

Loss computation in ferrite cores for power electronics

Riccardo Scorretti^{1,2}, Vittorio Bertolini¹, Marco Stella¹, Antonio Faba¹, Fabien Sixdenier², Ermanno Cardelli¹

¹ Engineering Department, University of Perugia, Via G. Duranti 96, 06125 Perugia, Italy

² Univ Lyon, CNRS, INSA Lyon, Université Claude Bernard Lyon 1, Ecole Centrale de Lyon, Ampère, UMR5005, 69100 Villeurbanne, France

Abstract—Ferrites cores are used in power electronics at increasingly higher frequencies, hence it is crucial to have predictive models to evaluate magnetic losses. In this article an original easy numerical homogenization method which allows to compute losses in ferrite cores excited by sinusoidal currents. The model requires only 5 parameters, which can be easily obtained. The model has been extensively validated through numerical simulations and experiments on three different ferrites.

Index Terms—Ferrites, magnetic losses, converters, numerical homogenization

I. INTRODUCTION

FERRITES are the most suitable components for medium-high frequency (several kHz to tens of MHz) reactors, due to their high magnetic permeability and low electrical conductivity. The crystallographic structure, made by conductive high-permeability grains, surrounded by thin dielectric boundaries, hinders the development of eddy currents [1], [2]. In the intermediate frequency range classical from eddy currents are unable to fully explain measured losses. There is a plethora of different dissipative phenomena at micromagnetic scale, which collectively contribute to the global losses in magnetic materials [3], among which spin damping is suggested by many authors as one of the principal “culprit” for anomalous magnetic losses. The purpose of this article is to propose a method to predict magnetic losses by using Finite Difference. An equivalent (homogenous) material is obtained by using simplifying assumptions on current paths. Anomalous losses are accounted for by a first-order model of the complex permeability, which allows to simulate ferrite cores in both frequency and time domain.

II. NUMERICAL HOMOGENEIZATION

At microscopic scale, ferrite consists of an assembly of grains and boundaries, hence the computational domain writes $\Omega = \Omega_g \cup \Omega_b$, where Ω_g and Ω_b are respectively the volumes occupied by grains and boundaries. The fundamental assumption of the proposed method is that for any path γ the macroscopic E-field is the average of the microscopic E-field:

$$\int_{\gamma} \mathbf{E} \cdot d\mathbf{l} \simeq \int_{\gamma} \mathbf{e} \cdot d\mathbf{l} \quad \forall \gamma \quad (1)$$

where capital and lower-case letters mean respectively homogenized and microscopic quantities:

$$\mathbf{e} = \begin{cases} \mathbf{e}_g & \text{in grain} \\ \mathbf{e}_b & \text{in boundary} \end{cases} \quad (2)$$

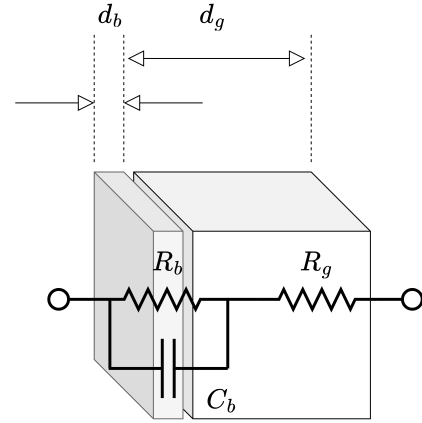


Fig. 1. Circuitual model of grain/boundary

Notice that this assumption is *false* in the general case, but in the case of soft ferrites it is acceptable if the frequency is high enough, so that eddy current paths are mainly inter-granular. Let $\delta_g = d_g/(d_g + d_b)$ and $\delta_b = 1 - \delta_g$ be respectively the ratio of grain and boundary linear dimensions, which can eventually be determined experimentally. The macroscopic E-field and current density write:

$$\mathbf{E} = \delta_g \langle \mathbf{e}_g \rangle + \delta_b \langle \mathbf{e}_b \rangle = \langle \mathbf{e} \rangle \quad (3)$$

$$\mathbf{J} = \langle \mathbf{j} \rangle \quad (4)$$

where the notation $\langle \cdot \rangle$ means spatial average, and:

$$\mathbf{j} = \begin{cases} \mathbf{j}_g = \sigma_g \mathbf{e}_g & \text{in grain} \\ \mathbf{j}_b = (\sigma_b + j\omega\epsilon_b) \mathbf{e}_b & \text{in boundary} \end{cases} \quad (5)$$

From these relations one finds the expression of the macroscopic equivalent resistivity:

$$\rho^{eq} = \frac{\mathbf{E}}{\mathbf{J}} = \delta_g \rho_g + \delta_b \rho_b = \langle \rho \rangle = \rho + \frac{1}{\sigma + j\omega\epsilon} \quad (6)$$

where $\rho_g = 1/\sigma_g$ and $\rho_b = 1/(\sigma_b + j\omega\epsilon_b)$ are the (complex) resistivities respectively in grain and boundary. The parameters ρ , σ and ϵ , which depend on δ_b , ρ_g and ρ_b can be estimated directly from macroscopic measurements of lumped parameters of the electrical circuit Figure 1, so that indeed it is not necessary to measure δ_g and δ_b . One reckons in (6) a mixture formula.

By using similar arguments, a similar expression of homogenized reluctivity is obtained:

$$1/\mu^{eq} = \nu^{eq} = \langle \nu \rangle = \delta_g \nu_g + \delta_b \nu_b \quad (7)$$

It is found that eddy currents alone under-estimate measured losses in ferrite cores at intermediate frequencies [2]. Hence it is mandatory to take into account anomalous losses, which in turn implies that the magnetic permeability must be complex-valued. We propose to use a first-order model:

$$\mu(\omega) = \frac{\mu_0 \mu_{DC}}{1 + j\omega\tau} \quad (8)$$

where the value of μ_{DC} is easily found in ferrite datasheets, and the time constant $\tau = 1/(2\pi f_c)$ has to be fitted from measurements, and falls in the range [1 MHz; 10 MHz]. This is compatible with available experimental measurements [2].

