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FINITE ELEMENT METHOD COUPLED WITH GENETIC ALGORITHM AS A DESIGN OPTIMIZATION TOOL OF ELECTROMAGNETIC DEVICES

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Abstract

In the paper the authors are presenting the optimization procedure based on application of Genetic Algorithm (GA) coupled with Finite Element Method (FEM), for design of electromagnetic devices. The result is a powerful optimization tool, which will be applied in particular for a design of: an axial field permanent magnet disk motor for direct EV drive; a single phase shaded-pole induction motor and an iron core coil. In the essence, the target is focussed towards finding more efficient model of each particular device, by optimizing and improving the design of an existing prototype model. Later, the obtained optimal solutions are thoroughly investigated through an analysis of their performance characteristics, derived from FEM computations. Some of the results, where is possible, are verified experiment-ally by measurements; showing a good agreement, they prove the proposed methodology for optimization of electromagnetic devices as reliable and accurate.

1. – INTRODUCTION

In engineering practice the concept of any optimization means creating better and more economical product or solution, by using existing resources. The need for design optimization of electromagnetic devices, arises because of the stiff competition among the producers at the one side, and because of the demand for their best performance characteristics, at the other. At the design stage of an electromagnetic device, all efforts are focus-sed to achieving desired device model on faster, more economical and more reliable way. During the applicati-on of an existing electromagnetic device for particular purposes, the main task is to improve its performance characteristics by relatively simple design modifications. Researchers have been using classical optimization techniques, mainly based on the gradient methods, a long time back. Recently, it is evident a wide introduct-ion of different evolutionary computational techniques, based on the stochastic approach. Such methods are claimed to be faster, more efficient and more successful when searching for the global optimum of a function.

The Genetic Algorithm (GA) is selected as the most suitable stochastic methodology for optimization of electromagnetic devices, comprehended in general sense. Various types of electrical machines are only particular representatives of electromagnetic devices. In the paper specific applications and gained results is presented.

2. – FINITE ELEMENT METHOD

The Finite Element Method (FEM) in the recent years has been found as very attractive method in the design and analysis of various electromagnetic devices. For compound and non-linear configurations, as those in electrical machines, Finite Element Method has been proved to be powerful numerical method for solution of electromagnetic field problems. An optimal designing procedure of electromagnetic devices requires the accurate calculation of the magnetic field distribution in all domain under consideration; this will enable an accurate determination both the characteristics and the parameters of the device, verifying the new developed

models. Both 2D and 3D magnetic field calculations are equally applicable for accomplishing of this task [1].
In general sense, electromagnetic devices are heterogeneous domains, assembled of various parts and materials, mostly non-linear, with prescribed boundary conditions. Hence, the magnetic field problem is defined as the variable coefficients type, and it can be solved by the numerical methods only. Certainly, FEM is the best approach to realize this task. The only request from the user is to carry out the proper mathematical and geometrical modeling of the device under consideration. Thus, a variability of the compound configuration both inside and/or outside of the electrical machine will be taken into account. The current sources and the boundary conditions should be also properly included in the FEM model of the devices.
The output results, presented in different ways, offer to "get inside" the device and "to see" its weak parts; this is considered as very useful when coupling FEM with some optimization procedures, enabling to examine and to prove the obtained optimal results.

3. – GENETIC ALGORITHM

Since fairly recent the Genetic Algorithms have been presented as computer algorithms, a wide range of applications have been appeared in various scientific areas. Consequently, they have been found as powerful and reliable tool for solving complicated tasks related to optimization problems in the area of electrical engineering . The previous publications of the authors, concerning the optimization of different electromagnetic devices, verify the method of GA as quite corresponding and powerful optimization method.
In their essence, the Genetic Algorithms are evolutionary searching algorithms, based on the rules of the natural genetics and the natural mechanics of unit selection.
The Genetic Algorithms are practically implemented in the most simplified natural way, based on the survival principles of the fittest unit. In this stochastic process, the least-fit solution is receiving the minor chance for reproduction; to the contrary, the most-fit solution is receiving the major chance to be reproduced. The reproductive success of a problem solution is directly linked to the fitness value, which during the evaluation has to be previously assigned. The process starts from a randomly created population of strings, and after a sufficiently large number of generations, it stops giving the optimal solution with the best features.
During the optimization, reproduction, mutation and crossover between the units and generations, determine the results finally achieved. The probability of their occurrence is recognized and determined through the corresponding genetic operators. Their percentage or per unit values of appearance in the genetic procedure, are always users' and problems' dependent. The experience and skill of the researcher is of great importance.

