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Two Approaches to Model Power Loss Under Increased Excitation Frequency

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This paper focuses on two models used for the determination of power loss components in steel samples under dynamic magnetizing conditions. The considered models differ in their approach as far as the possibility of distinguishing bulk and localized eddy currents is concerned. Two samples of non-oriented electrical steel differing in silicon weight contents are the subject of experiments. A comparison of the obtained results, as well as their discussion, is given in the paper.

topics: soft magnetic materials, core loss, loss separation, modeling

1. Introduction

The concept of loss separation in soft magnetic materials is considered an important problem for practitioners [1, 2]. The present paper is focused on two approaches to model power loss in chosen grades of electrical steel. For analysis, we have chosen non-oriented (dynamo) electrical steel with a thickness of 0.35 mm (grade M330-35A) as well as steel with silicon content increased up to 6.5% (grade JNEX, 0.1 mm thick, produced on commercial scale by the Japanese enterprise JFE Steel). The aim of the paper is to compare two possible approaches to the separation issue in terms of their predictive capabilities and accuracy. The first one relies on the so-called three-term separation scheme, which in the contemporary literature is usually ascribed to G. Bertotti [3]. The other one was proposed several years ago by one of the authors of the present paper [4].

As pointed out in a recent publication [5], non-oriented electrical steels are the most widespread soft magnetic material (SMM), accounting for around 80% of the total amount. They are commonly used as a core material in rotating electrical machines. According to [6], energy loss due to re-magnetization processes in electrical steels is estimated at a 5% level of the total produced energy worldwide. Therefore, a better understanding of energy dissipation processes in these SMMs may stimulate potential energy savings and reduction in environmental burden (greenhouse gas emission).

The range of produced non-oriented electrical steels includes several different types of steels, featuring miscellaneous silicon and aluminum content (the volumetric percentage of these two chemical elements is usually provided as a whole) and various sheet thicknesses. The volumetric silicon content in these materials is in the range of 1–3.7%, whereas for aluminum — 0.2–0.8%. Considering silicon content alone, it is expedient to introduce a distinction between low silicon steels (up to 2 wt% Si, used in household appliances), conventional steels (around 3.2 wt% Si), and high silicon alloys (around 6.5 wt% Si + Al).

Increase in silicon content in the alloy leads to significant changes in the material properties:

- the admixture of silicon significantly increases the resistivity of the material, which is equivalent to limiting its loss during remagnetization by limiting loss associated with the flow of eddy currents;
- the saturation induction value and the magnetostriction coefficient are reduced. This effect is more noticeable for high silicon alloys;
- the coefficient of magneto-crystalline anisotropy is reduced, which results in an increase in sheet permeability;
- magnetic aging (deterioration of magnetic properties of cores over time) is inhibited by capturing carbon atoms;
- the strength and stiffness of the considered alloys increases.

Aluminum affects the alloy properties in a similar way to silicon, which explains why it is sometimes used as its partial replacement. Article [7] draws attention to the fact that increasing the percentage of silicon and aluminum in the alloy may have an adverse effect on the mechanical properties of the alloy and the values of saturation magnetization and thermal conductivity. These parameters are also important in many applications. From the point of view of a manufacturer of electrical machines, it is desirable that the steel has a low level of loss and high values of magnetic permeability and thermal conductivity. From the steelmaker's perspective, it is preferred to keep the silicon and aluminum content as low as possible in order to make workability simpler.

The development of technology for producing sheets with increased silicon content is one of the latest achievements in contemporary research on soft magnetic materials [8]. Research on this group of SMMs was initiated in the mid-eighties of the last century in Japan [9–11]. Tests on magnetic properties of high silicon alloys produced in laboratory conditions, most often by rapid solidification of molten metal, have also been carried out in the USA and China. Alloys with approximately 6.5 wt% Si feature unique magnetic properties, such as almost zero magnetostriction, the highest value of permeability, and the lowest core loss among all electrical steels that contain silicon. Japanese enterprise JFE Steel Corp. is the only commercial producer of microcrystalline high-silicon steel (the brand name is JNEX).

Figure 1 depicts a comparison of material core loss per unit weight (commonly referred to as core loss density), measured at 1 T and 10 kHz. From Fig. 1, it is clear that electrical steels with increased silicon content are highly competitive against other comparable materials. Iron-based amorphous alloy, i.e., Metglas, features lower core loss, however, it is more difficult to process (harder workability, material available commercially only as cylinder-shaped cores wound of thin ribbon).

