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NEW ASPECTS OF POWER LOSSES IN FERROMAGNETIC CORES

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Abstract: The total power loss may be divided into three mayor types: the static hysteresis loss, the classical eddy-current loss, and the excess eddy-current loss. In the paper it has been shown that the hysteresis loss must be expressed by different formulae for lower and for upper values of magnetic flux density. On the base of the literature, can be stated that the physical properties of laminated ferromagnetic material – the conductivity and the permeability – are in the external layers of the sheet different than those in the internal layer. The classical eddy-current loss has been calculated taking the effect of sheet heterogeneity into account. The principal cause of the excess eddy-current loss in silicon-iron is the existence of domain structure. This loss has been expressed taking the domain structure and domain wall motion into account.

Keywords: Magnetic cores. Ferromagnetic materials. Power losses.

1 Introduction

In the designing of a magnetic circuit, the alternating flux is required to be produced in the minimum space and with minimum power loss. The two most important magnetic properties are therefore: the permeability and the loss coefficients. The permeability is not a directly informative quantity, since so much depends upon the value of the flux density B. Thus some materials which have very high permeabilities (such as e.g. permalloy) posses these high values only at very low induction densities, which with their higher cost debar them from use in electric machines and many others devices. The designer is more interested in the values of magnetic field strength H required to produce a given value of field density B, than in the ratio $\mu = B/H$.

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The comparatively pure iron sheets used in the early days of electrical engineering constructions has given place to non-oriented alloy steels, grain-oriented iron and, recently, to nanostructured ferromagnetic alloys. The chief alloying constituent is silicon – up to 5 %. It increases the permeability at low flux densities (but decreases it at high densities), reduces the hysteresis loss, and by augmenting the resistivity decreases the eddy-current loss.

The total average power loss per unit volume in ferromagnetic sheets under alternating flux, according to the phenomenological theory, may be divided into static and dynamic part:

$$P_{\mathrm{Fe}} = P_{\mathrm{st}} + P_{\mathrm{dyn}} \, . \tag{1}$$

The static component P_{st} is given by the hysteresis loss P_{Hy} determined by the interaction between the domain walls and the irregularities of the crystalline structure.

The dynamic component P_{dyn}, determined by induced currents, contains a classical eddy-current loss component P_{Ft} and also another component P_{ex} named the excess eddy-current loss:

$$P_{\mathrm{dyn}} = P_{\mathrm{Ft}} + P_{\mathrm{ex}} \, . \tag{2}$$

The division of total loss into constituent types shows that for grain oriented 3% SiFe steel the dominated part of losses is the excess loss. That is way the name “additional loss” is not used now.

2 Hysteresis loss

The hysteresis loss per unit volume is equal to the area enclosed by the quasi-static hysteresis loop times frequency:

$$P_{\mathrm{Hy}} = f \cdot \oint H \cdot \mathrm{d}B \, , \tag{3}$$

In engineering practice the following formulae are used for calculation of hysteresis loss in a unit volume:

– given by Steinmetz

$$P_{\mathrm{Hy}} = k_{\mathrm{Hy}} f B^{1,6} \, , \tag{4a}$$

– given by Richter

$$P_{\mathrm{Hy}} = k_{\mathrm{Hy}} f B^{2} \, , \tag{4b}$$

$$P_{\mathrm{Hy}} = f \, (a \, B + b \, B^{2}) \, , \tag{4c}$$

The formulae (4) are physically incorrect because the loss, due to the boundary hysteresis loop, cannot increases monotonically with the flux density. The loss can be calculated more precisely taking the magnetic saturation effect into account. Brailsford has given an approximate relationship between related hysteresis losses

$$\chi = P_{\mathrm{Hy}}/P_{\mathrm{Hy}\,s}$$

and related magnetic polarization J/J_s [5].

Where $P_{\mathrm{Hy}s}$ is the maximum value of hysteresis loss and J_s is the maximum (saturation) value of magnetic polarization (both for the boundary hysteresis loop).

Further consideration of this approach suggest that the Steinmetz formula might be applied to calculation of the hysteresis loss for the flux densities $B < 0{,}7\,B_s$. Approximately we become:

$$P_{\mathrm{Hy}}(B) = P_{\mathrm{Hy}s}\,0{,}87\,\frac{1}{J_s^{1,6}}\left(B - \mu_0 H\right)^{1,6} \;. \tag{5a}$$

The parameter

$$0{,}87\,\frac{P_{\mathrm{Hy}s}}{J_s^{1,6}} = f \cdot k_{\mathrm{Hy}} \;, \tag{5b}$$

where k_{Hy} is a hysteresis loss coefficient as in formula (4a).

Then, omitting the second expression in parenthesis, we get the formula (4a).

For the flux densities $B > 0{,}7\,B_s$ we get:

$$P_{\mathrm{Hy}} \approx k_{\mathrm{Hy}} f\left[1{,}15 B_s^{1,6} - 4{,}1\left(B_s - B\right)^{1,6}\right. \;. \tag{6b}$$

For the flux density $B \geq B_s$ the hysteresis loss are constant and equal

$$P_{\mathrm{Hy}s} = 1{,}15\, k_{\mathrm{Hy}} f\, B_s^{1,6} \;. \tag{6c}$$

3 Dynamic loss

Dynamic power losses, called also „apparent eddy-current losses” are associated with the macroscopic large-scale behaviour of magnetic domain structure of the ferromagnetic material. An adequate starting point for the investigation of dynamic power loss is to the use the existing techniques, which have been developed to elucidate and analyse the causes of power loss in perfectly homogeneous iron laminations.

