Magnetic losses in Si-Fe alloys for avionic applications

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(Submitted 2 November 2016; received 25 September 2016; accepted 12 December 2016; published online 8 March 2017)

This paper presents an experimental analysis of the rotational power losses of the magnetic materials of transformers, motors and actuators used in avionic environment. A large frequency range is investigated using a suitable experimental test frame developed to measure the power losses for a circular magnetization. The results about different silicon iron alloys with different textures and thickness are considered and compared. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

I. INTRODUCTION

In the avionic environment the operating frequency range of the electrical equipments is almost variable. In addition, modern power converters use signal controls with very large frequency ranges. This fact increases the power consumption in the magnetic cores of the electrical devices such as transformers, filters, motors and actuators, because of the presence of eddy currents, and this is a critical payload factor. For the design and optimization of these electrical systems can be very useful to characterize the magnetic behavior of the ferromagnetic materials used. In literature there are many papers about experimental measurements of specific power losses of ferromagnetic alloys at different frequencies.\(^1\)\(^-\)\(^3\) These works are mainly focused on scalar magnetization processes, while few data are available for rotational magnetization losses. To give a contribution about this issue, we present in this work a suitable experimental set-up used to characterize ferromagnetic alloys under rotational excitations at different frequencies. The data set presented can be useful for the numerical modelling of the electrical devices cited above. We have considered both non oriented (NO) and grain oriented (GO) Fe-Si alloy. In the first case the material grade is M400-65A (UNI EN 10106), the average value of the grains dimension is less than 1 mm, the thickness is 0.6 mm. This material is a Fully Finished material with high silicon density. The second one is the M130-30S (UNI EN 10107), the average dimension of the grains is about 1 cm, the thickness is 0.2 mm, the magnetic orientation is defined by a typical Goss texture.\(^4\) This material is obtained with a Nitriding technology with decarburization temperature at 830-860 °C. For these materials comparisons between losses at different frequencies are shown and discussed.

II. EXPERIMENTAL FRAME FOR THE MEASUREMENTS OF ROTATIONAL MAGNETIZATION PROCESSES

The power losses in the ferromagnetic cores of electrical machines used in avionic environment, are a critical issue since the frequency range of the operative currents and voltages can be very large, from 400 Hz to 800 Hz.\(^5\) In this work we present a characterization of the electrical steels used for these applications under rotational magnetization in the frequency range specified above. We take into account steel sheets of silicon iron alloys, where the specific power losses can be estimated by the magnetic field vector \(H\) and the magnetic induction vector \(B\) measured during the magnetization processes

\[
P = \frac{1}{\gamma T} \int_0^T \left( H_x \frac{dB_x}{dt} + H_y \frac{dB_y}{dt} \right) dt \tag{1}
\]
In this case we have considered a magnetization process where the vector $B$ and $H$ are always parallel to the steel sheet plane, in this way the $z$ component of the vector fields can be neglected. $P$ is the power loss, $T$ is the period of the detected signals, $\gamma$ is the mass density, $B_x$, $B_y$, $H_x$ and $H_y$ are the average value of the two components of $B$ and $H$ measured on a specific area of the steel sample. This area has to be far from the sample boundaries to neglect their effects. In the last years different experimental testers have been developed for the measurement of the rotational $B$ and $H$ vector during the magnetization processes in electrical steels; among them the square rotational single sheet tester (SRSST), the hexagonal rotational single sheet tester (HRSST) and the round rotational single sheet tester (RRSST).