III. NUMERICAL MODELING

A ferrite toroidal core is modeled in an axisymmetric domain by solving the following h-formulation:

$$\text{curl}(\rho^{eq} \text{curl} H) + j\omega\mu^{eq} H = 0 \quad (9)$$

The computational domain contains the core only. Dirichlet BC are imposed on the boundary, which boils up into imposing the magnetomotive force:

$$H = \frac{NI}{2\pi r} \quad (10)$$

A. Harmonic domain resolution

Formulation (9) is discretized by using Finite Differences in harmonic domain. In order to have an extremely fast resolution, the model is solved in 1D by assuming that current paths are approximately vertical [4].

B. Time domain resolution

In order to solve (9) in time domain it is necessary to discretize ρ^{eq} and μ^{eq} by using Tustin's method (aka Cranck-Nicholson) or any other integration scheme. In practice, ρ^{eq} and μ^{eq} are written in Laplace's domain:

$$\rho^{eq}(s) = \rho + \frac{1}{\sigma + \epsilon s} \quad ; \quad \mu(s) = \frac{\mu_0 \mu_{DC}}{1 + \tau s} \quad (11)$$

Then Laplace's variable s is replaced by an approximate discrete expression:

$$s \leftarrow \frac{2}{T_s} \frac{1 - z^{-1}}{1 + z^{-1}} \quad (\text{Tustin's method}) \quad (12)$$

where T_s is the time step. This allows to rewrite (9) in terms of Z-transform. By substituting (12) in (11), and then in (9), one finds a semi-discretized (in time) formulation, which can be further discretized in space by using FD or any other appropriate method:

$$\text{curl}(A_1 \text{curl} H_n) + B_1 H_n = \text{curl} A_2 \text{curl} H_{n-1} + \quad (13)$$

$$+ \text{curl} A_3 E_{n-1} + B_2 H_{n-1} + B_3 \frac{dB_{n-1}}{dt}$$

$$E_n = A_1 \text{curl} H_n + A_2 \text{curl} H_{n-1} + A_3 H_{n-1} \quad (14)$$

$$\frac{dB_n}{dt} = B_1 H_n + B_2 H_{n-1} + B_3 \frac{dB_{n-1}}{dt} \quad (15)$$

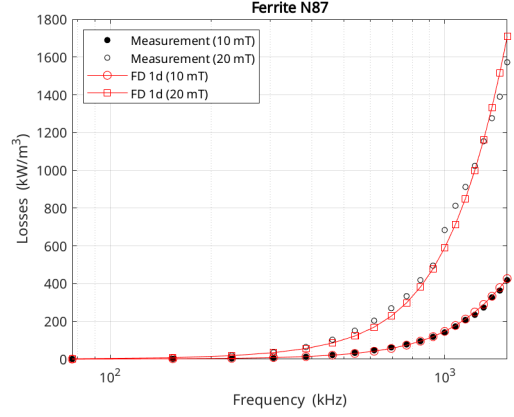


Fig. 2. Measured and computed losses in a N87 ferrite

where $A_{1...3}$ and $B_{1...3}$ are real-valued coefficients which depends only on the material and on T_s . At each time step H_n is computed by solving (13), where the source term (= the right-hand-side term of 13) is a function of the quantities H_{n-1} , E_{n-1} and $\frac{dB_{n-1}}{dt}$ known from previous time steps. Then (14) and (15) are evaluated to update the source term in view of the next time step.

IV. EXPERIMENTAL VALIDATION

Measurements of losses on a N87 ferrite have been taken on in the range 100 kHz – 2 MHz, where sinusoidal B-field of 10 mT and 20 mT have been imposed. The comparison between measured and computed losses is depicted in Figure 2. A quite good agreement is observed. Details on the experimental setup and on numerical values of material parameters will be provided in a longer article.

V. CONCLUSION

We devised a simple homogenization method to model in frequency and time domain a ferrite core, with a focus on loss prediction. It is worth noting that the proposed method requires only 5 parameters, 4 of which can be determined experimentally, and only one has to be fitted. Future work will be devoted to the extension on the nonlinear regime and implementation of the model in a spice-like circuit solver.

ACKNOWLEDGMENT

We gratefully acknowledge the CNRS (French National Council of Scientific Research) for the financial support under the IEA grant MoLeMag.

REFERENCES

- [1] S. Dobák, C. Beatrice, V. Tsakaloudi, and F. Fiorillo, "Magnetic Losses in Soft Ferrites," *Magnetochemistry*, vol. 8, no. 6, p. 60, Jun. 2022.
- [2] F. Fiorillo, C. Beatrice, O. Bottauscio, and E. Carmi, "Eddy-Current Losses in Mn-Zn Ferrites," *IEEE Transactions on Magnetics*, vol. 50, no. 1, pp. 1–9, Jan. 2014.
- [3] J. Goodenough, "Summary of losses in magnetic materials," *IEEE Transactions on Magnetics*, vol. 38, no. 5, pp. 3398–3408, Sep. 2002.
- [4] V. Bertolini, M. Stella, R. Scorretti, A. Faba, and E. Cardelli, "Eddy current losses model and physical parameters evaluation for ferrite magnetic cores in frequency domain," *Journal of Magnetism and Magnetic Materials*, vol. 594, p. 171905, Mar. 2024.