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Research article

Eddy current losses model and physical parameters evaluation for ferrite magnetic cores in frequency domain

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ABSTRACT

Accurate modeling of losses in ferrite cores is of high interest for power electronics design. Left aside the problem of modeling the constitutive law, accurate computation of losses require to model the 3d geometry, for instance by Finite Element (FE) analysis, which is computationally expensive. This hinders the practical usage of such models in circuit simulators which require "light" models. In this work we devise a new approximate method to take into account the microscopic structure of toroidal ferrite cores, which boils up into simple analytical formulas. The proposed method is compared to experimental measurements on a T38 ferrite core, and a FE model.

1. Introduction

Ferrite magnetic cores are widely used in power electronics because (up to several tens MHz). Two main loss mechanisms afflict magnetic cores: static hysteresis losses, and dynamic losses, which are caused by eddy currents and excess losses. Two kinds of eddy currents can be considered for ferrites due to its bi-phasic nature: intragranular [1,2] and intergranular eddy currents [3,4]. At low frequencies grain boundaries behave like a good insulator, thus the main part of the total eddy currents is generally given by the intragranular currents. However, the losses due to this mechanism are quite low. Increasing the frequency, grain boundaries become "permeable" due to displacement currents. The currents start to make global patterns along the whole core section, with a consequent increase in the losses. The excess losses globally account for different dissipative phenomena occurring at microscopic scale, such as domain wall motion, ferromagnetic resonance, spin damping [5], magnetostriction [6]. To date, a quantitative model to predict unambiguously the contributions of these effects does not exist. Anyway, at high frequency the contribution of excess losses on the total ones is usually low [3]. Intergranular eddy current losses generally dominate other kinds of losses when ferrite cores work at high frequencies. Hence it is desirable to have a reliable model to predict them, in order to evaluate the performances of these cores. In this work, a simplified approach is proposed for the evaluation of the intergranular eddy current losses. Under certain hypothesis, which will be detailed hereafter, losses can be calculated in a semi-analytical way. The model is characterized by very low computational effort, and it can be quite suitable for preliminary comparisons of different ferrites, in order to choose the best one for a particular application. The bi-phasic nature of the ferrite imposes the necessity of determining the geometric, electric and magnetic parameters of both grains and boundary to run the model. In [7] a model to study in time domain the effect of intergranular eddy currents in soft magnetic ferrites has been proposed. However the toroidal core has been modeled as a cylinder, and the physical parameters which describe the ferrite have been fitted so as to minimize the error with respect of experimental results. In this work, the core is modeled considering its toroidal shape, and the physical parameters have been derived from electric and magnetic measurements. In [8] an analytical approach to study the losses in toroidal cores for different values of skin depth is proposed. However, this model analyzes a purely resistive material (grain boundaries are not considered) and the expression of power losses shows an infinite sum of terms, with a consequent difficulty in the implementation of this approach in calculation codes. In this work, we propose an alternative, approximate approach which is, in our opinion, much simpler to implement (no infinite sum of terms), and which can be generalized to the case of nonlinear materials, which is of high practical interest. The simplified model is compared with both a numerical model discretized by the Finite Element method (FEM), and with experimental measurements performed on a Mn-Zn T38 ferrite.

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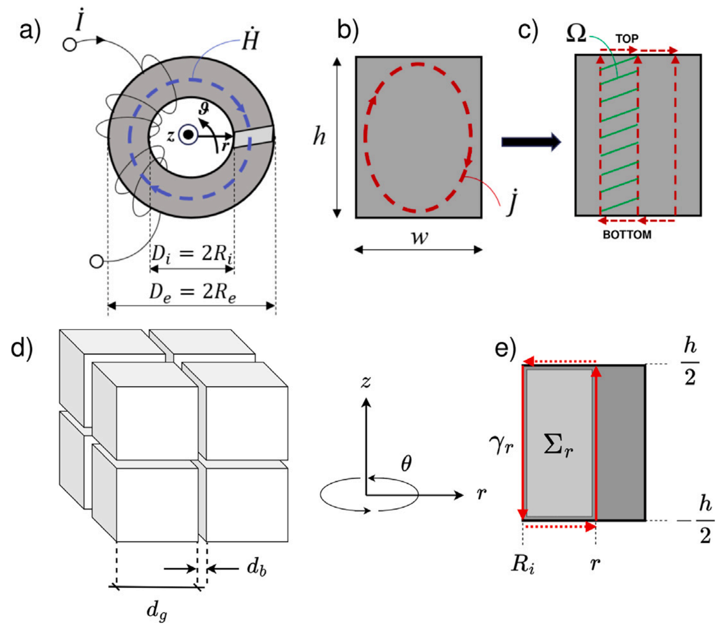

Fig. 1. Sketch of the toroidal ferrite core (a), sketch of the current path in the real (b) and simplified (c) model, schematic view of the core microstructure (d), integration path γ_r (e).

