Experimental Evaluation of Magnetostrictive Strain of Electrical Steel

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Abstract. Environmental noise pollution has gained increasing importance, over the past few years. Due to population growth along with a rapid urbanization and the increasing power supply needs, more and more electrical power transformers are set near or inside of urban agglomerations. This fact has generated several complaints regarding the noise produced by this equipment, forcing manufacturers to develop low noise solutions. As it is known, magnetostriction is one of the main sources of electrical machines noise. This research presents an experimental study in which magnetostriction properties of electrical steel are evaluated and analyzed. The magnetic flux density influence on the hysteretic strain behavior of magnetostriction was addressed, as well as the effect of a clamping load on the core joints. This study was addressed by means of an Epstein frame and a data acquisition system, where strain, current and voltage data is obtained and then processed in a data logging software. These measurements gave essential inputs for numerical models which simulate the power transformer core behavior, allowing a faster evaluation of noise mitigation solutions.

Keywords: Magnetostriction · Epstein frame · Power transformer · Noise

1 Introduction

Nowadays, more importance is given to noise pollution [4], what has yielded several regulations and directives that specify the maximum noise levels in sensitive zones, such as urban areas. Hence, industry is now compelled to manufacture quieter equipment, in order to fulfil these requirements.

In spite of being stationary machines, the active part of power transformers is a source of noise due to mechanical vibrations resulting from electromagnetic forces and magnetomechanical effects. Due to the increasing demands on power supply, more and more transformers are set near the final consumer, subjecting manufacturers to more restrictive specifications regarding noise levels.

J. L. Afonso et al. (Eds.): GreeNets 2018, LNICST 269, pp. 131–141, 2019.
https://doi.org/10.1007/978-3-030-12950-7_11

Transformers noise can be classified according to its source: core noise, instigated by the magnetostriction of the transformer core and by the Maxwell forces; load noise, caused by the action of electromagnetic forces on the windings; cooling noise, which is due to auxiliary cooling equipment. According to several studies [3,5,7], core noise is the dominant source of noise for transformers whose rating is below 150 MVA. Since transformers rated power is usually lower near consumption, the mitigation of core noise has been the focus of many studies during the past years. Maxwell forces occur whenever magnetic flux changes medium, these forces act to minimize magnetic reluctance, reducing the gap between electrical steel sheets, causing adjacent sheets to attract and to repel. Magnetostriction is the mechanical deformation a ferromagnetic material is subjected to, when polarized.

Due to the complexity of this phenomena, an analytical model is not capable of accurately predict transformers noise level. Therefore empirical models [7] or numerical methods, such as the finite element method (FEM) or the boundary element method (BEM), are used to calculate the noise radiation of a power transformer. The development of such FEM/BEM models requires the characterization of the magnetomechanical behavior of electrical steel sheets used in the core, through representative experimental set-ups.

This paper presents an experimental setup in which magnetostriction measurements were carried out, based on an Epstein frame concept.

2 Background and Related Work

When magnetized, a ferromagnetic material is subjected to a mechanical deformation which varies with the magnetic polarization. This magnetomechanical effect, named magnetostriction, is one of the causes of transformers core vibration, along with the Maxwell forces (which occur when the magnetic field faces a material of different magnetic permeability). Magnetostriction is an anisotropic material property with non-linear behavior, which is specific of each type of electrical steel, and thus it may only be determined experimentally.

The measurement of these properties can be performed with different setups, one of them is the Epstein frame. An Epstein frame comprises a primary and a secondary winding, disposed in four coils, and the testing specimens, forming an unloaded transformer, whose specifications are defined according to IEC 60404-2 [8]. This device may also be used to characterise the magnetomechanical behavior of the tested specimen, besides Technical Report IEC TR 62581 [9] describes the general principles and technical details regarding magnetostriction measurements by means of an Epstein frame or a Single Sheet Tester (SST).

The major part of the work developed on magnetostriction measurements was carried by means of a SST, mainly because of its simplicity. Anderson [1] developed a SST which was capable to measure magnetostriction, under applied mechanical stress, using a piezoelectric accelerometer. Javorski studied the frequency characteristics of magnetostriction using a modified SST [11] and formulated a numerical magnetostriction model based on those measurements [10].

Klimczyk [14] improved the experimental setup idealized by Anderson to study the influence of the specimen thickness, coating and residual stresses on the magnetostrictive behavior of electrical steel. Ghalamestani [6] also used a SST to carry out magnetostriction measurements, but instead of using accelerometers to measure the deformation, the author used an heterodyne laser interferometer.

