal shape of BLDCM are shown. They are: c_t – total cost, c_f – manufacture cost, c_e – maintenance cost, the ratios being computed as follows:

$$c_t = \frac{C_{t.var.mot}}{C_t} \qquad c_f = \frac{C_{f.var.mot}}{C_f} \qquad c_e = \frac{C_{e.var.mot}}{C_e} \qquad (5)$$

$C_{f.var.mot}$ – manufacture cost for the studied motor; C_f – manufacture cost of a reference motor.



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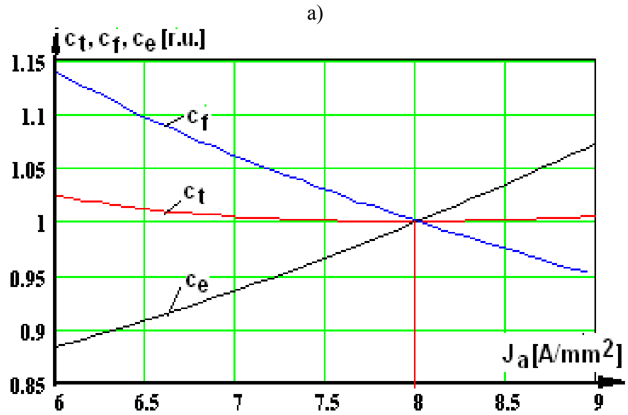

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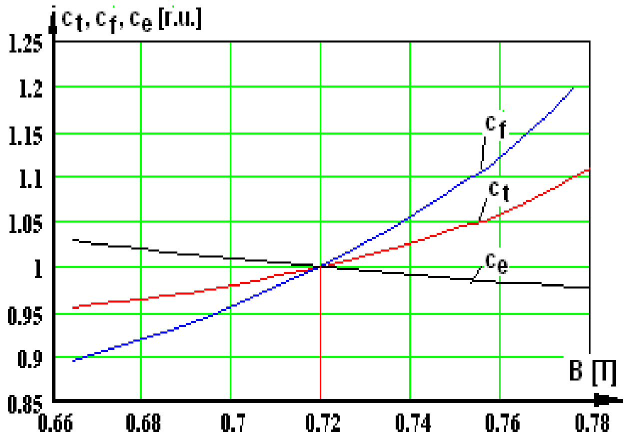

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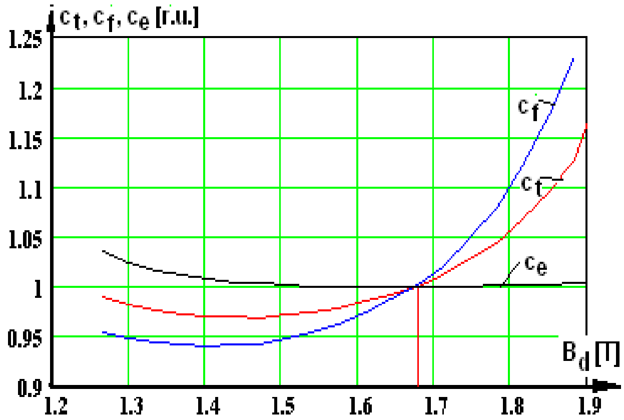

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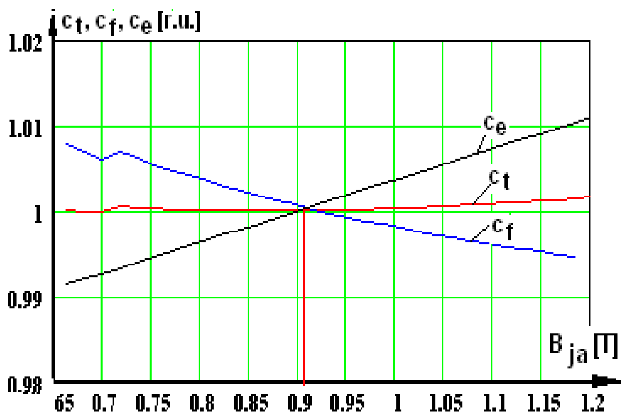

