Review of Core Power Loss Analysis Using Finite Element Methods
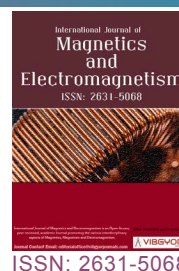
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Abstract

There are two principal methods are utilized to estimate the core power loss (CPL) in magnetic components: Empirical equations and hysteresis models. Both approaches need an anterior test or analysis to calculate the CPL. Most of them are based on improved Steinmetz equations. Tests are usually costly or the number of necessary tests is excessive for the component design development. 2D analyses using Finite Element are not good enough for several magnetic components for their lack of symmetries.

Non-symmetric magnetic cores are ones of the most common components in transformers and power converters and they don't have symmetries on the magnetic field distribution and only 3D models are competent to take account all the effects and phenomena.

Keywords

Core power loss, Eddy current loss, Hysteresis loss, Finite element analysis

Introduction

Losses in magnetic cores have been analyzed because of their particular importance to the component design in power electronics. Physicists study the features in magnetic materials, while design engineers in power electronics need to model the CPL. Nevertheless, there is a break between the power loss calculation theories, focused in material characteristics, and engineering applications. In consequence the devices designed cannot fully use the material capabilities.

One group of models are based on the Steinmetz equation where the coefficients are determined by fitting the loss model to the measurement experimental data. This model postulates purely sinusoidal flux densities. An increase of [1] was presented by Jordan in [2] where an iron loss model where the static hysteresis loss (HL) and dynamic eddy current loss (ECL) were divided. Pry and Bean added the excess loss factor or anomalous factor [3]. Bertotti developed a theory developing the losses by introducing the concept of magnetic objects, which led to excess loss in terms of the active magnetic objects and the domain wall motion [4,5]. Once the separation of the iron losses after the magnetizing processes was added, the losses caused by linear magnetization, rotational magnetization and higher harmonics were involved [6,7].

In the last times, the Steinmetz equation was im-

González-Teodoro et al. Int J Magnetics Electromagnetism 2019, 5:023

ISSN: 2631-5068 | • Page 2 of 5 •

proving. The Modified Steinmetz equation was presented in [8] for arbitrary waveforms and the Generalized Steinmetz equation [9] that presented the idea of the instantaneous iron loss is a single valued function of the flux density and the rate of change of the flux density. The improved Generalized Steinmetz equation [10] was developed to avoid the limitation in the third higher harmonic. For rectangular shapes voltages, the improved-improved generalized equation was published in [11].

To obtain a higher accuracy, hysteresis models (Preisach and Jiles-Atherton) were developed [12,13]. An improvement of the Preisach model was presented in [14] including a dynamic part divided in two sections describing the low and high values of the flux density. A friction hysteresis model based on energy approach where the magnetic dissipation from the macroscopic point of view is represented by a friction-like force was introduced in [15]. Advances for nonlinear behaviour were presented in [16]. A new model which describes the switching behaviour implemented in Matlab is in [17]. Analysis for non-sinusoidal signals for specific components used currently in power electronics has been studied in the last years [18-25].

The empirical and separation loss models are preferable and best suited for fast and rough iron loss definition. The complex hysteresis loss models are more adequate for an exact iron loss. They need much more knowledge about the material data or prior material measurements as well as more information about the flux density waveforms. Another huge issue is the integration into Finite Element tools.

Physics Analysis

The core power losses are based on Joule heating [26] and due to spin relaxation, although this last impact is only at frequencies in the medium-high frequencies. Hysteresis and eddy current losses are caused by the same physical phenomena: Every change in magnetization (which also occurs at DC magnetization) is a movement of domain walls and produces eddy currents creating Joule heating. The fact that hysteresis losses also arise at almost zero frequency is due to the macroscopic magnetization change, even it is slowly, the local magnetization the domains modifies quickly, which generates eddy current losses. In consequence, the engineering approach of loss separation into different loss types (the so-called hysteresis losses, eddy current losses and excess losses) is an empirical approach, trying to separate the different physical influences due to frequency and flux density variations in electromagnetic systems, rather than explaining the physical phenomena directly [27].

Engineering Analysis

The referenced break is produced because engineers usually design devices based on models with different coefficients than physicists use on their models.

However, these models are normally appropriate only for a defined frequency range, and practical disadvantages of most of these methods require additional measurements with a given material. Another additional issue is that these methods are only for static situations [1]. Other limitations are:

1) The models are based on eddy loss induced by domain wall motion; it doesn't match with empirical data for ferrites (Steinmetz equation coefficients).

2) It needs material and magnetic field data. Thus, it requires a simulation or essay to estimate the magnetic field into the core.

Core Power Loss Analysis using FEM

Most of the FEM [28,29] uses the Steinmetz equation with the defined parameters from the software or coefficient adjustments from the manufactures sheets on the program settings.

Also, there is another method to calculate the core power loss using FEM defined in [28] for the hysteresis and eddy current losses.

