Evolution of the loss components in ferromagnetic laminations with induction level and frequency

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Elsevier use only: Received date here; revised date here; accepted date here

Abstract

Results of numerical analysis of loss components in a conducting magnetic hysteresis medium are given. They explain inaccuracies of the widespread formula for the total loss evaluation and provide a basis for an engineering approach to loss prediction over a wide range of magnetization frequencies and flux densities.

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PACS: 75.50.Bb; 75.60Ej; 34.50.Bw

Keywords: Electrical steel; Loss separation; Frequency dependencies; Steel characterisation

1. Introduction

It is of a great practical importance and the purpose of numerous studies to find a simple engineering method of predicting the energy loss in magnetic alloy laminations undergoing cyclic magnetization. It has long been customary to base the iron loss evaluation on the loss separation principle, i.e. on the subdivision of the total energy $W_{\text{tot}}$ into components designated static-hysteresis loss $W_h$, classical eddy-current loss $W_{\text{clas}}$, and excess loss $W_{\text{exc}}$:

$$W_{\text{tot}} = W_h + W_{\text{clas}} + W_{\text{exc}}.$$  \hspace{1cm} (1)

Here, and throughout this paper, energy, $W$, is defined as that (in J/m$^3$) dissipated in unit volume per cycle $T=1/f$, $f$ being the magnetization frequency.

The prevalent form of (1) for regimes of sinusoidal induction of peak value $B_m$ is the expression [1]

$$W_{\text{tot}} = W_h + \frac{d^2 \pi^2 B_m^2}{6 \rho} f C B_m^{1.5} f^{0.5}$$  \hspace{1cm} (2)

where $d$ is the thickness of the lamination, $\rho$ is the material resistivity, and $C$ is a fitting parameter.

It should be remembered that the classical loss term in (2), $W_{\text{clas}}$, results from the well-known penetration equation and holds only if this equation is applied to a linear magnetic medium and if the frequency $f$ is sufficiently low for the skin effect to be negligible. Although these constraints play a crucial role in the loss evaluation, no previous attempts have been made to take them into account in the development of both the statistical loss theory [1] and corresponding methods of loss prediction ([2] and references included). We show that the saturating nature of $B$-$H$ curves of an actual ferromagnet does not allow one to transfer the ideas characterizing a linear medium to materials exhibiting saturation. The different mechanisms of skin effect at low and high induction levels can lead to the errors of all the terms in (2) and, consequently, to inaccuracy of the loss predictions based on this formula.

2. Classical loss in nonlinear magnetic medium

Perhaps the main source of the inaccuracy of (2) over a wide range of frequencies and flux densities is the error...
caused by the ‘truncated’ form of its classical component (3). In accordance with analytical solution of the penetration equation for a linear medium, the complete formula for the classical loss [1] can be written as the product $W_{\text{class}}F(\gamma)$ where the skin-effect function [3],

$$F(\gamma) = \frac{3(\mu_r - \sin \gamma)}{\gamma(\mu_r + \cos \gamma)},$$

(4)

is determined by the normalized frequency $\gamma = \frac{\mu_f \omega}{\rho}$ (here $\mu$ is the permeability of the linear medium). The plot of $F(\gamma)$ (dashed curve in Fig. 1) can be drawn either through (4) or solving penetration equation numerically and dividing the calculated loss by (3). The latter method is the only possible way when the dependence $B(H)$ is nonlinear. Since $F(\gamma) \leq 1$ it is often concluded that real classical loss is always less than that evaluated through (3). The fallaciousness of this inference can be illustrated by solving the penetration equation for a material with a nonlinear dependence $B(H)$.

To concentrate on the eddy current problem, we can first deal with an idealised hysterisis-free material with no excess loss. To keep the use of the normalized frequency $\gamma$, we also suppose that magnetization curve of the medium is the broken line 1-2 in the inset of Fig. 1 where the slopes $dB/dH$ of segments 1 and 2 are $\mu$ and $0.02\mu$, respectively. Skin-effect function $F$ in this case depends not only on $\gamma$, but also on the normalized peak induction $b_{\text{m}}$. A family of functions $F(\gamma, b_{\text{m}})$ obtained numerically for a number of $b_{\text{m}}$ is shown in Fig. 1 by solid lines. It can be seen in Fig. 1 that $F(\gamma, b_{\text{m}})$ is always greater than $F(\gamma)$ and can be greater than unity for high $b_{\text{m}}$.