2. Materials and methods

2.1. Intergranular eddy current model

The model describes intergranular losses in a toroidal magnetic core with rectangular cross section Fig. 1(a). A typical path for the magnetic field and the intergranular eddy current density is sketched in Fig. 1(b). $\dot{I}$ is the excitation current. The structure of the core is modeled as a regular lattice of cubic grains separated by very thin boundary Fig. 1(d). The material is assumed to be linear. Notice that this assumption is close to usual working conditions of such materials and it is verified experimentally [3]. The hypotheses of the model are:

1. The field reaction is neglected, hence the magnetic field depends on the distance from the center of the core only, according with Ampere's Law,
2. Intergranular eddy currents dominate, that is induced current follow a macroscopic path across the section, as sketched in Fig. 1(b).
3. The paths of eddy currents are further simplified as straight lines, as shown in Fig. 1(c). They close in the top and bottom boundaries of the cross section, considered as perfect conductors (they oppose a negligible resistance to the current).

Hereafter lower-case letters with $_g$ and $_b$ represent fields respectively in grain and boundary, whereas quantities in capital letters mean homogenized fields. From these hypothesis and the fact that the magnetic permeability $\mu_b \ll \mu_g$, it can be written that:

$$\mathbf{j}_g = \mathbf{j}_b = \mathbf{J} \quad ; \quad \mathbf{b}_g = \mathbf{b}_b = \mathbf{B} \tag{1}$$

Furthermore, the electric and magnetic field depend only on r and have only the component along the z and θ direction respectively. The model is derived in frequency domain, using the Maxwell equations for the circulation of the electric field and magnetic field under the previously listed hypotheses. By taking into account hypothesis (3), the circulation of the electric field along the path γ_r Fig. 1(e) writes:

$$\oint_{\gamma_r} \mathbf{e} \cdot \mathbf{dl} \simeq \int_{-\frac{h}{2}}^{\frac{h}{2}} e(r) dz + \int_{\frac{h}{2}}^{-\frac{h}{2}} e(R_i) dz \tag{2}$$

where $e(r)$ and $e(R)$ are the component along z of the electric field at microscopic scale at a generic r and for $r = R_i$ respectively. The contribution of the top and bottom segments is negligible due to hypothesis (3). By taking into account the structure Fig. 1(d) one can write:

$$\int_{-\frac{h}{2}}^{\frac{h}{2}} e(r) dz = h[\delta_g e_g(r) + \delta_b e_b(r)] = hE(r) \tag{3}$$

where:

$$\delta_g = \frac{d_g}{d_g + d_b}; \quad \delta_b = \frac{d_b}{d_g + d_b} \tag{4}$$

Eq. (3) shows the electric field written both with its grain and boundary grain components and as homogenized quantity. From this equation can be also seen how the homogenized electric field conserves the circulation, and it is the spatial average of the electric field. Notice that this is possible due to hypothesis (2): in general the homogenized electric field is *not* the average of the microscopic one. By using (1) one can define an homogenized electrical resistivity:

$$E = \frac{\delta_b}{\sigma_b + j\omega\epsilon_b} j_b + \frac{\delta_g}{\sigma_g} j_g = \rho_{eq} J \tag{5}$$

with:

$$\rho_{eq} = \frac{\delta_b}{\sigma_b + j\omega\epsilon_b} + \frac{\delta_g}{\sigma_g} \tag{6}$$

The homogenized resistivity is complex valued: it accounts also for inter-grain displacement currents. By using a similar argument one can write the homogenized magnetic field as:

$$H = \delta_g h_g(r) + \delta_b h_b(r) = \nu_{eq} B \tag{7}$$

where the homogenized reluctivity and permeability writes:

$$\nu_{eq} = \frac{\delta_b}{\mu_b} + \frac{\delta_g}{\mu_g} \quad ; \quad \mu_{eq} = \frac{1}{\nu_{eq}} \tag{8}$$