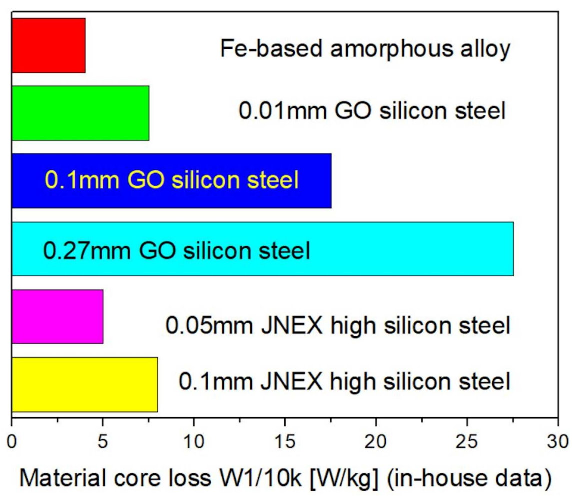

Fig. 1. Visual comparison of core loss for several alloys used in electrical engineering. Source: own work, based on JFE Steel Corp. promotional material.

2. Loss separation issue

One of the most controversial problems in magnetics is the proper description of energy dissipation in SMMs. According to the approach prevailing in contemporary literature, one can distinguish energy loss due to the hysteresis phenomenon and the flow of eddy currents in different time- and spatial scales. This approach is usually attributed to G. Bertotti, a representative of the so-called Torino school of magnetics [3], although the concept seems to be much older. Within Bertotti's framework, it is assumed that there exists a direct relationship between the macroscopic properties of an SMM subject to cyclic re-magnetization (power loss P, amplitude of flux density B_m, excitation frequency f) and the dynamics of the so-called magnetic objects (MOs) [12, 13]. The definition of MOs is, however, somewhat imprecise; in order to prove this we shall use a direct citation from the landmark paper [3]: "In particular, it has been shown that a single MO can be identified with a single Bloch wall in grain-oriented materials with large domains [20], whereas, in microcrystalline materials, the whole domain structure inside a single grain plays the role of a single MO [21], [22]."[†1]

An applied magnetic field with uniform spatial distribution tends to introduce a uniform distribution of magnetization within the sample cross-section. In a structurally homogeneous material, the equilibrium state is indeed achieved, and the loss related to the re-magnetization process is then given with the well-known expression for the so-called classical loss. The tendency to obtain a uniform distribution of magnetization is counteracted by structural inhomogeneities existing in the material, which are the sources of internal fields of magnetostatic origin, local coercive fields, and/or reaction fields related to eddy current flow. The internal fields feature highly inhomogeneous spatial distribution.

The "statistical" approach to the description of power loss within the SMM is based on an observation that domain wall movement during re-magnetization has a discontinuous character, which naturally leads to the concept that the

[†1]The reference numbers given in the quote come from work [3] — editorial note.

TABLE I

Fitting results for the M330-35A steel (Bertotti's formula).

B_m [T]		Parameter	Uncertainty	Residual SSQE	Adj. R-square
	K_1	0.00485	8.33×10^{-5}		
0.5	K_2	1.65×10^{-5}	1.07×10^{-6}	2.43×10^{-8}	0.99921
	K_3	1.19×10^{-4}	2.13×10^{-5}		
	K_1	0.01499	1.34×10^{-4}		
1.0	K_2	7.58×10^{-5}	3.88×10^{-6}	1.65×10^{-8}	0.99957
	K_3	2.56×10^{-4}	4.81×10^{-5}		
	K_1	0.03705	7.98×10^{-4}		
1.5	K_2	1.78×10^{-4}	2.32×10^{-5}	5.90×10^{-7}	0.99644
	K_3	2.70×10^{-4}	2.87×10^{-4}		

TABLE II

Fitting results for the M330-35A steel (two-term formula (2)).

B_m [T]		Parameter	Uncertainty	Residual SSQE	Adj. R-square
	K_4	0.00549	4.10×10^{-5}		
0.5	K_5	2.14×10^{-5}	1.58×10^{-7}	1.39×10^{-4}	0.99999
	α	2	–		
	K_4	0.01596	7.66×10^{-5}		
1.0	K_5	9.16×10^{-5}	9.11×10^{-7}	5.45×10^{-5}	0.99998
	α	2	–		
	K_4	0.03796	1.07×10^{-4}		
1.5	K_5	1.96×10^{-4}	1.28×10^{-6}	1.07×10^{-4}	0.99999
	α	2	–		

magnetization process might be described as a time–spatial stochastic process, which consists of random sequences of elementary magnetization changes, each of them corresponding to a sudden, localized jump of a segment of domain wall. Loss due to hysteresis is related to the dynamics of elementary jumps of single domain walls, which lead to the flow of significant, localized eddy currents even in the case when the average magnetization values change slowly. Dynamic loss, on the other hand, is the result of overlapping eddy current paths. If one assumes the time–spatial independence of jumps, one obtains the expression for classical loss. Taking into consideration the time- and spatial correlations between jump sequences leads to the introduction of an additional term, representing the so-called excess (anomalous) loss, into the energy balance equation.

