GEOMETRY OPTIMIZATION OF ELECTRIC MOTORS OF AUTONOMOUS VEHICLES ON ENERGY EFFICIENCY CRITERIA

Assoc. Prof. Eng. **Ion Voncilă**[1], Eng. **Elena Voncilă**[1], As. **Răzvan Buhosu**[1]

[1]„Dunărea de Jos" University of Galați

REZUMAT: Lucrarea abordează, într-o primă etapă, criteriile, metodele şi mijloacele de dimensionare ale proiectării clasice, unde eficiența energetică este un efect. Soluția propusă, în cadrul lucrării, este de inversare a procesului abordării clasice, astfel încât eficiența energetică să devină o cauză şi nu un efect. Algoritmii de optimizare geometrică – dezvoltați pe aceste noi principii, propuse în lucrare, într-o a doua etapă – vor urma o cale fractal-constructală: optimizarea unei unități fundamentale constructive, ce are un caracter holografic (analiza fractală) şi repetarea acesteia până la construirea întregului/motorului electric (sinteza constructală).

Cuvinte cheie: legea constructală, optimizare globală, mașini electrice, eficiență energetică

ABSTRACT: This paper primarily addresses the criteria, methods and sizing means of classic design which result in energy efficiency. The proposed solution is to reverse the classical approach process thereby transforming energy efficiency from an effect into a cause.New geometric optimization algorithms are developed in the second part of this paper based on the new proposed approach. These algorithms follow fractal-constructive criteria: optimisation of a holographic fundamental structural unit (fractal analysis) and reiteration of it until the whole (the electric motor) is built (constructal synthesis).

Keywords: constructal law, global optimization, electric machines, energy efficiency

1. INTRODUCTION

The design process of the electric machines – based on the classic deterministic concept – has two phases: the geometric configuration of the armature of the electric motor (including the electromagnetic calculation of stator and rotor) and the verification of the potential of the electric machine thus projected (the machine must have the capacity to develop the forces expected/required by the beneficiary), in terms of the thermal energy loss, which means in fact the verification of the viability of the whole structure. The algorithms of the design process are based on both analytical expressions (of the various physical measures of electric, magnetic and mechanical nature), which are rigorously determined by classical science [6], and on empirical coefficients of safety, resulting from a vast practical experience [7]. This combination of science and experimentation was judged as acceptable for the applications used in typical engineering applications, particularly in the industrial field. Oversized electric motors used in a certain activity have never been satisfactory, especially in terms of energy efficiency. Oversized motors will determine greater costs in production and long term exploitation and, implicitly, a shorter life cycle in relation to the potential of the machine. Another disadvantage would be that oversized motors need extra room, given the fact that the power of the electric machine is directly proportional to its size.

In the case of the electric machines utilized as traction motors for autonomous vehicles, two main constraints/restrictions are found: limited space/volume and a finite energy source. Taking into account the aforementioned constraints, the classical principle which allowed the use of oversized motors may no longer be applied successfully. This is the main reason which makes necessary the finding of new algorithms for design improvement. The new design process has to be realised and put into practice so that the determined geometric sizes of the electric machine have the optimal useful output for the entire application as well as high energy efficiency (for instance the maximum value of the useful torque developed by the motor) [3], [4], [5].

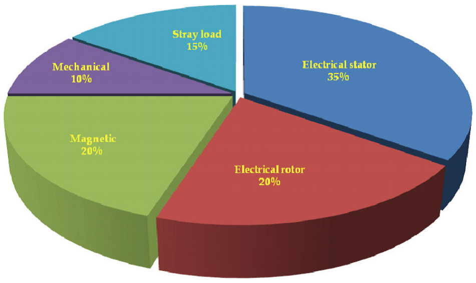

Fig. 1. Induction motor losses distribution [2]

2. CRITICAL ANALYSIS OF CLASSIC DESIGN ALGORITHMS FOR AC ELECTRIC MOTORS

The following elements are considered as given in the classic design process of electric motors: the nominal power or rated output power (the mechanical power available at the motor's shaft), the rated power supply of stator winding, the power factor (in the case of a three-phase electric circuit), the nominal efficiency level (established in relation to the nominal power/rated output power), the frequency of the currents flowing in the stator winding, and the synchronous speed. However, there are also several other parameters which have to be taken into consideration in the case of an asynchronous (induction) motor, namely: the synchronous speed (or the speed of the revolving magnetic field within stator), the current shock caused by the motor at the moment of starting as well as the shock caused by the starting torque.