Using (2), (3) and (7), the Faraday Law writes:

$$h[E(r) - E(R_i)] = -j\omega \int_{-\frac{h}{2}}^{\frac{h}{2}} \int_{R_i}^{r} \mu_{eq} H(r) dr dz \tag{9}$$

where j is the imaginary unit and $\omega = 2\pi f$ is the angular frequency. By hypothesis (1) the homogenized magnetic field is known at any point and writes:

$$H(r) = \frac{NI}{2\pi r} = \nu_{eq} B(r) \tag{10}$$

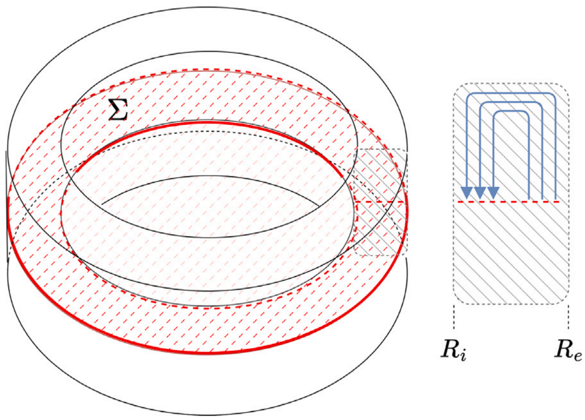

Fig. 2. Cross-section Σ where the constraint (12) is imposed.

where NI is the impressed magnetomotive force. By replacing (10) in (9) and integrating one obtains an analytical expression of the electric field:

$$E(r) = E(R_i) - NI\frac{j\omega\mu_{eq}}{2\pi}\log\frac{r}{R_i} \tag{11}$$

From Ampere's theorem, according with Fig. 2, it can be written:

$$\oiint \mathbf{j}\cdot\mathbf{ds} = 0 \quad\Rightarrow\quad \int_{-R_i}^{R_e} E(r)\, r dr = 0 \tag{12}$$

Notice that E does not depend on the conductivity: this is a direct consequence of hypothesis (1). When the reaction field is negligible, the electric field depends just by the b field (according with the Faraday Law), which is imposed. This aspect is remarked by (11). Notice also that knowing E is equivalent to knowing e_b or e_g because all these fields are linked together by (1) and (3), thus the problem can be formulated by taking as unknown e_b or e_g as well with no loss of information. Finally, the total losses on the core can be computed from the homogenized field or from fields inside grains and boundaries as:

$$P_{\text{loss}}\ [\text{W}] = \iiint \text{Re}[EJ^*] = \iiint \frac{|E|^2}{\text{Re}[\rho_{eq}]} \tag{13}$$

$$= \iiint \left(\delta_g\sigma_g|e_g|^2 + \delta_b\sigma_b|e_b|^2\right) \tag{14}$$

from which the specific losses P_{loss} [W/m^3] are obtained by dividing P_{loss} [W] by the volume of the core. It is worthy to observe the greater originality and usability of the microscopic fields approach (14), in comparison with the macroscopic one (13), because of its holds also for non-sinusoidal waveforms. Indeed, in the case of non-sinusoidal signals the approach to homogenisation presented in this work does not hold anymore and must be generalized.

2.2. Finite element analysis

In order to have a numerical reference, the homogenized model is implemented in a home-made software by using the Finite Element method (FEM), using the Galerkin's approach. Thanks to the rotational symmetry, an axi-symmetric **h**-formulation is used to solve the equations, where computational domain Ω is composed of the toroidal magnetic core only: find $\mathbf{h} \in \mathrm{F}$ such that:

$$(\rho_{eq}\,\text{curl}\,\mathbf{h}\,,\,\text{curl}\,\mathbf{h}') + j\omega(\mu_{eq}\mathbf{h}\,,\,\mathbf{h}') = 0 \quad \forall \mathbf{h}' \in \mathrm{F}_0 \tag{15}$$

where the notation $(\mathbf{u}\,,\,\mathbf{v}) = \int_\Omega \mathbf{u}\cdot\mathbf{v}$ is detailed in [9]. The source term is imposed as Dirichlet boundary condition through the magnetic field:

$$\mathrm{F} = \{\mathbf{h} \in \mathbf{h}(\Omega, \text{curl}) : h = \frac{NI}{2\pi r} \text{ on } \partial\Omega\} \tag{16}$$

where NI is the imposed magnetomotive force. The FE model is based on hypothesis (2) only, and gives up (1,3).