4. – GA OPTIMIZATION PROCEDURE

Design optimization of electromagnetic devices, and in particular electrical machines, is very important but quite complicated problem. In general, it is a complex multi-variable, non-linear and constrained procedure.
The authors have developed an original program for optimization of different types of electrical machines and electromagnetic devices by using the genetic algorithms; data representation, as an original contribution, are real-valued [2]. The program is successfully implemented for optimization and/or for optimal design of various types of electromagnetic devices [3-6]. Here, the optimization procedure is briefly explained.
During the procedure of a design optimization, after the relevant device parameters have been determined, and depending on the problem which is going to be solved, at the beginning an objective function – target function is selected, defined and derived by the user.
The optimization procedure always means searching for an extreme of the target function, i.e. for its maximum or minimum. In order to provide the derived solution to be practically acceptable, certain requirements should be satisfied; in this sense, some important electrical or magnetic quantities, such as winding current density, magnetic flux density in the air-gap or in the magnetic core, must be lower than the prescribed limits. Sometimes, other more rigorous constraints to a problem solution could be imposed to be satisfied.

4.1 - Selection of a target function

The method of genetic algorithm enables to create an optimal solution by optimization of certain device parameters and to derive a new model with improved performance characteristics. The main user task is always a definition, selection and development of the most suitable target function of optimization. Depending on the particular application, different approaches to this problem can be considered. The optimization procedure and objective function of should meet the requests and needs, either of users or of manufacturers.

• Knowing that the electromagnetic torque is one of the most important quantities of the electric motors, the first idea is to use its value as target function during the optimization procedure.

• The efficiency of electrical machines, through minimization of the losses, is always aiming to greater values; naturally, the other interesting target function is the efficiency factor of the device under consideration.

It is obvious that such definition of both target functions on the basis of which the electromagnetic device will be optimized, is always a maximizing problem.

• On the other hand, the producers are always aiming to achieve the maximum gain of the device, at the minimum expenditure; the such goal is focused to a minimum consumption of the active materials while building the electric and magnetic circuits: windings and cores of the particular electromagnetic device. Hence, the weight of copper and iron could be adopted as useful target function, as well. In this case of selection the objective function, it is obvious that the optimization problem will be defined as minimizing problem.

On the basis of the electric circuits theory and by using the corresponding methodology for determination of particular electromagnetic device performance characteristics, the most suitable mathematical model for implementation in each target function, corresponding to the optimization procedure by using the GA, will be derived. After, in dependence of each specific case, the design variables are selected, together with their mapping range. The better experienced researchers will faster reach the expected optimal problem solutions.

4.2 – Coupling FEM with GA

As previous mentioned, Finite element Method will be used as a powerful and reliable tool for examination and verification of new developed models of the devices, after the optimization procedure has been carried out. The best way is to present the magnetic field distribution in arbitrary chosen cross section of an electromagnetic device. The comparison with the corresponding basic model, will evidently show the achieved results.

5. – APPLICATIONS

From the bulk of results achieved by the authors so far, only a short presentation of three specific examples is given bellow. In the full manuscript, more detailed explanation of the derived target functions, the mapping range of the design variables and a broad analysis of the results will be included.

5.1 – Permanent magnet disk motor PMDM

This special type of electric motor is assigned for direct EV wheel drive. It is performed with two stators and one double sided rotor, carrying on the Nd-B-Fe permanent magnets [3]. In this case, the selected objective function $f(x)$ of optimization is efficiency factor with respect to geometrical dimensions as design variables, while keeping the rated electromagnetic torque T_n unchanged. The simplified scheme, showing the arrangement and the main dimensions of the permanent magnet disk motor (PMDM) with axial field is presented in Figure 1.