The main objective of the design process is to find the most appropriate geometric dimensions of the structure so that the entire system may be able to develop the corresponding forces (which, in fact, are established to meet the beneficiary's requirements). Thus, the conditions are restrictive and impose the following limitations: limited size, specific energy efficiency level (as a result of established efficiency of the motor and power factor), explicit requirements of power supply (tension), required shape (usually cylindrical), a specific number of poles (as a result of specific frequency and synchronous speed), given inertial load (by establishing the precise dimensions of the outside rotor diameter and materials that can be used in the fabrication process).

The electric motors design based on algorithms which impose very precise and restrictive conditions (in the authors' opinion), determining a limited choice of geometric dimensions, will have the following characteristics: it is a rigid algorithm which will not allow any changes of the restrictive conditions (mentioned above) and which will finally prevent any attempt at optimizing the energetic and thermal fluxes within the system; it is an algorithm which will require a great number of iterations with the aim to find the 'best' structure to match and satisfy the requirements; it is an algorithm which imposes from the start an over sizing of the motor, since it is necessary to use axial and radial air fans within the structure, in order to provide the cooling of the various component subsystems of the global system represented by the electric machine (the cooling process being also one of the compulsory conditions which ensures the motor's optimal functioning on a long term).

In order to gain some flexibility in the motor design process, a new approach seems the best choice. This new approach has to start from the principle that in the design process some optimal model for the functioning of the electric motor should be, first of all, projected on a small-scale (local optimization) and then applied to the large-scale system, a model which may be called integrated system of small-scale optimized subsystems). The algorithm proposed for the large-scale/global system optimization is based on a holographic principle and will facilitate the energy and thermal flows within the structure having as a result a better performance of the motor on a long term and higher energy efficiency. The improvement of energy efficiency has to be the major target of any motor design process where none of the structural elements (tension, frequency) is pre-established. Such an objective is all the more important in the case of electric motors utilized on autonomous electric and hybrid-electric motors.

The flexibility of the design algorithm entails at the same time a flexibility of the geometry of the structure which will allow the fulfillment of the new requirements (including the requirement of specific shape).

In the next stage, the paper tries to find new ways to present, at a macroscopic level, the relationships existing between the geometric dimensions of the specific structure of an electric motor and the methods of evaluating the energy efficiency level for a given geometric shape.

Considering that the total power (S_N), the rated speed of the shaft (n_N) and rated torque (M_N) are known, one may write the following relations:

$$M_N = F \cdot \frac{D_i}{2},$$

where F – is the periphery/tangential force applied to the rotor, and D_i stands for the inner diameter of the stator (corresponding approximately to the outer diameter of the rotor, without taking into consideration the air gap).

Consequently, we have $F = \frac{2 \cdot M_N}{D_i}$, on the one hand, and we have $F = F_S \cdot \pi \cdot D_i^2$, on the other hand, where F_S represents the surface force density.

Keeping in mind the relationship expressed above and the fact that $F_S = \frac{10^3 \cdot P_S}{\pi^2}$, where P_S is the specific (dynamic) power (understood as power to weight ratio and power to rotational speed), it results:

$$2 \cdot M_N = \frac{10^3 \cdot P_S}{\pi} \cdot D_i^3 \quad (1)$$

The specific power has the expression:

$$P_S = \frac{S_N}{\left(D_i^2 \cdot l_i\right) \cdot n_N}, \quad (2)$$

Then it results the expression:

$$\frac{D_i}{l_i} = \frac{2 \cdot \pi \cdot M_N \cdot n_N}{10^3 \cdot S_N} \quad (3)$$

where l_i is the ideal length of the motor.

As

$$D_i = 2\sqrt{2} \cdot \sqrt{\frac{J}{m}},$$

where J is the inertia moment of the rotor and m stands for the mass, considering the relationship expressed above (3), it results:

$$\sqrt{\frac{J}{m}} = 2{,}22 \cdot \frac{M_N \cdot n_N}{10^3 \cdot S_N} \cdot l_i, \quad (4)$$

an expression which proves that the radius of gyration in the case of an electric motor ($\sqrt{\frac{J}{m}}$) varies linearly with the ideal length of the machine (for a given geometric shape, in this case cylindrical).