2.3. Physical parameters evaluation

Specific measurements are set for the estimation of these parameters. The geometric parameters can be estimated by cutting the core and observing its cross section with an optical or electronic microscope. A statistical evaluation of the different grains and boundary grains thicknesses is made, and the mean values are used as d_g and d_b. The complete procedure is described in [7]. The electric parameters are estimated measuring the electric impedance of the core for a wide range of frequencies, typically from the DC to several MHz. An impedance $Z_{core} = R_g + R_b \parallel j\omega C_b$ is adopted to model the core, considering the pure ohmic nature of the grain and the ohmic-capacitive nature of the boundary. The parameters R_g, R_b and C_b are optimized to fit the trend of the real and the imaginary part of the measured impedance. This step is necessary since it is impossible to measure directly the necessary electric properties of the material. Anyway, the fitting is made on the model of the electric impedance, not on the model for losses prediction. Then, considering the constitutive relationship of the resistance and capacitance, σ_g, σ_b and ϵ can be derived. The complete procedure is detailed in [3]. Finally, the magnetic parameters can be estimated from magnetic measurements performed on the core using a volt-amperometric method, which allow to derive the material B-H loop. According with the hypothesis of linear behavior of the material, the homogeneous magnetic permeability can be found as the ratio between the maximum value of B and the maximum value of H. The magnetic permeability of boundary is assumed to be μ_0, and the homogenised permeability μ_{eq} is taken directly from the datasheet. Then, using (8) the relative magnetic permeability of grain can be calculated. The ferrite used in this work is a T38 with an outer diameter (D_e) of 20.3 mm, an inner diameter (D_i) of 9.6 mm, a cross section height (h) of 7.6 mm, a cross section width (w) of 5.3 mm and an initial permeability (μ_r) of 10 000.

The geometric and electric parameters for the specific T38 ferrite are taken directly from [3], since the ferrite studied in this paper is really similar to that one used in [3] (same material and quite the same geometric dimensions). Indeed, the two cores perform, from the losses point of view, in a very similar way. The ferrite has a mean grain thickness (d_g) of 10 μm, a mean boundary grain thickness (d_b) of 0.6 nm, a grain electric conductivity (σ_g) of 25 S/m, a boundary grain electric conductivity (σ_b) of 0.67 mS/m and a boundary grain electric relative permittivity of 33.

3. Results

The contributions of static losses, intragranular and intergranular eddy current losses are computed and compared, so as to put in evidence how the intergranular eddy current losses are the main contribution for the considered working frequency range. The contributions of specific static losses and intragranular eddy current losses [1] are evaluated as:

$$P_{hy} = fW_{loss}; \quad P_g = \sigma_g\left(\omega B_{\text{peak}}\, d_g\right)^2/8 \tag{17}$$

where W_{loss} is the specific energy loss by the material in quasi-static conditions. It is evaluated by measuring the losses with volt-amperometric method in the frequency range 800 Hz–1200 Hz imposing a B_{peak} = 10 mT, where the ferrite works in static conditions. The measured in this range is quite stable and equal to 0.4 mJ/m^3. The intragranular losses are derived under the hypotheses listed in [1] considering cubic grains. Also the intergranular losses are evaluated imposing B_{peak} and writing the NI term as $\sqrt{2}\frac{B_{peak}}{\mu_o\mu_{rg}}\pi R_m$, where R_m is medium radius of the core. Here above the results of the computed losses using (13) and (17), presented both in linear and double logarithmic axes for the frequency range 100 kHz–1 MHz. As it can be seen from Fig. 3, static losses and intragranular eddy current losses are negligible. The results predicted by the analytical model and the FEM model are compared with experimental data measured on the

