JSAEM Studies in Applied Electromagnetics, 4

ELECTROMAGNETIC PHENOMENA APPLIED TO TECHNOLOGY

Proceedings of
The Fourth Japanese and Polish Joint Seminar
on Electromagnetic Phenomena Applied to Technology
June 5 - 7, 1995, Oita, Japan

Supplement to Volume 4 of the Journal of the
Japan Society of Applied Electromagnetics
and Mechanics

Editors:

Masato Enokizono

Faculty of Engineering
Oita University
Oita, Japan

Takashi Todaka

Faculty of Engineering
Oita University
Oita, Japan

Electromagnetic Phenomena Applied to Technology
M. Enokizono and T. Todaka (eds.)

INVERSE OPTIMIZATION OF CORE SHAPE OF ELECTROMAGNETIC DEVICES USING GENETIC ALGORITHMS

Takeyoshi Yamamoto, Vlatko Čingoski, Yuuichi Harano and Hideo Yamashita

Electric Machinery Laboratory,
Faculty of Engineering,
Hiroshima University,
Kagamiyama 1-4-1, Higashihiroshima, 739 Japan

ABSTRACT

In this paper a new method for the inverse optimization of core shapes of electromagnetic devices using Genetic Algorithms is presented. For the generation of an initial population and its offspring, the available core area is directly encoded using binary technique. Two methods for selection of genes are proposed: non-restricted method and restricted method. Both methods are applied to the optimization of a metal mold cavity inside permanent magnet production equipment. Electromagnetic analysis is performed using the 2-D finite element method. The robustness of the Genetic Algorithm and the accuracy of the obtained results are very promising.

INTRODUCTION

Recently, Genetic Algorithms (GAs) have emerged as very practical and robust optimization tools and searching methods. Together with Neural Networks, GAs have been widely employed in various disciplines as a searching method for identifying optimal solutions. GAs emerged in the science scene as early as the 1970s, with the work of Holland [1]. As with other probabilistic searching methods such as simulated annealing and evolutionary strategies, GAs have a high probability of locating the global solution optimum in a multidimensional searching space.

The implementation of GAs in electromagnetic device optimization, especially inverse optimization, was recently proposed for electric machine shape pole design [2]. The robustness of the method and its ability to deal with optimization variables using their encoded binary representations, rather than directly, is very advantageous and promising.

In this paper the authors present a different approach to the inverse optimization of core shapes using again the principles of the GA search. We propose binary encoding for the initial population and its offspring using the core area itself. Initially, we define the entire available area that can be occupied by the "optimal" core shape. Each pair of triangular finite elements that construct the core area is established as a separate gene in the chromosome with two distinguished binary values, 1 and 0, physically resulting in either the existence or absence of the core area at any given position. Using the GAs main operators - reproduction, crossover and mutation - the searching pattern of GAs is established. Relatively easily and quickly, the optimal chromosome, which is nothing but the encoded information of the optimal solution (in our case the shape of the core), is achieved.

GENETIC ALGORITHMS IN BRIEF

As aforementioned, the GAs were developed by Holland [1] in the attempt to summarize his work on artificial system design that simulates some of the characteristics of the natural systems.

Therefore, the GAs are in fact a search algorithms based on the mechanics of natural selection and natural genetics [3]. The main goal in the GAs development was their robustness. Since where robust performance is desired, the nature does it better with its main features such as self-repair, self-guidance and reproduction, the development of an artificial system which can closely mimic the behavior of the nature is the main goal. The GAs are exactly that kind of a system: they start to search for the optimal solution of a problem from randomly crated population of chromosomes (strings). Those chromosomes that better fit the solution of the problem i.e. better suit the objective function, have larger possibility to survive and give new offsprings with the same (good) genes (information). Afterwards, through the process of crossover where the information (genes) were exchanged between any two randomly chosen chromosomes in the population, it is more likely that the information that better suit the objective function will be dominant in all chromosomes of a new generated and improved population. Occasionally, the third GAs operator - mutation will occur in order to protect the population of the complete loss of some important genetic information [3].

