Optimal Synthesis of Dual Frequency Transverse Flux Induction Heating of Metal Strips

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***Abstract*—The paper focuses on synthesizing the supply frequencies of the two coils of a transverse flux induction heater with the aim of achieving a uniform distribution of temperature in non-ferrous metal strips of different widths.**

Keywords—transverse flux induction heating, multi-objective optimization.

I. Introduction

The well-known process of transverse flux induction heating of non-magnetic metal strips has been proposed and studied since the middle of the last century for the advantages of using relatively low frequencies and the possibility of obtaining high electrical efficiencies. The acceptance of the process in industry has been very slow due to the complexity of designing and optimizing the inductors in order to avoid excessive localized heating which in particular can produce uneven heating of the strip edges. In fact, the optimal design of the inductor requires the control of the effects of many geometric and physical variables of the system, the frequency and the intensity of the supply current. For this reason, the major developments of the process for its application in industry occurred in the last twenty years with the availability of powerful numerical calculation means, application of mathematical optimization methods and invention and patenting of new inductor geometries. [1÷3]

Nowadays, these developments have led to the construction of industrial plants of considerable power, so that in new casting and rolling mill lines a total power up to 50 MW of transverse flux heaters is installed. [4] However, due to the complexity of the system geometry, the dependence of the characteristics of materials on temperature and, for the magnetic cores, on the intensity of the magnetic field, and the large number of variables that have influence on the results, even today a complete numerical optimization of the heater is not practicable. In recent years, some authors have examined the possibility of applying the so-called "Zone Control Heating" to the transverse flux induction heating, using inductors coils supplied at different frequencies. [5]

As known, the shape and value of the overheating or under-heating phenomena that occur at the strip edges depend, beside other factors, on the distance of the coils from the strip edges and the coil supply current and frequency. [6] This research aims to explore the possibility of obtaining a more uniform heating of nonmagnetic stainless steel strips of various widths by a transverse flux heater with two separate coils. As shown in Fig. 1, the over-heating or under-heating of the strip edges depend on the width of the inductor, that can be inner or outer with respect to the strip edges, on the distance between the strip edge and the coil edge and on the coil supply current and frequency.

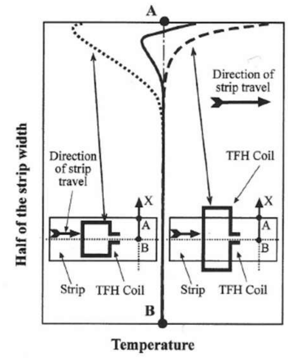

Fig. 1. Typical TFH coils: the coil on the left produces lower temperature on the strip edge (dotted line) while the one on the right produces higher temperature on the strip edge (dashed line). The combination of the effects may lead to a more uniform temperature distribution (continuous line) [3]

II. Model Description

The considered system is composed of

- an inductor with two couples of top and bottom coils one protruding (or ‘big’) and one "internal" (or ‘small’) to the tape edges, as schematized in figure 2; the dimensions of “internal” coil: 600x600mm, copper: 50x3 mm; distance from strip edge: 50 mm; dimensions of protruding coils: 900x600 mm, copper: 50x3 mm; distance from strip edge: 50 mm.
- the strips to be heated, moving in the gap between top and bottom coils at constant speed; strip: non-magnetic steel: 1 mm thickness, 700-750-800 mm width; gap: 60 mm
- top and bottom magnetic yokes used for concentration of magnetic field in the internal volume of the inductor; relative permeability: 50, no losses.

Transverse flux heaters produce a spatial distribution of the induced power that can be calculated by resorting to 3D models. In this research, the electromagnetic problem is solved by means of a standard vector potential formulation, where the metal sheet is described as a surface region [7]. A sequence of repeated 3D finite-element analyses, by varying frequency and current values, has been performed, this has made it possible to set up a database the subsequent optimization procedure was based on.

III. Inverse Problem

The goal of the inverse problem is to maximize the flatness of the profile of the total induced energy along the cross-section of the strip at the exit of the inductor system. The design variables are two independent supply frequencies and two inductor current intensities. The inverse problem identifies frequency and current values minimizing the following triplet of objectives, each of which contribute to make the energy profile along the cross-section of the strip as flat as possible:

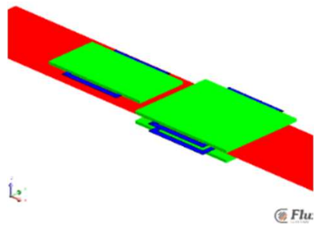

Fig. 2. Schematic of inductor (blue), strip (red) and magnetic yokes (green) system

$$f_1 = \frac{\max\quad {}_{t,w})-\min(E_{t,w})}{\max(E_{t,w})} \quad (1)$$

$$f_2 = \min\left(\sum_{i=1}^{N}\frac{|E_{t,i}(W)-E_{t,mean}(W)|}{\Delta E(W)}\right) \quad (2)$$

$$f_3 = \frac{\max(E_{s,w})-\min(E_{s,w})}{\max(E_{s,w})} + \frac{\max(E_{b,w})-\min(E_{b,w})}{\max(E_{b,w})} \quad (3)$$

where: $E_{t,w}$ is the total energy induced on the strip of 'w' width that is computed as the sum of the energy produced by the protruding inductor, $E_{b,w}$, and the internal inductor, E_{sw}. $E_{t,i}(w)$, with i=1,..N, is a set of N=10 energy values, sampled along the width of the strip; $E_{t,mean}(w)$ is the average of the N $E_{t,i}(w)$ values, $\Delta E(w)$ is the admitted variation (1%) around the average value $E_{t,mean}(w)$ equal to 5 MJ.

The inverse problem exploits the aforementioned database of energies, evaluated with a current amplitude of 1000 A_{rms} at different frequencies from 50 Hz to 1500 Hz with a step of 50 Hz, supplying one inductor at time. The optimization is performed by the Genetic Algorithm, MNSGA, as presented in [6]. The design variables are the frequency and current in each inductor. Due to the linearity of the model, the energy values in the database can be scaled, modifying the supplied currents with quadratic law, in order to reach the total energy required by the process.

IV. Results

The two inductors system was designed in order to heat 750 mm width strips. This preliminary analysis aims to investigate the possibility of heating strips of different widths (700 and 800 mm) within the same inductors fed at different frequencies. In Fig. 3, the improvement obtained for the 750 mm strips, where the small inductor is fed at 250 Hz and the big one at 50 Hz, is presented with the energy distributions that can be obtained by feeding both the inductors at the same frequency, of 250 Hz, 50 Hz and 150 Hz, respectively.

The figure shows that results are poorly sensitive to frequency variation when the strip is the one for which the inductor system has been designed, i.e. 750 mm. In Fig.4, the improved distributions calculated with the design variables related to the Pareto fronts for the three types of strips are presented. The distributions of induced energy are along half of the width of the strip (from the center to the edge) because of the system symmetry. In Fig. 5, the improvement obtained for the 800 mm strips, feeding the small inductor at 1050 Hz and the big one at 250 Hz, is presented together with the energy distributions that can be obtained by feeding both the inductors at the same frequency, 1050 Hz, 250 Hz and 650 Hz. For this case, the use of two appropriate optimal frequencies shows a more uniform distribution of the total induced energy and that this solution is non-dominated with respect to the tentative initial solution with respect to all three objectives

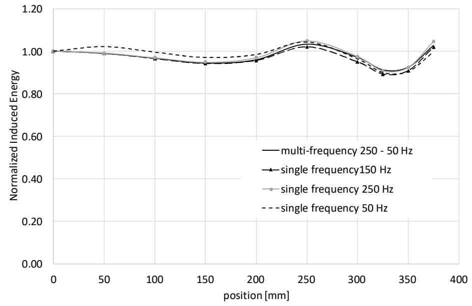

Fig. 3. 750 mm width strip. Improved distribution with dual frequency and the best distributions obtained with a single frequency.

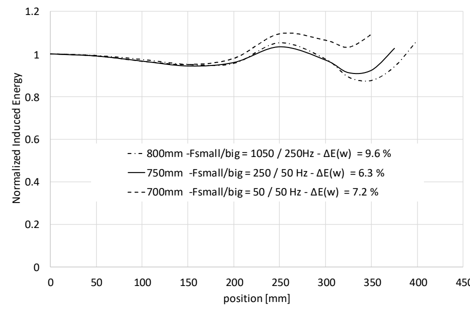

Fig. 4. Improved distribution of the induced energy at the exit of the inductors. (0 mm - Strip axis; 450 mm - Strip edge).

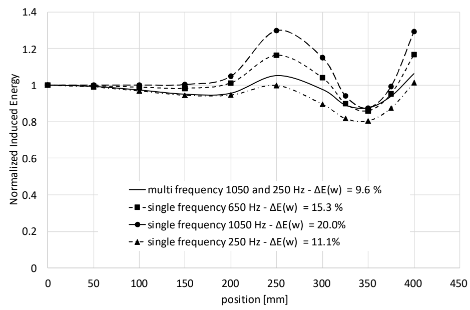

Fig. 5. 800 mm width strip. Improved distribution with dual frequency and the best distributions obtained with a single frequency.

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