AIP | Journal of Applied Physics

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Citation: J. Appl. Phys. **113**, 17A319 (2013); doi: 10.1063/1.4795618
View online: http://dx.doi.org/10.1063/1.4795618
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JOURNAL OF APPLIED PHYSICS **113**, 17A319 (2013)

Semi-physical parameter identification for an iron-loss formula allowing loss-separation

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(Presented 15 January 2013; received 9 November 2012; accepted 10 December 2012; published online 20 March 2013)

This paper presents a semi-physical parameter identification for a recently proposed enhanced iron-loss formula, the IEM-Formula. Measurements are performed on a standardized Epstein frame by the conventional field-metric method under sinusoidal magnetic flux densities up to high magnitudes and frequencies. Quasi-static losses are identified on the one hand by point-by-point dc-measurements using a flux-meter and on the other hand by extrapolating higher frequency measurements to dc magnetization using the statistical loss-separation theory (Jacobs *et al.*, "Magnetic material optimization for hybrid vehicle PMSM drives," in *Inductica Conference*, CD-Rom, Chicago/USA, 2009). Utilizing this material information, possibilities to identify the parameter of the IEM-Formula are analyzed. Along with this, the importance of excess losses in present-day non-grain oriented Fe-Si laminations is investigated. In conclusion, the calculated losses are compared to the measured losses.
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I. INTRODUCTION

The accurate prediction of iron losses of soft magnetic materials for various frequencies and magnetic flux densities is eminent for an accurate design of electrical machines in automotive applications. For this purpose, different phenomenological iron-loss models have been proposed describing the loss generating effects. Most of these suffer from poor accuracy at high frequencies as well as high values of magnetic flux densities.[1]

Recently, the IEM proposed an advanced iron-loss estimation formula, which takes the non-linear material behavior into account.[1] This formula describes the total iron losses as a contribution of hysteresis losses, classical Foucault eddy current losses, excess losses, and a fourth term called saturation losses. The IEM-Formula represents, utilizing this additional loss contribution, a significant improvement in loss determination at high magnetic flux densities and high frequencies.

Accurate loss calculation including the ability of loss-separation forms the basis for the selection of the most appropriate electrical steel grade, which suits best the specific working conditions in the rotating electrical machine. Such a development gives more physical insight in the specific trade-offs that are made during the machine design process in order to identify the particular specifications of electrical steels, which could be further developed for particular applications.

In this paper, a detailed analysis of parameter identification with the aim of physically interpreted parameters, allowing a loss-separation, is presented.

Possibilities for identifying the parameters are analyzed and proposed. The parameters are identified following the statistical loss theory,[2] which gives a comprehensive justification from the physical point of view. Along with this, the importance of excess losses is studied for non-oriented Fe-Si materials.

The mentioned new loss term in the IEM-Formula, related to the non-linear material behavior, will be identified. The frequency dependence of the parameters will be discussed, and the obtained parameter sets are compared.

II. EXPERIMENTAL METHODS AND PROCEDURE

For the metrological characterization of the non-grain oriented FeSi 3.2% laminations, measurements are performed at different standardized Epstein frame configurations (Fig. 1), i.e., frames with different number of windings for different frequency ranges, utilizing the field-metric method under sinusoidal magnetic flux densities up to high amplitudes.

Quasi-static losses are identified on the one hand by point-by-point dc-measurements using a flux-meter and on the other hand by extrapolating higher frequency measurements to zero frequency using the statistical loss-separation theory[2] (Sec. IV B).

Measurements were performed on 24 stripes (dimensions of 280 mm $\times$ 30 mm, Fig. 1(left)) of the soft magnetic material, which were arranged in the Epstein frame as follows. In one layer, the samples are arranged alternately in accordance with the rolling direction, i.e., a sample in the rolling direction is followed by a sample perpendicular to the rolling direction. In the layer immediately below, the sample arrangement is shifted by 90° (Fig. 1(right)). Thus, rotation of the individual sheets during the stacking process of stator and rotor lamination of electrical machines is taken into account to yield a magnetic isotropy of the measurement samples.

The material under study is a non-oriented FeSi 3.2% lamination with a thickness of 0.35mm — M235-35A. The measurements are performed between quasi-constant current and 2000 Hz and in the magnetic flux density interval 0.3 – 1.7 T.