The expression at number (4), after certain modifications, may also take the form:

$$\sqrt{\frac{J}{m}} = \frac{1}{2\sqrt{2}} \cdot \frac{P_N}{S_N} \cdot l_i \quad (5)$$

The relationship at (5) may also be written as:

$$P_N = \frac{1}{l_i} \cdot 2\sqrt{2} \cdot S_N \cdot \sqrt{\frac{J}{m}} \quad (6)$$

expression which indicates that the useful shaft power (in nominal value) is inversely proportional with the ideal length of the machine, for given electric values and specific rotor geometry (configuration), in point of shape and materials used in the manufacturing of the machine. Taking into consideration the relationship between D_i and the specific parameters of the rotor J and m, respectively, it results a very simple relation between the output power and the geometric dimensions of the electric motor:

$$P_N = S_N \cdot \frac{D_i}{l_i} \quad (7)$$

On the other hand, within the algorithm of the classic design, the following relation is also used:

$$\lambda = \frac{l_i}{\tau},$$

where $\tau = \frac{\pi \cdot D_i}{2 \cdot p}$ is the pole pitch (p represents the number of the pairs of poles).

As

$$P_N = S_N \cdot \eta_N \cdot \cos\varphi_{1N}, \quad (8)$$

where η_N is the nominal efficiency level of the motor, and $\cos\varphi_{1N}$ is the power factor (in nominal value), it results that from the relationships (7) and (8) one may deduce a relation between the geometric dimensions of the electric motor and the evaluation measures of energy efficiency, namely:

$$\frac{D_i}{l_i} = \eta_N \cdot \cos\varphi_{1N} \quad (9)$$

However, taking into account the algorithm that may be found in the classic design, one may obtain also the following expression:

$$\eta_N \cdot \cos\varphi_{1N} = \frac{2p}{\pi \cdot \lambda} = \frac{k}{\lambda}, \quad (10)$$

if p is known.

As a preliminary conclusion, it may be said that the motor performance in energy efficiency terms (as it is clearly highlighted by (9) and (10) expressions) are closely related with the geometry of the analysed structure. Consequently, there is a high probability that a geometric (constructive) optimization may determine also higher energy efficiency.

Table 1

Variation of geometric dimensions and performance parameters for asynchronous electric motors manufactured by small and medium power IMEB (Enterprise Electrical Machines Bucharest)

