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The effects of excitation conditions and annealing temperature on power loss in SMC cores

Abstract. *The paper considers the effects of excitation conditions (maximum induction, frequency) and annealing temperature on power loss dissipated in cores made of commercially available soft magnetic composites. The study has confirmed that the choice of annealing temperature has a significant impact on the magnetic properties of ready-made cores. It has been found that Somaloy 500 cores annealed at 450° C feature the lowest loss density in a wide range of excitation frequencies. The dependencies: total power loss versus frequency have been described using four alternative descriptions. The results indicate that the considered dependencies are equivalent and may be approximately described with a two-term formula of the form:* $P_{total} = W_{hyst} f + a f^2$.

Streszczenie. *W pracy przedstawiono wpływ parametrów wymuszenia (maksymalna indukcja, częstotliwość) oraz temperatury wyżarzania na straty mocy rozpraszane w rdzeniach z komercyjnie dostępnych kompozytów magnetycznych SMC. Stwierdzono, że wybór temperatury wyżarzania ma istotny wpływ na właściwości magnetyczne gotowych rdzeni. Zaobserwowano, że rdzenie z materiału proszkowego Somaloy 500 wyżarzone w temperaturze 450° C wykazują najniższe straty w szerokim zakresie częstotliwości magnesowania. Zależność strat całkowitych od częstotliwości opisano za pomocą czterech alternatywnych formuł. Wyniki badań wskazują na fakt, że rozważane zależności mogą być potraktowane jako równoważne i opisane za pomocą formuły dwuskładnikowej w postaci* $P_{total} = W_{hyst} f + a f^2$. ***Wpływ parametrów wymuszenia oraz temperatury wyżarzania na straty mocy rozpraszane w rdzeniach z kompozytów magnetycznych SMC***

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Keywords: Soft Magnetic Composites, magnetic properties, power losses, annealing temperature
Słowa kluczowe: Kompozyty magnetycznie miękkie, właściwości magnetyczne, stratność, temperatura wyżarzania

Introduction

Soft Magnetic Composites (SMCs) have recently gained an increased interest of scientific and engineering community due to a high potential for application range in electric machines, possibility to tailor up their magnetic properties, low production cost and easy recycling [1,2]. Magnetic properties of ready-made SMC cores are affected by a number of factors related to the morphology of SMC powder itself and to the processing conditions (heat treatment, compaction pressure, binder properties) [3].

The present paper is devoted to the effects of excitation conditions and annealing temperature on power loss dissipated in SMC cores. A companion paper [4] is focused on the effect of compacting pressure on power loss. The paper is structured as follows. Section 2 recalls briefly some contemporary descriptions of the $P_{total}(f)$ dependence. Section 3 presents state-of-the-art research results concerning the dependence of power loss on annealing temperature. In section 4 the results of measurements carried out on cores made of commercial SMC Somaloy 500 [5] at different annealing temperatures are presented. In the subsequent section 5 the modelling results and their discussion are presented. The paper ends up with conclusions.

Loss prediction and separation

1. Bertotti's theory

Loss prediction is an important issue for the designers of magnetic circuits. The problem is usually considered by performing a separation of total loss into a number of components [6]. At present the most comprehensive loss theory based on the loss-separation framework has been advanced by G. Bertotti, who has considered the dynamics of $\tilde{n}$ statistically independent ,,magnetic objects'' (MOs) in order to obtain a macroscopic description of magnetization variations within the magnetic material [7,8]. According to this researcher, loss dissipated at an increased excitation frequency is the result of a competition between the external magnetic field, which is uniform in space, and various local internal fields of different origin. The natural action of external magnetic field is to assure a homogeneous magnetization in the sample cross-section, what shall be obtained in a material without structural inhomogeneities. The tendency is opposed by the very existence of structural inhomogeneities in the material, which act as sources of internal magnetostatic fields, reaction fields due to localized eddy currents or local coercive fields.