Hysteresis loss is flowing in the forward and reverse directions magnetizes and demagnetizes the core alternatively during each AC cycle. This energy loss is dependent of the properties of particular core material and proportional to the hysteresis loop area.

$$P_{hysteresis} = \int_{vol} \frac{1}{2} \cdot \omega \cdot Im\left(\vec{B} \cdot \dot{\vec{H}}\right) dV \qquad (1)$$

Where $\vec{B}$ is the magnetic flux density, $\dot{\vec{H}}$ is the complex conjugate of the magnetic field and ω is the angular frequency.

Eddy current loss is an electric current step up by an alternating magnetic field. These losses arise from the fact that the core itself is composed of conducting material, so that the voltage induced in it by the varying flux produces circulating currents in the material. Eddy current loss depends upon the rate of change of flux as well as the resistance of the path, it is reasonable to expect this loss varies as the square of both the maximum flux density and frequency if the core is solid and made up from ferromagnetic materials, and it effectively acts as a single short circuited turn. Induced eddy currents therefore circulate within the core in a plane normal to the flux, and cause resistive heating of the core material.

González-Teodoro et al. Int J Magnetics Electromagnetism 2019, 5:023

ISSN: 2631-5068 | • Page 3 of 5 •

$$P_{eddy1} = \int_{vol} \frac{1}{2\sigma} \cdot \left(\vec{J} \cdot \vec{J}^{\cdot} \right) dV \qquad (2)$$

Where $\vec{J}$ is the current density, $\vec{J}^{\cdot}$ is the complex conjugate of the current density and σ is the conductivity in a structure.

For the component surfaces, the eddy current loss is defined by:

$$P_{eddy2} = \sqrt{\frac{\omega \mu_o \mu_r}{8\sigma}} \cdot \int \vec{H}_t \cdot \vec{H}_t^{\cdot} ds \qquad (3)$$

Where $\vec{H}_t$ is the tangential component of the $\vec{H}$ on the boundary and $\vec{H}_t^{\cdot}$ is the complex conjugate tangential component of $\vec{H}$ on the boundary.

Nevertheless, the modeling in FEA depends on the core symmetry and winding configuration. This dependency produces that the loss calculation in non-symmetric components through a 3D FEM is a difficult task due to the current hardware computational limitations [30].

The current computational limitations [31,32] provoke to perform some simplifications at the component modeling to achieve the performance of the 3D FEM simulation in operative way for the design engineers. The allowed simplifications depend on the magnetic field distribution (1D/2D/3D).

2D Models are not enough precise in FEM when there is non-axial symmetry. In addition, there important effect that there are only possible to analyze in 3D models as the air-gap and edge effects.

The air-gap effect defines when in the magnetic core is introduced a material with poor permeability (usually it's air), there is a discontinuity in the core. This situation produces that the magnetic flux disperses in the closed zone to the air-gap. The disperse flux affects the current distribution of the conductors near of the air-gap. This phenomenon is very similar to the skin and proximity effect. The current of the conductors tries to minimize the energy with its own distribution, so, the real section decreases and the losses increase.

The edge effect consists in the direction change of the flux when the conductors finish. In each winding belongs to the magnetic component, the conductors fill the high of the window, and then, the distribution of the field is practically in the same direction, so, when the field arrives at the up or down of the core window, the field has to change the direction and it appears another new distribution different the main one.

Also, when it is winded the primary and secondary in the same split of the component, this effect appears in the edge and in the space of the two closed turns of the winding modifying the magnetic field density into the core.

For power engineers, the equivalent parameters (L and R for the core) can be interesting for the optimization of the component.

The estimation *L* is by 3D simulation and the *L-I* curve described in [33] can be define using one of the outputs (*ϕ-I* curve) by differentiations as:

$$L(I) = \frac{d\phi}{dl} \qquad (4)$$

Where *ϕ* is the magnetic flux.

To obtain *R*, it is derived at the post-modeling step R-*I*$_{rms}$ curve by numerical integration described in [33] as:

$$R = \frac{\overline{p}}{l_{rms}^2} \qquad (5)$$

Where $\overline{p}$ the average value of the power and l_{rms} is the *rms* value of the current on the windings.

Conclusion

As it is mentioned previously, the complex hysteresis loss models are more adequate for an exact iron loss, however there is a huge issue is the integration into Finite Element tools.

The hardware computer limitation is not useful in CPU time spending for the power electronics engineers and the 3D FEM in higher frequencies (> 10 MHz), the time consuming is especially long and the error increases substantially.

There are different ways to get along with these limitations. Some simplifications in the 3D model could be a solution, but these kind of limitations may become in the next bottleneck for future works.

Another choice is moving the research to decrease the Finite Element numbers reducing the space moving closer the boundaries using the perfectly matching layers technique.

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González-Teodoro et al. Int J Magnetics Electromagnetism 2019, 5:023

ISSN: 2631-5068 | • Page 4 of 5 •

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González-Teodoro et al. Int J Magnetics Electromagnetism 2019, 5:023

ISSN: 2631-5068 | • Page 5 of 5 •

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