Identification of Equivalent Material Properties for 3-D Numerical Modeling of Induction Heating of Ferromagnetic Workpieces

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This paper presents a methodology to study nonlinear electromagnetic phenomena inside ferromagnetic pieces where eddy currents are driven by an external supply source in the medium frequency range. The proposed methodology takes, as reference, a nonlinear time-harmonic solution of the iron part and then identifies, by means of an optimization procedure, the magnetic permeability values of an equivalent layered linear material which would give the same value of Joule losses of the nonlinear case. This approach has been applied to a test configuration obtaining good results.

***Index Terms*—Induction heating, nonlinear time-harmonic eddy currents, optimization.**

I. Introduction

Electromagnetic modeling of induction heating process with ferromagnetic workpieces is not an easy task. Several conflicting phenomena have to be taken into account and several critical issues must be overcome in the discretized model. Supply frequency values in the range of some kilohertz and high magnetic permeabilities make the flux penetration depth very thin, in the order of some tenth of millimeter. This phenomenon is contrasted by the nonlinearity of material, which prevents surface value of magnetic flux density to go beyond saturation value. As a result of the balance between these two effects an abrupt change in material characteristics takes place in the surface layer of the workpiece and influences the most important parameter of the industrial process, which is the power transferred from the inductor coil to the material to be heated. Notwithstanding these difficulties, the effort in research to use numerical modeling has been very high [1], [2]. From the numerical viewpoint, this peculiarity makes the analysis not easy. The most difficult points can be summarized as follows.

- The need for a fine discretization near the surface of the workpiece is necessary, which usually contrast with the overall dimensions of the problem under analysis: skin depth of some millimeters must live together with inductor dimensions that are usually in the range of centimeters. This consideration has brought to the development of surface impedance analysis codes, which avoid volume discretization; see, for instance, [3].
- Volume discretization must be used if local power density data are to be subsequently transferred to a thermal analysis code.
- Nonlinear time-harmonic behavior must be considered requiring thus a suitable nonlinear solver.

In 3-D structures, a complete nonlinear study is still very computational intensive [4]. One possible approach to reduce the computational cost of the analysis is to replace the nonlinear material with an equivalent linear one. Different equivalent criteria can be implemented [5] and their use leads to a nonhomogeneous distribution of material permeability values.

In this paper, an alternative approach to what was presented in [5] to obtain an equivalent linear material is proposed. The approach is based on some simplifying assumptions, which can usually be made in induction heating problems.

- Due to the above cited differences in dimensions between skin depth, and transversal dimensions, field quantities usually lie parallel to workpiece surface.
- Material characteristics change, at least in a first approximation, more rapidly along piece depth than in the other directions.

Following the previous considerations, the simplified approach to the nonlinear study is based on the subdivision of the workpiece in layers parallel to the workpiece surface. Each layer has a unique value of magnetic permeability, which is estimated by means of an identification procedure aimed at obtaining the same value of Joule power losses computed in a through nonlinear simulation. The use of identification procedures is not new since it has been attempted already in [6]. In the following, details about the proposed approximated method are given and accuracy of results obtained in a case study are discussed. Eventually, an analysis of the reliability of equivalent material approach also in configurations different from the one used for the identification, for instance, at different distances between inductor coil and workpiece, is presented.

II. Identification of Equivalent Material

Analysis of induction heating problems in 3-D structures are currently still a difficult task. Field solutions can be carried out but their computational costs are still very high, as it can be guessed in the companion paper [4]. Design of inductors and evaluation of their efficiency require numerical tools that must give reliable results in computational time compatible with parametric studies and, hopefully, in optimization. It must be remarked that the most important quantity to be evaluated, in this kind of studies, is the power dissipated in the ferromagnetic part to be heated and the efficiency of the whole process computed

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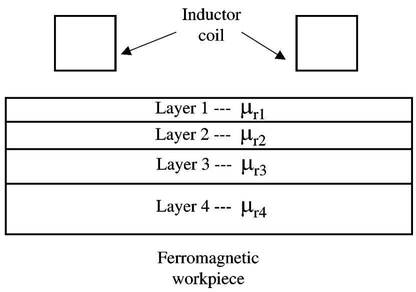

Fig. 1. Layers of homogeneous linear material.

as the power transferred to the piece divided by the total power dissipated both in piece and in inductor coil. As a consequence, the study will be focused on the following aspect: how to get a reliable value of power transferred to the ferromagnetic part by means of an equivalent linear material.