The problem of loss prediction reduces itself to the examination of the dependences of $\tilde{n}$ MOs on excitation frequency f, amplitude of flux density B_m and microstructure. From the practical point of view the theory relies on loss separation into three terms, each of them corresponds to a different time- and spatial scale, what can be written in the first approximation as

$$P_{total} \cong W_{hyst} f + af^2 + bf^{1.5} \quad (1)$$

where W_{hyst} is energy lost due to hysteresis, a and b are constants for a given level of flux density. The values of these coefficients depend on geometry and material properties. In crystalline materials the term af^2 describes the so-called classical eddy current loss, whereas the term $bf^{1.5}$ - the excess loss. In powder materials, the counterparts of bulk and localized eddy currents responsible for the classical and the excess loss, respectively, are the inter-particle and intra-particle eddy currents, cf. Fig. 1.

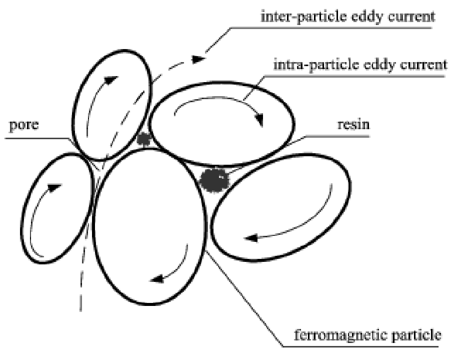

Fig. 1. A schematic depiction of inter-particle and intra-particle eddy currents in SMC. Source: own work, based on [1, 9, 10]

It should be recalled that Equation (1) implies the simplest relationship between the number $\tilde{n}$ of active MOs and the value of excess field H_{exc} which is interpreted as the difference between the actual value of local magnetic field acting on the magnetic objects and their averaged threshold field V_0 (the difference between the coercive fields of two interacting MOs). A linear relationship $\tilde{n} \cong H_{\mathrm{exc}}/V_0$ is postulated, what results in the fixed value of ,,excess'' loss exponent equal to 1.5 (cf. the third term in Equation (1). As pointed by the theory developer [8,11] this approach is valid for $f \geq 1..10$ Hz in the case of crystalline materials. The simplified description given with Eq. (1) shall be referred to in the paper as the simplified Bertotti model (SBM).

Taking into account the non-zero value $\tilde{n}_0$ of MOs in the quasi-static excitation conditions $(f \to 0)$ i.e. $\tilde{n} = \tilde{n}_0 + H_{\mathrm{exc}}/V_0$ leads to a modification of the formula for total loss [8]

$$P_{\mathrm{total}} \cong W^{*}_{\mathrm{hyst}} f + cf^2 + df\left(\sqrt{1+ef} - 1\right) \quad (2)$$

where W^{*}_{hyst} is energy lost due to hysteresis, c, d and e are constants for a given level of flux density. In the limit $e >> 1$ the relationships (1) and (2) coincide, however these two forms are not fully equivalent, as shall be proven in the subsequent section. Therefore the asterisks are introduced in order to distinguish the values of energy lost due to hysteresis in different descriptions. The relationships between the quantities occurring in Eqs. (1), (2) and the internal variables $\tilde{n}$, V_0 are given in the Appendix. The description given with Eq. (2) shall be referred to as the extended Bertotti model (EBM).

2. Alternative descriptions

Sokalski *et al.* [12] have suggested the relationship $P_{\mathrm{total}}(B_{\mathrm{m}}, f)$ in the form of a generalized homogenous formula. A Maclaurin series expansion of the formula up to the second order term results in the quadratic polynomial with respect to f

$$P_{\mathrm{total}} = B_{\mathrm{m}}^{\beta}\left[\Gamma_1 f / B_{\mathrm{m}}^{\alpha} + \Gamma_2 \left(f / B_{\mathrm{m}}^{\alpha}\right)^2\right] \quad (3)$$

where α, β are the scaling exponents, Γ_1, Γ_2 are constants for a given level of flux density. It is straightforward to notice that this approach (for two-term expansion) is equivalent to relationship (1). Recently the extended description derived from the generalized homogenous formula has been applied to loss dissipation in SMCs [13]. However the aforementioned paper lacked an extended analysis of the accuracy concerning the relationship (3). It should be remarked that an analogous two-term polynomial dependence of power loss on frequency has been considered previously in engineering calculations e.g. by Boll [14].

