Predicting magnetic losses in HGO steel sheets under distorted induction waveform

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ABSTRACT

We show that the magnetic losses of thin high-permeability grain-oriented Fe-Si sheets can be coherently assessed under sinusoidal and non-sinusoidal induction waveform by the analytical formulations provided by the Statistical Theory of Losses. Results are provided regarding the energy loss measured in 0,18 mm thick commercial sheets under sinusoidal induction and its change, for given peak polarization value J_p, with the distortion introduced by a third harmonic of defined amplitude J_{p3} and phase φ_3 relationships with respect to the fundamental component. It is shown that accurate prediction of the 50 Hz losses at $J_p = 1.7$ T for distortion generated by third harmonic peak polarization ratio $J_{p3}/J_{p1} = 0.1, 0.2$, and φ_3 ranging between 0° and 180° can be made by the sole knowledge of the sinusoidal losses.

I. **INTRODUCTION**

Pure sinusoidal regime is seldom achieved in magnetic cores, but their use in applications is still based on normative specifications and data sheets referring to the magnetic characterization performed under sinusoidal induction waveform. Novel applicative landscapes, accompanying the evolution of the electrical machines along the road to sustainable generation and transmission of the electrical energy, increasingly imply the integration of the magnetic cores with a driving electronic circuitry and make the working regimes of the cores generally depending on complex excitation waveforms. This is the case, for example, of grain-oriented (GO) steel cores used in turbogenerators and switched reluctance motors [1] [2], in solid state transformers [3] [4], and under the general circumstances occurring with power and distribution transformer cores supplying non-linear loads [5].

A meaningful approach to magnetic losses in steel sheets subjected to non-sinusoidal induction has been pursued in the literature by an array of methods. Empirical-phenomenological models, like the popular Steinmetz' model, its various extended/improved versions [6][7], and suitably modified classical formulas [8] have been proposed. Practical advantages in calculations, inherent to these models, are obscured by the feeble connection they have with the physical reality of the magnetization process. This is, on the contrary, the starting point of the Statistical Theory of Losses (STL) and the therein derived physical concept and formulation of the loss decomposition mechanism [9]. Originally developed for the prediction of the power loss in magnetic sheets subjected to constant rate of change of the magnetization, the STL was generalized later to sinusoidal and non-sinusoidal induction derivative [10] [11]. One obvious limitation of the STL approach is the eventual appearance of deep skin effect at high frequencies, which is accounted for either by making approximate phenomenological corrections to the involved statistical parameters [12] or by solving the Maxwell's diffusion equation for the non-linear medium [13]. This requires the identification of the magnetic constitutive equation of the material, which is hysteretic in nature, and the use of numerical methods. It is shown that the matter can be simplified by associating such equation with the normal magnetization curve [14].

For the specific case of GO sheets, criticism has been raised in the literature regarding the concept of loss decomposition, on the ground that the classical eddy current losses may have a loose meaning for a material endowed with a coarse domain structure [15] [16]. Consequently, it would be more appropriate to talk of dynamic loss $W_{\mathrm{dyn}}(f)$, without distinguishing between classical $W_{\mathrm{class}}(f)$ and excess loss $W_{\mathrm{exc}}(f)$ components. In this case, however, one will resort again to a phenomenological formulation [16]. The physical modeling of the motion of an ensemble of antiparallel domain walls (dws) under rated flux derivative, emulating the actual magnetization process in the GO sheets, shows, however, that $W_{\mathrm{class}}(f)$ emerges as a natural effect of long-range eddy currents and the statistics of the individual walls [9]. We can therefore justifiably write, whatever the case, the measured energy loss at any frequency as

$$W(f) = W_{\mathrm{hyst}} + W_{\mathrm{class}}(f) + W_{\mathrm{exc}}(f), \qquad (1)$$

where the hysteresis (quasi-static) loss component is, as far as deep skin effect is not involved, independent of frequency. The present experiments, performed in thin high-permeability GO sheets, endowed with slab-like domain structure, fit excellently with the STL. It is shown that, starting from the STL-guided decomposition of $W(f)$, measured from DC to 200 Hz under sinusoidal flux, we can predict with high accuracy the evolution of the 50 Hz energy loss following different degrees of distortions, as obtained with the introduction of a third harmonic of variable phase and amplitude.