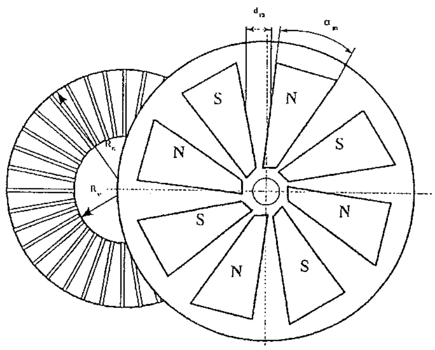


Figure 1. Cross section of PMDM arrangement

The optimization problem is solved as maximizing procedure of the objective function $f(x)=\eta$, expressed as:

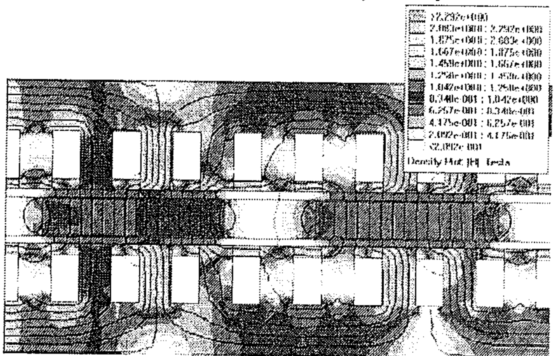
$$\eta = f(R_v, R_n, \alpha_m, l_m, \delta, d_w, b_k) = \frac{T_n\omega_m}{T_n\omega_m + P_{Cu} + P_{Fe} + P_f} \quad (1)$$

Basing on experience and skills, corresponding variables constraints and limits are implemented in GA program. Some of the most interesting output results, achieved through the optimization procedure, and compared to the basic motor model accepted as prototype, are presented in Table I. In the optimized model efficiency is improve-ed for 3.77%; even more, the volume of the PM, the most expensive part, is decreased by significant 32.3%.

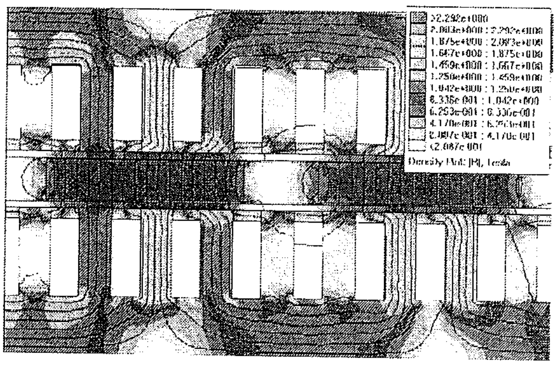
Table I PMDM prototype and GA solution comparison

Parameter	Description	Prototype	GA Solution
I [A]	phase current	8.723	8.734
R [Ω]	phase resistance	1.245	0.553
P_{cu} [W]	copper loss	345.43	153.9
P_{Fe} [W]	iron loss	15.038	21.11
W_S [turns]	No. of turns/coil	13	11
V_m [m^3]	Volume of PM	0.0005018	0.0003397
η [%]	**Efficiency**	**83.19**	**86.33**

By using an original approach to numerical calculation of the magnetic field distribution in PMDM[4] the quasi-3D FEM, previously proved as practical and quite accurate, is applied. The PM disk motor is divided into 5 radial layers and opened in a linear form. Calculations are carried out for each of the five segments, at different rotor positions and for a range of loading conditions. Bellow, the comparative results for the 3rd segment only, at rated operating condition, for the prototype and for the new derived optimized motor model, obtained from the FEM computations of the magnetic field distribution, are presented in Figure 2. (a) and (b), respectively.



(a) Prototype motor model



(b) GA optimized motor model

Figure 2. Magnetic field distribution across the 3rd layer at rated load in PMDM

5.2 – **Single phase shaded pole motor SPSPM**

Method of GA as a powerful optimization tool is applied to a single phase shaded pole motor "Mikron" product, in this investigation adopted to be basic model-*BMM* [5]. Rated data of the motor are: 2p=2; U_n=220V; f_n=50Hz; I_{1n}=0.125A; P_{1n}=18W; n_n=2520rpm. Design optimisation variables are selected to be: current density Δ [A/mm^2], main stator winding number of turns W, magnetic flux density B [T], angle of rotor skewing α_{sk} [deg]. Mathematical model of the SPSPM is developed. Electromagnetic torque as target function is derived [6].

$$T_{em} = f(W, S_{Cu}, B_\delta, \Delta, \alpha_{sk}) \qquad (2)$$

In the derived optimal motor model-*OMM*, at slip s_n=0.16, an important increase of the electromagnetic torque T_{em}, by 42.5% is achieved; even more, the efficiency factor η is increased for 24.45%; But, it is emphasized that the gained result is due to an increase of stator winding current by 34.4%, too. Only a brief survey of both motor model quantities is presented in Table II.

