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3D FINITE ELEMENT BASED OPTIMIZATION OF SHEET HEATING IN TRANSVERSE FLUX INDUCTORS

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Abstract*: This paper is focused on the optimization of transverse flux inductors for the continuous heating of metallic sheets. The goal of the optimization process is to obtain a minimum non-uniformity of the transversal profile of the power induced in the sheet, the objective function being evaluated by using a 3D finite element model.*

1. INTRODUCTION

The optimal design in engineering supposes a good understanding of optimization methods and phenomena involved in the device operation. Many theoretical and experimental studies involving optimizations in transverse flux induction heating systems were focused in the last period on the study of transversal non-uniformity of temperature across the sheet width. This non-uniformity of transversal profile of sheet heating is the result of the non-uniform pattern of the induced currents in the sheet.

The geometry of a transverse flux inductor (TFI) with six coils shown in Figure 1 emphasizes the fact that the moving parts of magnetic core and the cooper screens can be displaced in transversal (Oy) and normal (Oz) directions with respect the moving sheet. The positions of these TFI components influence the non-uniformity of transversal profile of power induced in the sheet.

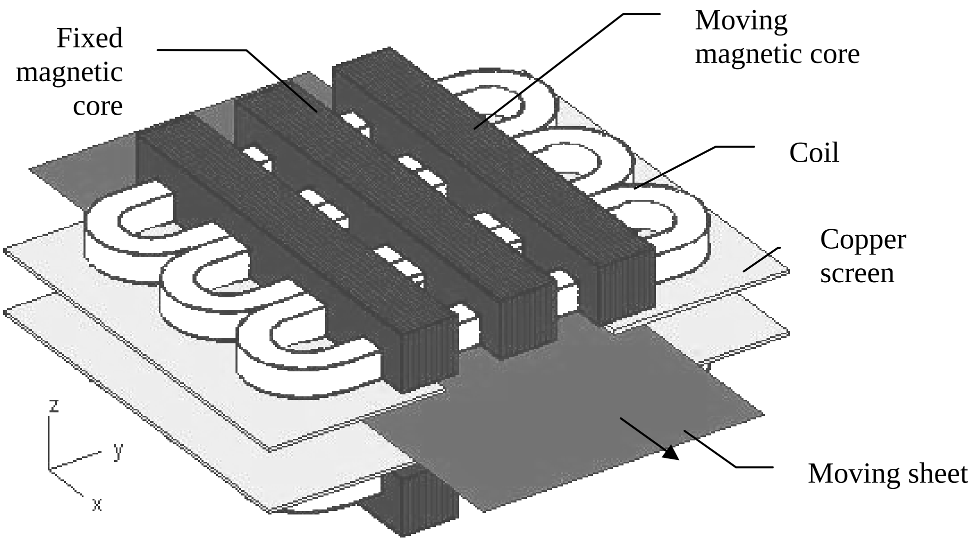

Fig. 1. Geometry of a transverse flux inductor

2. FORMULATION OF THE OPTIMIZATION PROBLEM

The device studied in this paper is a TFI inductor with six coils, used for heating an aluminum sheet of thickness $a = 0.6\ mm$, resistivity $\rho = 0.05 \cdot 10^{-6}\ \Omega m$ and width $2b = 1500\ mm$.

The positions of the moving magnetic cores and copper screens of the inductor with respect to the sheet to be heated, Fig. 2, are characterized by the geometrical parameters:

(1) the coordinate y_m of the symmetry plane of mobile magnetic core that characterizes its position in transversal direction Oy;
(2) the width b_s of the screened region of the sheet to be heated;
(3) the distance Δ_s between the two copper plates of the two electromagnetic screens,

