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Noninvasive sensor patch for internal magnetic core characterization

Sorelle H. Nguedjang Kouakeuo¹, Aurélie Solignac², Ruth V. Sabariego³, Laurent Morel⁴, Marie-Ange Raulet⁴, Borel Toutsop¹, Pierre Tsafack¹, Benjamin Ducharme⁵

¹Faculty of Engineering and Technology, University of Buea, Buea, Cameroun

²SPEC, CEA, CNRS, Université Paris-Saclay, CEA Saclay, 91191 Gif-sur-Yvette, France

³Dept. of Electrical Engineering (ESAT), KU Leuven, Campus EnergyVille, 3600 Genk, Belgium

⁴Laboratoire Ampère, Université de Lyon, 69621 Villeurbanne, France

⁵ELyTMax IRL3757, CNRS, Univ Lyon, INSA Lyon, Centrale Lyon, Université Claude Bernard Lyon 1, Tohoku University, benjamin.ducharme@insa-lyon.fr

Real-time magnetic core condition monitoring is a promising technique for rapid fault detection. In this domain, significant progress is forecasted by achieving precise local measurements. In this study, we propose an innovative solution to measure local magnetic properties, which is well suited to real-time monitoring and magnetic circuit evaluation. The proposed sensor is a one-piece device that is flat enough to be placed noninvasively between the laminations at distinct positions in the magnetic core. It measures the magnetic excitation and induction fields in two dimensions, which can be used as local inputs for real-time condition monitoring.

Index Terms—local defect, magnetic laminations stack, magnetic sensor, predictive maintenance

I. INTRODUCTION

ENERGY efficiency can play a crucial role in mitigating climate change. Numerous strategies, including novel geometrical designs, materials, technologies, have been proposed to improve electrical energy conversion rates. In this study, we focused on the real-time control of the magnetic core properties at which energy transformation occurs. Most magnetic cores used to achieve energy conversion are made of electrical steel sheet stacks. Electrical steel is an iron alloy designed for specific magnetic properties such as low power loss, high permeability. Stacking and coating electrical steel laminations allow to considerably improve the efficiency of ferromagnetic core. However, losses remain significant, and manufacturers are looking forward to achieve more improvements. During the machining processes, mechanical stresses may considerably affect magnetic properties. Furthermore, undesirable edge burrs can appear around the cut edges and punched holes, giving rise to interlaminar faults (ILFs) and deteriorating the magnetic core efficiency. ILFs can also occur during an operation due to multiple reasons, such as wearing out of insulation coating, vibration of loose windings, arcing from winding failure, ineffective cooling, transportation, and/or installation. Magnetic core condition monitoring (MCCM) has been proposed to improve performance and durability. It consists of a real-time inspection of the magnetic circuit performances to detect defects and predict a decrease in electromagnetic converter efficiency. Current MCCM is always performed by controlling the input and output electrical signals. This simple approach limits the magnetic core diagnostic to average quantities and renders it impossible to geolocalize eventual defects. Due to geometrical constraints, current laminated magnetic core characterizations are limited to either global information (averaged through the cross section) or surface inspections. Embedding any instrumented measuring system inside a laminated magnetic core has been up to very

recently difficult. However, in [1], printed electronics have been used to perform such measurements. In this study, we locally characterize a laminated magnetic core using a novel method that is described in the second section of this manuscript. The method is experimentally validated in the third section.

II. LOCAL CHARACTERIZATION

A. Magnetic Induction Measurement

The Magnetic Needle Probe Method (MNPM) is used to record magnetic flux variations in a laminated ferromagnetic core by surface measurement (details in [1]). MNPM is limited because of weak electromotive forces, especially in the low-frequency range. However, considerable advances have been achieved in analogue and digital electronics. Improvements in the MNPM have resulted in numerous applications, such as local non-uniform electromagnetic field investigations, cutting-edge stress, stress-induced peening processes and homogenization analysis in lamination stacks. The Printed Magnetic Needle Probe Method (PMNPM) as described in [3], satisfies all the aforementioned conditions. The test probe is replaced with a printed conductive layer, which results in a negligible leakage flux. The thickness of the whole sensor (a conductive ink layer, $\approx 30 \mu\text{m}$) makes it almost unnoticed when embedded in stacks of steel sheets.

B. Magnetic Excitation Measurement

The PMNPM is a non-intrusive method for measuring a local directional flux variation through the cross-section of a laminated core. Here, the average flux density B_a is obtained by time integration. For a complete hysteresis cycle plot, the tangent surface field H_{surf} should be recorded using small giant magneto resistance (GMR) sensors. GMRs allow detecting up to less than a few nanoteslas beyond substantial frequency and temperature ranges. GMRs consist of multiple thin layers, including two ferromagnetic deposited thin films isolated by a metallic nonmagnetic spacer. The total active part thickness is typically smaller than 100 nm.

