Loss Analysis of a Mn-Zn Ferrite Core with the Spatial Network Method
Taking the Dynamic Magnetic Loss into Account

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A circuit model was developed to analyze the electromagnetic field in ferrites, for contribution to the design of power circuits by taking into account the power loss in the high-frequency region. The ferrite power loss in the high-frequency region consists of the hysteresis loss and the dynamic magnetic loss. This paper proposes a novel model for electromagnetic field analysis, which is able to compute the magnetic, eddy current and displacement current losses, based on the spatial network method. The validity of the method is verified by comparing the computed power losses with those obtained by the finite element method.

Keywords: ferrite, dynamic magnetic loss, spatial network method

1. Introduction

Ferrite cores are used for DC-DC converters that operate at high frequencies, ranging from hundreds of kilohertz to several tens of megahertz. Estimation of the loss distribution for each element in a power circuit is an important task in their design. Circuit simulators are commonly used for power circuit design. On the other hand, the finite element method (FEM) is often applied to the electromagnetic field analysis of transformers and inductors. However, combining the FEM with circuit simulators is not simple, especially when taking into account the non-linearity and losses of magnetic materials. Power circuit engineers require a circuit simulation tool that can simultaneously estimate the losses of not only semiconductor devices, but also of magnetic devices. Because circuit engineers are familiar with circuit simulators, it is preferable to develop an electromagnetic field analysis model, which can be easily incorporated into the circuit simulators.

For this purpose, a novel circuit model that is able to analyze the electromagnetic fields and power losses of a Mn-Zn ferrite core was developed. The model deals with not only the hysteresis loss but also the dynamic magnetic loss. This model is still under development, this paper reports the timely validation of the model by comparing the computed power losses with those obtained with the FEM using field phasors, i.e., the non-linearity is not considered.

2. Field Analysis Model Based on Spatial Network

A method that analyze the electromagnetic fields by dividing the space including electric and/or magnetic materials, and allotting electrical circuit elements to each of the divisions is well-known in, for example, distribution circuits for transmission lines, wave guides, light cables and so on. The spatial network method (SNM), which has several different names depending on the field of study, is the same type of method and has been applied to numerous magnetic problems. This paper presents a novel SNM that takes into account the hysteresis and dynamic magnetic losses in addition to the Joule heat losses in a Mn-Zn ferrite core, and which has not been reported before.

The dynamic magnetic loss parameter, \( \lambda_d \), has been introduced to enable the estimation of iron loss in ferrite cores excited at high frequencies ranging from hundreds of kilohertz to several tens of megahertz. A resistor consuming the dynamic magnetic loss for a one-turn wound ferrite core, is expressed by

\[
R_d = \frac{\lambda_d A}{l} \tag{1}
\]

where \( A \) and \( l \) are the cross-sectional area and the length of the magnetic path of the core, respectively. Similarly, the hysteresis loss is assumed to be consumed by

\[
R_h = \frac{h A}{l} \tag{2}
\]

where \( h \) is the hysteresis parameter. Both of \( R_d \) and \( R_h \) are connected in parallel to the inductance, given by the reciprocal of the magnetic resistance for the magnetic path considered, as shown in Fig. 1 (a).

Mn-Zn ferrites have not only magnetic properties, but also dielectric characteristics, i.e., large permittivity and dielectric losses caused by the displacement currents flowing through the grain boundaries which generate Joule heat in the grains. The equivalent circuits for the eddy and displacement currents are given as the series and parallel circuits of the resistors and capacitors shown in Fig. 1 (b).

The Mn-Zn ferrite core used is a toroid, of which the inner and outer diameters are 52 and 72 mm, respectively, and the height is 10 mm. The magnetic path of the core is assumed to be straight. The cross-section of the magnetic path is divided into \( n \) frames, as shown in Fig. 2, for the currents induced by the electric fields in the core and the magnetic fluxes generated by the currents.

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The circuits of Figs. 1 (a) and 1 (b) are applied to the excitation circuits and equivalent electrical circuits for the frames shown in Fig. 2, respectively, taking account of the Faraday’s and Ampere’s laws; the electric circuit for analyzing the electromagnetic fields in the core is derived as shown in Fig. 3, where leakage fluxes are not considered.

Using the same medium parameters for the core as in past studies, (2) and (3), each of the power loss summations consumed by each of the excitation coil is $100E-9$, $100E-6$, $100E-3$, and $100E+0$, respectively. The number of turns of excitation coil is $N$ and the currents and magnetic fluxes are depicted by $i$ and $\phi$, respectively. The circuits of Figs. 1 (a) and 1 (b) are applied to the excitation circuits and equivalent electrical circuits for the frames shown in Fig. 2, respectively, taking account of the Faraday’s and Ampere’s laws; the electric circuit for analyzing the electromagnetic fields in the core is derived as shown in Fig. 3, where leakage fluxes are not considered.

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\[
\frac{d\phi}{dt} = \frac{1}{N} i_1
\]

\[
\frac{d\phi}{dt} = \frac{1}{N} i_2
\]

\[
\frac{d\phi}{dt} = \frac{1}{N} i_3
\]

\[
\frac{d\phi}{dt} = \frac{1}{N} i_4
\]

Fig. 3. Equivalent electric circuit for the core

These frequency characteristics of the power losses were obtained using the expressions given in section 1. The mean value over the cross-section for the maximum instantaneous magnetic induction is 20 mT; the solid lines and circles show the computed results obtained by the SNM and FEM, respectively.

Fig. 4. Frequency characteristics of the power losses. The mean value over the cross-section for the maximum instantaneous magnetic induction is 20 mT; The solid lines and circles show the computed results obtained by the SNM and FEM, respectively.