It is natural to ask the question: Why GAs are better than other optimization and searching algorithms, especially knowing that the main GAs operators are very simple in their nature? The GAs, in general avoid the local minimum of the objective function. They search for the optimal solution in the entire solution space not in the local neighborhood of the current point. They also use directly the objective function which improves the searching speed and its quality. Finally, the GAs instead of using directly the optimization variables, they work with their encoded values. Thus, the GAs become independent of the problem specification, the physical characteristics of the optimized function or even its amplitudes. As a result, today the GAs are considered one of the most efficient and robust searching procedures. Their main points according to Goldberg [3] can be summarize as follows:

- GAs does not work with the parameters itself but with their encoded expressions.
- GAs search from a population of points, not a single point.
- GAs use directly objective function as a optimization criterion, not its derivatives or any other auxiliary information.
- GAs transition rules are rather probabilistic, not deterministic.

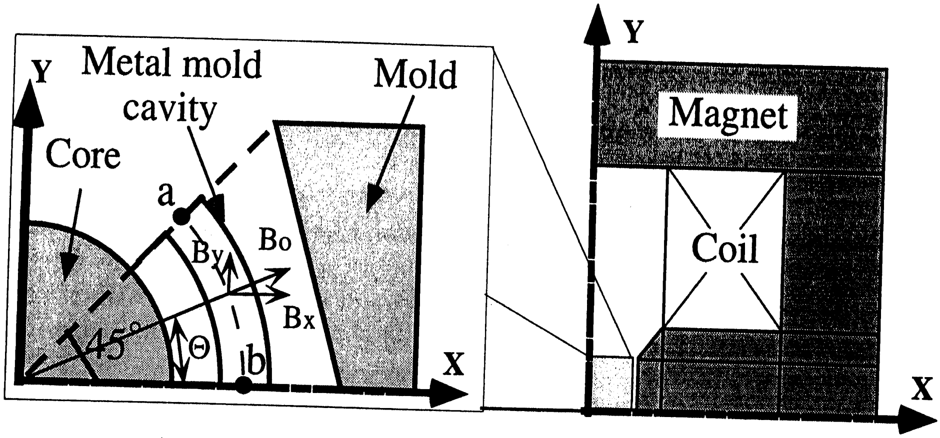
OPTIMIZATION PROBLEM

The model that was treated for core shape optimization is presented in Fig. 1. Figure 1*a* is a close-up figure of the area in question, while Fig. 1*b* shows the entire analyzed model. We define the following problem:

Find the optimal shape of the core and mold inside permanent magnet production equipment which results in the constant intensity value of magnetic flux density $\mathbf{B}$ *along arc line* $\mathbf{a}-\mathbf{b}$, *and with defined direction of the magnetic flux vector* $\mathbf{B}_0$ *according to its position:* $B_x = \mathbf{B}_0 \cos\theta$ and $B_y = \mathbf{B}_0 \sin\theta$.

The following objective function was defined:

$$O = \sum_{k=1}^{m} \left[\{B_{0kx} - B_{kx}\}^2 + \{B_{0ky} - B_{ky}\}^2 \right] \longrightarrow \min , \qquad (1)$$



a) close-up view b) entire model

Fig. 1. Analyzed model

where m is the total number of observation points along arc line $a - b$, B_{0kx} and B_{0ky} are the desired values of magnetic flux density $x-$ and $y-$components at point k, respectively. B_{kx} and B_{ky} are the obtained values for magnetic flux density $x-$ and $y-$components at each optimization step - for each new genetic population.