Chwastek [15] has suggested a phenomenological formula of the form

$$P_{\mathrm{total}} \cong W^{**}_{\mathrm{hyst}} f + gf^{1+\gamma} \quad (4)$$

where W^{**}_{hyst} is energy lost due to hysteresis, g and γ are constants for a fixed value of flux density. The value of exponent $1+\gamma$ is restricted neither to 2 nor to 1.5; on the contrary, γ may take fractional values. The approach the loss due to eddy currents in different time-and spatial scales as a total, thus it does not distinguish the classical and excess terms. Previously a similar relationship has been considered by Saito *et al.* [9]. It seems important to notice that Anhalt and Weidenfeller [16] have found in their analysis of dynamic loss in SMCs that the number of active domain walls i.e. a quantity directly affecting loss, might be subject to a fractional power law.

In an earlier paper [17] Szczygłowski *et al.* have considered freeing the exponent in the power law used in the description of excess loss in some contemporary amorphous materials. This approach has recently been extended to SMCs by Jankowski *et al.* [18]. On the other hand it is also possible to envisage a somewhat similar formula for total loss in the form of a power law; examples may be found in the papers [19,20].

Effect of annealing temperature on magnetic properties of SMC cores

The issue has been considered by other researchers. Lefebvre *et al.* [21] have studied the effect of different thermal treatment conditions (modified annealing temperature and atmosphere – N_2, air and H_2 on the electrical, mechanical and magnetic properties of heat-treated and resin-impregnated specimens prepared with iron-0.75 wt % ethylene bisstearamide. They have found that parts with good mechanical and low frequency AC properties might be obtained by pressing a high purity iron powder mixed up with a lubricant and heating the parts at moderate temperature ($T < 500^{\circ}$ C) in order to eliminate the lubricant and create bonds between the iron particles.

Shokrollahi and Janghorban [22] have examined the influence of warm compaction on magnetic properties of Fe-based powder material with approximately 4 % Si adhesive. They have found that the optimal conditions for the compacted sample were: pressure 800 MPa, annealing temperature 550° C. In the subsequent paper [23], the authors have compared the effectiveness of two methods: two-step thermal annealing and magnetic field annealing. They have concluded that an appropriate annealing treatment might be helpful for elimination of residual stresses and internal defects within the material.

Taghvaei *et al.* [24] have focused on the influence of annealing treatment on the magnetic properties of iron-phosphate-silane and iron-phosphate powder SMCs. They have found that an increase of annealing temperature in the range $\langle 400^{\circ}\,\mathrm{C}; 500^{\circ}\,\mathrm{C}\rangle$ allowed one to decrease coercivity and microstrain of the samples. On the other hand, maximum permeability and saturation magnetization increased with annealing temperature; for example saturation magnetization for the sample annealed at 550° C was about 40 % higher than for the as-made sample.

Recently Fuzheng Yin et al. [25] have examined the effects of annealing temperature (in argon atmosphere) and excitation frequency (up to f = 100 kHz) on magnetic and mechanical properties of iron-based SMCs. They have found that SMC resistivity is highly sensitive against variations of annealing temperature, what in turn has a direct impact on magnetic properties (permeability, power loss), as pointed out previously by Lefebvre [21]. The optimal annealing temperature for the examined cores was found to be $T \approx 400^{\circ}$ C (the tests in Ref. [25] have been carried out using 100° C increments).

Measurements

1. Measurement setup

Magnetic composites on the basis of commercial Somaloy 500 [5] have been prepared by compression moulding. Kenolube [5] has been used as the lubricant. Figure 2 depicts the morphology of the examined material obtained from a scanning electron microscope JSM-7600F produced by JEOL.