II. **EXPERIMENTAL PROCEDURE.** -1

The magnetic losses and hysteresis loops were measured for defined J_{p} = 1.7 T in 0.18 mm thick Epstein strips of commercial HGO Fe-Si, according to the IEC 60404-2 standard (Epstein test frame). Sinusoidal and non-sinusoidal flux waveforms were imposed by digital feedback, implemented in the operation of a wattmeter-hysteresisgraph setup [17]. This is endowed with a 12-bit LeCroy HDO 4054 for signal acquisition, with the primary winding supplied by an NF HSA 4014 high-speed power amplifier driven by an Agilent 33220A arbitrary function generator. The energy loss was first measured up to 200 Hz with sinusoidal induction. Fig. 1a shows the measured $W(f)$ curve, together with its components. Once the classical loss is calculated by the standard equation

$$W_{\mathrm{class}}(f) = (\frac{\pi^2}{6\delta})\sigma d^2 J_{\mathrm{p}}^2 f \quad , \qquad \text{[J/kg]} \qquad (2)$$

where σ and δ are the conductivity and the mass density of the material and d is the sheet thickness, the quantity $W(f)$ - $W_{\mathrm{class}}(f) = W_{\mathrm{hyst}} + W_{\mathrm{exc}}(f)$ is plotted against $f^{1/2}$ (Fig. 1b). For the investigated HGO alloy it is $\sigma = 2.083 \cdot 10^6$ $\Omega^{-1}\mathrm{m}^{-1}$ and δ = 7650 kg/m^3. As predicted by the STL, a linear dependence of this quantity on $f^{1/2}$ is observed, vindicating the related physical model for the case of coarse domain structure. It is also is an obvious confirmation of the absence of skin effect. The measurements were then performed at 50 Hz by introducing a third harmonic $J_3(t)$ of peak amplitude $J_{3\mathrm{p}}$ in the ratio $R = J_{3\mathrm{p}}/ J_{1\mathrm{p}}$ = 0.1 and R = 0.2 to the fundamental harmonic and relative phase shift φ_3 ranging between 0° and 180°. For any phase shift, $J_{1\mathrm{p}}$ and $J_{3\mathrm{p}}$ were adjusted in order to maintain J_{p} = 1.7 T everywhere. Examples of imposed $J(t)$ and dJ/dt non-sinusoidal waveforms

$$J(t) = J_1 \cos \omega t - R J_1 \cos(3\omega t + \varphi_3) \qquad \frac{\mathrm{d}J(t)}{\mathrm{d}t} = -\omega J_1 \sin \omega t + 3\omega R J_1 \sin(3\omega t + \varphi_3) \qquad (3)$$