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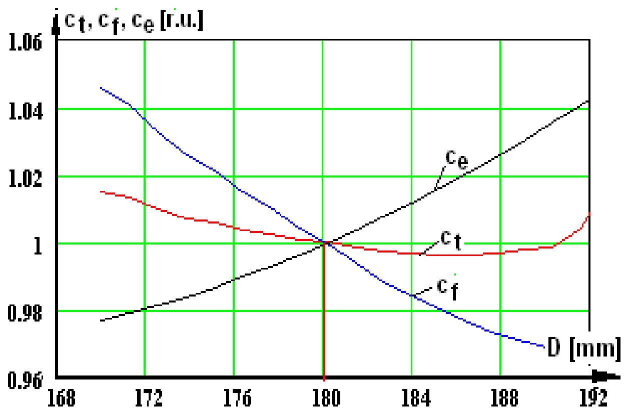

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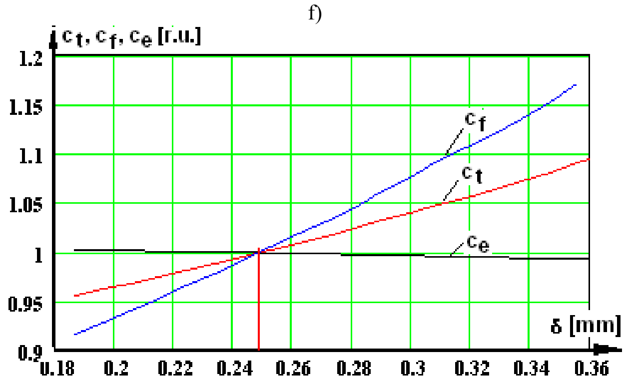


g)

Fig. 2. Variation curves of c_t, c_f, c_e – total- manufacture- and maintenance costs with respect to the main variables: a) A - current load, b) J_a – current density in the induced core, c), d), e) B, B_d, B_{ja}, -magnetic flux densities in airgap, tooth and yoke of induced circuit, f) D – motor diameter, g) δ -airgap.

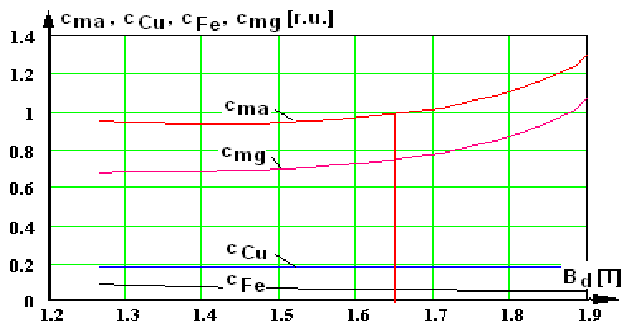
By analyzing these figures one can establish the most weighted variables in the optimization of the transversal shape of BLDCM. The results are given in table no.1 for all three main costs, expressed in percent for each variable.

Table no. 1

Studied cost	Variable and growth %						
Total cost	B_d 19.2%	B 15.2%	δ 13.9%	A 3.1%	J_a 2.5%	D 1.9%	B_{ja} 0.2%
Manufacture cost	B_d 32.3%	B 31.1%	δ 25.1%	J_a 19.2%	D 8.1%	A 6.9%	B_{ja} 1.2%
Maintenance cost	J_a 19.5%	D 6.2%	B 5.8%	B_d 4.1%	A 2.4%	B_{ja} 2.1%	δ 1.5%