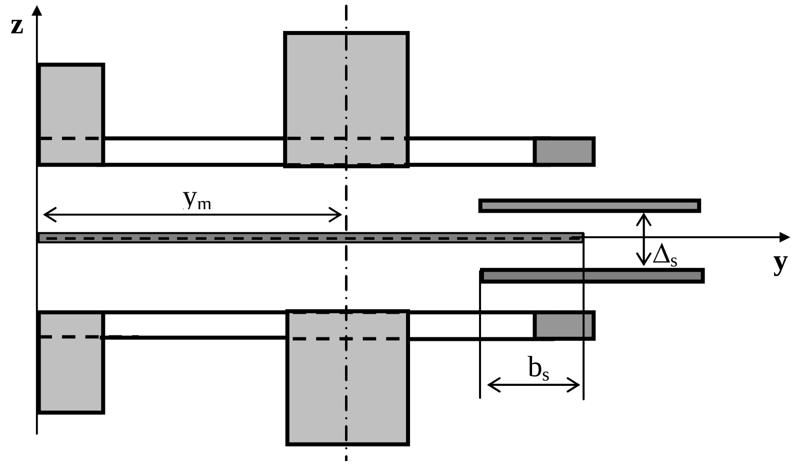

Fig. 2. Position of inductor magnetic cores and electromagnetic screens

These are the three design variables of the optimization process of the inductor geometry.

For given values of the other specific data of the inductor, the optimization process with respect to the three previously defined parameters, aims to define an inductor that satisfies the criteria of a minimum non-uniformity of the *transversal profile of the induced power density* induced in the sheet.

The transverse flux induction heating process used for continuous heating of thin metallic sheets supposes the passing of the sheet through zones with higher and lower levels of induced power volume densities. By integrating the volume density of the induced power along the inductor we obtain a quantity that reflects the level of transversal non-uniformity of the temperature at the end of the heating. If *pint* is the integral of volume density of induced power along Ox coordinate, Fig. 1, the *transversal profile of the induced power density* is the function:

$$P(y/b)=[pint(y/b)-pint(0)]/pint \tag{1}$$

that depends on the relative transversal coordinate y/b, where b represents the half sheet width. This function, Fig. 3, provides an image of the transversal temperature non-uniformity of the sheet at the end of the heating.

In order to characterize the level of heating non-uniformity in transverse flux heating, we propose to use a criterion defined by formula:

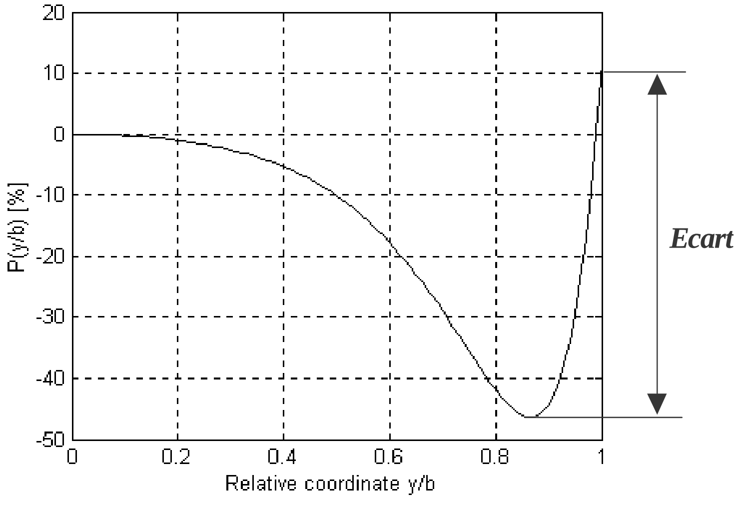

Fig. 3. Transversal profile of induced power density

$$\mathrm{Ecart}=\max\{P(y/b)\}-\min\{P(y/b)\} \qquad (2)$$

The objective function *Ecart* is evaluated on a limited search domain by the 3D finite element analysis of the electromagnetic field.

The three parameters of the optimization problem y_m, b_s and Δ_s are characterized by the following restrictions that define the search domain:

$$\begin{gathered} 0.22b < y_m < b\,, \\ 0.5\Delta < \Delta_s < \Delta, \\ 0 < b_s < (b - y_m \cdot b + b_{cm}/2)\,, \end{gathered} \qquad (3)$$

where $\Delta = 170$ *mm* is the inductor air-gap and $b_{cm} = 180$ *mm* is the width of the mobile magnetic core. The inductor pole pitch is $\tau = 800$ *mm*, and the supply frequency is $f = 130$ *Hz*.

