EFFECT OF CURRENT HARMONICS ON THE HYSTERESIS LOSSES IN SOFT MAGNETIC MATERIALS

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Key words: Hysteresis losses, Nonsinusoidal regime, Harmonics, Preisach hysteresis model, Single sheet tester.

The paper presents an efficient numerical procedure, which estimates the hysteresis losses in the FeSi materials, for periodic nonsinusoidal magnetic field having the harmonic spectrum revealed by industrial measurements made for transformers supplying various consumers. The used hysteresis model is a scalar classical Preisach model, its statistical distribution function being identified from the symmetrical cycles, measured by an industrial equipment – a single sheet tester (SST). The numerical procedure is adapted to the soft magnetic material, by using a nonuniform meshing of Preisach triangle.

1. INTRODUCTION

Soft magnetic materials are used in electromagnetic devices, as transformers or electrical machines, the associated losses being very important for design and exploitation [1]. Industrial nonlinear consumers impose a nonsinusoidal regime that increases the magnetic losses, their prediction being a subject frequently treated in scientific literature [2–4]. This estimation of magnetic losses in ferromagnetic materials is a very old scientific subject, the first methods being analytical [5]; the well-known Steinmetz formula was improved in [6] or extended for nonsinusoidal problems [7].

For a magnetization cycle, the hysteresis losses are given by Warburg law, but the heat generated for an open transformation cannot be computed; even its experimental determination is very difficult, because the rise in temperature is small (0.0003 $^{\circ}$C for annealed iron after a complete cycle [8]). The entire magnetic evolution being a mix between reversible and irreversible processes (magnetic domain wall displacement and/or magnetization vector rotation), the thermal behavior depends on the material. In fact, some old experiments revealed alternating heating and cooling intervals [9].

A useful estimation of the magnetic losses involves the accurate modeling of hysteresis curves; for a nonsinusoidal regime, the minor cycles are also involved

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and must be modeled [10]. An accurate hysteresis modeling involves special techniques and many numerical difficulties [11] or the numerical correction of the measured data used by the model identification [12]. The geometry of the magnetic core also must be taken in consideration for the magnetic field computation [13]. An alternative approach could be the modeling by nonlinear circuits, which are analyzed in frequency domain [14]. The resulted losses estimation is very useful for the intentional reduction of the maximum load capacity (derating) for the in-service power distribution transformers that operate under nonsinusoidal steady state condition [15].

Our study starts from real measurements made for an industrial transformer supplying various consumers. One uses these periodic nonsinusoidal profiles for the magnetic field, which is applied to the magnetic material, and one estimates the associated hysteresis losses in the FeSi sheets. The used hysteresis model is a scalar classical Preisach model, its statistical distribution function being identified from the symmetrical cycles, measured by an industrial equipment – a single sheet tester (SST). The numerical procedure is adapted to the soft magnetic material, by using a nonuniform meshing of Preisach triangle. The proposed approach could be the first estimation of the hysteresis losses in a magnetic core, especially if the magnetic field is known or it can be computed for each point of the magnetic core.

2. HYSTERESIS PREISACH MODELING AND LOSSES EVALUATION

The hysteresis classical Preisach model considers the magnetic material being composed by hysterons having rectangular hysteresis cycles; it is a scalar model – the orientation of the vector magnetic magnitudes is the same. The distribution of the up- and down-switching values (*a*, *b*) of the magnetic field *H* (model input), characterizing each hysteron (Fig. 1), must be identified from the available experimental data. Our study uses an industrial single sheet tester (SST Brockhaus® C310) to measure the magnetic field *H* and the magnetic polarization *J* for a nonuniform set of symmetrical hysteresis cycles of various amplitudes (47 cycles). The model output *J* is computed as:

$$J(H) = \iint_{S_+(H)} P(a,b)\cdot \mathrm{d}a\cdot \mathrm{d}b - \iint_{S_-(H)} P(a,b)\cdot \mathrm{d}a\cdot \mathrm{d}b, \tag{1}$$

where $P(a,\ b)$ is the Preisach distribution function and S_+, S_- are the areas corresponding to the positive and negative saturated hysterons in the Preisach triangle ($-H_s \le b \le a \le +H_s$) represented in Fig. 1.

