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Interlaminar faults in a GOFeSi laminated magnetic core: measurements and simulations

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Grain-oriented silicon steel (GOFeSi) laminations are massively used as magnetic cores in electrical energy converters (motors and transformers). Edge burrs can appear during the manufacturing process and be at the origin of interlaminar faults (ILFs). In a recent paper, we described an efficient simulation method for GOFeSi laminations. This technique simultaneously solves the magnetic diffusion equation and a fractional differential equation for the material law. It produces excellent results across a large bandwidth of frequencies and is limited to only two parameters for the dynamic contribution. This study extends this method to predict the influence of interlaminar faults. We successfully reproduce experimental data for aligned ILFs and predict their impact in different working conditions. This work provides potential improvements in transformer reliability and defect detection.

Index Terms—Magnetic hysteresis, fractional derivatives, electrical steel, magnetic core, interlaminar faults.

I. INTRODUCTION

THE MAGNETIC core is a critical component in electromagnetic energy converters. It plays a vital role in converting electrical to mechanical energy and vice versa. This conversion is essential for various applications ranging from industrial machinery to power generation in plants. The magnetic core's primary function is maintaining a concentrated and appropriately directed magnetic field within the converter. Its magnetic property has a significant impact on the overall efficiency. Magnetic cores are typically constructed from electrical steel laminations. This type of steel is tailored to induce excellent magnetic properties [1].

Condition monitoring of magnetic cores is crucial for reliability. It involves methods like visual inspection, core loss, and impedance measurements.

Laminated magnetic cores are prone to degradation over time. They face challenges such as corrosion, thermal cycles, and vibrations. Geometrical abnormalities and residual stress from manufacturing processes, including cutting and welding, can exacerbate these issues [2]. Edge burrs, observed around cut edges and punched holes, act as electrical contact points, leading to InterLaminar Faults (ILFs). ILFs are also induced by vibrations or mechanical stress during operation. These defects generate unexpected magnetic fields and eddy currents between laminations, resulting in high local power loss, significant heat generation, and the formation of hot spots. While a few faults may not immediately impact converters' performance, cumulative losses become substantial over extended usage periods. In cases where ILFs occur on both sides of a lamination stack, the additional eddy currents significantly affect transformer efficiency, emphasizing the need for advanced monitoring beyond conventional methods. Proactive quality control measures for magnetic cores should be implemented early on to prevent the propagation of ILFs and potential machine failures.

The assessment of magnetic laminated core quality and condition monitoring is now a domain of active research, and advanced experimental processes have been proposed to precisely evaluate the impact of ILFs on overall electromagnetic converter performance [3]. While some initial simulation methods have been described, they predominantly focus on power and thermal exchanges, leaving the magnetic behavior of laminated cores largely unexplored.

In a recent paper, we introduced an innovative simulation method for the magnetic behavior of GO FeSi laminations. This technique combines the resolution of the magnetic diffusion equation with a fractional order differential equation as the material law. Remarkable simulation results were achieved across a broad frequency range, exceeding 10 kHz [4], using minimal parameters (only two for the frequency-dependent contribution). This article details the successful extension of this simulation method to a stack of laminations incorporating ILFs and predicts their impact on the resulting magnetic core performance.

II. SIMULATION METHOD

A. Single lamination of GOFeSi

The simulation process used in this study originates from a method initially introduced in [5]. This technique models the magnetic behavior of a soft ferromagnetic lamination by simultaneously solving the magnetic field diffusion equation (Eq. 1) and a time-dependent material law (Eq. 2). In the case of a ferromagnetic lamination, where the thickness ζ is reduced compared to both width and length, a one-dimensional (1D) resolution of the diffusion equation is sufficient for obtaining accurate simulation results (Fig. 2, right part):

$$\sigma \frac{\partial B}{\partial t} = \frac{\partial^2 H}{\partial x^2} \quad (1)$$

Here, x is in the thickness direction. A finite differences discretization is typically applied for the resolution. In [5], an extensive frequency range test revealed that a first-order

differential equation (analogous to viscous behavior) offers limited accuracy. Eq. 2, incorporating a fractional derivative term, produces much superior results. In this equation, ρ is a constant, and $H_{stat}(B)$ represents the magnetic excitation field required for obtaining magnetic flux density B in the quasi-static regime:

$$\rho \frac{d^n B}{dt^n} = H - H_{stat}(B) \quad (2)$$

As discussed in previous works [6], fractional derivatives are mathematical operators balancing the frequency effect differently from an integer order derivative. It gives flexibility and accurate results across a significant frequency range.

B. Lamination stacks fully short-circuited on the lateral sides

The simulation of the ILFs has been done through an incremental process. Instead of simulating directly local ILFs, we found it more straightforward to start with stacks of two, three, and four laminations fully short-circuited on both their lateral sides.