3. FINITE ELEMENT TFI ANALYSIS

The 3D **numerical model** of the studied TFI device involves several types of volume and surface regions, Fig.4, characterized by the following formulations of the electromagnetic field:

- *Magnetic cores* – magnetic and non-conductive volume regions, where the formulation in total magnetic scalar potential Φ is used. The equation to be integrated in these regions is:

$$\mathrm{div}\,[\mu\cdot(-\,\mathrm{grad}\,\Phi)] = 0 \qquad (4)$$

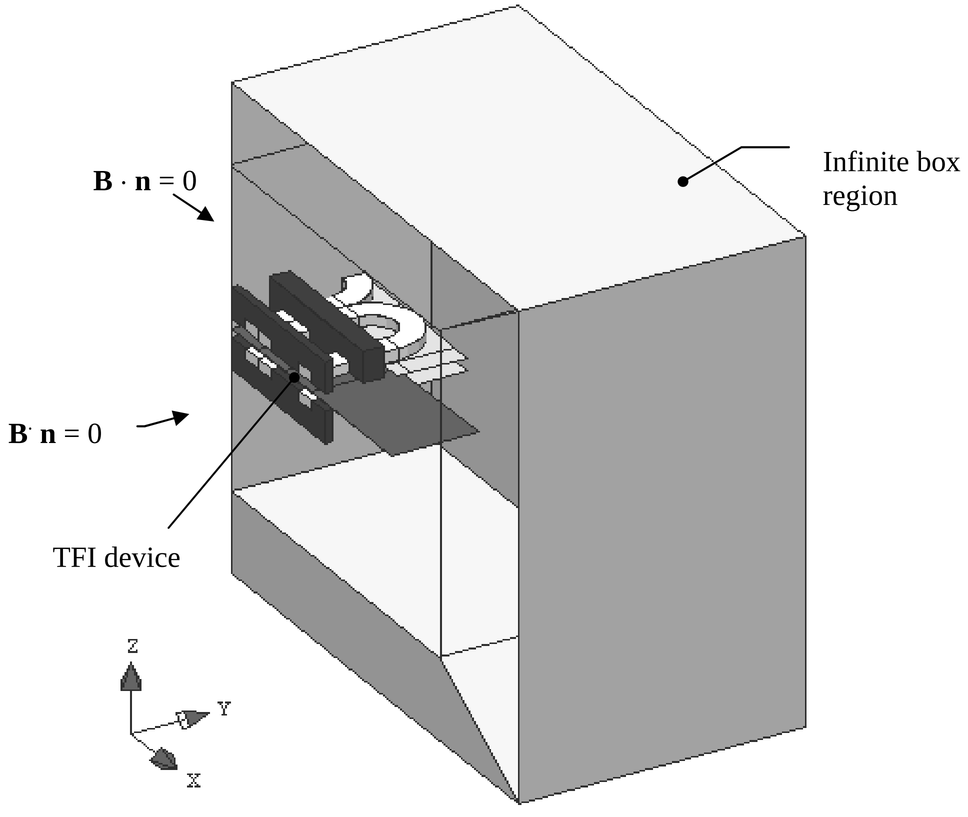

Fig. 4. Computation domain of electromagnetic field and associated boundary conditions

- *Metallic sheet* and *electromagnetic screens* – flat eddy current regions modeled as surface regions, where a special surface formulation of the electromagnetic field is used. This formulation, called *Hyperb_J_Conductor* formulation in Flux3D, supposes that the variation of the electromagnetic field on the sheet thickness is defined by the 1D analytical solution characterizing the electromagnetic field diffusion in an infinitely extended plane plate situated in an unidirectional and tangential oriented magnetic field .
- *Surrounding air* – non-magnetic and non-conductive volume region that includes the stranded type inductor coils - source of the electromagnetic field, where the reduced magnetic scalar potential Φ_r is used. The equation associated with this formulation is:

$$\mathrm{div}\,[\mu_0(-\,\mathrm{grad}\,\Phi_r + \mathbf{H_0})] = 0 \tag{5}$$

The inductor magnetic field $\mathbf{H_0}$ generated by the inductor coil regions is computed using the Biot – Savart formula.

A special feature of Flux3D software package, named infinite box, is used to model the open boundary of the problem. Other *boundary conditions* expressed in potentials are $\partial\Phi / \partial n = 0$ and $\partial\Phi_r / \partial n = 0$, equivalent with the condition $\mathbf{B} \cdot \mathbf{n} = 0$ on boundaries (symmetry planes) where the magnetic field in tangential oriented.

4. TECHNIQUES OF TFI OPTIMIZATION

The optimization techniques used to minimize the quantity ***Ecart*** that represent the objective function of this study include a deterministic algorithm and a stochastic one. The deterministic algorithm is represented by the Simplex Algorithm and the stochastic one is represented by the Genetic Algorithms (GA).