3.1 Classical component of eddy-current loss

The so-called „classical" model disregards the very presence of magnetic domains in ferromagnetics and assumes a magnetization process in a linear isotropic homogeneous space.

From Maxwell's equations, omitting the displacement current, the classical average eddy-current loss P_{Ft} in a unit volume of the sheet is given by equation:

$$P_{\mathrm{Ft}} = \frac{2\mu_0^2}{g}\gamma\chi \int_0^{g/2} \frac{2}{T}\left\{\frac{\mathrm{d}}{\mathrm{d}t}\int_0^{x_0}\left[H(x,t)+M(x,t)\right]\mathrm{d}x\right\}^2 \mathrm{d}t\mathrm{d}x\,, \tag{7}$$

where γ is the conductivity of the plate, g is the sheet thickness and T is the period of time functions.

Considering a sinusoidal magnetic field density change in time at frequency f we get for the eddy-current loss the relation:

$$P_{\mathrm{Ft}} = \frac{1}{24}\gamma B_m^2 \omega^2 g^2 \chi\ , \tag{8}$$

where $\chi \leq 1$ is a parameter, which depends on the skin effect [7].

From investigations on laminated material it is found that the physical properties – conductivity and permeability – in the external layers of the lamina are different than those in the internal layers. For investigation the effect of sheet heterogeneity on eddy-current loss we will consider the structure in which the thickness of the external layer is g_2 and the internal layer is g_1. The conductivities of internal and external layers are γ_1 and γ_2, respectively, and permeabilities μ_1 and μ_2, respectively.

If we assume that the lamination is homogeneous and has an average conductivity given by:

$$\gamma_{\mathrm{av}} = \frac{\gamma_1 g_1 + \gamma_2\left(g - g_1\right)}{g} = \gamma_1\left[k_g\left(k_\gamma - 1\right) + 1\right], \tag{9}$$

and an average permeability given by

$$\mu_{\mathrm{av}} = \frac{\mu_1 g_1 + \mu_2 \left(g - g_1 \right)}{g} = \mu_1 \left[k_g \left(k_\mu - 1 \right) + 1 \right] , \tag{10}$$

where

$$k_g = \frac{g - g_1}{g} ; \; k_\mu = \frac{\mu_2}{\mu_1} ; \; k_\gamma = \frac{\gamma_2}{\gamma_1} . \tag{11}$$

The loss $(P_{\mathrm{Ft}})_{\mathrm{heter}}$ in heterogeneous lamina can be compared with the loss $(P_{\mathrm{Ft}})_{\mathrm{hom}}$ in homogeneous lamina. From Maxwell's equations, after transformations, we get the coefficient for the case in which total flux in the lamina vary sinusoidal in time:

$$\varepsilon_B = \frac{\left(P_{Ft} \right)_{heter}}{\left(P_{Ft} \right)_{hom}} \approx 1 + \frac{\left(k_\gamma - k_\mu \right) k_g \left(1 - k_g \right) \left[k_\mu k_g + 2 \left(1 - k_g \right) \right]}{\left(k_\mu k_g + 1 - k_g \right)^2 \left(k_\gamma k_g + 1 - k_g \right)} . \tag{12}$$

The coefficient ε_B for $k_g = 0{,}2$ can rise to 1,4.

3.2 Excess eddy current loss

From experimental measurements it has been shown that the excess eddy-current loss – equation (2), is responsible for between 30 % to 90 % of the total power loss of a grain oriented silicon iron and between 90 % to 99 % of the total power loss of a nanostructured ferromagnetic materials. A convenient method to define the magnitude of the excess eddy-current loss compared to the classical eddy-current loss is the factor defined as:

$$k_{\mathrm{ex}} = \frac{P_{\mathrm{dyn}}}{P_{\mathrm{Ft}}} = 1 + \frac{P_{\mathrm{ex}}}{P_{\mathrm{Ft}}} . \tag{15}$$

It can be shown that the excess factor for the case of multi domain structure is [2; 8; 10]:

$$k_{\mathrm{ex}} = \frac{48 d}{\pi^3 g} \sum_{n = \mathrm{odd}}^{\infty} \frac{1}{n^3} \operatorname{ctgh} \frac{n \pi d}{2 g} , \tag{16}$$

where: g is the sheet thickness, and d is the domain size.

For large values of d/g, that is for large domains, the excess coefficient is

$$k_{\mathrm{ex}} = 1{,}628\frac{d}{g}. \tag{17}$$

4 Conclusion

The experimental results indicate that the static hysteresis loss reaches a maximum value (constant value) at high flux densities due to saturation effect. The classical eddy-current loss calculated for a sheet which is considered to be undivided in domains grows due the heterogeneity of the magnetic material. The excess loss is determined by the local eddy-current that settles themselves around the moving domain walls and depend on the individual and collective behaviour of these walls.

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