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Iron Loss Analysis of Ferrite Cores

H. Saotome, T. Kawai and Y. Sakaki

Department of Electrical and Electronic Engineering, Chiba University, 1-33 Yayoi, Inage, Chiba 263, Japan

Abstract. Iron loss measurement of ferrite cores up to MHz range is carried out. Taking the DC magnetic hysteresis, the eddy and displacement currents into account, the electromagnetic fields and iron losses in the cores are computed. As a result, increasing the exciting frequency, the computed iron loss becomes considerably smaller than the experimented one. In order to explain the difference between them, a new magnetic field component yielding a dynamic magnetic loss is assumed and added to the magnetic field of the DC magnetic hysteresis. This assumption is verified by evaluating the iron loss frequency characteristics for different size cores of the same ferrite material.

1. INTRODUCTION

Ferrites have not only magnetic properties but also conductive and dielectric properties, which gives the equivalent lumped circuit of a ferrite core, as shown in Fig.1. When a sinusoidal voltage V is applied to a ferrite core, the primary current I is divided into the exciting current I_M , the eddy current I_E and the displacement current I_D . They are "lag", "in-phase" and "lead" currents with respect to the voltage, respectively. Assuming the resistances R_M , R_E and R_D , the iron loss measured from V and I can be decomposed into the magnetic, eddy current and displacement current losses. However, it is difficult to obtain these resistances from core dimensions in a high frequency range, because the interaction between the electric and magnetic fields occurs, i.e., the skin effect should be taken into account.

Figure 1: Equivalent lumped circuit of a ferrite core.

2. FIELD AND LOSS ANALYSIS

In order to evaluate the iron loss in consideration of the electromagnetic field distribution in a ferrite core, a toroidal-shaped core having a circular cross-section is assumed. With the zeroth and first order Bessel functions J_0 and J_1 , the magnetic field H and the electric field E inside the core are respectively given by

$$H(r) = H_R \frac{J_0(kr)}{J_0(kR)} \dots \dots \dots (1), \quad E(r) = -\frac{j\omega\Phi}{2\pi R} \frac{J_1(kr)}{J_1(kR)} \dots \dots \dots (2),$$

where r : the radius coordinate of the circular cross-section, R : the radius of the circular cross-section, H_R : the magnetic field intensity at $r = R$ (boundary condition), Φ : the total magnetic flux phasor in the circular cross-section, ω : the exciting angular frequency, $j = \sqrt{-1}$ and $k = \sqrt{\omega\mu(\omega\epsilon - j\sigma)}$. Also, μ : the complex permeability, ϵ : the complex permittivity and σ : the conductivity (real number). With (1) and (2), the magnetic loss P_M , the eddy current loss P_E and the displacement current loss (dielectric loss) P_D are respectively obtained by

$$P_M = \pi l \int_0^R [H(r)\{j\omega B(r)\} + \overline{H(r)}\{j\omega B(r)\}] r dr \dots \dots \dots (3), \quad P_E = 2\pi l \sigma \int_0^R E(r)^2 r dr \dots \dots \dots (4),$$

$$P_D = \pi l \int_0^R [E(r)\{j\omega D(r)\} + \overline{E(r)}\{j\omega D(r)\}] r dr \dots \dots \dots (5),$$

where $B = \mu H$, $D = \epsilon E$, l : the average magnetic flux path length and $\overline{}$ denotes a conjugate complex number. The sum of (3)-(5) gives the iron loss P .

We have three different size cores of the same Mn-Zn ferrite, of which dimensions are listed in Table 1. Their cross-sections