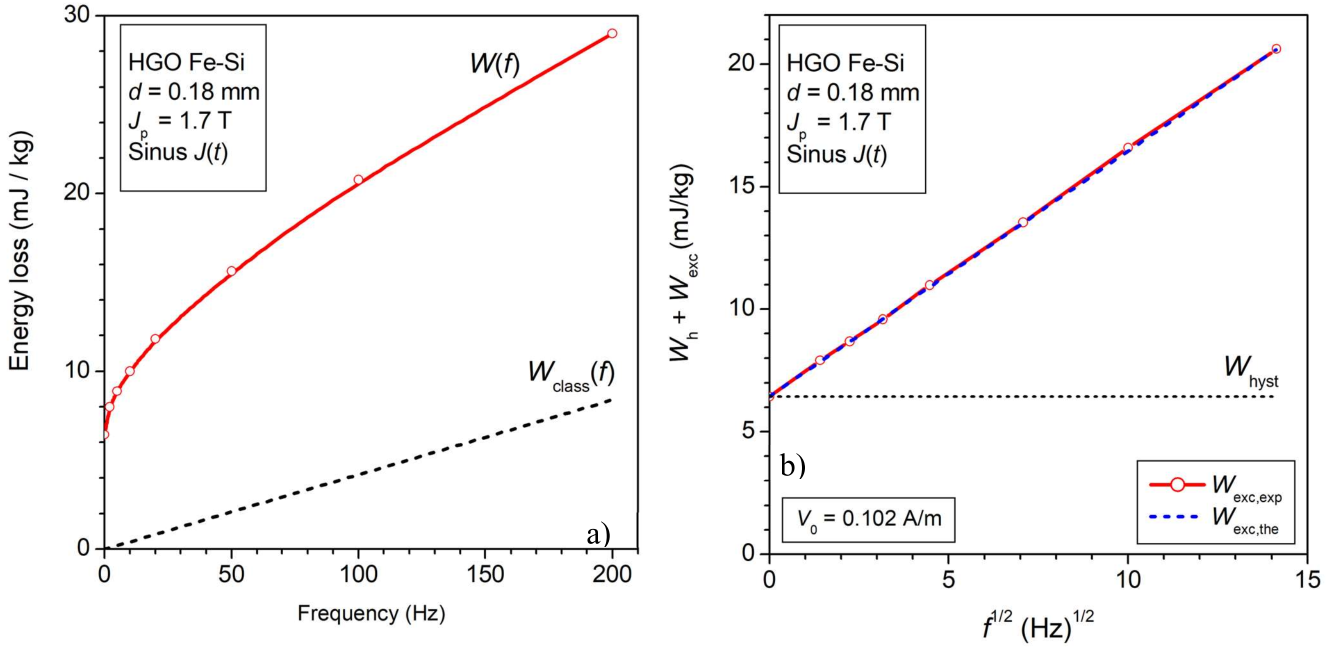

Fig. 1 – a) Energy loss versus frequency measured in a 0.18 mm thick HGO Fe-Si sheet under sinusoidal polarization of peak value $J_p = 1.7$ T. The classical loss component W_{class} is calculated with (1). b) The quantity $W(f) - W_{class}(f) = W_{hyst} + W_{exc}(f)$ is plotted versus $f^{½}$. Following the STL, this behavior is interpreted in terms of hysteresis loss W_{hyst} independent of frequency and $W_{exc}(f) \propto f^{1/2}$.