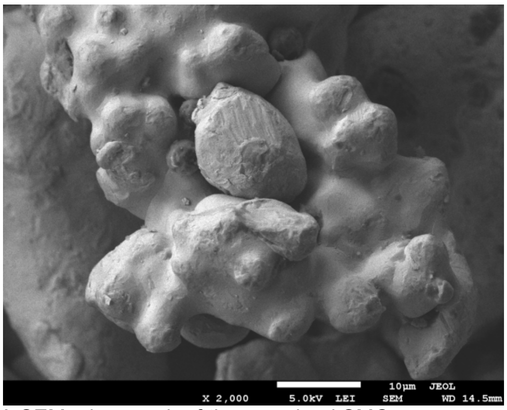

Fig. 2. A SEM micrograph of the examined SMC

The magnetic powder has been filled into a die and compacted at 800 MPa. The samples have been subject to different annealing temperatures from the range $\langle 400^\circ\ C; 600^\circ\ C\rangle$ The curing time was equal to 30 minutes. The compacted samples were in the form of cylinder-shaped rings; external diameter 55 mm, internal diameter 45 mm, height 5 mm. Measurements of hysteresis loops of the prepared cores have been carried out using a hysteresisgraph (AC/DC Hysteresisgraph for Hard and Soft Magnetic Materials AMH-20K-HS produced by Laboratorio Elettrofisico – Walker LDJ Scientific) in accordance with international standard IEC 60404-6. The shape factor of secondary voltage was equal to $1.111 \pm 1.5\,\%$, what implies a sine induction waveform in the sample. Loss densities have been determined by calculation of the areas of measured hysteresis loops. The maximum measurement error of total loss density did not exceed 3 %.

2. Modelling, discussion

The dependence: total loss density vs. maximum induction at $f = 50$ Hz was fitted to the Steinmetz equation $y = kx^l$. Measurements carried at mains frequency may be considered in the first approximation as yielding a reasonable approximation to the quasi-static case, taking into account the specific morphology of SMCs i.e. the presence of insulating resin layer, which limits to a large extent the flow of inter-particle eddy currents. The validity of the Steinmetz equation in reference to SMCs has been proven previously [26]. Figure 3 depicts the measurement data points and the fitting lines. It can be stated that the power law allows one to obtain excellent fitting results in all considered cases. Figure 4 depicts the estimated values of the Steinmetz exponent l and their uncertainty bounds for different annealing temperatures.

Figure 5 depicts the dependencies of total power density at $f = 50$ Hz on annealing temperature for three levels of maximum inductions. From the Figure it is clear that the increase in annealing temperature results in a decrease of total loss density. Taking into account that at mains frequency the dominant component of total loss is related to hysteresis, this conclusion is consistent with the results of Ref. [21] and the effect may be attributed to a lowered number of pinning sites within SMC. The effect is more pronounced for higher inductions.

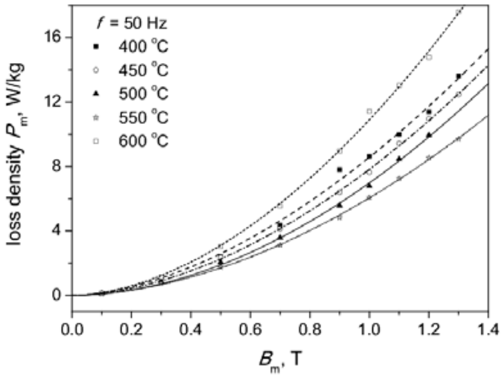

Fig. 3. The dependence of power loss density on maximum induction for f = 50 Hz. The lines denote fitting to the Steinmetz power law