Let us define the cost of used active materials as follows:

$$C_{ma} = C_{Fe} + C_{Cu} + C_{mg} \tag{6}$$



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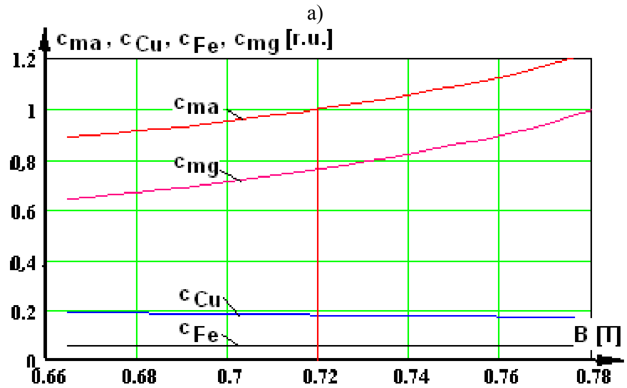

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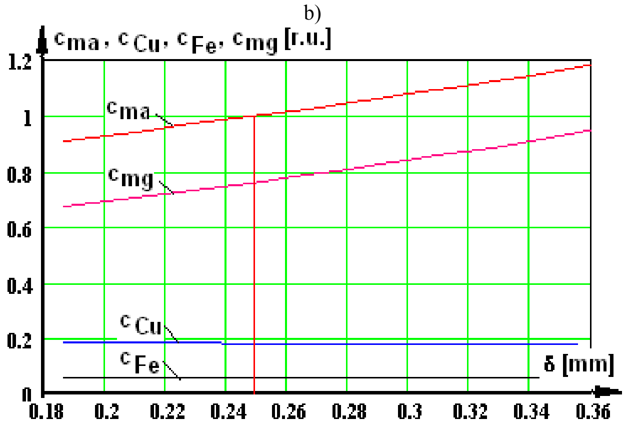

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Fig.3. Variation curves of c_{ma}, c_{Cu}, c_{Fe}, c_{mg} – active material costs: copper, iron, magnet with respect to: a) B_d – magnetic flux density in tooth, b) B – magnetic flux density in airgap, c) δ – airgap length.

C_{Fe} , C_{Cu}, C_{mg} – costs of iron, copper and magnet.

For the first three variables (B_d – magnetic flux density in tooth, B – magnetic flux density in airgap and δ - aigap) which are the most weighted in the optimization of the total cost, a deeper study will be performed.

The research results are shown in fig. 3, where the simulations reveal the evolution of the costs for the active materials. The relative values were computed as follows

$$c_{Fe} = \frac{C_{Fe}}{C_{ma.m}} \quad c_{Cu} = \frac{C_{Cu}}{C_{ma.m}} \quad c_{mg} = \frac{C_{mg}}{C_{ma.m}} \tag{7}$$

C_{Fe} – iron cost for the studied motor; $C_{ma.m}$ – iron cost for a reference motor.

B.Technical and economic performances

Table no. 2 shows analyzes results of technical and economic performances for two relevant versions of motors.

By studying the results of table no. 2, one remarks that at the optimized motor the manufacture cost is much smaller with 27.9% and a slight growth of the maintenance cost with 8.01%.

Because the manufacture cost is more weighted, it results a reduction of the total cost with 9.11%.

The optimized motor accomplishes the required overall dimensions, its weight results 8.69% higher, meaning a higher consumption of active materials.

The developed optimal design software allows the data transfer towards another dedicated program to perform the design drawings of the studied motor, e.g. longitudinal and transversal cross section, manufacturing details of some parts (e.g. stator subassembly, rotor subassembly, stator silicon steel sheet, etc.).

Table no.2

	C_t (E)	C_f (E)	C_e (E)	m (kg)	m_{Cu} (kg)	m_{Fe} (kg)	η	D_e (mm)	L_e (mm)
Optimal motor	303.8	142.5	161.3	7.75	1.033	2.752	0.817	210	82.4
Real motor	331.5	182.2	149.3	7.57	0.916	2.531	0.828	208.2	79.6

These drawings Fig.4,…, Fig.7 are very useful in technology design to build the programs for computer numerical control machines, to plan the manufacture technological process, etc.