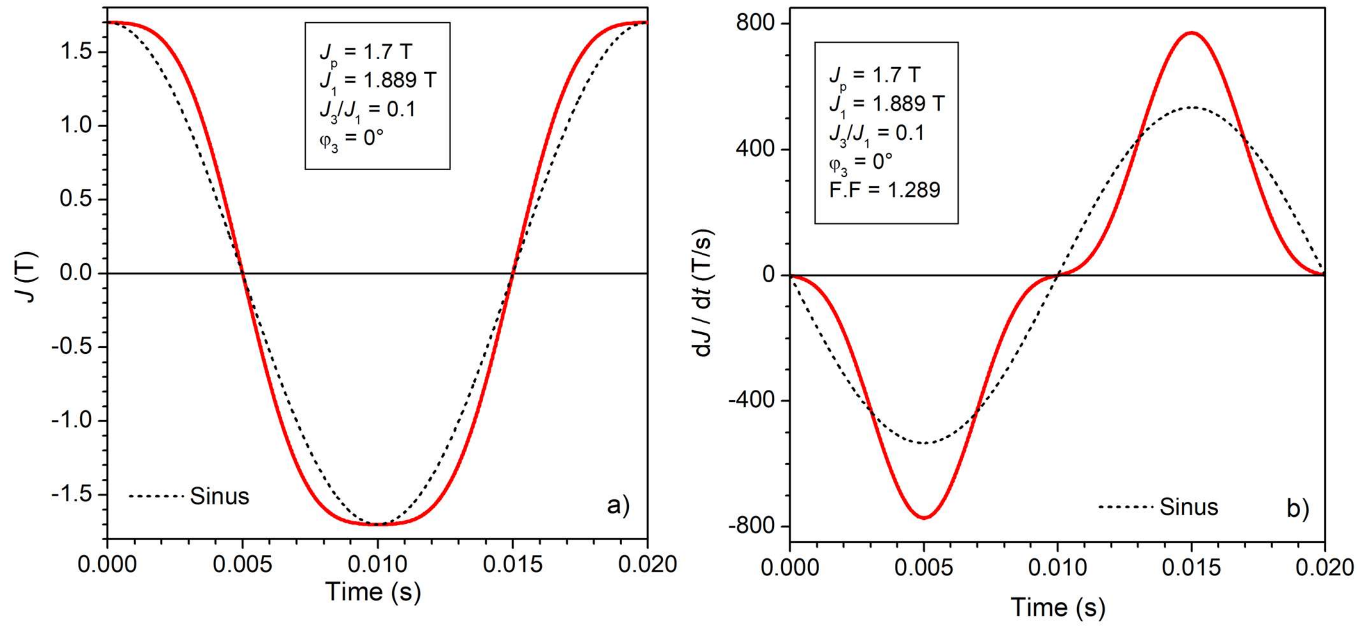

Fig. 2 – a) Polarization waveform of peak polarization $J_p = 1.7$ T composed of a fundamental harmonic of amplitude J_{p1} and a third harmonic of amplitude J_{p3} in the ratio $R = J_{p3}/J_{p1} = 0.1$ and phase shift $\varphi_3 = 0$ (see Eq. (3). The dashed line belongs to the sinusoidal $J(t)$ of equal J_p value. b) Time derivative of $J(t)$.

are provided in Figs. 2 and 3. The whole set of investigated $J(t)$ waveforms is shown in Table 1. Fig. 4 illustrates the experimental evolution of the hysteresis loops at 50 Hz and J_p =1.7 T under different degrees of distortion of $J(t)$. It is noted in Fig. 4 that the condition $R = 0.2$ and $\varphi_3 = 2°$, leads to the generation of a minor loop of local peak amplitude $\Delta J_p = 0.07$ T.

III. **ENERGY LOSS vs. WAVEFORM DISTORTION AND ITS PREDICTION**

The $W(f)$ behavior under sinusoidal polarization $J(t)$ shown in Fig. 1 is assessed by means of loss decomposition, where $W_{\mathrm{class}}(f)$ is calculated by Eq. (1) and the quantity $W(f)$ - $W_{\mathrm{class}}(f) = W_{\mathrm{hyst}} + W_{\mathrm{exc}}(f)$, plotted against $f^{1/2}$, permits one to straightforwardly separate W_{hyst} and $W_{\mathrm{exc}}(f)$. The latter perfectly fits into the theoretical prediction by the STL, according to the equation

$$W_{\mathrm{exc}}(J_{\mathrm{p}}, f) = (\frac{8.76}{\delta})\sqrt{\sigma G S V_0(J_{\mathrm{p}}) f}\, J_{\mathrm{p}}^{3/2}, \qquad \text{[J/kg]} \qquad (4)$$

where G = 0.1356, S is the cross-sectional area of the sample under test, and the parameter V_0, having the dimension of a magnetic field, is a statistical parameter, to be found by equating (4) with the experimental $W_{\mathrm{exc}}(f)$ in Fig. 1b. V_0 bears a precise physical meaning, because it relates to the statistics of the local coercive fields involved with the dw motion. We find, in the present case of HGO sheets, the value $V_0(J_{\mathrm{p}} = 1.7\ \mathrm{T}) = 0.102$ A/m.

A basic physical assumption lying behind Eq. (4) is the possibility do define the instantaneous power loss