However, an Epstein frame resembles better a power transformer operation, since the effects of the lamination stacking, and clamping might not be neglected. Behlacen [2] studied magnetostriction by means of an Epstein frame, using a force transducer to compute the magnetostrictive forces and then converted them to deformation and strain values.

This work aims to acquire and to evaluate the anisotropic magnetostriction of an electrical steel sheet, where its frequency characteristics were addressed, as well as the influence of magnetic polarization and clamping loads applied on the joints in the magnetostriction curves. These measurements are the first step to compute the sound power level of a power transformer, providing inputs required by a commercial FEM software to predict magnetostriction along the transformer core, based on the magnetic field it is subjected to. The workflow of this numerical study is presented on Fig. 1. Future works also include experimental validation of numerical simulations under different conditions, which are representative of a full-size power transformer.

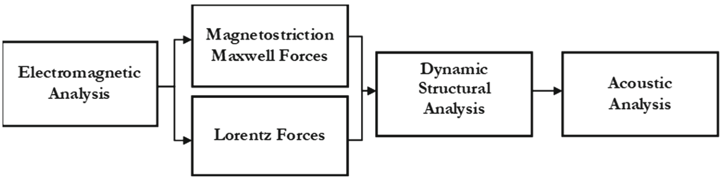

Fig. 1. Numerical simulations workflow.

3 Experimental Measurements

3.1 Experimental Set-Up

The magnetostriction measurements were carried out on an Epstein frame, by means of strain gauges. The strain data was acquired and then processed by a data acquisition system, which synchronized the strain signal with the current and voltage signals. The Epstein frame used in this work, Fig. 2, matches the characteristics listed on the IEC standard previously referred [8].

Tested specimens were assembled according to standards, in double lapped joints [8] and with their rolling direction parallel to the magnetizing direction [11].

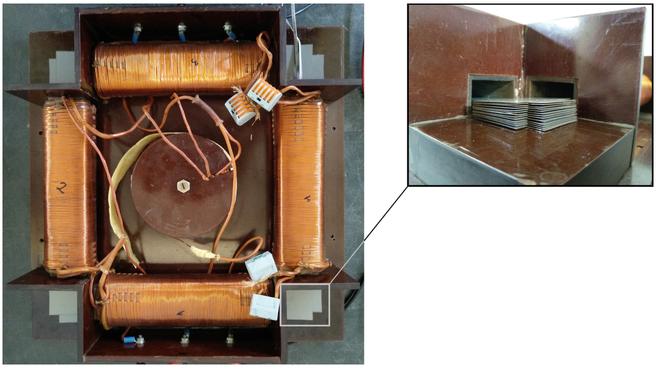

Fig. 2. Epstein frame.

Electrical Steel Specimens. In order to test electrical steel that is used in power transformers, several strips of grain oriented electrical steel *PowerCore*® H105-30 from ThyssenKrupp were collected. The characteristics of the tested electrical steel are shown in Table 1. Electrical strips dimensions were determined based on IEC/TR-62581, to ensure a magnetic path of 0.94 m [8].

Table 1. *PowerCore*® H105-30 properties.

Parameter	Value	Units
Saturation polarization	2.03	T
Coercive field strength	5	A/m
Density	7650	kg/m^3
Resistivity	0.48	$\mu\Omega m$
Length	300	mm
Width	30	mm
Thickness	0.3	mm

Strain Gauge. For a discrete and local measurement of magnetostriction, strain gauges were used and placed in one strip of the tested specimen. The strain rosette has a temperature response matched to steel (HBM K-XY31-3/350) and two measuring grids (0°/90° T rosette).

The coating of the electrical strip was removed allowing a direct contact with the steel. The strain gauge was attached to the strip using an HBM Z70 adhesive, and connected to the data acquisition system with AWM 2651 cables. These cables were twisted, like shown on Fig. 3, in an attempt to compensate any electromagnetic interferences. In addition, to avoid the effects of the double-lap joints (test specimen edges) the gauge was positioned in the middle of the strip, as shown on Fig. 3.

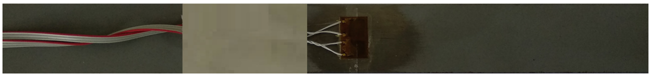

Fig. 3. HBM K-XY31-3/350 on the specimen.

Autotransformer. In order to better control the voltage and current fed into the circuit, a Zenith V8HM autotransformer was connected to the Epstein frame for power supply.