By analyzing these drawings, the designer or manufacturer can detect technical or technological problems in order to perform the required corrections.

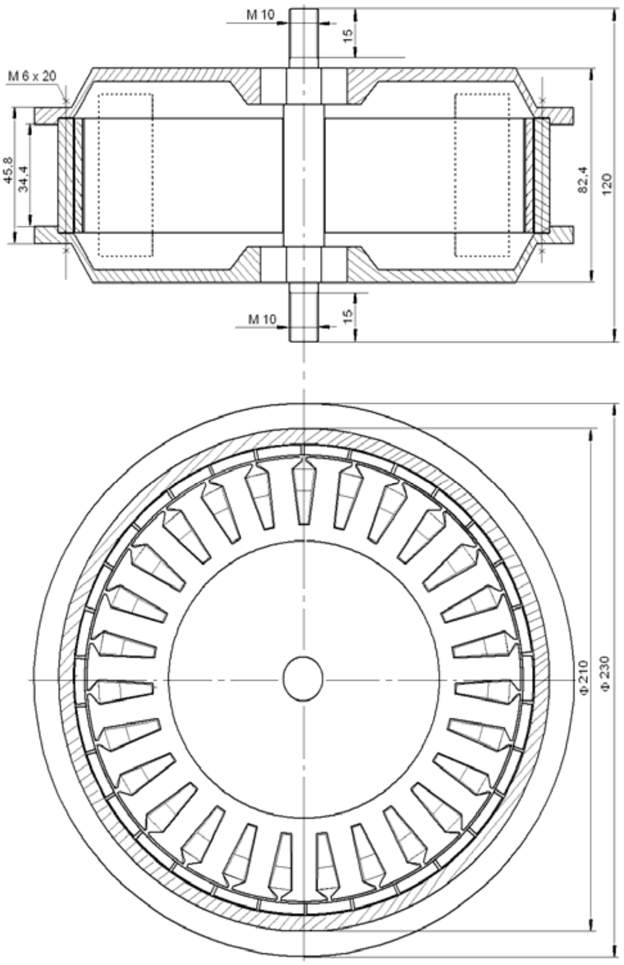

Fig. 4. General assembly with longitudinal and transversal cross section.

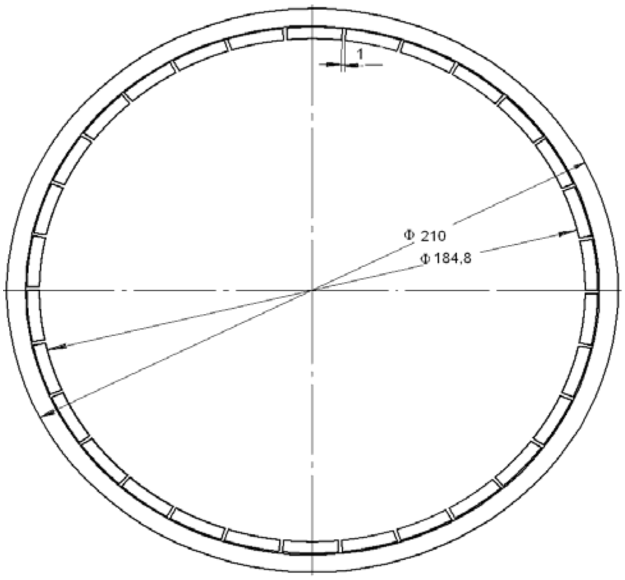

Fig. 5. Rotor subassembly.