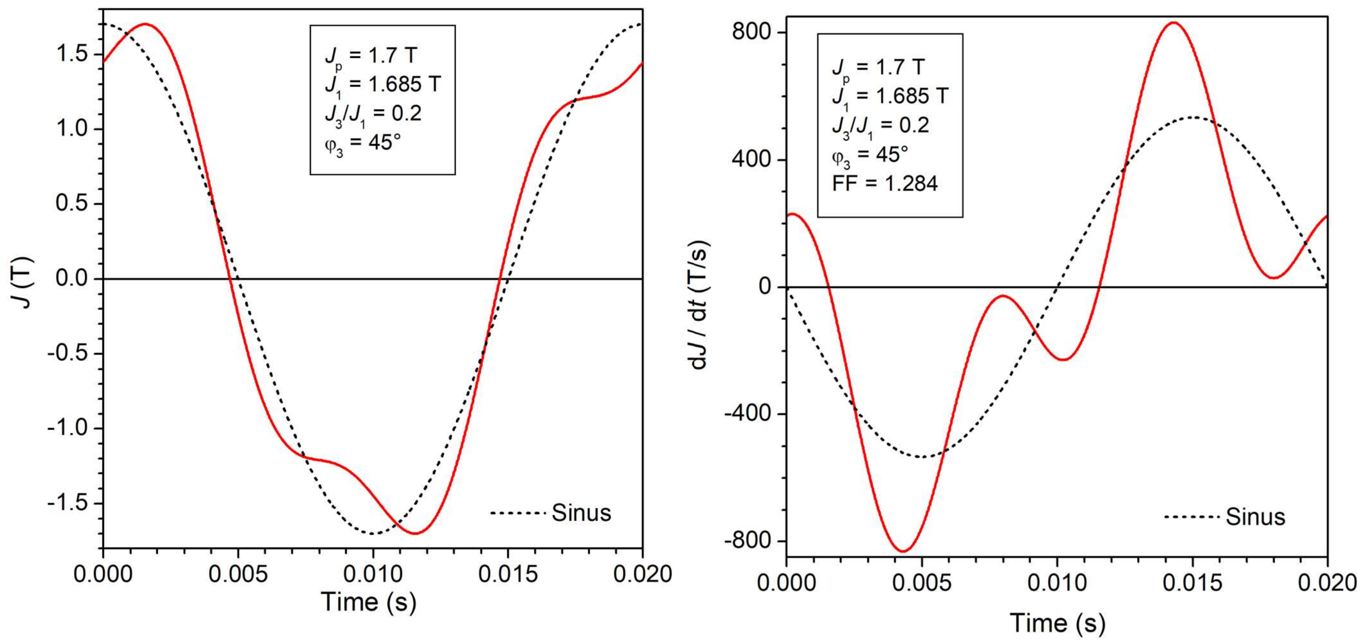

Fig. 3 –As in Fig. 2 for $R = J_{\mathrm{p3}}/J_{\mathrm{p1}} = 0.2$ and phase shift $\varphi_3 = 45°$.

for all the components [9] [10]. This permits us to find the average power loss, that is, the energy loss per cycle, by integrating the instantaneous loss over the period. As far as the distortion is not engendering local minima of the polarization along the period T, the hysteresis loss is independent of the polarization waveform. Under these circumstances, we need to calculate $W_{\mathrm{class}}(f)$ and $W_{\mathrm{exc}}(f)$ as a function of the specifically envisaged $J(t)$. We therefore write, according to the definition of instantaneous classical power loss

$$W_{\mathrm{class}}(J_{\mathrm{p}}, f) = \frac{\sigma d^2}{12\delta} \cdot \int_0^T (\frac{\mathrm{d}J}{\mathrm{d}t})^2 \mathrm{d}t\ . \qquad \text{[J/kg]} \qquad (5)$$

We calculate, at the same time, the excess loss by a similar integration [11]

$$W_{\mathrm{exc}}(J_{\mathrm{p}}, f) = \left(\frac{1}{\delta}\right)\sqrt{\sigma G S V_0} \cdot \int_0^T \left|\frac{\mathrm{d}J}{\mathrm{d}t}\right|^{3/2} \mathrm{d}t. \qquad \text{[J/kg]} \qquad (6)$$

It is immediately obtained that, for $J(t) = J_\mathrm{p}\cos\omega t$, Eq. (4) is retrieved. For all the harmonic combinations illustrated in Table 1, Eqs. (5) and (6) have been calculated and added to W_{hyst} in Eq. (1). The comparison between measured and predicted loss figures is provided in Table 2. Fig. 6 equivalently shows the dependence of the experimental and theoretically predicted energy losses as a function of the parameter φ_3, normalized to the energy loss value measured under sinusoidal $J(t)$.

