Multi-objective design of a power inductor: a benchmark of inverse induction heating

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***Abstract*— In the paper, a bi-objective optimization problem characterized by coupled field analysis is investigated. The optimal design of a pancake inductor for the controlled heating of a graphite disk is considered as the benchmark problem. The Pareto front trading off electrical efficiency and thermal uniformity is identified by means of a standard algorithm of evolutionary computing. A mesh-inspired definition of thermal uniformity is proposed.**

Keywords—induction heating, coupled problem

I. Introduction

Induction heating is applied in several thermal processes for achieving a prescribed temperature distribution in the workpiece. In fact, induction heating is able to localize the heat sources inside the workpiece with high efficiency and good temperature control. Design of inductors implies the solution of coupled electromagnetic and thermal fields, along with the use of optimal design procedures to identify the best possible device or process. In the paper, an approach in terms of multiobjective optimal design [1] is presented; this approach generalizes a benchmark of inverse induction heating [3-5], where the original design was improved in terms of temperature uniformity using a single objective. Here, an automated procedure of bi-objective optimization based on NSGA-II algorithm [1, 6] has been used to solve a multiphysics inverse problem: both magnetic and thermal fields are synthesized at the same time, in order to fulfill prescribed objective functions. Specifically, the temperature uniformity in the workpiece is searched for in a twofold way: a classical min-max criterion, and a new one named "criterion of proximity". A family of improved solutions, found using both criteria, is considered in a comparative way.

I. Direct and inverse problem

The device, considered as a benchmark problem for optimization, is a graphite disk with an inductor exhibiting 12 copper turns (pancake inductor) the two most internal of which, as well as the two most external, are located at the same height. All turns are series connected and carry a current of 1000 A_{rms} at 4000 Hz [3-5, 7]. A ferrite ring might be incorporated under the two most internal turns as a flux line concentrator. Fig. 1 shows the axial-symmetric model of the device with the graphite disk to heat; the design variables are also shown.

The magnetic problem is solved by means of finite-element analysis in time-harmonics conditions, in terms of **A**-V formulation [8-16]. The actual current distribution in each turn is taken into account to correctly evaluate the inductor efficiency. The thermal problem is solved in steady-state condition, assuming the power density in the disk, which is computed from the magnetic field analysis, as the source term [17]. The thermal domain takes into account only the graphite disk, along the boundary of which the condition of heat exchange holds. Values of both electrical and thermal conductivities are considered at the expected steady-state average temperature.

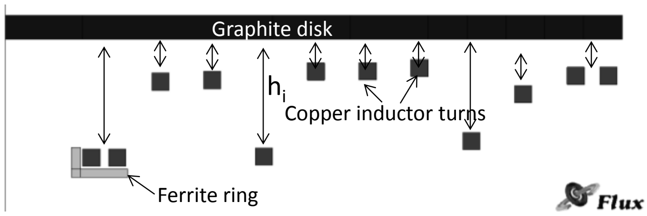

Fig. 1 Geometry of pancake inductor with 10 design variables.

As far as the inverse problem is concerned, two design criteria have been defined. The electrical efficiency, η, defined as the ratio of active power transferred to the disk to the one supplied to the inductor, is to be maximized. Moreover, the uniformity of temperature profile in the graphite disk at thermal steady state is to be maximized. Accordingly, having defined the 10-dimensional vector g of geometric variables, the following two objective functions have been implemented:

$$f_1(g) = 1 - \eta(g) \quad (1)$$

$$f_2(g) = \left[N_{\max} - \sup_j N_j\left(|T_j(g,\gamma) - T_i(g,\gamma)| < \frac{\Delta T^*}{2} \right) \right] j \neq i \quad (2)$$

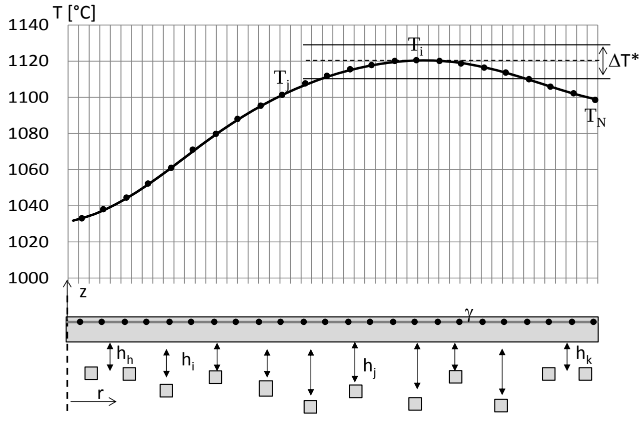

Fig. 2 Example of "criterion of proximity".

where f_2 is named "criterion of proximity" and is based upon a tolerance interval, ΔT*, around a give temperature value. An example is shown in Fig. 2: the reference path γ in the disk is sampled by means of N_{max} points; for each point, the corresponding temperature T_i, $i=1,N_{max}$ is evaluated and compared with the temperature T_j, $j=1,N_{max}$ $j\neq i$, of all the other sampling points. A T_j value is considered to satisfy the "criterion of proximity" if the condition $|T_j - T_i| < \Delta T^*/2$ holds. For a given T_i value, f_2 is the number of T_j values, $N_j(|T_j - T_i|<\Delta T^*/2)$, that satisfy the "criterion of proximity". Actually, the value of index $j=1,N_{max}$ that minimizes the right-hand side of (2) is searched for.