Taking into account the strong nonlinear shape of the magnetic characteristic and the narrow hysteresis cycles for a standardized FeSi sheet, the measured points on hysteresis cycles are not equaly spaced, generating a nonuniform meshing of the Preisach triangle. Data measured by SST directly give the discreet values of

Everett integral $T(i, j)$ (integral of Preisach function P over the triangle having the corner (i, j) in Fig. 1).

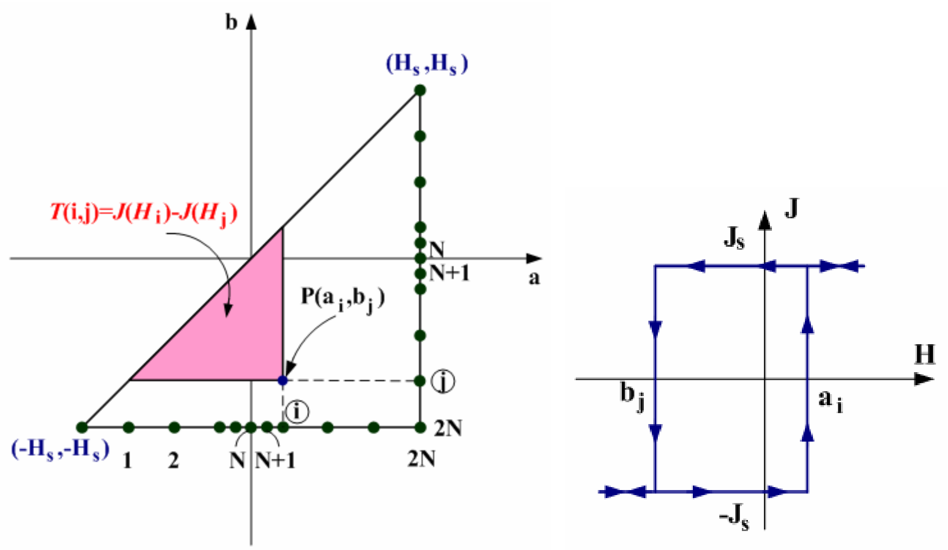

Fig. 1– Preisach domain (left) and the hysteresis cycle of a hysteron (right).

The measured magnetic characteristics for grain-oriented (GO), Fe-Si sheets having various angles between the sheet longitudinal axis and the anisotropy easy axis are presented in Fig. 2. The 47 measured minor symmetrical cycles (for each orientation angle) are not visible, being very narrow. The identified Everett integral values are shown in Fig. 3 for easy axis orientation.

The model output J can be computed for any value of the model input H, starting from the identified Everett distribution and knowing the magnetic history (previous H-J values), recorded in Preisach domain by the line between S_+ and S_-.

The magnetic energy density of an electromagnetic body w_m (in J/m^3), whose evolution starts from a reference state having $H = 0$, can be computed from Poynting theorem:

$$w_m = H \cdot B - \int_0^H B \cdot \mathrm{d}H \, . \tag{2}$$

For a hysteresis cycle corresponding to a sinusoidal magnetic field, the final and the initial states are the same, obtaining Warburg theorem. The relation (2) has the advantage to show the material energy evolution, even if the applied magnetic field is periodic, but nonsinusoidal.

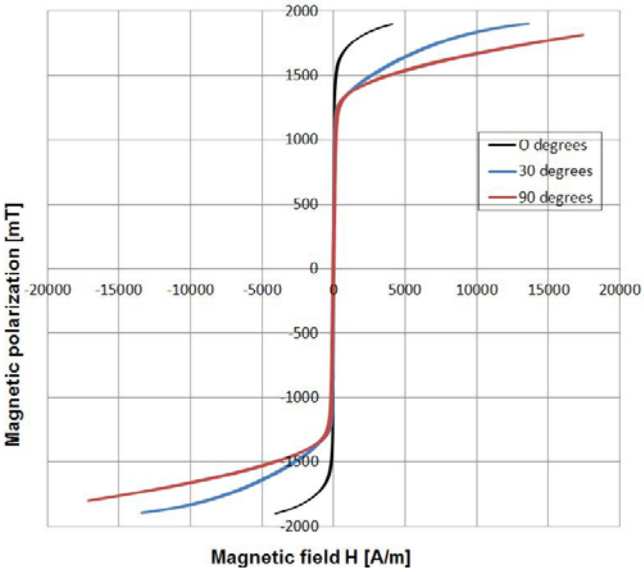

Fig. 2– Measured magnetic characteristics for grain-oriented (GO) Fe-Si sheets for various values of angle between the sheet longitudinal axis and the anisotropy easy axis.