Table 1 – The investigated set of $J(t)$ waveforms made of fundamental $J_1(t)$ and third harmonic $J_3(t)$ components, according to $J(t) = J_1\cos\omega t - RJ_1\cos(3\omega t + \varphi_3)$. The harmonics are in the ratio $R = J_{3p} / J_{1p}$ and are phase shifted by the angle φ_3. The peak value of the resulting waveform is induction is always J_p = 1.7 T.

$R = J_{3p}/J_{1p}$	φ_3 (°)	J_p (T)	J_{1p} (T)	J_{3p} (T)	Form Factor dJ/dt
0.1	0	1.7	1.889	0.1889	1.289
0.1	30	1.7	1.807	0.1807	1.233
0.1	45	1.7	1.759	0.1759	1.200
0.1	60	1.7	1.714	0.1714	1.169
0.1	90	1.7	1.639	0.1639	1.118
0.1	150	1.7	1.555	0.1555	1.061
0.1	180	1.7	1.545	0.1545	1.054
0.2	2	1.7	1.937	0.387	1.375
0.2	30	1.7	1.76	0.352	1.337
0.2	45	1.7	1.685	0.337	1.284
0.2	60	1.7	1.622	0.3244	1.236
0.2	90	1.7	1.527	0.3056	1.164
0.2	150	1.7	1.428	0.2856	1.088
0.2	180	1.7	1.417	0.2834	1.080