In practice, both functions (1) and (2) have to be minimized with respect to design variables shown in Fig. 1. Objective (1) refers to the magnetic domain, while objective (2) refers to the thermal one: a multiphysics and multiobjective inverse problem is so originated.

II. RESULTS

Fig. 3 shows the Pareto front of problem (1)-(2) approximated after 100 iterations using the NSGA-II algorithm [1,6] for the case without ferrite ring. An example of temperature profile for the two solutions located at Pareto front ends, and also for two other solutions located along the front and reported in Table 1, are represented in Fig. 4.

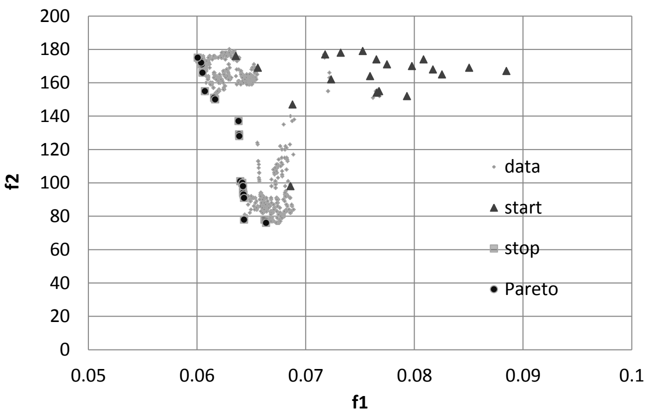

Fig. 3 Approximated Pareto front of problem (1)-(2).

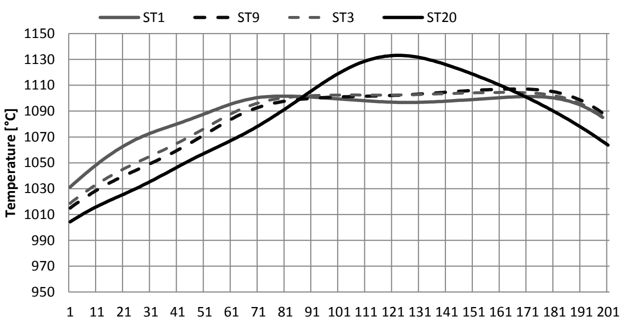

Fig. 4 Temperature paths along line γ for in Table 1.

TABLE I

BEST SOLUTIONS IN TERMS OF THERMAL UNIFORMITY AND EFFICIENCY. H_I IN [MM].

	h_{1-2}	h_3	h_4	h_5	h_6	h_7	h_8	h_9	h_{10}	h_{11-12}	f_1	f_2
s1	53.7	60.0	18.4	60.0	39.3	46.7	20.6	44.6	17.1	43.0	0.066	76
s3	54.7	51.7	16.6	60.0	43.5	45.9	33.1	46.1	23.5	44.3	0.064	94
s9	55.1	48.7	13.4	59.9	43.7	45.9	32.4	46.0	27.8	44.8	0.064	137
s20	59.9	4.8	60.0	32.8	47.3	59.4	59.8	47.7	48.5	38.4	0.060	175

Fig. 6 shows the turn positions for the two solutions located at the Pareto front ends.

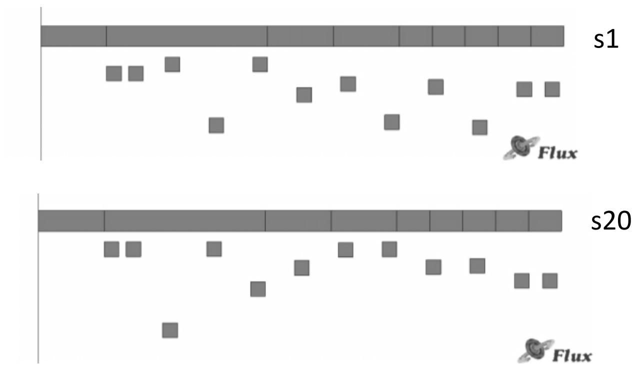

Fig. 6 Turn positions for solution S_1 and S_{20}.

The formulation of both field analysis and optimization problem for the case incorporating a ferrite ring, as well as computational data, will be discussed in the full-length paper.

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