The main difference among these measurement frames is the sample shape which is square in the first case, hexagonal in the second and circular in the last one. We used the RRSST to study the magnetic behavior and the relative losses at different frequencies of the silicon iron alloys taken into account. In the figure 1 we show the two samples used for this characterization, the first one is a NO steel with 0.6 mm of thickness and the second one is a GO steel with 0.2 mm of thickness. The diameter of the disk sample is 7 cm. In the sample center two orthogonal coils are wrapped to measure $B_x$ and $B_y$ inside the material. Few turns are in general sufficient to obtain a high signal noise ratio, in this case we used three turns. The distance between two opposite holes of the sample is 2 centimeters. The position of the two orthogonal coils is critical for the GO sample because their dimension is close to the grain size. For this reason we have removed the coating on the GO sample before the sample cutting to see the grains distribution and chose an area where several grains are inside the two coils. In this way the measured values are more representative of the average behavior of the material, while a measurement on a single grain can be quite different. To measure the two components of the magnetic field we have used an array of biaxial hall sensors (Sentron©, 2SA-10, BiAxial, DC - 15 kHz). This array is used to extrapolate the value of the magnetic field vector on the sample surface as are explained with more details in Ref. 8. The device used for the sample magnetization is a stator of an induction motor with two orthogonal windings (Leporis©, ML 90S - 2, 1.5 kW, 230 V, 9 A) supplied by means two linear amplifiers (Elgar©, 3001/223, 5 Hz - 5 kHz, 3 kVA). The signals are generated using a programmable board (National Instruments©, USB 6995, 16-Bit, 1.25 MS/s) with two output to drive the amplifiers. The figure 2 describes this experimental set-up.
III. FEED-BACK ALGORITHM

The magnetization processes of ferromagnetic materials are physics phenomena with non linear and hysteretic behavior, therefore a reference shape of the magnetic induction loop has to be obtained in order to have repeatable measurements. In this work we considered circular rotation of the magnetic induction as reference shape for each $B$ amplitude and frequency for both NO and GO steel samples. A magnetic induction with constant amplitude during the rotational loop can be obtained by means a suitable feed-back control, in particular in this section we present the algorithm implemented for this scope.

The programmable board generates two output signals for the amplifiers 1 and 2 with a rate of 40 ksample/s, and the input channels of the board receive the voltage signals from the $B$ and $H$ sensors with the same sample rate (see figure 2). The feed-back algorithm is based on an iterative procedure: at each step a rotational magnetic field is applied on the steel sample and the measured values of $B_x$ and $B_y$ versus time are compared with two reference signals, that are two orthogonal sinusoids, digitally created. The percentage of the displacement between the measured $B_x$ and $B_y$ and the reference signals is used to increase or decrease the values of the output voltages created by the output channels of the programmable board. This procedure can generate an oscillatory behavior of the magnetic induction values around the reference signals, therefore to obtain a fast convergence a smoothing parameter can be used for the correction factor. The smoothing parameter increases when the frequency of the magnetization process increases. Using this strategy we performed a series of three measurements at 50 Hz, 400 Hz and 800 Hz for both NGO and GO steel samples. For each frequency a series of circular magnetic inductions with different amplitudes have been obtained using the feed-back control described above. The magnetic induction amplitude changes from 0.2 Tesla to 1.6 Tesla with a step of 0.2 Tesla and the complete set of circular loops are obtained in about 30 minutes. For the power losses computation the average values of clock-wise and counter-clock-wise data are used. These experimental results can be a reference data for the evaluation of the numerical models based on the Finite Element Method and suitable magnetic models developed and presented in previous papers.9–13

![Fig. 3](image-url)

**FIG. 3.** Magnetic induction and magnetic field loops during rotational magnetization processes at 800 Hz. (a) and (b) circular magnetic induction and magnetic field loops for NO; (c) and (d) circular magnetic induction and magnetic field loops for GO.
IV. RESULTS AND DISCUSSION

In this section we show the $B$ and $H$ loops and the corresponding power losses computed using the equation (1). In the figure 3 are shown the typical loops of the magnetic induction and the magnetic field measured. The magnetic induction loops are almost circular for the feedback procedure described above, while the magnetic fields loops are irregular, and in the case of the GO sample the anisotropy behavior of the material is much more evident. In the figures 4 and 5 we present the power losses: in the first one is reported the comparison between NO and GO sample at industrial frequency (50 Hz) and in the second one the comparison is shown for the typical avionic frequencies (400 Hz and 800 Hz). At lower frequency the NO sample behavior is better than the GO sample since the texture anisotropy of the material, and the corresponding hysteresis losses result prevalent respect the eddy current phenomena, as expected. At higher frequencies an opposite behavior has been evidenced: the sheet thickness plays an important role and the NGO sample with higher thickness gives higher specific losses.

As concluding remarks we can summarize that in this work:

We performed an experimental set-up for electrical steel evaluation for the avionic application, the feedback procedure proposed has been demonstrated to be efficient and reliable, the results
obtained confirm the complexity of the magnetization processes under rotational excitation, and, in particular, how the choice of the texture anisotropy and the sheet thickness can be fundamental for the power losses reduction.

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