Starting from the analysis of the results obtained in a full 3-D nonlinear time periodic solution of a test case problem, it can be seen how material properties, in particular magnetic permeability, change very rapidly along the thickness of the workpiece, while they remain almost uniform on planes parallel to piece surface.

These considerations suggest that the nonlinear material could, at least in a first approximation, be substituted by a succession of layers with uniform permeability value. As it can be seen in Fig. 1, each layer is made of a linear material with homogeneous permeability value. This arrangement can approximate the actual situation of the nonlinear material, which, due to the flux skin effect, works in the saturation region of the nonlinear curve near the surface of the workpiece while its value of magnetic flux density decreases with the thickness.

A qualitative description of the problem can be done by means of (1) and (2). It is possible to note how the Joule power losses in ferromagnetic parts are largely affected by the permeability value

$$p = k\frac{\rho}{\delta}H^2 \tag{1}$$

$$\delta = \sqrt{\frac{2\rho}{\omega\mu_r\mu_0}} \tag{2}$$

where ρ is the electrical resistivity of the material, μ_r is the relative magnetic permeability, ω is the angular frequency of the current or voltage supply, is H is the surface value of magnetic field, k is a coefficient dependent on the ratio between geometrical dimensions of the workpiece, and δ is penetration depth. It is worth noting that (1) and (2) are here used just to give a qualitative description of the problem. In the following part of the paper, all the computations are made by the commercial code CST EM Studio.

Considering a simplified structure made by an inductor coil with impressed sinusoidal root mean square (rms) current over a plane ferromagnetic workpiece, the value of power losses in the piece can be computed. If permeability of the linear ferromagnetic part is used as parameter (with fixed values of resistivity and supply frequency) the curve of power losses versus permeability value can be obtained. The analysis of Fig. 2 highlights that a low value of permeability gives rise to a low value

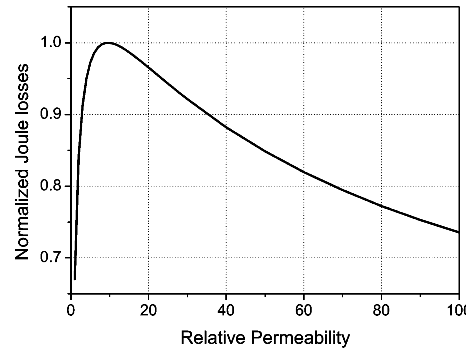

Fig. 2. Joule losses versus relative permeability of the ferromagnetic workpiece for fixed values of resistivity and supply frequency.

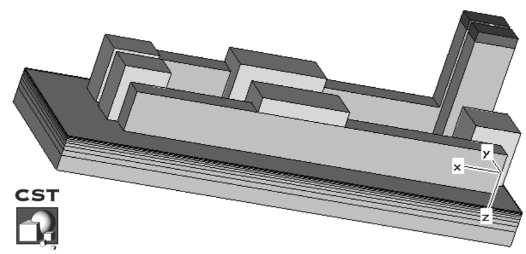

Fig. 3. Geometric domain used as test case for the proposed procedure.

of Joule losses; this fact can be attributed to the high reluctivity value experienced by the magnetic flux. As a consequence, the local values of magnetic flux density and thus of power losses are reduced. On the other hand, high values of permeability increase the flux skin effect. This fact creates a very low penetration depth of current density and thus a global reduction of Joule losses.

It is thus difficult to find a suitable value of permeability: values too low or too high than the right one can underestimate Joule losses. From these considerations stems the idea of using an optimization routine, which, adopting permeability values of some layers as degrees of freedom, could find the permeability profile that gives the same value of Joule losses computed by a nonlinear analysis.

The identification of the equivalent material is performed inside the computational environment CST EM Studio [7], by using an internal optimization routine based on the Powell implementation of the quasi-Newton algorithm. The 3-D ferromagnetic part is subdivided in layers parallel to its surface. The thickness of each of these layer is assumed to follow a logarithmic rule along the depth to approximate the diffusion of flux density. Each layer has a parametric uniform value of magnetic permeability that is driven by the optimization routine.