It should be noted that at low peak inductions ($b_{\text{m}}<0.3$), the function $F(\gamma, b_{\text{m}})$ is only slightly larger than $F(\gamma)$. The reason is that flux density exceeds the level $B_0$ only in surface layers of the sheet, while the other layers operate on the ‘linear’ segment 1 of the magnetization curve. Another magnetization mechanism takes place at high inductions ($b_{\text{m}}>0.9$). In this case, a considerable number of the layers adjacent to the surface approach saturation. This increases their reluctance and results in the displacement of the magnetic flux to the centre of the sheet. This leads to the levelling of the peak flux densities over the sheet cross section making the term skin-effect inapplicable. Unlike the linear medium, dependencies $B(t)$ for all sheet layers become nonsinusoidal and phase shift between ‘saturated’ and ‘unsaturated’ layers approaches 180° (the magnetization process becomes resembling that in the material with the stepwise magnetization curve where eddy current loss at $b_{\text{m}}=1$ is $1.5W_{\text{class}}$ [1]). It can be shown analytically that at the ideally stepwise $B-H$ curve and $b_{\text{m}}<1$ the loss is written as $1.5W_{\text{class}}b_{\text{m}}$ so there is a multitude of expressions explaining the curves in Fig. 1. In particular, Fig. 1 shows that formula (3) turns out to be “correct” for moderate induction region ($b_{\text{m}}=0.8$) where the errors due to neglecting the saturation and skin effect cancel each other. Although the curves in Fig. 1 have been constructed for a specific slope of segment 2 and the concise analysis above is rather qualitative, it is useful for understanding the processes in the real medium discussed in Section 4.

3. Numerical instrumentation

The study of the frequency evolution of the loss components can be carried out using the magnetodynamic model (MDM) of a conducting ferromagnetic sheet [4], which is a finite-difference (FD) solver of the penetration equation. The magnetic field $H(x, t)$ and the magnetic induction $B(x, t)$ at every point of axis $x$ (it is normal to the sheet surface) are linked by a history-dependent static hysteresis model (SHM) combined with an external dynamic model. The high accuracy of the MDM allows us to use it as a reference material thus avoiding possible errors encountered in real measurements.

For a periodical excitation the total energy $W_n$ is calculated as the area enclosed by the steady-state dynamic loop which is a dependence of the average induction on the surface magnetic field. The superscript $n$ in $W_n$ and in the designations introduced below signifies that these losses are found numerically.

Using the MDM two sets of nodal hysteresis loops are constructed simultaneously for all nodes of a FD grid of the $x$-
axis. The loops of the first set (partly shown in the lower part of Fig. 2 and lying within the static major loop) are built by the static component of the MDM, i.e. by the SHM. The averaged area of these loops is the hysteretic loss, $W^n_h$, which may be called “static” only in the sense that it is calculated with the static hysteresis model. The curves in the upper part of Fig. 2 are nodal loops obtained by the MDM as a whole. The averaged area of these loops is a total hysteresis loss, $W^n_h + W^n_{exc}$, that allows us to calculate the excess (or dynamic hysteretic) loss $W^n_{exc}$. Finally, the eddy current loss, $W^n_{ec}$, is determined by the local eddy-currents (formula (10) in [4]) and verified independently by calculating the difference $W^n_{tot} - (W^n_h + W^n_{exc})$.

4. Loss component frequency evolution

In this paper the MDM is applied to a non-oriented (NO) electrical steel ($d=0.5\,\text{mm}$, $\rho = 0.43\,\mu\Omega\text{m}$) and to a grain-oriented (GO) electrical steel ($d=0.26\,\text{mm}$, $\rho = 0.48\,\mu\Omega\text{m}$).

As might be expected, the loss $W^n_{ec}$ calculated numerically differs from the value of $W^n_{clas}$. If the error of the simplified formula (3) is evaluated by the ratio $R_{clas} = W^n_{clas}/W^n_{clas}$ (it plays the role of the skin-effect function of the real medium) then the change of this ratio with frequency should be qualitatively similar to that predicted in Fig. 1. This is illustrated in Fig. 3 where the values of $R_{clas}$ calculated through the MDM are represented by solid lines.