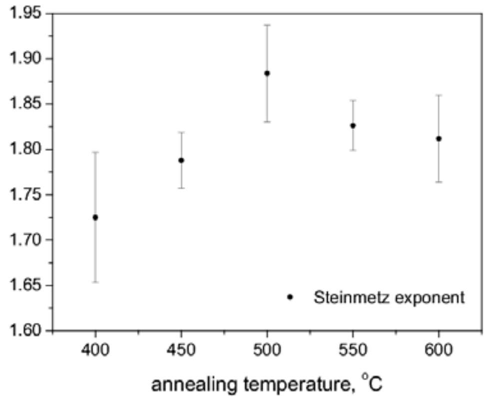

Fig. 4. The values of Steinmetz exponent for curves from Fig. 3

The considered dependencies may be described quite accurately with straight fitting lines for temperature range $\langle 400^\circ\ C; 550^\circ\ C\rangle$. Above 550° C (case not shown in Figure 5) the inorganic binder is decomposed, what results in a sudden worsening of magnetic properties[1]. Therefore for the composition Somaloy + 0.5 % Kenolube the analysis is limited up to 550° C. Temperature range above 550° C does not have a technological significance. The results reported by Gilbert et al. [27] which reveal a sudden drop of resistivity for $T \geq 550^\circ$ C provide another proof of the above-given reasoning.

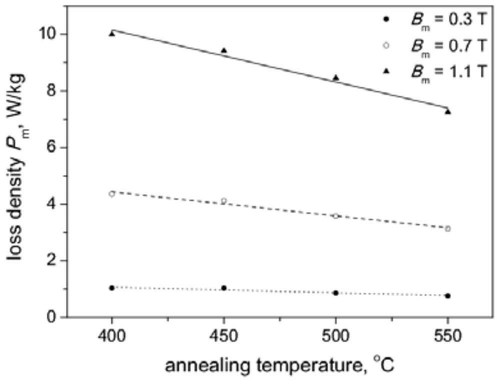

Fig. 5. Power loss density vs. annealing temperature for different levels of magnetic induction. Excitation frequency f = 50 Hz

[1] an abrupt increase of total loss density in low frequency range is depicted in subsequent Figure 7.

Figures 6 and 7 depict the dependence $P_{\text{total}}(f)$ for 0.3 and 0.7 T, respectively. Lines denote fitting to the relationship (4). The average absolute error between the measured values and those from modelling did not exceed 9 %. The values of exponent γ were found to depend on the B_{m} value and for the cases depicted in Figures 6, 7 belonged to the range $\gamma \in \langle 0.6714;1.1514 \rangle$.

From the Figures a conclusion may be drawn that annealing temperature has a substantial impact on magnetic properties of SMC cores at increased excitation frequencies. The lowest loss is obtained for $T = 450^{\circ}$ C. This conclusion is consistent with the results presented by Fuzheng Yin et al. [25].

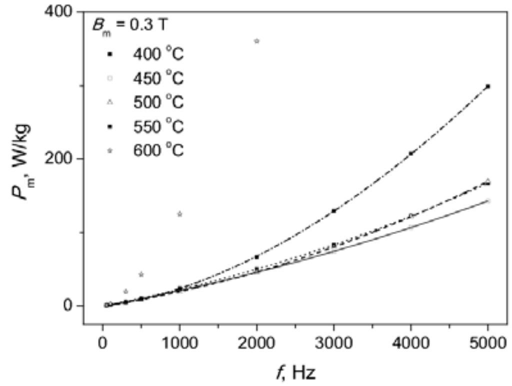

Fig. 6. Total power loss density vs. excitation frequency for $B_{\text{m}} = 0.3$ T. The lines denote fitting to relationship (4)

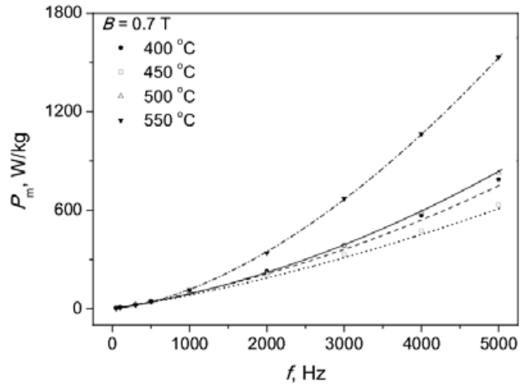

Fig. 7. Total power loss density vs. excitation frequency for $B_{\text{m}} = 0.7$ T. The lines denote fitting to relationship (4)

The fittings to the relationships (1) and (2) have also been applied and their results are comparable to those presented in Figs. 6 and 7. The average absolute error between the measured values and those from modelling did not exceed 12.4 % for SBM and 14.2 % for EBM. However it is interesting to notice that the estimation procedure (based on Levenberg-Marquardt algorithm) returned three times negative values of b parameter in the SBM description. Such negative excess loss is surely non-physical. This fact may indicate that it is desirable to use the extended Bertotti's description instead of the simplified one for this kind of magnetic materials. On the other hand, the values of parameters d and e returned by the estimation procedure for the EBM model were close to zero, thus the predicted dependence of total loss versus frequency was of the form $P_{\text{total}} \cong W_{\text{hyst}} f + af^2$, what is consistent with the results obtained by Kollár et al. [10].