The proposed approach is used to study a structure for induction heating reported in Fig. 3. The inductor is made by a hollow conductor (for cooling purposes) supplied by 5052-A rms, 8.6-kHz alternating current (ac). In order to locally increase the induced current values, six flux concentrators made of laminated iron are placed around the conductor. The workpieces dimensions are $28 \times 14 \times 7$ cm^3. The objective function to be minimized is the absolute value of the difference between the global power (power losses in iron and in copper inductor) computed in the linearized configuration and the one obtained from

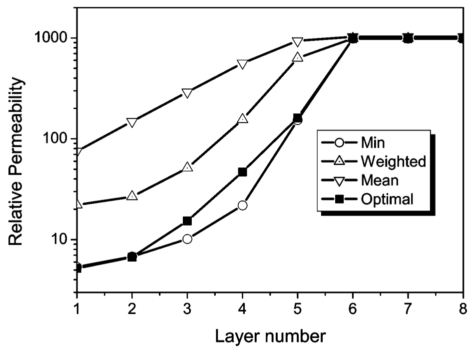

Fig. 4. Relative permeability profiles versus layer number: min, weighted, and mean obtained by the nonlinear solution and optimal obtained by the identification process.

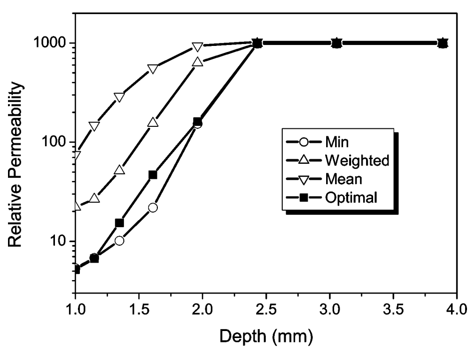

Fig. 5. Relative permeability profiles versus thickness: min, weighted, and mean obtained by the nonlinear solution and optimal obtained by the identification process.

a nonlinear analysis of the same structure. Using the permeability of five layers as degrees of freedom, the procedure was able to find a distribution of permeability values which reduced the error to a value of 0.17% of the nonlinear power requiring 70 evaluations of the objective function.

By plotting the permeability value versus layer number and/or depth, its profile can be obtained, in terms of the layer number, as in Fig. 4 and of the actual thickness as in Fig. 5.

In both Figs. 4 and 5, optimal permeability profile is compared with other profiles obtained by the nonlinear computation. By postprocessing the nonlinear solution and computing for each element of the layer its permeability, it is possible to obtain the actual value of permeability on the layer: the minimum value, the mean value, and a weighted value obtained by multiplying each element permeability by the power density of the element.

As it can be seen in Figs. 4 and 5, the optimal profile is almost similar to the minimum one, but the total losses obtained by means of these profiles are quite different. Fig. 6 shows this comparison; the best result is obtained employing the optimal profile (the error is 0.17%), which is followed by the result relative to the minimum profile (the error is 0.17%). For the sake of completeness, Fig. 6 includes also the result of the weighted and mean profiles even if their use leads to a higher error. Mean and weighted profiles give larger error on power values arriving at 10%. By considering the analysis reported in Fig. 2, it can be guessed that minimum permeability profile underestimates the value of Joule losses by giving rise to a larger value of reluctivity of the flux path (point on the left of the maximum) while the other two underestimate it because of a large value of electrical resistance (point on the right of the maximum).

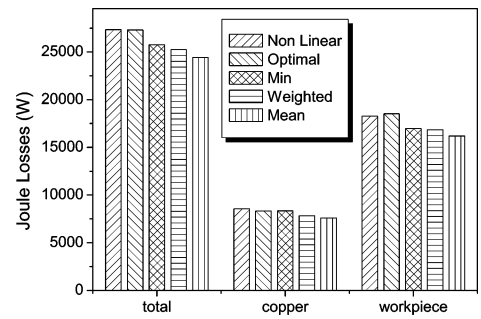

Fig. 6. Joule losses results.

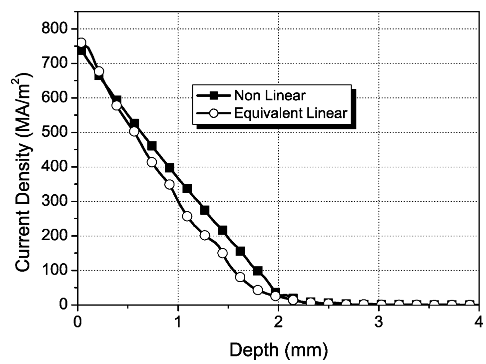

Fig. 7. Current density along the depth of ferromagnetic part: comparison between nonlinear and equivalent linear case.