Data Acquisition System. For data acquisition, a National Instruments data acquisition system composed by a CompactDAQ-9188 Chassis was used. Data regarding current, voltage and strain were acquired using NI-9227, NI-9244 and NI- 9236 input modules, respectively, with a sampling time of 2 ms. Apart from data acquisition, the system allows the constant monitoring of magnetizing current and voltage supply in primary winding, with a PC and a dedicated software system developed in Labview. Through the data logging software, an interface algorithm was created to calculate magnetic field – $H(t)$ – and magnetic polarization – $B(t)$ – using Eqs. (1) and (2), where N_1 and N_2 are the number of turns of the primary and secondary windings, respectively, l the magnetic path length, $I(t)$ is the current, A the magnetic active area and $U_2(t)$ the voltage on the secondary winding [13,15]. As a result, magnetostriction could be plotted as a function of $B(t)$ or $H(t)$.

$$H(t) = \frac{N_1 \cdot I(t)}{l} \tag{1}$$

$$B(t) = -\frac{1}{N_2 \cdot A} \int U_2(t)dt \tag{2}$$

Figure 4 shows the experimental set-up scheme employed in this study.

3.2 Measurement Procedure

The excitation was made using the power grid ($f \approx 50$ Hz and $U_{rms} = 230\,\mathrm{V}$), by means of the autotransformer, which allows the step-down and control of the voltage applied to the primary winding.

Before measurements initialization, preliminary calculations were performed for variables definition. Peak magnetic polarization (B_{peak}) is predicted based on the effective secondary winding voltage (U_{2rms}). Finally, the power supply

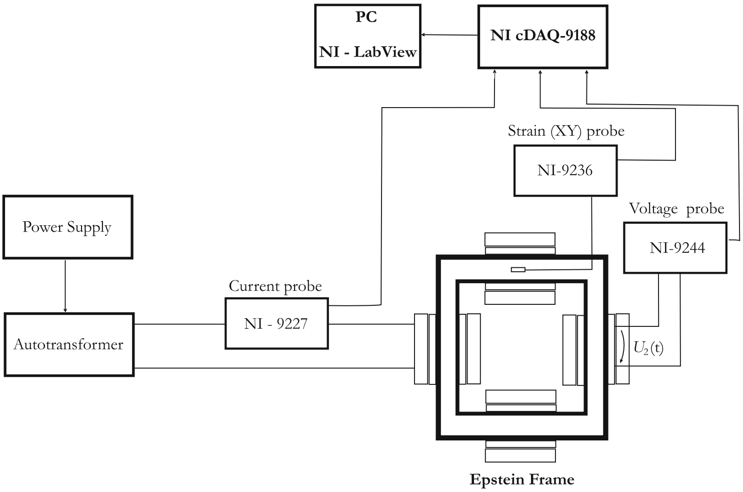

Fig. 4. Experimental set-up.

output should be slowly increased until the secondary voltage has reached the desired value [8]. When the desired peak magnetic induction is achieved, the data is collected.

Eighteen experimental measurements were conducted. On these tests, three parameters were evaluated: magnetic polarization, B; number of laminations, n_l; clamping load on the core joints, F. Three levels of magnetic polarization were considered: 1.5, 1.7, 1.9 T; as for the laminations three arrangement were tested: one, four and thirteen strips per limb.

4 Results and Discussion

Initially, magnetostriction frequency characteristics were studied. According with literature review [11], for an excitation frequency of 50 Hz, magnetostriction presents a fundamental component of 100 Hz (double the excitation frequency), and respective harmonics. However, the acquired signal exhibited a distorted behavior, possibly due to electromagnetic interference, especially when compared to those of IEC TR-62581 [9].

Therefore, to ensure a representative magnetostriction loop, a FFT (Fast Fourier Transform) analysis was conducted. Through this analysis, it was concluded that, in addition to the fundamental component, other harmonics were present, some of which were related with magnetostriction multiple harmonics, the others were related with the power grid (50 Hz and odd harmonics) and other parasite signals. To work around the problem, magnetostriction fundamental frequency and respective harmonics were identified and isolated. Moreover, rigid body motion (0 Hz) was also taken into account. Figure 5 shows the filtered magnetostriction spectrum for an iron core composed by thirteen steel sheets per