Different morphologies of SMMs used in practice imply different mappings of "internal" quantities n (number of MOs) and H_{exc} (excess field). Article [14] includes a compilation of formulas useful for determining $n = n(H_{exc})$. In particular, the relationship used for NO steel with 3.2 wt% Si is $n = H_{exc}/V_0$, where V_0 is a phenomenological parameter related to microstructure. The value of this parameter should be constant, however, the dependence $V_0 = V_0(B_m)$ disclosed in [15] for the NO steel is an indirect proof of the existence of weak points in Bertotti's theory.

Paper [14] additionally provides a more complicated relationship for the dependence $n = n(H_{exc})$ in microcrystalline 6.5 wt% Si steel, however, no explanation for the specific choice of a second-order polynomial in the form $n = n_0 + \frac{H_{exc}}{V_0} + (\frac{H_{exc}}{V_0})^2$ is provided.

From the practitioner's perspective, Bertotti's theory reduces to the following relationship for total power loss (valid for the simplest "internal" relationship $n = H_{exc}/V_0$)

$$P = K_1 f + K_2 f^2 + K_3 f^{3/2}, \tag{1}$$

where K_1, K_2, and K_3 are coefficients, whose values depend on maximum flux density. Note that the values of exponents are fixed to "2" and "3/2" — they correspond to two limiting cases of weak and strong skin effect. The first term corresponds to the Steinmetz relationship [16], the second one is the relationship for "classical" eddy current loss [17], whereas the third one is interpreted as the excess (anomalous) loss due to eddy currents induced around moving domain walls.

In [4], it is argued that the distinction between macroscopic and microscopic eddy currents in SMMs is hardly possible, and thus loss separation into three terms is somewhat artificial. In order to overcome this deficiency, an alternative relationship was proposed

$$P = K_4 f + K_5 f^{\alpha}, \tag{2}$$

TABLE III

Fitting results for the JNEX steel (Bertotti's formula).

B_m [T]		Parameter	Uncertainty	Residual SSQE	Adj. R-square
0.4	K_1	0.0019	5.49×10^{-5}	6.18×10^{-9}	0.99317
	K_2	2.05×10^{-6}	5.00×10^{-7}		
	K_3	2.06×10^{-5}	1.17×10^{-5}		
0.8	K_1	0.00592	6.77×10^{-5}	9.39×10^{-9}	0.99929
	K_2	6.26×10^{-6}	6.16×10^{-7}		
	K_3	1.16×10^{-4}	1.44×10^{-5}		
1.2	K_1	0.01316	2.49×10^{-4}	7.37×10^{-8}	0.99827
	K_2	1.19×10^{-5}	2.79×10^{-6}		
	K_3	3.83×10^{-4}	5.82×10^{-5}		

TABLE IV

Fitting results for the JNEX steel (two-term formula (2)).

B_m [T]		Parameter	Uncertainty	Residual SSQE	Adj. R-square
0.4	K_4	0.00196	1.69×10^{-5}	6.16×10^{-9}	0.99432
	K_5	5.38×10^{-6}	1.54×10^{-7}		
	α	0.9	–		
0.8	K_4	0.00631	4.83×10^{-5}	5.02×10^{-8}	0.99682
	K_5	2.06×10^{-5}	4.39×10^{-7}		
	α	0.9	–		
1.2	K_4	0.01445	1.72×10^{-4}	4.62×10^{-7}	0.99133
	K_5	5.40×10^{-5}	2.06×10^{-6}		
	α	0.9	–		

where the fractional exponent α accounts for eddy currents dissipated in all time- and spatial scales in the sample. Two-term expression (2) was proposed by analogy to the Poynting theorem. Let us notice that K_4 should take comparable values to K_1 (this term is the Steinmetz formula, representing quasi-static loss due to hysteresis). Both (1) and (2) have the same number of degrees of freedom (three parameters), which facilitates their comparison.