At the beginning, a 2-D finite element mesh was developed. Each pair of triangular finite elements were treated as one cell in the model, resulting in a set of available quadrilateral areas (Fig. 2). Afterwards, the initial area of the core and the initial area of the mold of the excited magnet were established. The initial population, which consisted of 20 strings (chromosomes), was generated randomly. The value of each gene inside the strings was randomly defined as 1 - if the gene represented the encoded quadrilateral area belonging to the core area or 0 - if the gene represented the encoded quadrilateral area belonging to the air region. The string lengths varied depending on the developed 2-D mesh and the order of the generation. Using the objective function (1), the average fitness of each string was defined and strings with the largest fitness were reproduced constructing another set of new 20 strings using a crossover operation. Next, we computed the fitness of each new generated string again using the objective function (1). Finally, from both sets of strings, the second population (children) was generated by selecting 20 strings from among those with the largest fitness value. The simplified algorithm of the proposed GA procedure is presented in Fig. 3. Optimization procedure was repeated until a minimization of the objective function (1) was achieved. The parameters of the GA optimization procedure must be defined before the searching process begins. In our case, the following parameters were selected: a one hundred number of the generations, a crossover rate of 0.6 and a mutation rate of 0.05.

METHODS FOR SELECTION OF GENES

As aforementioned, in our research we employed strings with various lengths depending on the order of the generation and the developed 2-D finite element mesh. Also, we already pointed out that each cell (gene) inside the string was established as a pair of triangular finite elements consisting quadrilateral area and had a binary value 0 or 1. In this paragraph, we would like to discuss the method of gene selection. In other words, we would like to explain more physically what was the criterion that a certain quadrilateral area must satisfied in order to become a possible cell

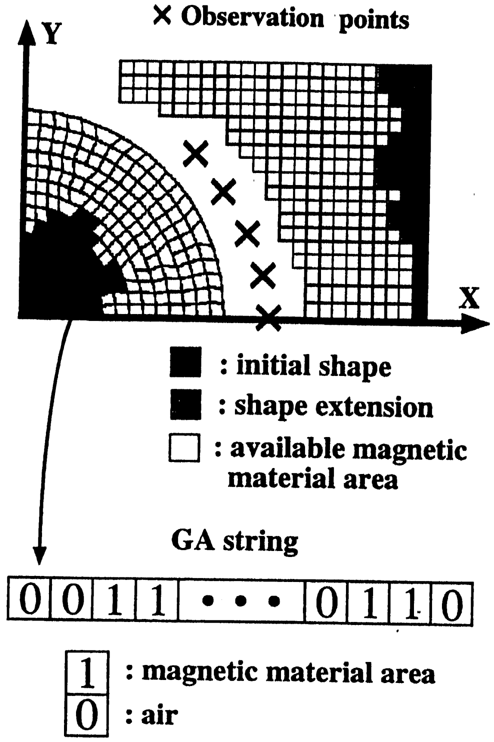


Fig. 2. Model suitable for GA implementation

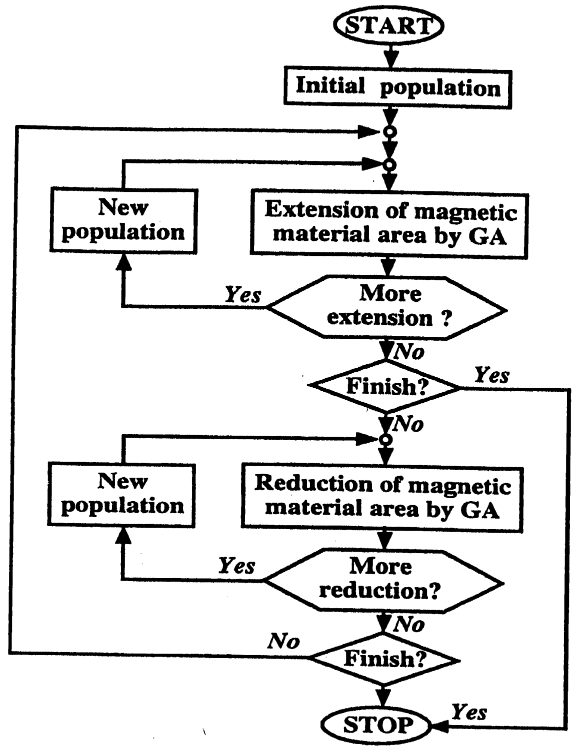


Fig. 3. Algorithm

(gene) inside the strings. Each cell with binary value 1 represents encoded information that at this area a magnetic material belonging either to the mold or to the core exists. On the other hand, we have to take into account that each new selected cell (gene) must be connected with the previously established magnetic material area - simply the arbitrary "flying"cells of magnetic material inside the entire available magnetic material area are not allowed. Therefore, the following criteria were taking into account in order to establish any new cell (gene) inside the string:

1. New cell must be in the adjoin neighborhood of the previously established magnetic material area;
2. The extension and reduction of the magnetic core area is enabled only in the radial direction;
3. The extension and reduction of the mold are is enabled only in the direction of x-coordinate.
4. The extension and reduction of the core and mold area are established in cycles - first extension then reduction, then again extension and so on. Switching from extension to reduction and visa verse is enabled using objective function.

The method that satisfied all aforementioned criteria in our research was named *non-restricted method.* As can be seen from Figs. 4*a* and 4*b*, in this method each new cell is selected as a natural extension (Fig. 4*a*) or reduction (Fig. 4*b*) of the previously established magnetic material area in the appropriate direction - for the magnetic core area radial direction and for the mold area x-coordinate direction. This method is easy for numerical implementation, but unfortunately usually results in very complicated and rather not physically applicable shapes of magnetic core and mold area. Therefore, we developed another method named *restricted* which successfully overcomes this problem. For this method, one additional criterion was necessary to be satisfied in order to include a possible cell inside the newly generated sting. This additional criterion can be formulated as:

- The difference between two adjoin gene candidates must be less or equal to two. In other words, if the distance between two adjoin cells is larger than two cells, then this possible cell will not be included inside the newly generated string (see Fig. 5).

This additional criterion acts like a constrain and enables generation of optimal solution with better physically acceptable magnetic core and mold shapes. The obtained solution by this method results in optimal shapes of the magnetic core and mold area with smoother surfaces.