C. Complete Low-Thickness Sensing Solution

PMNPM deposition is associated with thickness concerns on the edges of the lamination stack because of electrical contacts [3]. In this study, we solved this problem and improved the overall electrical connections by depositing two GMRs (0 and 90°) and printing two needle probes on the same patch (Fig. 1)

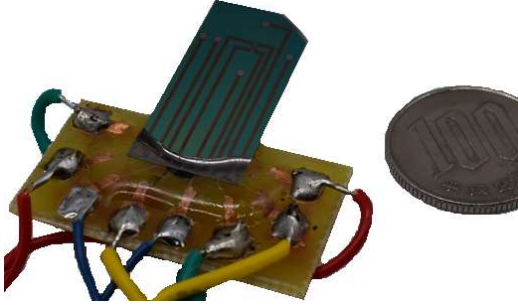


Fig. 1 Single patch sensor.

III. EXPERIMENTAL VALIDATION

The experimental setup validating the new sensing solution is based on the IEC 60404-3 standard that defines the use of a single-sheet tester to characterize the electrical steel lamination. It is comprehensively described in [1] and [3]. Note that some differences exist: the use of a single yoke, the yoke dimensions, the primary winding being wound around the yoke instead of the tested specimens, and a stack of 10 laminations replacing the single sheet of electrical steel for stack tests.

All the tested GO FeSi specimens were picked up from the same batch. As provided by the manufacturer and previously characterized by the team [1], their physical properties at room temperature are available in [1] and [3]. In the first experimental tests, a single instrumented ferromagnetic sheet was laid on the yoke. Measurements with the sensor patch were monitored at various frequencies and amplitudes. The experimental results are displayed in Fig. 2.

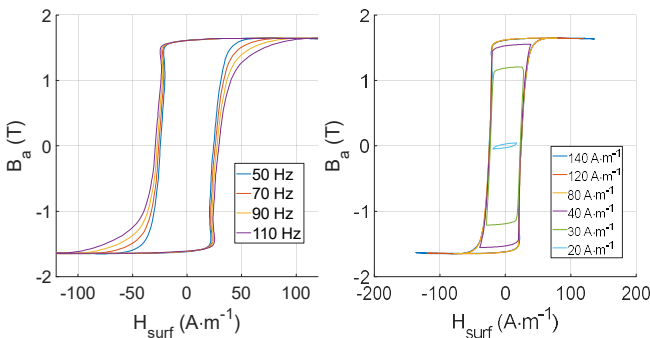


Fig. 2 Single lamination tests (left: vs. frequency, $\max(H_{\text{surf}}) = 120 \text{ A}\cdot\text{m}^{-1}$, right: vs. H_{surf} amplitude, $f = 50 \text{ Hz}$)

The sensor size allows for measurements in the middle of the lamination far from the edges at which inconsistency in the MNPM could affect the measurements. Thus, all measurements were performed in the central zone of the laminated sheet. Then, the 2D capability of the sensing solution was subsequently tested by positioning the sensor patch at 45°.

This first series of tests were completed to verify the cohesion between the experimental results and the manufacturer information. Next, a pile of 10 electrical steel laminations, including the instrumented laminations, was used to validate the sensor in a stack configuration. The instrumented sheet was moved in every stack position, and various excitation levels and frequencies were tested. All tests were performed at room temperature.

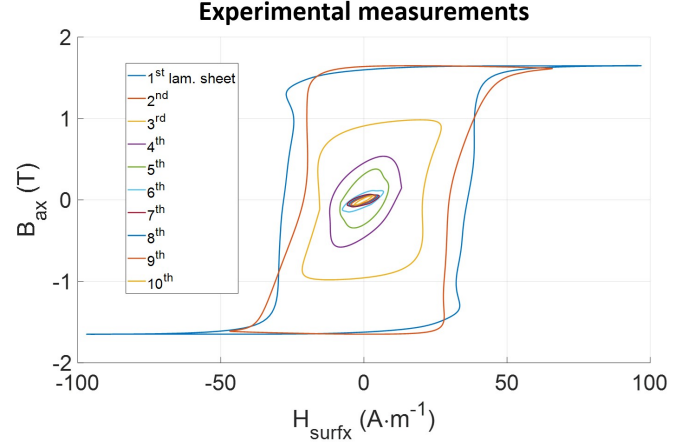


Fig. 3 local hysteresis cycles measured with the sensor patch.

I. CONCLUSION

A 100- μm thick patch sensor (the thickness of which can still be significantly reduced), combining the magnetic needle probe method and giant magneto resistance sensors, has been proposed to provide in-plan magnetic characterization inside a ferromagnetic sheet stack. The patch has been first tested on a single ferromagnetic laminated sheet. A 2D measurement has been proposed by comparing the two pairs of sensors in an experimental condition that required the sensor to provide the same information. Next, stack tests have been performed by positioning the sensor patch between every lamination.

The fragility of the sensor patch was the most critical concern for high technology readiness level (TRL) developments. The thinned patch should be meticulously handled, especially during polish treatments. The use of flexible substrates is plausible but constitutes time-consuming developments beyond the scope of this work.

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