The remark concerning the negative b values requires a further explanation. Some similar problems with the three-terms loss formulas most often in the context of non-standard materials of excitation conditions have been reported previously e.g. by Zirka et al. [28] (low B_{m} case) or Boglietti and Cavagnino [29] (excitation from Pulse Width Modulation supply systems). The simplified Bertotti's model introduces fixed values of exponents corresponding to two limiting cases concerning flux penetration within the magnetic material. The parameters a and b may be interpreted as weights, which indicate the levels of bulk and localized eddy currents in dependence on the average flux density in the sample.

Fish *et al.* [30] and Szczygłowski *et al.* [17] have suggested the possibility to free the restrictive exponent value equal to 1.5 for the loss component related to the so-called excess (or localized) eddy currents. It should be remembered that the relationship (1) is approximate, as the parameter a describes the so-called classical (bulk) loss, which is derived from Maxwell equations under severe simplifications (assumptions of material linearity and homogeneity). In order to improve the description for SMCs, a number of modifications have been proposed by different authors. De Wulf et al. [31] have considered the possibility to introduce a correction factor for conductivity (this quantity appears implicitly in the classical formula, i.e. $P_{\text{clas}} = \sigma(\pi z B_{\text{m}})^2 / (\eta\rho)$, where σ is conductivity, z is a characteristic dimension, η a geometry-related constant, whereas ρ is material density). This approach has recently been followed by Appino *et al.* [32], where a correction factor has been introduced in order to replace the true microstructure of the SMC with a homogenized medium with uniform rectangular grains. A similar homogenization scheme, but for a spherical particle shape, has been proposed in Ref. [6]. On the other hand, Kollár et al. [10] have focused on the possibility to modify the geometry-dependent constant η.

It should be remarked that the considered relationships allow one not only to predict the values of total loss, but also to carry out loss separation into the components related to hysteresis and eddy currents. In Figure 8 an example of loss separation is presented. Two descriptions, i.e. the extended Bertotti's model, (Eq. (2) with the d and e values set to zero), and the power law, Eq. (4) are compared. The modelled values of total loss density (given at the bottom of the Figure) correspond to much extent to the measured counterparts – the maximum error does not exceed 3.7 %. The difference in the evaluation of individual contributions to the total loss density is within 5 % bounds.

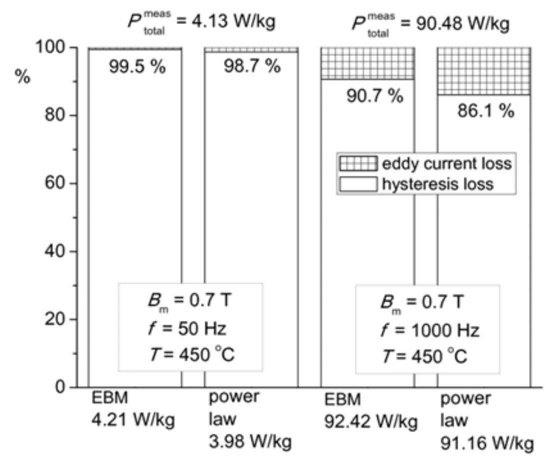

Fig. 8. Loss separation for two exemplary values of excitation frequency

Conclusions

In the paper the effect of annealing temperature on power loss density of SMC cores has been studied. It has been noticed that the choice of annealing temperature has a significant influence on magnetic properties of the cores. The lowest power loss density in a wide excitation frequency range has been obtained for the core annealed at $T \approx 450^\circ$ C.