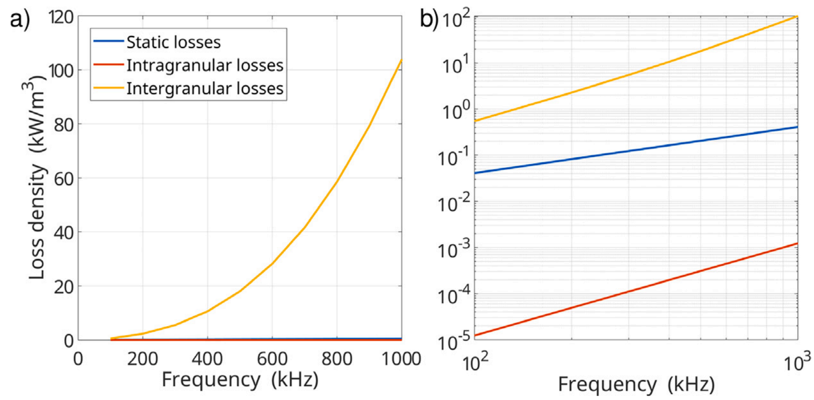

Fig. 3. Comparison between static losses, intragranular eddy current losses and intergranular eddy current losses.

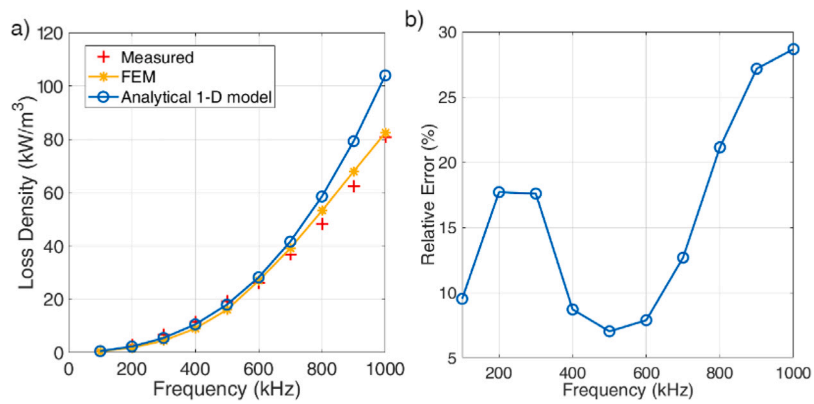

Fig. 4. Comparison between predicted and measured losses (a). Relative error committed by analytical model towards the measurements (b).

T38 Ferrite on the frequency range 100 kHz–1 MHz. The comparison is presented in Fig. 4. One observes that the FE model obviously performs better than the analytical one. However, the analytical 1-D model is able to predict the values of the losses with an error lower than the 30% for every measured point. This prediction can be performed in few fractions of second, so the analytical model could represent a very interesting compromise between simplicity, accuracy and computational effort. Furthermore, the implementation on the model of the possibility to take into account the field reaction could reduce the gap with the measurements introducing just a small complication on the model (in that case, the 1-D model can be solved just in numerical way considering the same other hypotheses).

4. Conclusions

A model to easily compute the core losses due to intergranular eddy currents on a Mn-Zn ferrite with ac excitation has been presented. The possibility to derive the losses in an analytical way (under the given hypothesis) makes the model very fast from a computational point of view. The procedures to derive the average geometric, electric and magnetic parameters for both grains and grain boundaries have been shown. The performances of the model in the prediction of the losses are compared with measurements and with a FE model, which is retains only hypothesis (2) and this it is more general with respect of the analytical model. Despite the FE model can obviously grants more accurate results, the presented model is an interesting compromise between results accuracy and short computational time. It can be a valuable tool for the design of electronic devices, where short simulation time is crucial [10]. As future development, the impact of the field reaction on the model should be evaluated and the applicability of the model should be extended in time domain. By using this approach the parameters of material structure are used explicitly in the computation of homogenized properties (whereas by using numerical homogenization these properties come out from the resolution of a partial differential equation). This provides some insight about the effect of each parameter on the losses, and can be a useful tool for magnetic material manufacturers.

CRediT authorship contribution statement

Vittorio Bertolini: Writing – review & editing, Writing – original draft, Validation, Software, Formal analysis, Data curation, Conceptualization. **Marco Stella:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Data curation, Conceptualization. **Riccardo Scorretti:** Writing – review & editing, Writing – original draft, Validation, Supervision, Formal analysis, Data curation, Conceptualization. **Antonio Faba:** Writing – review & editing, Writing – original draft, Supervision, Software, Formal analysis, Data curation, Conceptualization. **Ermanno Cardelli:** Writing – review & editing, Writing – original draft, Validation, Supervision, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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