Simplex Algorithm (SA) is a deterministic algorithm that is very robust, rapidly convergent and easy to implement. This algorithm has the ability to analyze the relief of the objective function and to converge rapidly towards the closest local minimum point. The main disadvantage, that is common to all the determinist methods, consists in leading to the same solution that is not necessarily the global minimum in case of objective functions with many local minimums. This drawback was surmounted by restarting the algorithm for several times from initial starting points randomly chosen in the searching domain. Then, the smallest value of the objective function selected from the list of the minimum points is considered as the global minimum of the optimization problem.

This algorithm was applied to the optimization problem characterized by the objective function *Ecart* and three design variables: y_m, Δ_s and b_s. This TFI optimization problem is based on a precise evaluation of the objective function using the 3D finite element model of TFI described in the previous section. This 3D model was developed in the Flux3D software package, while the Simplex Algorithm was implemented in Flux command language.

Genetic algorithms (GA) are evolutionary techniques robust and easy to implement. Genetic algorithms handle a population of candidate solutions that evolves at each iteration t of the algorithm, called generation. Each candidate solution or individual is encoded as a chromosome by using some alphabet, like binary strings, real numbers or vectors. Each chromosome has a measure of fitness via a fitness function, which is derived from an objective function. The evolution is simulated through this fitness function and the genetic operators. Genetic algorithms seem to be very promising in electromagnetic devices design, due to their capability to provide solutions to difficult design problems. The main disadvantage of this kind of optimization algorithms is given by the relatively large number of evaluations of the objective functions until the optimum point is found.

The GA with a population of 50 chromosomes, tournament selection, arithmetic crossover, uniform mutation and 20 generations was applied in the same conditions for the minimization of the objective function *Ecart*, with the same three design variables and using the Flux3D finite element model of the TFI and the Flux command language.

5. OPTIMIZATION RESULTS

The optimization results obtained using the *SA* are presented in Table 1. The stop criterion corresponds to the relative error of 0.5 % with respect to the minimum of *Ecart* objective.

Table 1 Simplex Algorithm (SA) optimization results

y_m [mm]	b_s [mm]	Δ_s [mm]	*Ecart* [%]	No. eval.
414	52	135	20.894	36
409	84	164	20.993	39
411	94	164	20.871	59

By studying the results in Table 1 we can notice that the points of minimum in the three cases are close to one another, but they correspond to different values of the three optimization parameters. This proves that in our case we deal with an objective function with many local minimums. The number of evaluations in the three cases is quite small.

The optimization results obtained using a *GA* characterized by a population of 26 individuals and 10 generations, are presented in Table 2. The time required for the evaluation of a single individual is about 5 minutes and the total computation time for the entire optimization process is about 22 hours on a Pentium IV, 1.7 GHz.

Table 2 Genetic Algorithms (GA) optimization results

y_m	b_s	Δ_s	*Ecart* [%]	No. eval.
0.422	0.119	0.121	21.487	260

The *GA* results in Table 2 are not so satisfactory compared with the solution obtained using the *SA* with respect to the number of evaluations. However, better results are expected for larger numbers of generations.

The graphical results presented in Fig. 5, correspond to the positions of mobile magnetic core

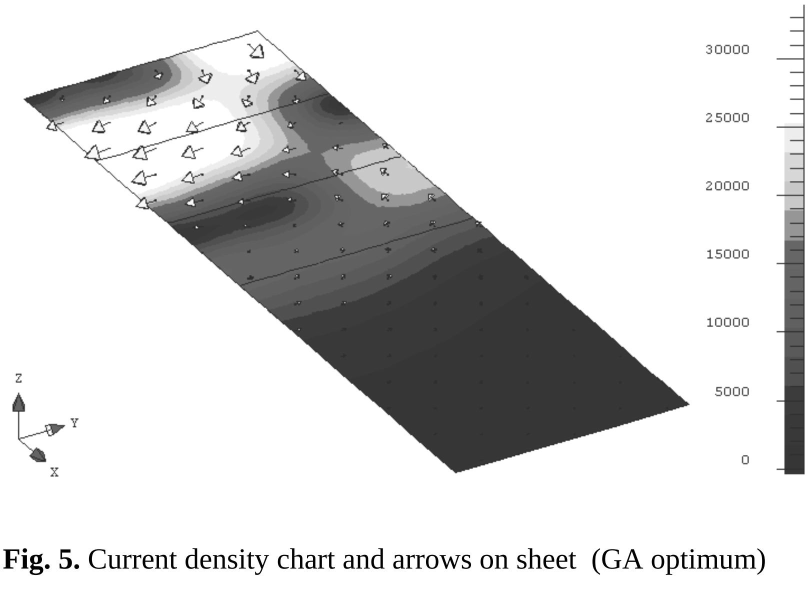

Fig. 5. Current density chart and arrows on sheet (GA optimum)