For low excitation frequencies the dependence power loss vs. maximum induction follows quite accurately the Steinmetz relationship. The Steinmetz exponent is dependent on the annealing temperature and attains the highest value for 550° C. In the useful temperature range i.e. up to 550° C, loss density decreases upon increase of annealing temperature. This effect may be explained by a successive release of strains within the material due to the existing pinning sites.

For the analysis of the dependence total power loss vs. excitation frequency, four alternative descriptions have been considered. Two of them are derived from Bertotti's model, whereas the other two have been suggested by some of the authors of the present paper. It has been found that in some attempts to fit the experimental data with the simplified Bertotti's formula negative values of excess loss have been obtained. Therefore it seems reasonable to favour the extended Bertotti's model, which takes into account the non-zero value of ,,magnetic objects" in quasi-static excitation conditions. It is interesting to notice that the extended Bertotti's model predicts the quadratic dependence of eddy current loss on excitation frequency, what is consistent with the results reported by other researchers. A similar character of the dependence follows from the power law, Eq. (4), in which the exponent $\gamma \in \langle 0.6714; 1.1514 \rangle$. It has been shown that it is possible to obtain comparable estimates of loss components related to hysteresis and eddy currents in the total loss balance using the extended Bertotti's model and the power law given with Equation (4).

Appendix - Derivation of loss vs. frequency dependence for the Bertotti's theory

The so-called excess field strength in Bertotti's theory is given with the relationship

(A1) $$H_{\text{exc}} = \frac{\sigma G S}{\tilde{n}(t)} \frac{\mathrm{d}B}{\mathrm{d}t}$$

where $G \approx 0.1357$, σ is material conductivity, whereas S is sample cross-section area. The corresponding excess loss per cycle per unit volume is calculated from the relationship

(A2) $$P_{\text{exc}} = \frac{1}{T} \int_0^T H_{\text{exc}}(t) \frac{\mathrm{d}B}{\mathrm{d}t} \mathrm{d}t$$

In subsequent calculations the sine B waveform is assumed, in accordance with international standard IEC 60404.

Assuming a simple linear dependence $\tilde{n} = H_{\text{exc}} / V_0$ (the SBM description, Eq. (1)), one obtains after time averaging

(A3) $$P_{\text{exc}} \approx 8 \sqrt{\sigma G S V_0} \left(B_{\text{m}} f\right)^{3/2}$$

In some cases instead of 8, the numerical factor 8.76 is quoted. This is the approximate value of the expression $2/3\Gamma^2(0.25)$ where Γ is the Euler gamma function. For details the Readers are referred to Ref. [8].

Instant value of loss term due to classical eddy currents is given with expression

(A5) $$P_{\text{clas}}(t) = \frac{\sigma z^2}{2\eta} \frac{\mathrm{d}B}{\mathrm{d}t}$$

where η is a geometry-related factor (in SI units $\eta = 6$ for laminations, $\eta = 16$ for cylinders), whereas z is a characteristic sample dimension. After time averaging the loss term due to classical eddy currents per unit volume for sine B waveform is given with the relationship

(A6) $$P_{\text{clas}} = \frac{\pi^2}{\eta} \sigma \left(z B_{\text{m}} f\right)^2$$

Assumption of non-zero $\tilde{n}_0$ term in the relationship $\tilde{n} = \tilde{n}_0 + H_{\text{exc}} / V_0$ leads to a quadratic equation to be solved with respect to $H_{\text{exc}}(t)$ (fulfilled at any time instant t)

(A7) $$\frac{1}{V_0} H^2_{\text{exc}}(t) + \tilde{n}_0 H_{\text{exc}}(t) - \sigma G S \frac{\mathrm{d}B}{\mathrm{d}t} = 0$$

The real root of the above-given equation is introduced into the relationship (A2), yielding

(A8) $$P_{\text{exc}} \approx 8 B_{\text{m}} f \left(\sqrt{\sigma S V_0 B_{\text{m}} f} - \tilde{n}_0 V_0 / 4\right)$$

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