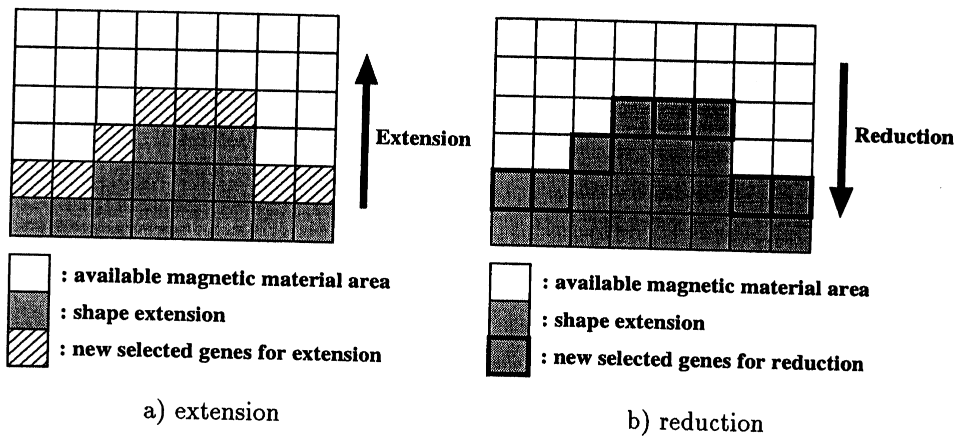


Fig. 4. Gene selection in non-restricted method a) extension b) reduction

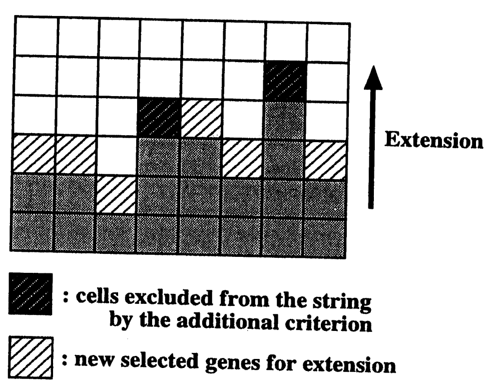


Fig. 5. Gene selection in restricted method - extension

OBTAINED RESULTS AND DISCUSSION

Non-restricted Method

The results obtained by the non-restricted method for optimization of the analyzed metal mold cavity inside permanent magnet production equipment are presented in Figs. 6 and 7. Fig. 6*a* represent the initial shape of the metal mold cavity before the optimization process is conducted. The obtained core and excited magnet wall shapes are presented in Fig. 6*b* (after the 26th generation) and in Fig. 6*c* (after the 41st generation). Additionally, the desired intensity of magnetic flux density vector **B** of 1.5 $[T]$ along line $a - b$ (see Fig. 2) and its vector distribution together with initial results and the results after the 26th and 41st generation are presented in Fig. 7. From Figs. 7*a* and 7*b* it is clear that the obtained results are very close to the desired results. The largest error can be observed for angles approaching 45°. It is interesting to point out that even though the obtained results show acceptable accuracy, the obtained shape of the core and of the the metal mold were not smooth and not easy physically applicable as we had expected.

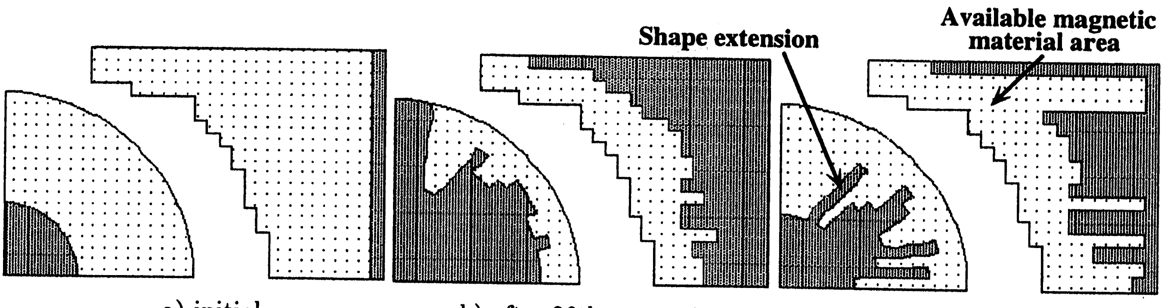
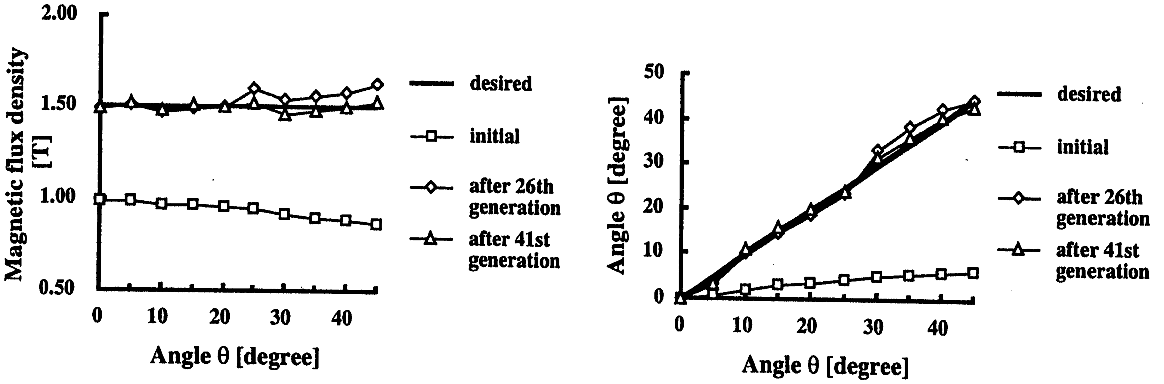