Table II SPSPM basic and GA optimized model

Quantity	BMM	OMM
Main winding turns per pole *W*	1744	1566
Stator current I_1 [A]	0.126	0.168
Short circuit coil current I_3 [A]	0.0063	0.0083
Rotor current I_2 [A]	0.0878	0.1176
Input power P_1 [W]	18.11	21.667
Output power P_2 [W]	4.149	6.1775
Efficiency factor η [/]	0.229	0.285
Electromagnetic torque T_{em} [mNm]	**18.075**	**25.76**

Magnetic field calculation are carried out in 2D domain of the shaded pole motor, by using time-harmonic FEM [7]; the flux distribution, at slip 0.16, in the both motor models is presented in Figure 3. and 4., respectively.

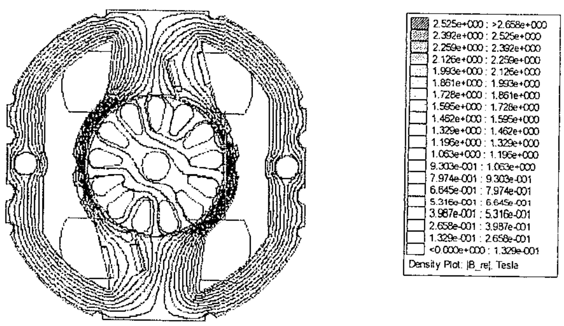


Figure 3. Magnetic flux plot at slip s=0.16 in SPSPM-BMM

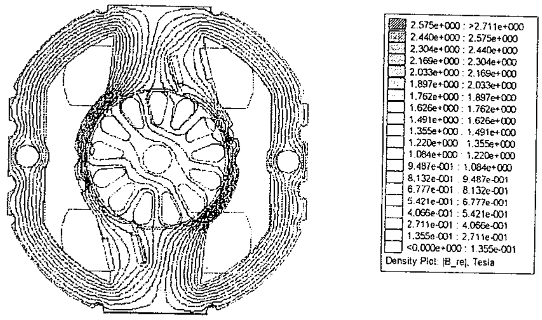


Figure 4. Magnetic flux plot at slip s=0.16 in SPSPM-OMM

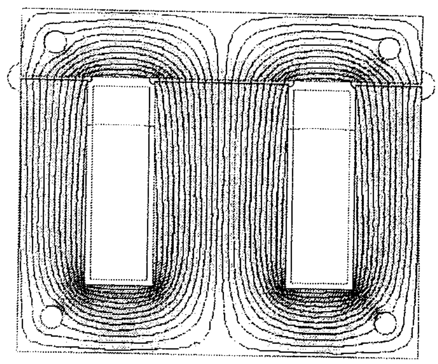


Figure 5. Magnetic field distribution at rated load in ICC-BM

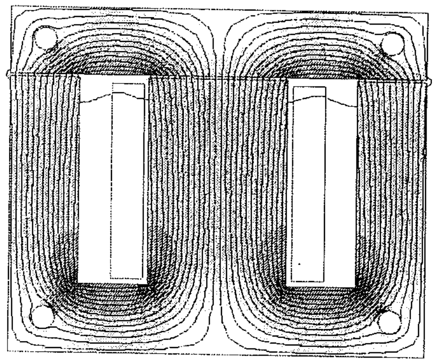


Figure 6. Magnetic field distribution at rated load in ICC-OM

5.3 – Iron Core Coil ICC

Inductance iron core coils, also called reactors, are used for various purposes in electrical engineering practice. Depending on the power, reactors are performed as single phase, or three phase. As more economically they are usually made with an iron core; but, for adjustment of the requested value of the inductance, an air-gap is always anticipated.