No.	P_N [kW]	No. of poles ($2p$)	η_N	$\cos\varphi_{1N}$	D_i [mm]	l_i [mm]	$\frac{D_i}{l_i}$ (achieved motor)	$\eta_N \cdot \cos\varphi_{1N}$ (achieved motor)	Margin of variation $\frac{1}{\lambda}$ (design algorithm)	Margin of variation $\frac{k}{\lambda}$
1	0.8	2	0.78	0.845	78	60	1.300	0.6591	1.11-1.66	0.706 - 1.055
2	**0.8**	**4**	**0.77**	**0.775**	**85**	**75**	**1.133**	**0.59675**	*0.555-0.769*	0.707 – 0.979
3	1.1	2	0.79	0.87	78	75	1.04	0.6873	1.11-1.66	0.706 - 1.055
4	**1.1**	**4**	**0.791**	**0.77**	**85**	**95**	**0.894**	**0.60907**	*0.555-0.769*	0.707 – 0.979
5	1.5	2	0.80	0.86	84	80	1.05	0.688	1.11-1.66	0.706 - 1.055
6	**1.5**	**4**	**0.81**	**0.80**	**92**	**100**	**0.92**	**0.648**	*0.555-0.769*	0.707 – 0.979
7	*0.8*	*6*	*0.745*	*0.705*	*92*	*100*	*0.92*	*0.52522*	**0.434-0.588**	0.829 – 1.123
8	2.2	2	0.83	0.865	84	100	0.84	0.71795	1.11-1.66	0.706 - 1.055
9	**2.2**	**4**	**0.83**	**0.825**	**92**	**125**	**0.736**	**0.68475**	*0.555-0.769*	0.707 – 0.979
10	*1.1*	*6*	*0.74*	*0.72*	*92*	*125*	*0.736*	*0.5328*	**0.434-0.588**	0.829 – 1.123
11	3	2	0.84	0.87	98	100	0.98	0.7308	1.11-1.66	0.706 - 1.055
12	**3**	**4**	**0.83**	**0.84**	**104**	**125**	**0.832**	**0.6972**	*0.555-0.769*	0.707 – 0.979
13	*1.5*	*6*	*0.76*	*0.735*	*114*	*115*	*0.991*	*0.5586*	**0.434-0.588**	0.829 – 1.123
14	1.1	8	0.77	0.65	114	115	0.991	0.5005	0.333-0.434	0.848 – 1.105
15	4	2	0.87	0.875	98	125	0.784	0.76125	1.11-1.66	0.706 - 1.055
16	**4**	**4**	**0.85**	**0.845**	**104**	**145**	**0.717**	**0.71825**	*0.555-0.769*	0.707 – 0.979
17	*2.2*	*6*	*0.79*	*0.76*	*114*	*150*	*0.76*	*0.6004*	**0.434-0.588**	0.829 – 1.123
18	1.5	8	0.79	0.67	114	145	0.786	0.5293	0.333-0.434	0.848 – 1.105
19	5.5	2	0.86	0.875	112	125	0.896	0.7525	1.11-1.66	0.706 - 1.055
20	**5.5**	**4**	**0.86**	**0.865**	**124**	**150**	**0.826**	**0.7439**	*0.555-0.769*	0.707 – 0.979
21	*3*	*6*	*0.812*	*0.78*	*138*	*145*	*0.951*	*0.63336*	**0.434-0.588**	0.829 – 1.123
22	2.2	8	0.785	0.70	138	135	1.022	0.5495	0.333-0.434	0.848 – 1.105
23	7.5	2	0.875	0.82	112	150	0.746	0.7175	1.11-1.66	0.706 - 1.055
24	**7.5**	**4**	**0.87**	**0.85**	**124**	**195**	**0.635**	**0.7395**	*0.555-0.769*	0.707 – 0.979
25	*4*	*6*	*0.829*	*0.78*	*138*	*180*	*0.766*	*0.64662*	**0.434-0.588**	0.829 – 1.123
26	3	8	0.782	0.71	138	180	0.766	0.55522	0.333-0.434	0.848 – 1.105
27	10	2	0.875	0.88	140	150	0.933	0.770	1.11-1.66	0.706 - 1.055
28	**10**	**4**	**0.88**	**0.85**	**152**	**180**	**0.844**	**0.748**	*0.555-0.769*	0.707 – 0.979
29	*5.5*	*6*	*0.856*	*0.80*	*172*	*145*	*1.186*	*0.6848*	**0.434-0.588**	0.829 – 1.123
30	4	8	0.835	0.74	172	150	1.146	0.6179	0.333-0.434	0.848 – 1.105
31	13	2	0.883	0.882	140	185	0.756	0.77880	1.11-1.66	0.706 – 1.055
32	**13**	**4**	**0.894**	**0.848**	**152**	**235**	**0.646**	**0.75811**	*0.555-0.769*	0.707 – 0.979
33	*7.5*	*6*	*0.867*	*0.805*	*172*	*190*	*0.905*	*0.69793*	**0.434-0.588**	0.829 – 1.123
34	5.5	8	0.836	0.70	172	190	0.905	0.5852	0.333-0.434	0.848 – 1.105

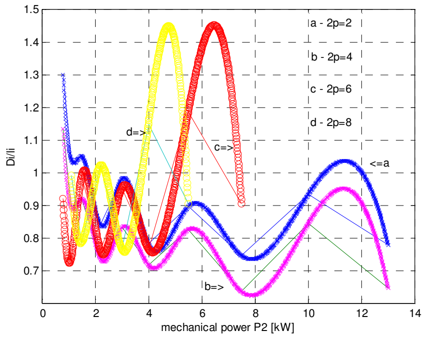

Fig. 2. Variation $\frac{D_i}{l_i}$ = f(P) for motors made by IMEB

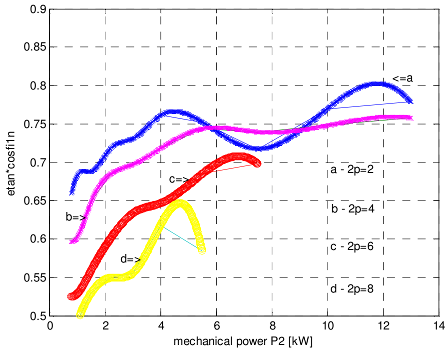

Fig. 3. Variation $\eta_N \cdot \cos\varphi_{1N}$ = f(P), for motors made by IMEB