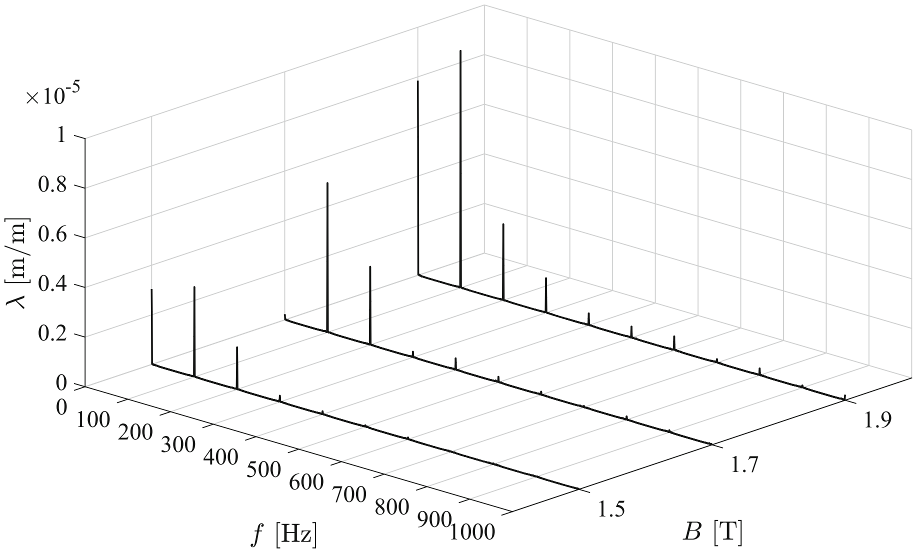

Fig. 5. Magnetostriction frequency spectrum.

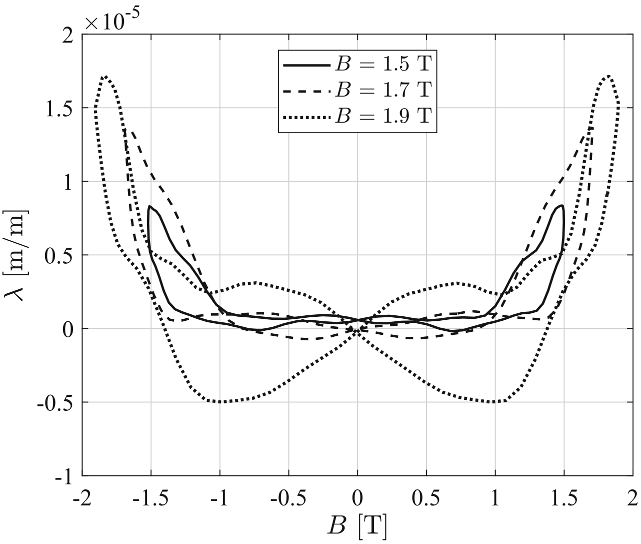

Fig. 6. Magnetostriction as a function of the magnetic polarization (13 strips per limb).

limb, under three induction levels. As it can be verified, the first two harmonics (100 and 200 Hz) show a greater contribution; however, for higher polarization values, the influence of higher harmonics rises.

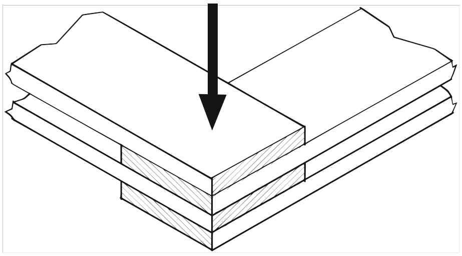

Fig. 7. Load applied on the lap joints

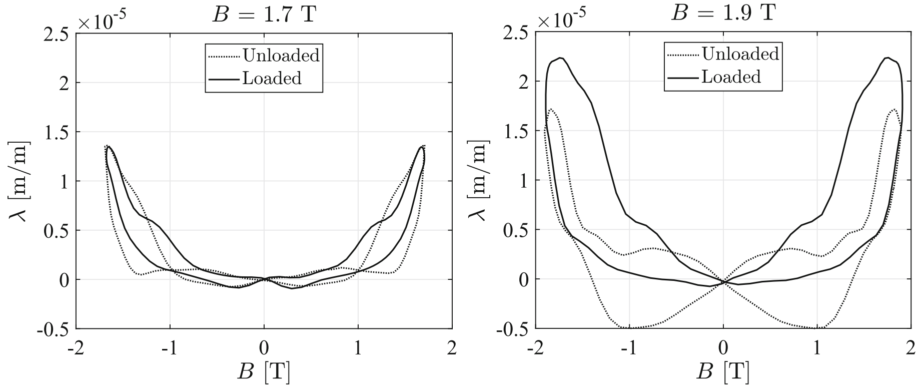

Fig. 8. Influence of a clamping load applied on the core joints.