Fig. 6. The shape of metal mold cavity obtained by the non-restricted method



a) Intensity of magnetic flux density vs. position

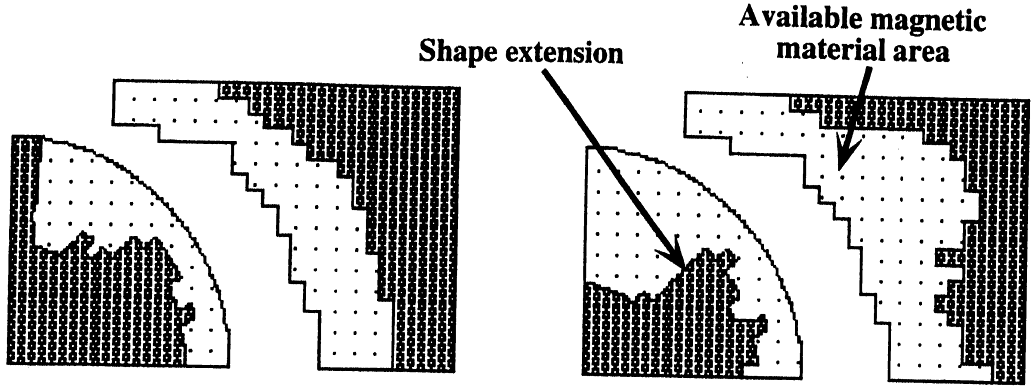
b) Direction of magnetic flux density vector vs. position

Fig. 7. Obtained results by the non-restricted method

Restricted Method

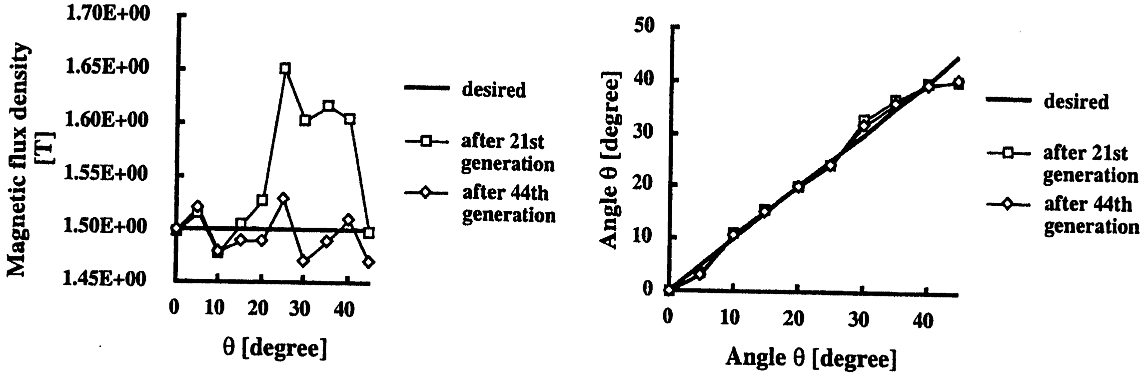
The results obtained by the restricted method are presented in Figs. 8 and 9. In this case a several cycles of extension and reduction had to be performed. However, since the changes of the intensity of magnetic flux density and the direction of its vector after the third cycle were extremely small, we regarded the obtained results after the second cycle as enough accurate to be established as an optimal results.

The extension of the shapes in the first cycle and the reduction of the shapes in the second cycle were finished after the 21st and 44th generation, respectively. The obtained magnetic core and mold shapes are presented in Fig. 8*a* (after the 21st generation) and in Fig. 8*b* (after the 44th populations). From Fig. 8*b*, it is clear that the obtained shapes of magnetic core and mold area