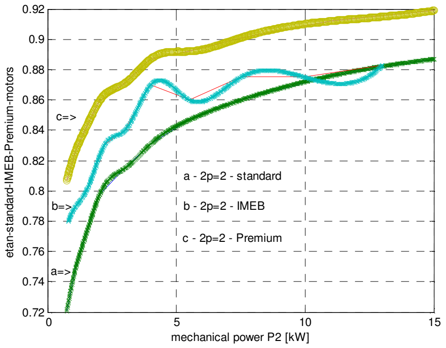

Fig. 4 Comparison between performances of the motors made by IMEB, standard values of the efficiency (performance) levels and efficiency of the Premium motors at 50 Hz, for 2p=2

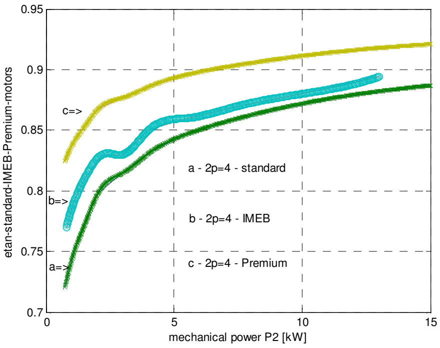

Fig. 5. Comparison between performances of the motors made by IMEB, standard values of the efficiency (performance) levels and efficiency of the Premium motors at 50 Hz, for 2p=4

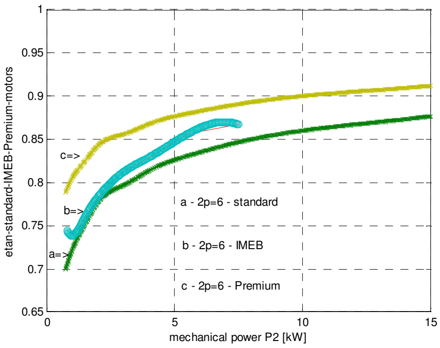

Fig.6. Comparison between performances of the motors made by IMEB, standard values of the efficiency (performance) levels and efficiency of the Premium motors at 50 Hz, for 2p=6

As a result of the critical analysis presented so far, several observations can be made:

- in the case of the classic design algorithm, the best correlation between the geometric dimensions and high energy efficiency levels may be obtained when the average value of the number of the pairs of poles for the whole range of the analysed cases, namely, when $2p = 4$;
- at the same power, for a smaller number of pairs of poles, it may be observed that a greater discrepancy exists between the relation of geometric dimensions ($\frac{D_i}{l_i}$) and the product of the energy efficiency ($\eta_N \cdot \cos\varphi_{1N}$), for motors fabricated so far;
- when the values expressing power are equal and when there is a variation in the relation $\frac{1}{2}$ of the number of pairs of poles, the relationship between geometric dimensions ($\frac{D_i}{l_i}$), and the product of the energy efficiency ($\eta_N \cdot \cos\varphi_{1N}$) remains relatively constant (an error smaller than 6%) for motors

manufactured so far; thus, a better correlation between geometric dimensions and high energy efficiency levels is possible and at the same time necessary for the modern applications which impose spatial limits, precise shapes and low environmental impact;

- there are great possibilities for the improvement of the energy efficiency factor for electric motors, and one of the most important of these possibilities is the research, analysis and application of new design algorithms (as shown in the comparative analysis – Fig. no. 4,5,6); from the comparative analysis presented in the paper, it results very clearly that the Premium motors are neatly superior to all other classes of electric motors of small to medium power, Premium motors having the highest energy efficiency levels.