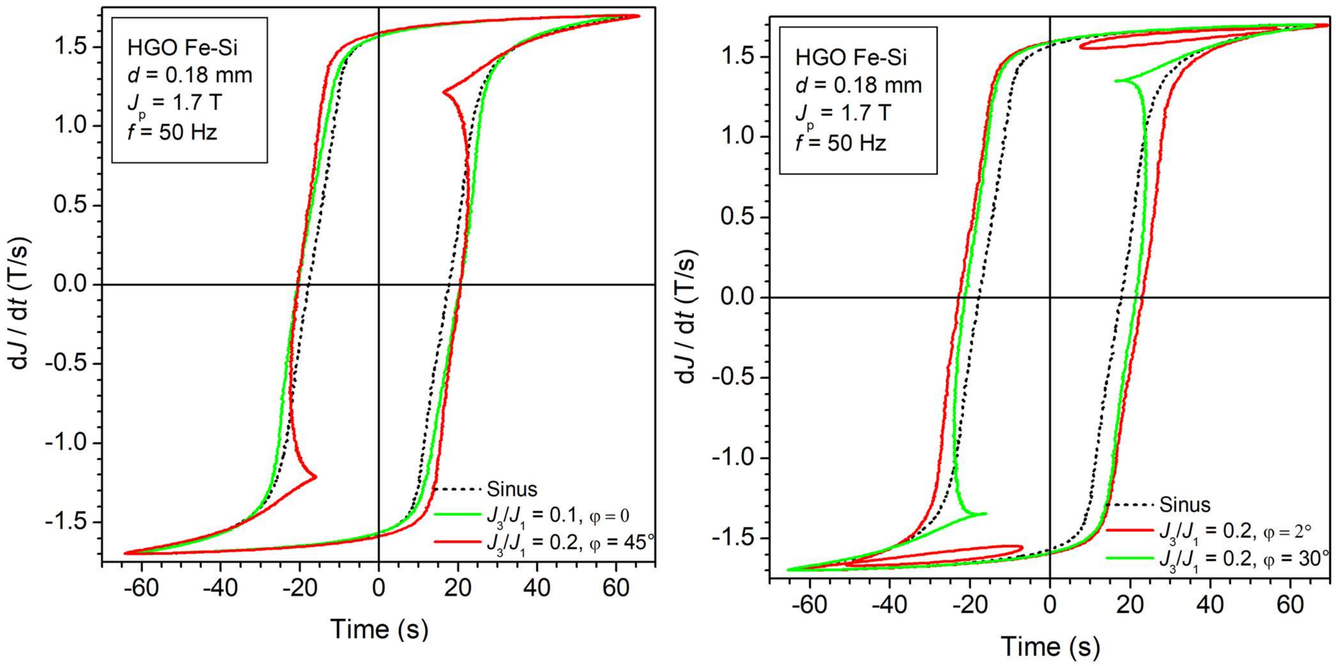

Fig. 4 – Hysteresis loops measured at 50 Hz under sinusoidal and non-sinusoidal polarization $J(t)$ for J_p = 1.7 T. To note the formation of a minor loop for the combination J_{3p}/J_{1p} = 0.2 and phase shift φ_3 = 2 °. In this case we need to account for a small additional contribution to W_{hyst}.

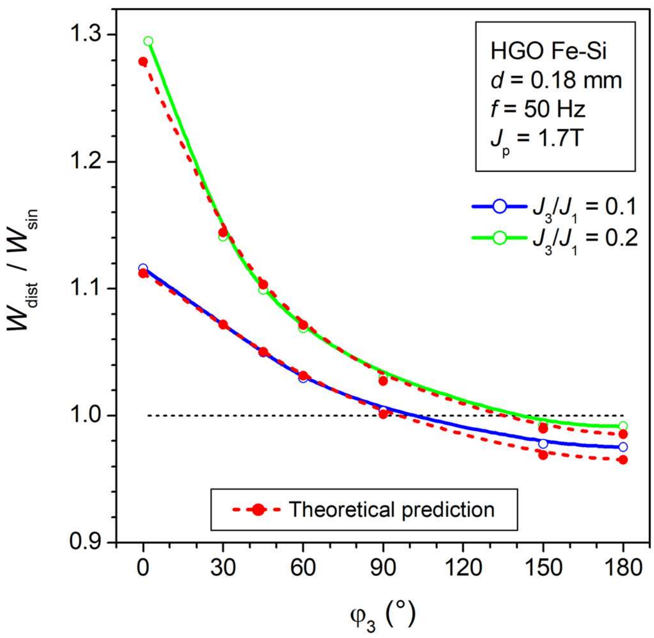

Fig. 5 - Evolution with the degree of distortion of the 50 Hz energy loss measured at J_p = 1.7 T in the HGO Fe-Si sheets (solid lines) and its prediction by use of Eqs. (5) (6), and (1) (dashed lines).

Table 2 – Measured and predicted 50 Hz energy losses at 50 Hz at J_p = 1.7 T versus the parameters identifying the distorted polarization waveform. The loss figure measured under sinusoidal $J(t)$ is 16.44 mJ/kg. Th difference between the measured and predicted loss figures is of the order of the measuring uncertainty.

φ_3 (°)	J_3/J_1	W_{meas} (mJ/kg)	W_{calc} (mJ/kg)	J_3/J_1	W_{meas} (mJ/kg)	W_{calc} (mJ/kg)
0	0.1	17.45	17.392	---	---	---
2	---	---	---	0.2	20.25	20
30	0.1	16.7646	16.762	0.2	17.845	17.897
45	0.1	16.42	16.427	0.2	17.1895	17.252
60	0.1	16.1	16.133	0.2	16.7165	16.756
90	0.1	15.7	15.655	0.2	16.1095	16.064
150	0.1	15.29	15.152	0.2	15.525	15.482
180	0.1	15.25	15.098	0.2	15.509	15.411

CONCLUSIONS

The energy losses of thin high-permeability grain-oriented sheets have been measured at 50 Hz under various degrees of distortion introduced, for given peak polarization value J_p = 1,7 T, by a third harmonic component of variable amplitude and phase shift. It is shown that, starting from the experimental results obtained under sinusoidal magnetization, the Statistical Theory of Losses permits one to accurately predict the behavior of the loss figure imposed by the evolution of the magnetization waveform. The theory permits one, in particular, to separately calculate the effect of distortion on the classical and the excess loss components, with the hysteresis (quasi-static) loss remaining unaffected, but for the case where a local minimum of the $J(t)$ waveform (additional minor hysteresis loop) enters into play. The degree of accuracy of the calculated loss figures is comparable with the experimental measuring uncertainty.

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