III. THE IEM-FORMULA

In order to model the non-linear material characteristic, particularly for high frequencies and high magnetic flux

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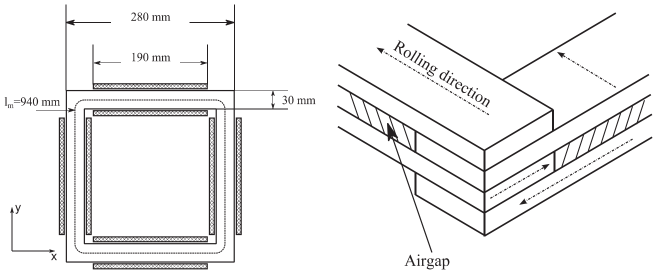

FIG. 1. Outline of the Epstein frames (left). Sample arrangement in different layers (right).

densities, the IEM proposed and validated an additional loss term with a higher order for B (which means higher than B^2 for the classical Foucault eddy current losses).[1,3]

The proposed mathematical formulation with higher order B term reads as follows:

$$P_{IEM} = a_1\hat{B}^{\alpha}f + a_2\hat{B}^2 f^2(1 + a_3\hat{B}^{a_4}) + a_5\hat{B}^{1.5}f^{1.5}, \quad (1)$$

where $\hat{B}$: magnetic flux density in Tesla (T); f: fundamental frequency in Hertz (Hz); a_i: fitted material parameters; α: exponent of the hysteresis losses.

Hysteresis losses, classical Foucault eddy current losses, and excess losses are included (respectively as terms with a_1, a_2, and a_5 coefficients), as well as the additional higher order $\hat{B}$ term $a_3\hat{B}^{a_4}$.

IV. SEMI-PHYSICAL PARAMETER IDENTIFICATION

Taking advantage of the information gained through the material characterization, possibilities to identify the parameters are analyzed and presented as follows.

The parameters a_1, α, a_2, and a_5 in Eq. (1) are identified following the statistical loss theory,[2] which gives a comprehensive justification from the physical viewpoint. Along with this, the importance of excess losses in today's non-oriented electrical steels is analyzed.

Next to this, the frequency dependence of the parameters a_3 and a_4, related to the non-linear material behavior, is studied and subsequently a fixed parameter set is derived, resulting in the ability of a loss-separation.

TABLE I. Identified parameters for M235-35A.

Method	a_1	α
Point-by-point	0.015763	1.91
Extrapolated	0.016318	1.93

A. Classical Foucault losses

The parameter a_2 correlating with the classical Foucault eddy current losses can easily be calculated by the macroscopic equation[3]

$$a_2 = \frac{\pi^2 d^2}{6\rho\rho_e}, \quad (2)$$

with the sheet thickness d, the material specific density ρ, and the specific electrical resistivity ρ_e of the soft magnetic material.

B. Hysteresis losses

As a part of the semi-physical parameter identification, the parameters a_1 and α, describing the hysteresis losses, have to be determined. Two different approaches are used.

One is based on dc-loss measurements (point-by-point quasi-static loss measurements using a flux-meter) at a standard Epstein frame finding the best parameter set for the description of the hysteresis losses

$$E_{DC} = a_1 \cdot B^{\alpha}. \quad (3)$$

The alternative method uses the statistical loss-separation theory to obtain the dc-properties as explained in Refs. 4 and 5.

A comparison of the results is shown in Fig. 2. From the agreement of the two methods results directly that the lengthy point-by-point method is not absolutely necessary. The resulting parameters differ only marginally (Table I).

C. Excess losses

In order to determine the parameter a_5, the theoretical approach to excess alternating losses P_{ex}[4,6,7] is employed.

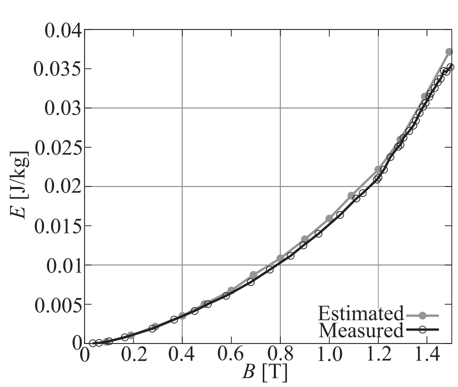

FIG. 2. Comparison of point-by-point dc-loss measurements (measured) and through extrapolation estimated ones (estimated) for M235-35 A.

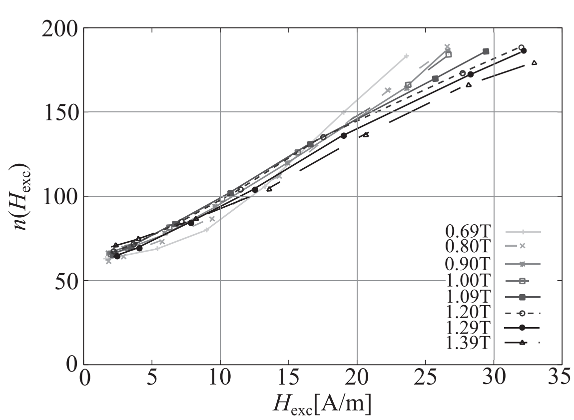

FIG. 3. The number of magnetic objects as a function of the excess field H_{exc} in dependence on the magnetic flux density for M235-35 A.