3. GEOMETRIC AND ENERGY EFFICIENCY OPTIMIZATION OF ELECTRIC MOTORS (ACCORDING TO CONSTRUCTAL ANALYSIS)

The most evident aspect emphasized by the present analysis is that the algorithms used in typical AC machine design, in which the shape of the machine is given (namely, cylindrical), has as primary limitation the manufacturing of highly efficient structures. In the case of standard algorithms, the limitations are caused by the use of a great number of coefficients, a fact which finally determines the over sizing of the geometric structure. It is very well known that over sizing will increase the energy consumption, hence the low efficiency energy levels.

A much better principle would be that according to which the structure is flexible, it may be adjusted for a given useful work, so that the losses be minimal and the flows of magnetic energy and thermal (heat) losses may be optimal. This is the very essence of the constructal principle [1], [2]. The implementation of such a principle requires a great flexibility in the choice of the shape of the structure. But this is also a prerequisite of the modern applications in the domain of autonomous vehicles and systems for the conversion of renewable energy into electric energy etc.

Therefore, the constructive geometric optimization of the electric motors will have to obey the constructal principle, i.e. to allow for the continuous flow of a seed body – locally optimized (from a geometric and energetic point of view) – until an entire structure is generated (global optimization). The algorithm to be applied for the design and construction of an electric motor is, in this case, the following:

- the optimal number of ridges of the
- the optimal number of slots in the ferromagnetic core/cores of the electric motor's armature will be determined according to technical/economic criteria and environmental impact [9];
- the structure's seed body is generated while taking into account the symmetries which can occur within it (eg given a cylindrical symmetry structure, a seed body of relatively a quarter of the motor can be used for the slot-fitted ferromagnetic core). This seed body is the first core optimized in terms of the *Di* diameter;
- based on a dynamic iterative process, an entire geometric structure is generated (in keeping with the previously selected symmetry criteria) along the ideal length of the motor (l_i) which ensures maximum energy performance.

The resulting geometric structure has a global geometric and energetic optimum which is sure to also allow for an increased reliability of the new electric motor.

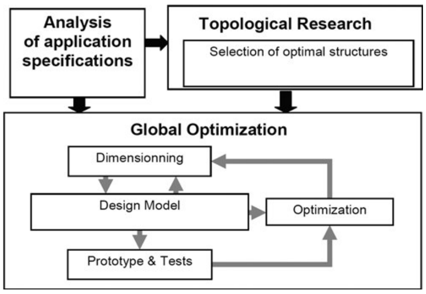

Fig. 7. Design optimization methodology [10]

Global optimization allows for all factors: electrical, magnetic, thermal, economic and, of course, environmental.

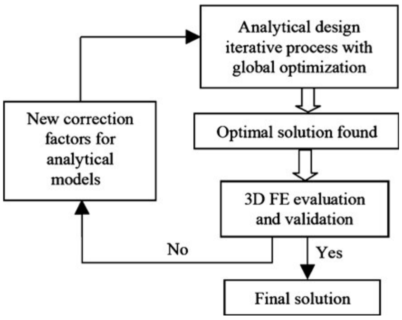

Fig. 8. Flowchart of a design method with global optimization and model error correction [10]

Figure 7 shows the global optimization algorithm outlined above, while Fig. 8 highlights the fact that any structure (developed according to a design) must be validated before being put into practice.

4. RESULTS

By applying such an algorithm we can obtain high potential electrical motor structures (in terms of both power and energy efficiency). The potential of the structure obtained by applying the constructal algorithm is reflected in Table 2.

Table 2

Variation of geometric dimensions and performance parameters for asynchronous small and medium electric motors designed on the constructal algorithm. Comparative analysis with the Premium motor.