a) after 21st generation b) after 44th generation

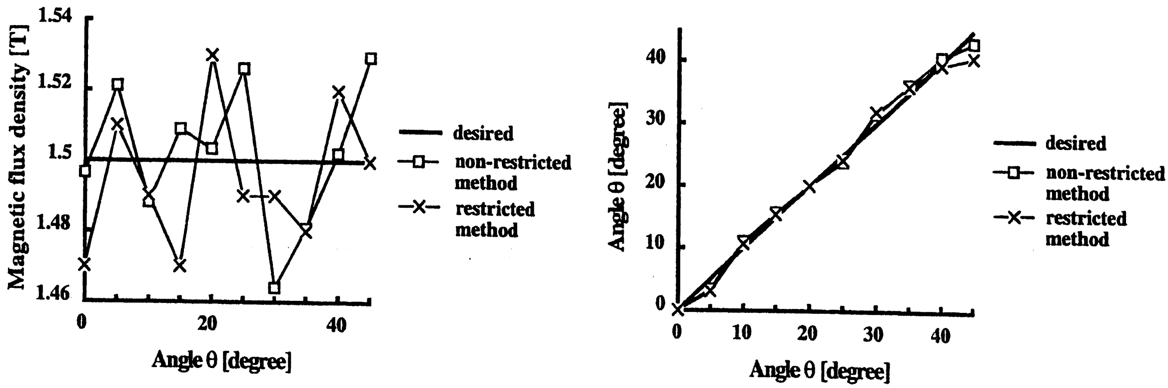
Fig. 8. The shape of metal mold cavity obtained by the restricted method



a) Intensity of magnetic flux density vs. position

b) Direction of magnetic flux density vector vs. position

Fig. 9. Obtained results by the restricted method



a) Intensity of magnetic flux density vs. position

b) Direction of magnetic flux density vector vs. position

Fig. 10. Compared results

are smoother than those obtained by the non-restricted method. The CPU time using SG work station type *Indigo*^{2} was about 3000 seconds per generation.

Compared Results

Next, we compared the final results obtained by both methods: the non-restricted method and the restricted method. The compared results are presented in Fig. 10 and in Table I. In Fig. 10 the compared results for both method along with the desired results are presented, while in Table I the maximum and average relative errors for both methods are presented.

Table I The maximum and average relative errors

	Magnetic flux density			
	Intensity Values		Direction	
	Non-restricted	Restricted	Non-restricted	Restricted
Maximum Error [%]	2.39	2.00	1.91	4.35
Average Error [%]	1.08	1.13	1.00	1.17

From Table I it is obvious that the obtained results by the both methods are very close in-between. While the maximum relative error is less than 2.4 [%] in case of intensity values of magnetic flux density and less then 4.4 [%] in case of the direction of its vector, the average relative errors are almost the same for both methods and are in the range of only 1 [%]. Since the obtained optimal shapes of magnetic core and mold area are smoother for the restricted method than for the non-restricted method, the restricted method is preferable as a optimization tool resulting in physically applicable shapes.

CONCLUSIONS

A new approach for the inverse optimization of core shapes of electromagnetic devices using a GA searching process was presented. The proposed method was applied for design optimization of metal mold cavities inside permanent magnet production equipment. A method for directly encoding the entire available core area using binary coding was introduced. The obtained results show high accuracy with the desired results. Two different methods for selection of the genes inside the strings: the non-restricted method and the restricted method were proposed. The obtained optimal shapes by the non-restricted method were not smooth and physically applicable. To solve this problem additional constraint condition was added like in the restricted method resulting in smoother shapes of the core and mold magnetic area. The robustness and simplicity of the GAs show that this method has much potential and is very promising as an optimization tool.

References

[1] J. H. Holland: "Adaptation in Natural and Artificial Systems," *University of Michigan Press, Ann Arbor*, Michigan, 1975.

[2] G. F. Uler, O. A. Mohammed and C. S. Koh: "Utilizing Genetic Algorithms for the Optimal Design of Electromagnetic Devices," *IEEE Transaction on Magnetics*, Vol. 30, No. 6, November 1994, pp.4296-4298.

[3] D. E. Goldberg: "Genetic Algorithms in Search, Optimization and Machine Learning," *Addison-Wesley*, Massachusetts 1988.