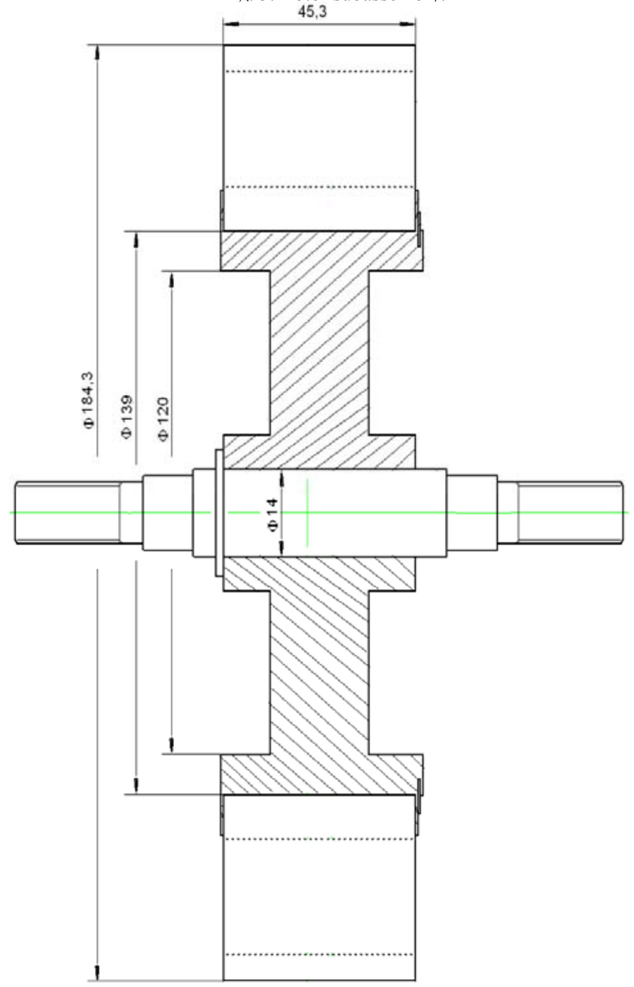

Fig. 6. Stator subassembly.

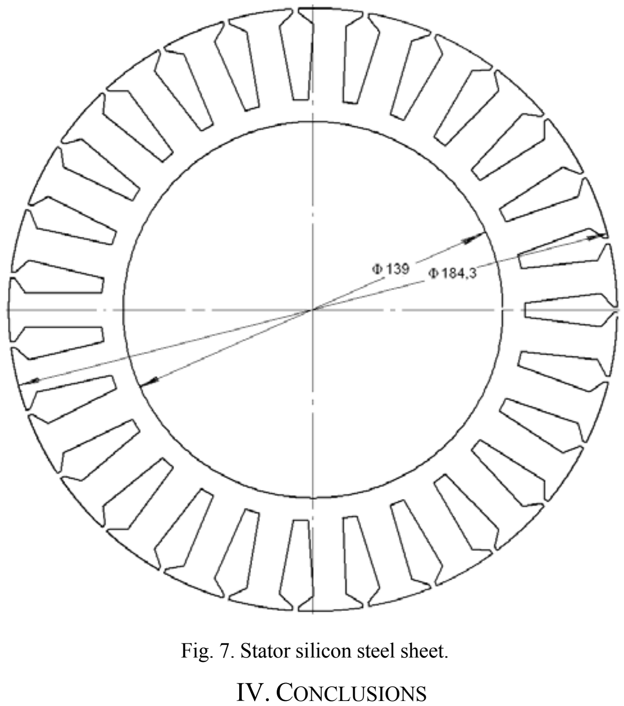

Fig. 7. Stator silicon steel sheet.

IV. CONCLUSIONS

In order to define the “local optimum” one searches for an optimal transversal shape geometry of the motor, by complying the overall dimensions, the optimization criterion being C_t – minimum total cost.

The problem of local optimization is solved successively for all required variables, and it results the optimal values of these variables which define the essence of the transversal geometry, meaning the configuration of the "optimal steel sheet".

The developed design software is flexible because it allows changing the optimization criterion, so that the design engineer can easily achieve other customer requirements. By the transversal shape optimization one can reduce significantly the total cost, the manufacture cost or the maintenance (operation) cost.

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