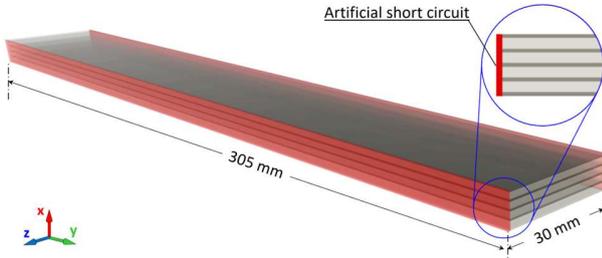


Fig. 1. Stack of four laminations fully short-circuited on its lateral sides.

Even if these stacks do not exactly behave like bulk material where the thickness ζ^* would be equal to x times ζ , similarities are high enough for the simulation described previously to be applied to the newly formed stacks with relatively good accuracies. Adjustments must be made to better match the experimental results, mostly by creating a degraded pseudo-conductivity σ^* and using it as an equivalent σ in the simulation process.

C. Lamination stacks partially short-circuited on the lateral sides (ILFs)

The last step of the simulation process consists of considering local short circuits (10 mm wide aligned ILFs short-circuiting the four laminations; see Fig. 2 for illustration).

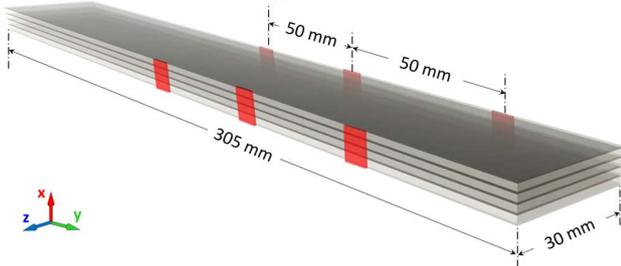


Fig. 2. Stack of laminations with three aligned ILFs.

Good simulation results are obtained by combining the behavior of a flawless stack $H_{surfF}(B_a)$ and a fully short-circuited one $H_{surfSC}(B_a)$. This combination relies on Eq. 8 below obtained at a given flux density B_a :

$$H_{surf} = \alpha H_{surfF} + \beta H_{surfSC} \quad (1)$$

$$\alpha + \beta = 1 \quad (2)$$

III. EXPERIMENTAL SETUP

Standard Epstein-size strips of CGO 3 % SiFe, with a thickness of 0.3 mm and a measured electrical conductivity of $\sigma = 2.169 \cdot 10^6 \text{ S}\cdot\text{m}^{-1}$, referenced as M105-30P, were used in this study. A computer-controlled magnetizing system based on a double yoke single strip tester (SST) was used to magnetize the test samples. All test samples were magnetized under controlled sinusoidal induction. More details about the experimental setup will be given in the extended version of this article.

IV. COMPARISON SIMULATION/MEASUREMENT

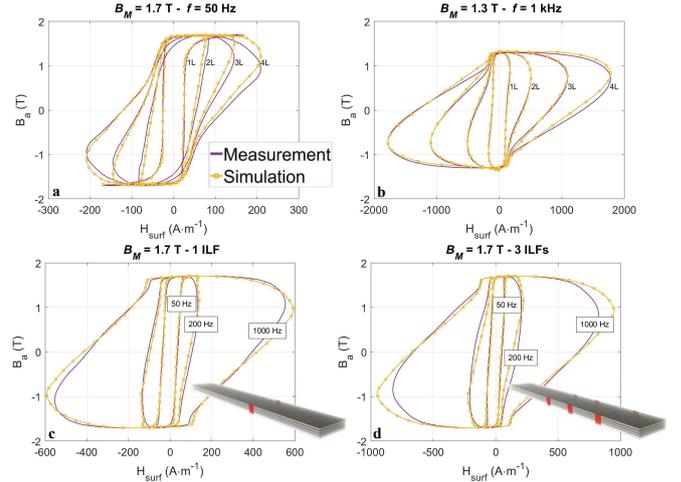


Fig. 3a, b Comparisons measurement/simulation, stacks of laminations fully short-circuited on their lateral sides. Fig. 3c, d Comparisons measurement/simulation, stacks of four laminations with one or three aligned ILFs.

V. CONCLUSION

This study marks progress in understanding the impact of ILFs on laminated magnetic cores. The 1D resolution limits the spatial discretization, resulting in simulation times that are quite reasonable (less than 30 seconds for a stack of four laminations). In the forthcoming extended paper, the model's predictive capabilities will be leveraged to forecast variations in magnetic loss in a stack of four laminations, including two and four aligned ILFs, and a stack of six laminations with one and three aligned ILFs.

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