Magnetic losses in non-oriented steel sheets under generic two-dimensional flux loci: prediction and measurements

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The evaluation and measurement of magnetic losses under two-dimensional (2D) induction is an important aspect of electrical machines design because 2D fluxes are widely present in machine cores. The formulation of a comprehensive two-dimensional magnetic hysteresis model of magnetic sheets, by which the loss is calculated under whatever polarization loci (alternating, circular, elliptical, etc.) and time behaviour, has been accomplished to little extent so far. In principle, however, a rational approach to the 2D magnetic losses and their frequency dependence can be pursued in non-oriented sheets, following the physical principle of loss separation, where the measured loss W is expressed as the sum of the hysteresis W_{hyst}, excess W_{exc}, and classical W_{class} components [1]. To describe such a method, we consider the simple case of an elliptical flux locus $\boldsymbol{B}(t) = (B_x, B_y)$ characterized by the peak induction B_p along the major axis and the ratio a between minor to major axis lengths (a = 0, alternating induction; a = 1, rotating induction). The classical loss W_{class} is given, under negligible skin effect, by the expression

$$W_{\mathrm{class}} = \sigma d^2/12 \cdot \int_0^T [(\mathrm{d}B_x/\mathrm{d}t)^2 + (\mathrm{d}B_y/\mathrm{d}t)^2]\mathrm{d}t\,, \qquad (1)$$

where σ is the conductivity, d is the sheet thickness, T is the period, and $B_x(t)$ and $B_y(t)$ are the induction components. The hysteresis loss for the given elliptical flux loci is

$$W_{\mathrm{hyst}}(J_p, a) = W_{\mathrm{hyst}}^{(\mathrm{ALT})}(J_p) + W_{\mathrm{hyst}}^{(\mathrm{ALT})}(aJ_p) \cdot (R_{\mathrm{hyst}}(J_p) - 1) \qquad (2)$$

where $J_p \cong B_p$, $W_{\mathrm{hyst}}^{(\mathrm{ALT})}(J_p)$ is the alternating hysteresis loss, and $R_{\mathrm{hyst}}(J_p) = W_{\mathrm{hyst}}^{(\mathrm{ROT})}(J_p)/W_{\mathrm{hyst}}^{(\mathrm{ALT})}(J_p)$. $R_{\mathrm{hyst}}(J_p)$ is little dependent on specific lamination type [2]. The excess loss is

$$W_{\mathrm{exc}}(J_p, a, f) = g(a)\cdot\{W_{\mathrm{exc}}^{(\mathrm{ALT})}(J_p, f_0) + W_{\mathrm{exc}}^{(\mathrm{ALT})}(aJ_p, f_0)\cdot[R_{\mathrm{exc}}(J_p) / g(1) - 1]\}\cdot\sqrt{f} / \sqrt{f_0}\,, \qquad (3)$$

where $W_{\mathrm{exc}}^{(\mathrm{ALT})}(J_p, f_0)$ is obtained at the reference frequency f_0 (e.g. 50Hz), $R_{\mathrm{exc}}(J_p) = W_{\mathrm{exc}}^{(\mathrm{ROT})}(J_p)/W_{\mathrm{exc}}^{(\mathrm{ALT})}(J_p)$ and the function g is, under sinusoidal induction,

$$g(a) = \sqrt{(2\pi)} / 8.76 \int_0^{2\pi} [\sin^2(\varphi) + a^2\cos^2(\varphi)]\mathrm{d}\varphi \cong \sqrt{(1+2.22a^2)}. \qquad (4)$$

$R_{\mathrm{exc}}(J_p)$ is basically independent of frequency [1]. Eq. (3) is generalized to non-sinusoidal $B_x(t)$ and $B_y(t)$ waveforms, that is, generic 2D induction loci, through suitable extension of (4) as

$$g(\boldsymbol{J}/J_p) = \sqrt{(2\pi)} / (8.76\cdot J_p^{3/2}) \int_0^{2\pi} (\mathrm{d}J_x/\mathrm{d}\varphi)^2 + (\mathrm{d}J_y/\mathrm{d}\varphi)^2]^{3/4}\mathrm{d}\varphi, \qquad (5)$$

with $\varphi = 2\pi f \cdot t$. Comparison with the experiments is made in non-oriented Fe-(3.2 wt%)Si sheets of thickness d = 0.356 mm, electrical conductivity $\sigma = 2.04\cdot10^6$ S/m over an extended range of peak polarization values (0.1 T ≤ J_p ≤ 1.9 T) and frequencies (2 Hz ≤ f ≤ 1 kHz).

[1] C. Appino, et al., *Int. J. Appl. Electr. Mech.* 44 (2014) 355.

[2] F. Brailsford, *J. Inst. Elect. Eng.*, 84 (1939) 399.