No.	P_N [kW]	No. of poles ($2p$)	D_i [mm] (optimised motor)	l_i [mm] (optimised motor)	$\frac{D_i}{l_i}$ (optimised motor)	$\eta_N \cdot \cos\varphi_{1N}$ (optimised motor)	η_N (Premium motors)	η_N (optimised motor)	$\cos\varphi_{1N}$ (optimised motor)
1	1.1	4	83	100	0.830	0.823	0.841	0.915	0.900
2	1.5	4	83	100	0.830	0.832	0.853	0.920	0.905
3	2.2	4	93	110	0.845	0.841	0.867	0.925	0.910
4	3	4	98	115	0.852	0.852	0.877	0.928	0.918
5	4	4	103	120	0.858	0.858	0.886	0.933	0.920
6	5.5	4	105	122	0.860	0.861	0.896	0.934	0.922
7	7.5	4	108	125	0.864	0.864	0.904	0.936	0.923
8	11	4	115	130	0.884	0.883	0.914	0.945	0.935
9	15	4	120	135	0.888	0.887	0.921	0.948	0.936

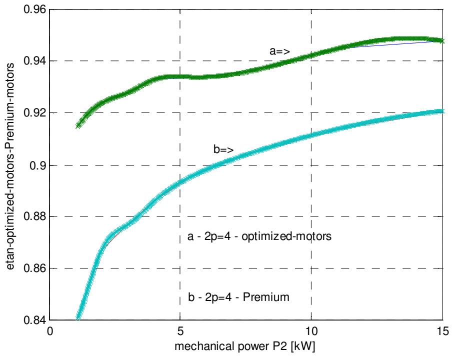

Fig. 9. Comparison between the output of motors optimized through constructal algorithm and Premium motors at 50 Hz, for 2p=4

Figure 9 presents energy efficiency results for motors with cylindrical symmetry, following optimization based on constructal criteria (comparison is made with Premium motors at $2p=4$).

5. CONCLUSIONS

First and foremost, this paper represents a critical analysis of the classic design algorithm which, due to the high number of correction factors, generally leads to a geometric over-estimation for the given forces. Moreover, this paper indicates that this over-estimation leads to a drastic reduction of the structure's output in terms of energy efficiency of the conversion processes.

Second, this research has indicated the inability of the classic design algorithm to produce electric motors – of suitable shape and size - for modern applications on autonomous electric vehicles and in the field of renewable energies conversion into electricity (wind power, tidal power etc).

The intention was to find an algorithm which, for a given application provides high potential electric motors with low environmental impact (low losses, suitably flexible geometry, allowing reuse of important subassemblies at the end of its life-cycle).

In the near future, computer assisted programs for electric motor design will have to include in their libraries (besides types of materials, their physical and chemical characteristics and classical design structures) geometric structures (or appropriate subroutines) optimized based on constructal criteria (the principle of volume-point continuous flow).

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About the authors

Assoc. Prof. Eng. **ION VONCILĂ** PhD,
„Dunărea de Jos" University of Galați
email: Ion.Voncila@ugal.ro

Electrical engineer of the University "Politehnica" of Bucharest, from 1987. Phd of the „Dunărea de Jos" University of Galati. from 2000. Specialization in the complex problem of solving electromagnetic field obtained in the Collaborator Project, developed in collaboration with University "Politehnica" of Bucharest. Specializations in the field of electric machines and renewable energy obtained in Tempus Program at the University of Science and Technology of Lille, France, in 1998, respectively, at the University of Grenoble, France, in 2001. Research areas: design and constructive optimization of electrical machines, permanent magnet bearings and couplings.

Eng. **ELENA VONCILĂ** PhD Student,
„Dunărea de Jos" University of Galați
email: Elena.Voncila@ugal.ro

Graduated at Faculty of Electrical Engineering and Electronics in 2006, Specialization „Electric Drives in French language", at the „Dunărea de Jos" University of Galati, Romania. Master's Degree studies in 2008 at the Faculty of Electrical Engineering and Electronics, Specialization „Informatic systems for Transport Control and Electric Energy Conversion". Phd student from 2009 at „Dunărea de Jos" University of Galati, currently on stage at „Carlos III" University of Madrid, Spain. Her recent interests are focused on modeling and simulation of advanced power sources and electric vehicles.

Assistant Eng **RĂZVAN BUHOSU**
„Dunărea de Jos" University of Galați
email: Razvan.Buhosu@ugal.ro

Graduated at Faculty of Naval and Electrical Engineers in 1998, specization Electromechanic at the „Dunărea de Jos" University of Galati. Master's Degree studies in 1999 at the Faculty of Naval and Electrical Engineers. Phd student from 2000 at „Dunărea de Jos" University of Galati. . Research areas: design, modelling and simulation of electrical machines for autonomous vehicles.