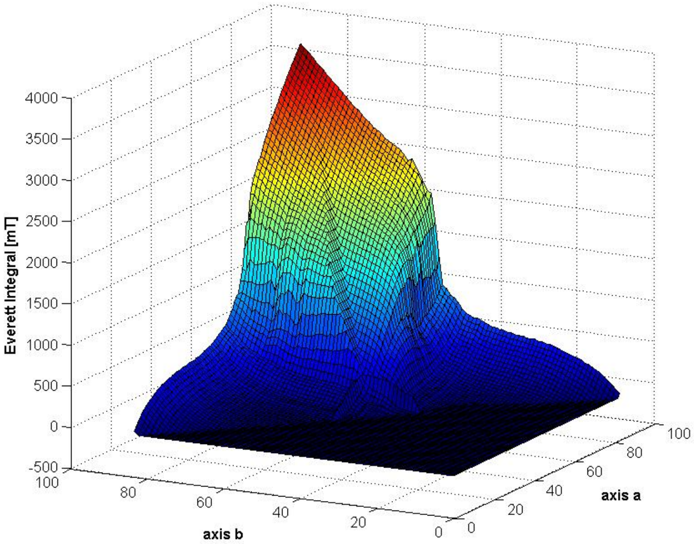

Fig. 3– Everett integral values identified for (GO) Fe-Si sheet magnetized on the anisotropy easy axis.

3. SPECTRUM OF THE MAGNETIC FIELD HARMONICS

The investigated grain-oriented FeSi sheets are widely used for transformer cores. Consequently, one will use the harmonics profile revealed by measurements made for industrial transformers, whose monitoring shows a nonsinusoidal working regime, even the supplied voltage is sinusoidal (50 Hz). The main sources of this periodic nonsinusoidal behaviour are the nonlinear character of the load and the magnetic nonlinear material of the transformer core. Our study will consider two specific harmonics profiles, which are presented in Fig. 4. The total harmonic distorsion (THD) values are 21.94 % for *Profile 1* and 94.52 % for *Profile 2*. The corresponding amplitudes and phases of the harmonics are presented in Table 1.

The weighting of harmonics will determine different profiles of the magnetic field *H*, which is applied to the magnetic material. The reconstruction of the *H* evolution in time generates the profiles shown in Fig. 5, assuming the same maximum value that corresponds to the saturation state of the soft magnetic material.

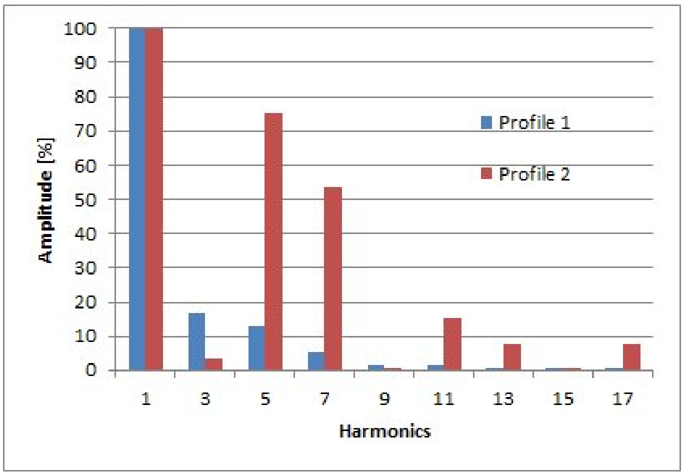

Fig. 4 – Harmonics spectrum.