For smaller sizes, the design of an iron core coil is often similar to a single phase shell type transformer. If it is taken into consideration that iron core consumes a large amount of magnetic sheets, the iron core coils have always a significant weight; the coil winding, made from copper wire, is an additional active materials weight. Consequently, when optimizing the design of an iron core coil, it is always reasonable to select as an objective function of optimization, the total mass of built-in iron and copper, i.e.:

$$f(x) = m\,(n, \mathrm{W}, \mathrm{B}_m, g^*, \mathrm{G}) = \mathrm{MIN}|f(x)| \qquad (3)$$

In this particular case, optimization problem is solved by minimization of the above function, where optimization variables are: number of magnetic sheets in axial direction n, meaning the depth of core l_{Fe}; number of coil turns W; the magnetic flux density in core B_m; air-gap length g^*; current density in the coil winding G. The most interesting results, for the basic model – BM of iron coil core, as well as for the GA optimized model – OM, are given in Table III. Magnetic flux distribution, in the both ICC models is presented in Figure 5. and Figure 6.

From the optimized and initial results, it is evident that an important saving of the active materials consumption by 35.8% is achieved, meaning an important decrease of production costs of the iron core coil.

Table III Comparison of the results for ICC models

Quantity	BM	OM
Core depth l_{Fe} [mm]	35	25
Number of turns W	608	504
Flux density B_m [T]	0.753	0.82
Current density G[A/mm^2]	4.44	4.54
Air-gap length [mm]	1.63	1.0
Copper wire diameter [mm]	0.7	0.56
Winding current I [A]	1.15	1.094
Leakage inductance [H]	0.12	0.056
Magnetizing inductance [H]	0.27	0.208
Copper weight m_{Cu} [kg]	0.394	0.1615
Iron weight m_{Fe} [kg]	1.268	0.9055
Total mass m [kg]	**1.662**	**1.067**

At the same time, the typical values of electric and magnetic quantities, show a significant increase, what means better use of built-in active materials (copper and iron). Although in the previous figures, because of the 2D presentation of the ICC cross-section is not evident, the axial length is decreasing for 28.57%.

6. - CONCLUSIONS

In the paper, an approach to optimization procedure of electromagnetic devices by using the coupling of finite element method – FEM and genetic algorithm - GA is presented. Genetic algorithm has been proved to be the most reliable and robust method for solution of different optimization problems. Depending on the problem which is solving, the main task of the user is always to derive the best fitted target which is going to be achieved during the optimization procedure, and after, the well defined objective function of optimization.

On the other hand, the Finite Element Method is offering an excellent tool for verification and comparison of the obtained achievements. The authors have found this combination as a powerful tool in the design procedure of electromagnetic devices.

As objects of investigation, and examples of application of the proposed procedure, three electromagnetic devices are taken into consideration:

• An axial field permanent magnet disk motor for direct EV drive: the optimization procedure is focussed to maximize the efficiency factor, keeping the shaft torque constant and equal to the rated; the additional advantage of the new derived motor model is a significant decrease of the permanent magnets' volume.

• A single phase shaded pole motor: in this particular case, starting from the point of the motor application the authors suggest as an objective function to consider the electromagnetic torque as one of the most important quantities during running the motor. But, it should be emphasized that optimization process is subordinated to few restrictions imposed by particular requirements. An important limit is to keep the same cross section of the stator and rotor magnetic core. Consequently, the optimization procedure is principally focussed to the main stator winding and its parameters, and the other related quantities. The result of optimization is a new derived motor, with both the torque and the efficiency factor improved.

• An iron core coil, assigned for lightings: starting from the point of its application, the objective function which is minimizing is the total weight (mass) of copper and iron, as the most important active materials; The additional gain are greater current and flux densities, meaning their more economical usage. The next task is foreseen to be an optimization procedure with less constraints, allowing more freedom in the selection of the quantities that can be changed. The results of this paper could serve as a good guide.

The three presented devices in the paper, analyzed by using FEM, have been examined experimentally, too; in this way, where possible, some of the calculated results of the initial – basic models, have been verified by measurements. Showing a good agreement, they prove the proposed methodology for optimization of the electromagnetic devices as reliable and accurate.

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