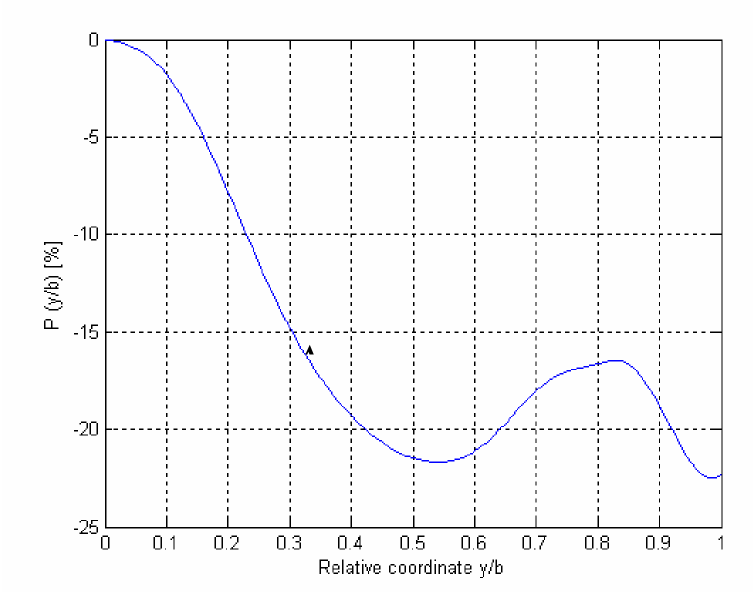

Fig. 6. Profile of the integrated induced power density in the aluminum sheet (GA optimum)

and copper screens defined by the data in Table 2. The orientation and the magnitude of the currents induced in the sheet, Fig. 10, are in accordance with the source of the electromagnetic field that is the current in the coils of the TFI inductor.

The presence of the electromagnetic screens made of copper ensures the reduction of the magnetic field in the region between the two plates, respectively on the lateral side of the heated sheet. Thus the combined action of the mobile magnetic core and copper screen ensures a relatively reduced variation of the transversal profile in the range y/b = (0.33 - 1.0), no more than 6 %. However the complete profile, Fig. 12, characterized by the *Ecart* ≈ *- 22 %* shows that the sheet is “under-heated” in this region. The solution to further reduce the *Ecart* consists in the reduction of the air-gap of the mobile magnetic core in order to increase the magnetic field, and respectively the induced power.

6. CONCLUSIONS

This paper proves that the optimization algorithms can be successfully used in the design of electromagnetic devices.

The Flux3D software allows the implementation of optimization algorithms in general and of GA in particular to solve optimization problems with the drawback that sometimes the time required to find adequate solutions can be very long. The most important time in the optimization problem is required by the evaluation of objective functions due to the complexity of the 3D finite element model. In such cases more advanced hardware and parallel computation are more adequate since they can significantly minimize the computation time.

REFERENCES

[1] V. Fireteanu, B. Paya, M. Popa, T. Tudorache, "Optimal parameters of transversal flux inductors", Proc. of COMPUMAG2003, Saratoga Springs , July 2003.

[2] P. Di Barba, F. Dughiero, S. Lupi, A. Savini, "Optimal shape design of devices and systems for induction heating: methodologies and applications", Proc. of HIS-01 Seminar , Padua, September 2001.

[3] V. Fireteanu, Y. Neau, B. Paya, T. Tudorache, "Parameters of transversal non-uniformity of induced power in transverse flux induction heating", Proc. of OPTIM 2002 Conference, Brasov, May 2002.

[4] S. Galunin, M. Zlobina, Yu. Blinov, B. Nacke, A. Nikanorov, H. Schulbe, “Numerical optimization in design of induction heating systems”, Proc. of HES-04 Symposium, Padua, June 2004.

[5] D.E. Goldberg, J. Richardson, "Genetic algorithm with sharing for multimodal function optimization", Proceedings of the Second International Conference on Genetic Algorithms, 1987.