Table 1

Harmonics amplitudes and phases (relative to the fundamental) for the nonsinusoidal waveforms

	Harmonic order	**1**	**3**	**5**	**7**	**9**	**11**	**13**	**15**	**17**
Profile 1	Amplitude [%]	100	16.8	12.8	5.4	1.8	1.5	0.7	0.1	0.2
	Phase [degrees]	0	23	–166	–65	128	–78	89	–56	–9
Profile 2	Amplitude [%]	100	3.6	75.4	53.7	0.5	15.1	7.9	0.5	7.8
	Phase [degrees]	0	–97	168	–18	–155	129	–111	53	–12

The magnetic evolution for a periodic nonsinusoidal input involves minor hysteresis cycles, due to the distortions produced by the harmonics, and the hysteresis losses will be increased, according to Warburg theorem. The harmonics having magnitudes and relative phases that change the evolution type (increasing or decreasing) will generate supplementary minor hysteresis loops.

Our tests will consider grain-oriented (GO) Fe-Si sheets having the magnetic characteristics presented in Fig. 2. Inside a magnetic core (*e.g.* a transformer yoke), the magnetic field is oriented under various angles in respect with the sheet anisotropy easy axis. Consequently, the hysteresis losses estimation is influenced by the sheet anisotropy. Our simulation will use two GO Fe-Si materials, having the sheet cutting angle of 0 degrees (*Material A* – the sheet longitudinal axis is the anisotropy easy axis) and 30 degrees (*Material B*), in order to show this dependence.

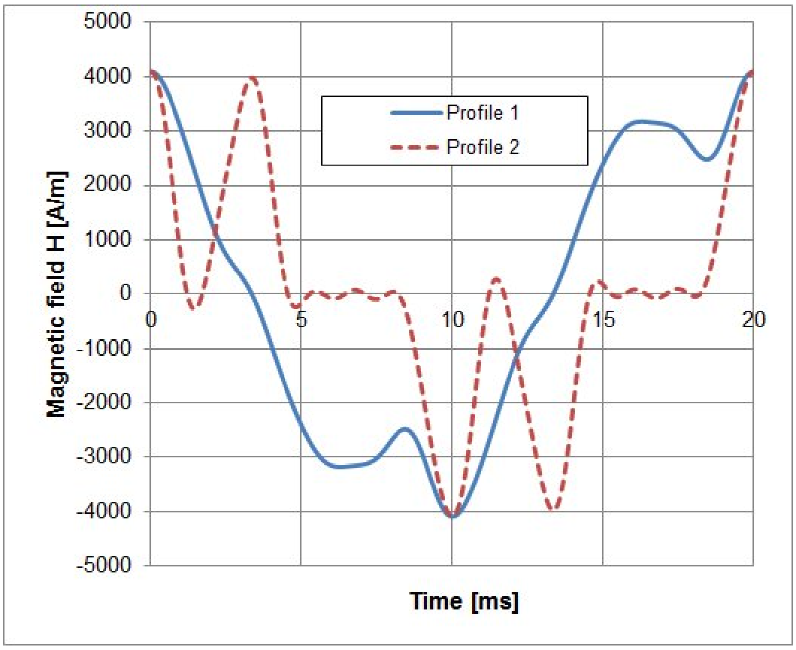

Fig. 5– Profile of the magnetic field applied to the magnetic material.

4. **HYSTERESIS LOSSES EVALUATION**

The effect of the distorted magnetic field (hysteresis model input) on the magnetic polarization (hysteresis model output) is simulated by Preisach modeling of the considered GO FeSi samples measured with SST. The magnetic energy density is computed with (2), considering the time origin being the moment when the demagnetizing begins, after the evolution on the first magnetization curve. The results are presented in Fig. 6 for *Material A* and in Fig. 7 for *Material B*.

The simulation results for the two harmonics spectrum cases are presented in Table 2. For all cases, the hysteresis losses are bigger for *Material B*, showing that the corners of a magnetic core, where the applied magnetic field is not alligned to the sheet magnetization easy axis, are characterized by a higher heating, being very important for an optimal design. The THD value is strongly connected to the nonsinusoidal hysteresis losses, but it is not the only parameter, the harmonics phases correlation also having a role in the distorted *H* profile. It could be mentioned that the hysteresis losses added by harmonics can be neglected for small THD: for *Profile 1* with THD = 21.94 %, the supplementary losses are 2.83 % for *Material A* and 4.25 % for *Material B*.