of the magnetic flux path are almost square so that the electromagnetic field in the cores can be approximately computed by (1) and (2) where the area of the circular cross-section should equal each of the square areas. As a result, the iron loss P is obtained from (3)-(5). The experimentally obtained frequency characteristics of the iron loss in each core are depicted by solid circles (●) in Fig. 1, where the maximum flux density $B_m = 20$ [mT]. The iron losses are measured with "B-H/Z ANALYZER, HP E5060A (Hewlett-Packard Japan, Ltd.)". The frequency characteristics of the computed iron losses for the small core are depicted by the chained line with the medium parameters listed in Table 2. The experimented results are a couple of ten times larger than the computed ones in MHz range. The difference between them is called the residual loss. If the residual loss is caused by the eddy current, we can assume an equivalent conductivity for the high frequency current. The broken lines of Fig. 2 show the frequency characteristics of the iron loss for the small and large cores when we assume the conductivity $\sigma = 550$ [S/m] for the eddy current. The value $\sigma = 550$ [S/m] which is quite different from the DC conductivity listed in Table 2 is determined in order to explain the residual loss at 10MHz for the small core. However, it is not suitable in the lower frequency range for the small core and overestimated for the large core even though the small and large cores are made of the same ferrite. On the other hand, assuming that the residual loss is caused by the magnetic field (not the eddy current), we can introduce

$$H = \frac{1}{\mu_0 \mu_r} B + j \frac{\omega_0}{\lambda_{h0}} B + j \frac{\omega}{\lambda_f} B \dots \dots (6),$$

where μ_r : the relative permeability, λ_{h0} [Ω/m] is the hysteresis parameter obtained from the hysteresis loss or the complex permeability at $\omega = \omega_0$, λ_f [Ω/m] is the dynamic magnetic loss parameter, and these are all real numbers. The magnetic field component expressed by the third term on the right hand side of (6) increases in proportion to the exciting frequency and the product of this magnetic field and ωB yields the dynamic magnetic loss. The solid lines of Fig. 2 show the computed iron losses with (6) where $\lambda_{h0} = 530$ [Ω/m] ($\omega_0 = 2\pi \times 1000$ [rad/s]) given by the complex permeability in Table 2, $\lambda_f = 53$ [kΩ/m] and other parameters are the same as used for the chained line. From Fig. 2, it is clarified that the residual loss is the dynamic magnetic loss derived from (6). Percentage evaluation of the magnetic (including not only the hysteresis loss but also the dynamic loss), eddy current and displacement current losses at 3MHz is listed in Table 3. The equivalent dielectric loss increases with an increase of the cross-section of the magnetic flux path. However, the eddy current losses are less than 1%.

Table 1: Core dimensions [mm].

Core	Din*	Dout*	Height
Small	6.0	10.0	1.9
Medium	9.7	19.0	4.8
Large	31.0	51.0	9.9

*Din: Inner diameter, Dout: Outer diameter.

Table 2: Medium parameters of the ferrite.

σ [S/m]	μ [H/m]	$\frac{1}{\varepsilon}$ [F/m]	ε_r	g [S/m]
0.012	$(3400 - j152)\mu_0$	$\frac{1}{\varepsilon_0 \varepsilon_r} + j \frac{\omega}{g}$	18000	4.5

μ_0 : Permeability of free space.

ε_0 : Permittivity of free space.

Table 3: Percentage evaluation of P_M , P_E and P_D at 3MHz.

Core	P_M [%]	P_E [%]	P_D [%]
Small	98.9	0.0	1.1
Medium	93.7	0.1	6.2
Large	79.6	0.2	20.2

3. CONCLUSIONS

The iron loss of ferrite cores is analyzed by separating the magnetic, eddy current and displacement current losses and by taking account of the interaction between the magnetic and electric fields. As a result, it is revealed that the residual loss of ferrites is the dynamic magnetic loss explained by the magnetic field intensity which leads the magnetic flux density by 90 degrees. The frequency characteristics of the iron loss of the same ferrite are consistently explained by the unique value of the dynamic magnetic loss parameter in spite of the variation of core dimensions. Therefore, the dynamic magnetic loss parameter represents how the iron loss increases with respect to the exciting frequency and we can evaluate ferrites with this parameter, without a graph like Fig. 2. In order to decrease the iron loss in high frequency range, it is necessary for a ferrite to have a large value of the dynamic magnetic loss parameter. In addition, in case of large cores, reducing the permittivity is effective to decrease the iron loss caused by the displacement current. However, reduction of the DC conductivity with respect to the present value is not necessary.

Iron loss P [W]

Figure 2: Frequency characteristics of the iron loss.