DESIGN OF A FOIL-COILED INDUCTOR FOR THE HEATING OF STEEL WIRES

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INTRODUCTION

The main advantage of induction heating over other heating methods resides in its speed and efficiency of heating. In some cases however, practical constraints can make a high efficiency hard to obtain by using classical solenoid inductors (as in Orfeuil) [1]. As a consequence, the performance of other inductor geometries should be studied. This paper deals with the design of a foil-coiled inductor as a possible alternative for classical coils.

THE FOIL-COILED INDUCTOR CONCEPT

The foil-coiled inductor consists of a wide, thin copper sheet, which is coiled around an insulating central tube. A certain air gap is left between consecutive layers to allow cooling. The electrical connection of the inner layer is realized through a copper bar which is placed in parallel with the insulating tube. The steel wire that is to be heated, travels through the central tube. An inductor of this kind is shown in figure 1.

MODELLING OF THE INDUCTOR

When modeling a classical inductor, it is sometimes sufficient to consider only one turn of the coil (as in Henrotte et al) [2]. As a consequence, classical inductors can be studied by using relatively small models. In case of the foil-coiled inductor, the entire inductor has to be incorporated in the model. This leads to considerably larger models which can not be handled directly. Therefore, the following approach has been used.

In a first stage, material properties were considered temperature-independent and a nonlinear behaviour of the iron was supposed. A time-harmonic, nonlinear calculation was performed to solve the following convection-diffusion equation (as in Hameyer) [3] for the axisymmetric problem by the finite element method :

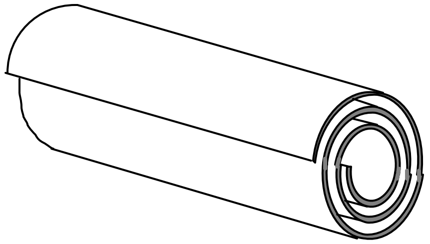

Figure 1 Foil-coiled inductor.

$$-n \frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial (rA_q)}{\partial r}\right) - n\frac{\partial^2 A_q}{\partial x^2} + jws A_q = -s\Delta \mathrm{V} \qquad (1)$$

There is no motion term on the left hand side, since the velocity-induced magnetic field is negligible with respect to the main field in this application (as in Henrotte et al.) [2]. Consequently, the magnetic field is symmetrical along the length of the inductor and it is therefore sufficient to model one half of the inductor. To perform the time harmonic calculations with a nonlinear material, an approximated phasor approach was used (as in Hedia et al.) [4]. When solving this model, the current density distribution at the surface along the wire is obtained as shown in figure 2.

The current density appears to vary sharply towards the edges of the inductor, both in the wire and in the inductor itself. However, it quickly levels out to a constant value towards the middle of the inductor. Hence, it is sufficient to model only 10% of the inductor length. This model is shown in figure 3a. In addition, a second model representing the middle section of the inductor was constructed. Figure 3b shows the second model. It was used to verify whether the first model was sufficiently long, i.e. whether it extended far enough towards the region with a constant solution (cfr figure 2).

For these computations, the GetDP-software (General software Environment for the Treatment of Discrete Problems) was used (developed by Geuzaine) [5].

DESIGN PARAMETERS

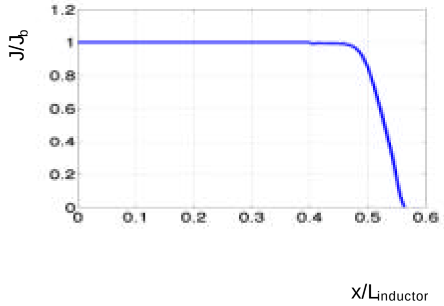

Figure 2 Current density along the wire. (Axes are relative to the inductor's length L_{ind} and maximum current density J_b respectively)

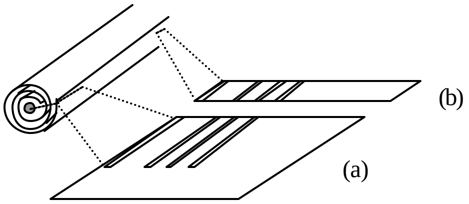

Figure 3 Two models of the foil-coiled inductor.

Since inductor efficiency is a primary concern, the influence of several coil dimensions on efficiency was examined. As an example, figure 4 shows the influence of inductor length and applied voltage on efficiency. The results of numerous calculations made the dimensioning of the prototype possible.

COUPLED THERMAL-ELECTROMAGNETIC COMPUTATION

In a second design stage, the temperature-dependency of the material properties of the wire (σ and μ_r) was considered. In each time step a nonlinear time-harmonic calculation and a transient thermal calculation are required. Since this would require too much computational expenses, it was decided to perform the coupled calculations on the second model only, i.e. no end-effects were considered. The error caused by this assumption is relatively small. This can be seen on figure 5. The solid line indicates the actual power density in the wire. The inductor's edge is at x = 0.5. It can be seen that the power density in the wire gradually drops to zero when it leaves the inductor. The dotted line shows the power density used in the coupled calculations. The relative error can be estimated by means of the results shown in figure 5:

$$dP = \frac{P_{wire}^{actual} - P_{wire}^{calc}}{P_{wire}^{actual}} = \frac{\frac{0.1\,p_b}{5}}{0.5\,p_b + \frac{0.1\,p_b}{5}} \approx 3.8\,\% \qquad (2)$$

MEASUREMENTS

A comparison between measured and computed results is collected in table 1. The agreement is rather good.

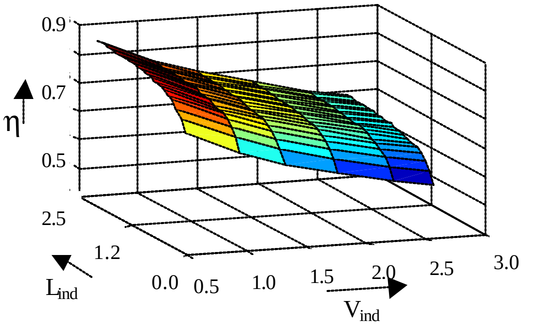

Figure 4 Influence of applied voltage and inductor length on efficiency. (values are relative to a fixed basis)

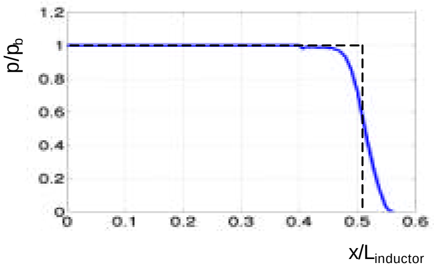

Figure 5 Power density in the wire versus longitudinal coordinate. (Axes as in fig. 2)

TABLE-1 Comparison between measurements and calculations.

	measurements	calculations
V_{supply}	244	244
P_{wire}	530	630
T_{in} [°C]	25	25
T_{out} [°C]	341	390
$\eta_{inductor}$	-	46 %

CONCLUSIONS

Foil-coiled inductors can not be modeled in the same way as a classical inductor. For nonlinear, time-harmonic electromagnetic calculations, end-effects can be considered accurately. Even though this is not possible for coupled thermal-electromagnetic calculations, the calculated results without end effects are satisfactory accurate. This has been verified by measurements.

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