The influence of the magnetic polarization on the magnetostriction of the test specimen was also addressed. According to previous studies [1,6], peak-to-peak magnetostriction rises when the magnetic polarization increases. This trend was verified in the tested specimen, as shown in Fig. 6. Moreover, the magnetostriction loop is distorted when polarization rises, especially when the polarization is beyond the knee point of the hysteresis loop (B-H). This fact may be explained by a greater influence of higher harmonics (300 Hz and higher) on the magnetostrictive behavior of the specimen, as can be seen in Fig. 5. The impact of a clamping load on the lap joints of the Epstein frame, like displayed on Fig. 7, was also investigated. In order to load the joints, four 1.6 N weights were used. Figure 8 shows the obtained results. It was verified that the magnetostriction loops were distorted, yet the peak-to-peak and zero-to-peak magnetostriction values remained the same. The curve of higher polarization was the most misshaped, to the extent that the compressive strain could no longer be observed.

Besides magnetic hysteresis, magnetic materials are characterized based on the mechanical hysteresis [12]. In Fig. 9, magnetostriction is represented as a function of the magnetic field, for an excitation of 1.5 T. The mechanical hysteresis due to the magnetic excitation can be observed on Fig. 9.

In fact, the characterisation of the mechanical hysteresis of electrical steel was one of the main concerns of this investigation. For numerical computation of magnetostriction along the laminated iron core, FEM software require the mechanical hysteresis loop, in order to correlate the magnetic field with magnetostriction.

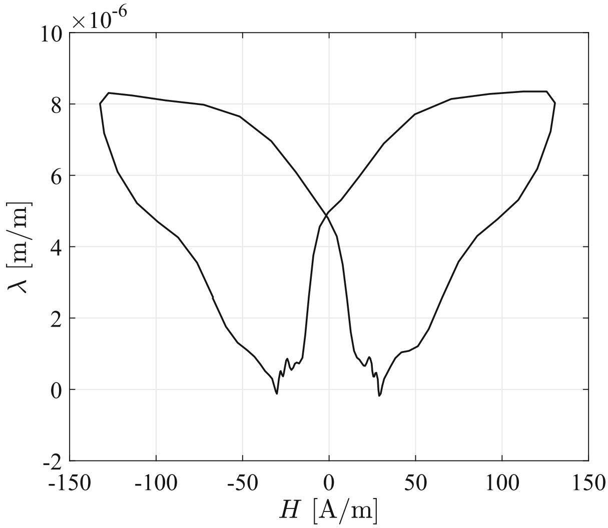

Fig. 9. Magnetostriction as a function of the magnetic field.

5 Conclusions and Future Work

Magnetostrictive behavior of grain oriented electrical steel was studied by means of an experimental set-up based on an Epstein frame. For the magnetostriction measurements, the generated signal of a strain rosette was acquired and processed via a dedicated software system. Current and voltage data was also acquired and synchronized with the strain data. Through the data software system, these two signals were processed in order to obtain the magnetic field and polarization, so that the magnetostriction curves could be extracted.

The frequency characteristics of magnetostriction were also addressed. The measured results allowed to conclude that the first two harmonics are the most significative, yet when the magnetic flux density gets closer to saturation, higher harmonics gain more influence.

In addition, this study revealed that the applied load on the core joints has influence on the hysteretic behavior of magnetostriction, since significant differences could be observed throughout the acquired data. With a view to further comprehend the influence of this load, additional measurements will be conducted with different weights.

Future research activities include additional magnetostriction measurements using Fiber Bragg Grating (FBG) sensors and a Laser Interferometer for comparison with previous results. Additionally, different types of grain oriented electrical steels will be tested, as to discern which are the optimal solutions to decrease power transformers noise radiation.

From this study and in order to simulate the real operation of a power transformer, a modified Epstein frame with a clamping system on two limbs will be created. The new system will allow the characterization of magnetostriction, tanking into account the clamping pressure and the stress state of the other limbs.

Regarding the obtained results, the magnetostriction loop as a function of the magnetic field can be applied to numerical simulations, allowing the evaluation of power transformer noise radiation.

Acknowledgements. This work is supported by the project POCI-01-0247-FEDER-024035, with the acronym *Quiet Transformer 2*, co-funded by the European Regional Development Fund (ERDF) through COMPETE2020 - Programa Operacional de Competitividade e Internacionalização (POCI) under the “Portugal 2020” Programme.

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