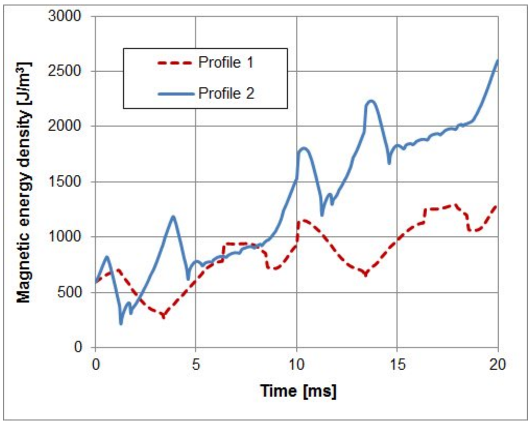

Fig. 6 – Evolution in time of the magnetic energy density for nonsinusoidal magnetic fields applied to *Material A* (0 degrees in respect with the easy axis).

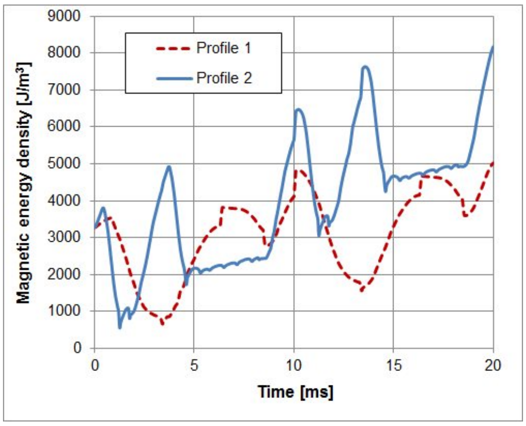

Fig. 7 – Evolution in time of the magnetic energy density for nonsinusoidal magnetic fields applied to *Material B* (30 degrees in respect with the easy axis).

Table 2

Nonsinusoidal hysteresis losses for two harmonics profiles (presented in Fig. 5)

		Material A **(FeSi GO_0 deg)**	***Material B*** **(FeSi GO_30 deg)**
Profile 1	THD [%]	21.94	21.94
	Nonsinusoidal hysteresis losses [W/kg]	13.43	30.88
	Hysteresis losses added by harmonics [%]	2.83	4.25
Profile 2	THD [%]	94.52	94.52
	Nonsinusoidal hysteresis losses [W/kg]	22.39	47.93
	Hysteresis losses added by harmonics [%]	71.44	61.82

The obtained results show the importance of this evaluation of the nonsinusoidal hysteresis losses in anisotropic soft magnetic materials, like those used for magnetic cores. For example, this estimation could allow a safety derating of an industrial transformer, designed for sinusoidal conditions, but supplying a nonsinusoidal consumer.

5. CONCLUSIONS

The presented method allows to estimate the nonsinusoidal hysteresis losses for anisotropic soft magnetic materials used for magnetic cores. The numerical procedure, implemented in MATLAB®, combines the identification of Preisach hysteresis model for grain-oriented FeSi sheets, measured with a single sheet tester (SST), with the computation of the magnetic polarization corresponding to the magnetic field values related to nonsinusoidal profiles revealed by measurements made for transformers supplying nonsinusoidal consumers. The sequence of the magnetic field values determines the evolution on minor hysteresis cycles. Our method allows the computation of the hysteresis losses in the soft magnetic material (grain-oriented FeSi sheets) for this complex evolution, corresponding to nonsinusoidal functioning conditions. The THD value and the harmonics phases correlation influence the added hysteresis losses for nonsinusoidal steady state regime.

The tests were made for the same magnetic material, but with different sheet cutting angles that change its anisotropy and magnetic characteristics. The obtained results show that this parameter is very important for the hysteresis losses level and outline the major role of the transformer yoke corners for the losses, especially under nonsinusoidal conditions. Consequently, a refined predetermination of the hysteresis losses must consider the core geometry, the losses estimation being done for each subdomain of the core, using the local magnetic field value, which is computed by a numerical procedure, like the finite element method.

The accuracy of the presented numerical procedure is maximized by using nonuniform meshing of the Preisach domain, which is correlated with the shape of the material magnetization curves.

An advantage of our method is that the necessary measured data (magnetic material characteristics used for the hysteresis model identification) are provided by an industrial single sheet tester. The method uses the static Preisach hysteresis model, but it can be improved by considering a dynamic hysteresis model for higher frequencies.

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