3. Modeling examples

For the NO steel grade M330-35A, modeling was carried out for three values of magnetic flux density (0.5, 1.0, and 1.5 T), which are often provided in the catalogs of steel producers. The considered frequency range was 5–400 Hz for this steel. In order to facilitate fitting, the relationships (1) and (2) were transformed (measured values of power loss density were divided by excitation frequency), and thus energy dissipated per unit mass and per volume was determined. The determined values of coefficients along with their uncertainties and other measures of quality of fit (residual sum of squared errors (SSQE), adjusted R-square) are provided in Tables I and II. Measurements were carried out using a Single Sheet Tester device connected to a digital computer used for signal waveform control and data acquisition.

When fitting the $P = P(f)$ dependence using (2) for the examined steels, we tried to use the same value of exponent α regardless of excitation flux density. For the examined NO steel, it was found that the value which might be assumed for subsequent analysis was equal to $\alpha = 2$, thus the relationship (2) reduced itself to Bertotti's formula with the third term skipped. Therefore, there would be no need to introduce the concept of anomalous (or excess) loss in order to describe the energy dissipation process for this material. This conclusion is consistent with the observations by Brailsford [18]. Let us notice that despite the residual sums of squared errors, which are the measure for deviations of experimental data points from the predicted trends (curves obtained with (1) or (2)), are smaller for Bertotti's formula (1), the uncertainties in determined values of model parameters are considerably higher. The estimated values of K_4 are somewhat higher than their counterparts from (1), i.e., K_1.

Tables III and IV contain the fitting results for the microcrystalline steel with increased silicon content. Since the explanation for the necessity to use more complicated relationships for $n = n(H_{exc})$ (leading to the altered formula for total loss) was missing in [14], and, on the other hand, the producer of this SMM claims that this steel is isotropic, we used the same relationships (1) and (2) for fitting as in the previous case. We used data for three equidistant values of flux density, namely 0.4, 0.8, and 1.2 T, corresponding to three different regions

TABLE V

Loss separation for chosen data points (M330-35A).

	Measured	(1)	(2)
1 T, 50 Hz	1.03 $\frac{W}{kg}$	1.03 $\frac{W}{kg}$	1.03 $\frac{W}{kg}$
Dynamic [%]	25	27.2	22.3
Hysteresis [%]	75	72.8	77.7
1.5 T, 50 Hz	2.39 $\frac{W}{kg}$	2.39 $\frac{W}{kg}$	2.39 $\frac{W}{kg}$
Dynamic [%]	22.5	22.5	20.6
Hysteresis [%]	77.5	77.5	79.4

TABLE VI

Loss separation for chosen data points (JNEX).

	Measured	(1)	(2)
1.2 T, 50 Hz	0.816 $\frac{W}{kg}$	0.823 $\frac{W}{kg}$	0.814 $\frac{W}{kg}$
Dynamic [%]	13.3	20	11.2
Hysteresis [%]	86.7	80	88.8
0.8 T, 50 Hz	0.350 $\frac{W}{kg}$	0.353 $\frac{W}{kg}$	0.350 $\frac{W}{kg}$
Dynamic [%]	10.6	16.1	9.9
Hysteresis [%]	89.4	83.9	90.1
0.8 T, 400 Hz	4.285 $\frac{W}{kg}$	4.298 $\frac{W}{kg}$	4.331 $\frac{W}{kg}$
Dynamic [%]	39.6	44.9	41.7
Hysteresis [%]	60.4	55.1	58.3

on the magnetization curve. In this case, the value of exponent α was fixed at 0.9. The considered frequency range was 10–400 Hz for this grade. Magnetic measurements in this case were also carried out using a computerized Single Sheet Tester device.

The final verification of the usefulness of both considered formulas is their predictive ability for several chosen data points. We compared the results of the computations with the experimental results, where the loss separation was determined using the method of two frequencies [19]. The results are compiled in Tables V and VI. It can be stated that both relationships (1) and (2) yield quite comparable results as far as the values of total loss density are concerned. The second formula describes the loss separation components slightly better than Bertotti's formula for the microcrystalline JNEX steel, however, generally speaking, it can be stated that both considered relationships were found to be useful for practical computations.

4. Conclusions

Both two- and three-term formulas for power loss separation can be useful for the prediction of the quasi-static and dynamic component(s) of total power loss in the case of the examined non-oriented steel grades.

The quasi-static component is dominant at lower frequencies, in particular at power frequency. It can be noticed that its contribution to the total loss decreases with the increase in frequency. Therefore, special attention will be paid in future research to the more accurate calculation of the model parameter related to this loss component for a wider range of frequencies. Future work might also be focused on a comparison of dependencies $P_{\text{model}} = P_{\text{model}}(f)$ for nominally the same magnetic material but measured with different methods (Epstein frame, Single Sheet or Strip Tester) in order to analyze the effect of measurement technique on the values of model parameters and predictive capabilities of both considered power loss separation schemes.

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