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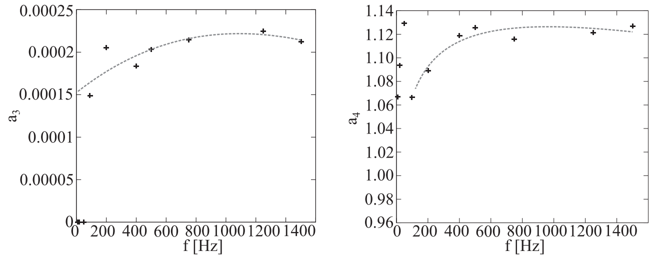

FIG. 4. a_3 (left) and a_4 (right) as a function of frequency for M235-35A. The dashed lines represent polynomial trend lines.

The theory assumes that a progressive increase of the magnetizing frequency leads, as a consequence of eddy current magnetic fields, to an increase of the number of independent sample regions, so called magnetic objects,[6] where magnetization is simultaneously reversed. For poly-crystalline materials, the excess losses are calculated as follows:

$$P_{\mathrm{ex}} = 8.76 \cdot \sqrt{\sigma G S V_0} \cdot \hat{B}^{1.5} \cdot f^{1.5} = a_5 \cdot \hat{B}^{1.5} \cdot f^{1.5}, \tag{4}$$

with σ the material electrical conductivity, G a dimensionless statistical coefficient, S the sample cross-section, and V_0 an internal field describing the microstructure-driven pinning effects on domain wall motion. Thus, the only parameter to be determined is V_0.

V_0 is connected to the dependence of the number of active correlation regions n on the excess magnetic field H_{exc},[4–6] i.e., it is related to the gradient (Fig. 3)

$$n(H_{\mathrm{exc}}) = \frac{16\sigma G S \hat{B}^2 f^2}{P_{\mathrm{ex}}}. \tag{5}$$

Thus, a_5 can be completely calculated (at intermediate inductions and at frequencies for which no significant skin effect occurs[7]) from material dependent properties,[6] resulting in the value $a_5 = 0.00068$.

D. Non-linear (saturation) losses

Parameters a_3 and a_4 are related to the non-linear material behavior at high frequencies and magnetic flux densities. For this reason, the dependence of both parameters on the frequency is studied, i.e., at each measured frequency the IEM-Formula (1) is fitted mathematically to the measurement data using the physically determined parameters a_1, a_2, a_5, and α. The only constraint is that a_4 is restricted to be smaller than a value of 2 and larger than 0. Results are depicted in Fig. 4. It is remarkable that both parameters vary only in a small area. A slight increase of a_3 towards higher frequencies and an almost zero value at low frequencies can be recognized. This is in-line with the physical explanation of this additional loss term.

Based on these results, two constant values of a_3 and a_4 are assumed in the following, i.e., $a_3 = 0.0002$ and $a_4 = 1.12$.

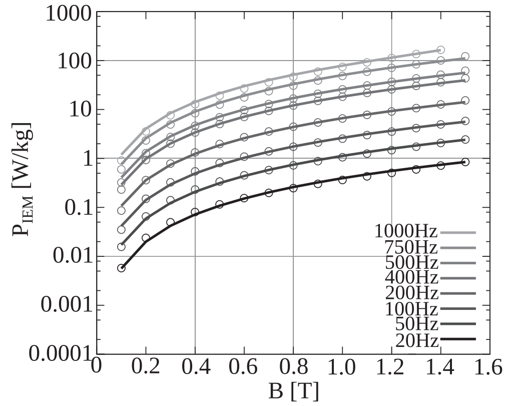

FIG. 5. Comparison of the IEM-Formula (1): straight lines—with measurements; circles—at different frequencies, employing the parameter set collected in Sec. IV for M235-35 A.

V. COMPARISON TO MEASUREMENTS

Subsequently the IEM-Formula is compared to the measurements. The used parameter set consists of the one identified in Sec. IV. The presented resulting losses for different flux density waveforms underline the accuracy of the developed loss model and parameter identification procedure (Fig. 5). The non-linear loss term accounts for up to 15% in the investigated frequency and flux density range and would be even more significant for loss calculations in electrical machines.

VI. CONCLUSIONS

This paper presents a semi-physical parameter identification approach for the recently proposed iron-loss formula, the IEM-Formula.[1] Measurements are performed on a standardized Epstein frame by the conventional field-metric method under sinusoidal magnetic flux densities up to high amplitudes and frequencies. Utilizing this material information, possibilities to identify the parameters of the IEM-Formula are analyzed. In conclusion, the calculated losses are compared to the measured data underlining the accuracy of the loss model.

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