It is instructive to calculate $R_{clas}$ by solving the penetration equation where $H(x, t)$ and $B(x, t)$ are linked by the SHM only (this SHM solver, SHM-S, does not take into account the excess loss, and therefore yields underestimated total loss). The frequency dependence of $R_{clas}$ found through the SHM-S at $B_m=1.5\,\text{T}$ is shown in Fig. 3 by dashed curve. The smaller values of $R_{clas}$ obtained through the MDM illustrate the fact [5] that by introducing the excess loss component into the Maxwell solver one obtains simultaneously the increase of the total loss and decrease of the classical loss.

It is natural to expect that this phenomenon should be more pronounced in GO steel where the excess loss contribution to the total loss is usually much larger than that in NO steel (the corresponding percentages in NO and GO steels considered here are 42% and 6% at 50 Hz, 1.5 T). The difference between the values of $R_{clas}$ evaluated by means of the MDM and SHM-S is seen in Fig. 4.

The larger $R_{clas}$, i.e. the larger eddy current loss obtained with the SHM-S at high $B_m$ is explained by high permeability of GO steel along its major loop that makes the magnetization process similar to that calculated in the material with the stepwise $B-H$ curve. On the contrary, magnetization changes in the MDM are damped by the dynamic component of its hysteresis model which decreases the rate of change of the induction at any point inside the sheet and therefore the eddy current loss. However, even in this case there is no sense in applying the reducing skin-effect function $F(\gamma)$ to the high induction regime, i.e. to the main operating regime of high power electrical machines. At the same time, neglecting skin-effect at low induction levels may lead to the unphysical effect of a negative excess loss. This artifact is met when calculating the loss contribution due to a minor hysteresis loop of duration $T_m$ and peak-to-peak amplitude $2B_m$. Following the idea of the equal loss parameters of nonsymmetrical and centrosymmetrical minor loops with the same $B_m$ [2] and taking into account that $1/T_m$ is much higher than $1/T$, one is forced to employ low-frequency formula (3) at indefinitely high frequencies. Since the span $2B_m$ is usually less than 1 T, formula (3) can give the values exceeding the measured dynamic loss. This is illustrated in Fig. 5 where dashed straight lines have been calculated using two first terms on the right-hand side of (2). As the most part of these lines lies above measured loss curves (they are shown by solid lines), the third (excess) loss term in (2) should be negative. On the contrary, dash-dotted curves in Fig. 5 represent the sum of the hysteresis and eddy-current losses evaluated through the MDM. Along the whole their length these curves are situated below measured loss curves that is correct physically.
The use of the MDM also allows us to analyze the frequency behaviour of the hysteresis loss, which is usually regarded as frequency independent. The different character of this behaviour at different $B_m$ is shown in Fig. 6 using the ratio $W_h^n(f)/W_h(0)$, where $W_h^n(f)$ and $W_h(0)$ are static hysteresis losses at frequency $f$ and at $f=0$.

As can be seen from Fig. 6, the loss $W_h^n$ increases with frequency, although this rise becomes less pronounced with increasing average induction.

In concluding the paper we discuss the question of the excess loss evaluation. According to [2], coefficient $C$ in (2) and consequently the excess loss term of this expression should be found individually for every $B_m$. It is noteworthy that due to the inaccuracy of (3) the value of $W_{exc}$ in (2) depends on both $B_m$ and $f$. To evaluate the conventional subtraction technique, according to which $W_{exc} = W_{tot} - (W_h + W_{clash})$, we have compared the excess loss thus calculated with the loss $W_h^n$ found through the MDM. The relative errors of $W_{exc}$ versus the value of $B_m$ for which these errors were obtained are shown in Fig. 7 where the errors evaluated at 50 and 100 Hz are represented by solid and dashed curves, respectively.

The significant values of the error and especially its dependence on $f$, raise a doubt about the possibility of evaluating the number of simultaneously active regions, which is the basic concept of the loss separation theory [1]. The deviation of the loss components in (2) from their real values makes this analytical expression too approximate and determines the necessity for engineering approaches to the loss prediction tied more closely with experimental data. The possibilities and limits of these approaches are discussed in [6].

Acknowledgements

The work was supported by EPSRC Grant EP/C518616/1 which also provided Visiting Fellowships for Prof. Zirka at the Wolfson Centre for Magnetics, Cardiff University, U.K.

References