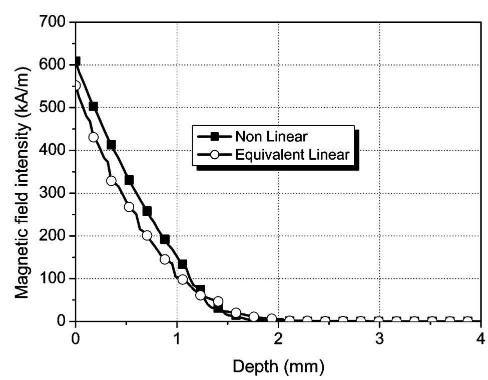

Fig. 8. Magnetic field along the depth of ferromagnetic part: comparison between nonlinear and equivalent linear case.

The target of the optimization is to reach a permeability profile that would give the same power losses inside ferromagnetic part. This choice is reflected also in local variables. By looking at the field variables along the depth of the ferromagnetic part it can be seen that current density and magnetic field have a behavior very close to that of the nonlinear solution (see Figs. 7 and 8, respectively), while locally magnetic flux density can have a large deviation from the nonlinear one (see Fig. 9).

III. Sensitivity of Results

The permeability profile obtained by the optimization procedure can be used to compute the power transferred to the workpiece in the structure used but this result on its own would be al-

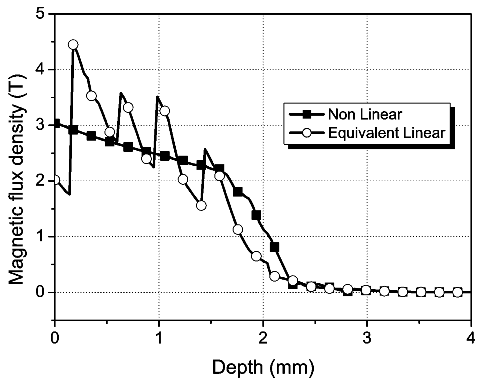

Fig. 9. Magnetic flux density along the depth of ferromagnetic part: comparison between nonlinear and equivalent linear case.

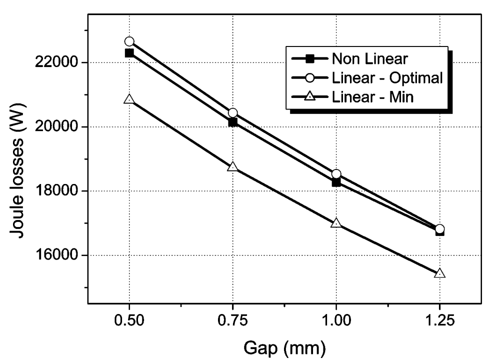

Fig. 10. Sensitivity analysis for gap variation. Joule losses in the workpiece.

most useless because optimization can be run only when a thorough nonlinear analysis has been performed. One of the advantage of this approach relies on the stability of the results obtained also in configurations similar to the one used for identification. In particular, the permeability profile obtained by identification is able to give sensible results also when the distance between the inductor coil and the ferromagnetic workpiece is changed. In Fig. 10, the value of Joule losses in the ferromagnetic workpiece is plotted versus its distance from the coil. The linearized permeability profile is identified at a nominal distance of 1 mm and then it is changed to 0.5–1.25 mm. As can be seen, the relative error on the power transferred to the iron part remains almost unchanged and follows the same trend of the nonlinear one. At the same time, it can be seen that the power computed by using the minimum permeability profile follows the same trend but with a larger error on the absolute value.

IV. Conclusion

The study of the nonlinear eddy current problem involved in induction heating is currently still complex and usually computationally intensive. In this paper, an approximated approach to treat the nonlinear material by a linear one subdivided in homogeneous layers has been proposed. The main advantages of the proposed method stay in the possibility of using a linear time-harmonic analysis of the structure but keeping the correct value of power transferred to the iron piece. On the other hand, the method relies on the identification of the permeability profile by an optimization procedure that minimizes the error with respect to the one computed by a complete nonlinear analysis of the structure, so that at least one analysis of this kind must be performed.

Looking at the results obtained up to now, the permeability profile obtained is quite stable so that other configurations, different from the one used for identification, can be analyzed keeping a good level of accuracy.

In the future, some study to link the permeability profile to the material and supply characteristic of the problem will be performed.

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