MODELING LOSSES IN FERRITE CORES UNDER SQUARE VOLTAGE WAVEFORMS

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The manufacturers data for commercial ferrite grades are given for sinusoidal waveforms, although the voltage in the typical applications in power electronics resemble much more to square waves. A new ferrite loss model is presented. The model is checked with measurements on two different ferrite grades, with square waves with a large variation in duty ratio. The good matching validates the proposed model.

Keywords: ferrite core losses, loss models

1. INTRODUCTION

The high importance of losses in magnetic cores induces their study. A practical approach for computing high-frequency ferrite core losses for arbitrary voltage waveforms is presented in [1,2]. Models using square dependence on the flux density and a more complex frequency dependence are proposed in [3,4]. A technique to predict a more accurate magnetic core loss for pulsed operation is presented in [5]. The modern loss theory is summarized in [6]. But, the practical disadvantages of most of the proposed methods are the required additional measurements with a given material and parameter calculations.

This paper gives more accurate modeling of the losses under non-sinusoidal waveforms. The models are validated by experimental data measurements.

2. PROPOSED MODEL OF THE FERRITE LOSSES

2.1 Identification of the Steinmetz Equation

The most popular formula for core loss is known as the 'Steinmetz equation' [7]:

$$P_{loss} = k\, f^{\alpha}\, \hat{B}^{\beta} \tag{1}$$

where $\hat{B}$ is the peak induction, P_{loss} is the average power loss per unit volume and f is the frequency of the sinusoidal excitation. For common used power ferrites, α=1.2–1.9 and β=2.3–3. For square waves of 50% duty ratio the equation (1) looses in accuracy, but remains still a good approximation. When the same peak induction is maintained, but with a duty ratio δ of 5% (or 95%), our calorimetric experiments show more than doubled losses compared to sine wave and the prediction of (1)!

A reference frequency for sine wave voltage is defined with a reference power and induction:

$$k_{ref} = \frac{P_{ref}}{B_{ref}^{\beta}\, f_{ref}^{\alpha}} \tag{2}$$

$$P = k_{ref}\, B^{\beta}\, f^{\alpha} = P_{ref}\left(\frac{B}{B_{ref}}\right)^{\beta}\left(\frac{f}{f_{ref}}\right)^{\alpha} \qquad (3)$$

The parameter β is fitted at the reference frequency (100kHz), for the reference induction (0.1T), and other levels (0.05 and 0.15T). The parameter α is determined using the losses at the reference induction at higher frequency. A second sine wave frequency of 250kHz is taken as is lies between the second and third harmonic of the first reference frequency 100kHz.

The values α and β for two ferrite grades are given here: 3F3 and N67, obtained after measuring the corresponding cores. The found value of β at 100°C is higher than the value at 25°C. The value of α is higher at 100 kHz than at 25 kHz. All the found values are shown in Table I.

TABLE I
MEASURED MATERIAL CONSTANTS AT THE REFERENCE CONDITIONS
SINE WAVE VOLTAGE

Material Grade	K_{ref}	α	β	Measuring conditions
3F3	0.0482	1.842	3.06	100°C, 100 kHz
N67	0.1127	1.76	2.94	100°C, 100 kHz
3F3	17.26	1.31	2.9	100°C, 25 kHz

The parameters α and β are quite close to the actual data sheets.

2.2 Proposed Model of Ferrite Losses

To include the frequency dependence of the losses, a dependence on *dB/dt* with power α is proposed. As a result the following loss model is proposed:

$$P_{NEW} = \left(\frac{\Delta B}{2}\right)^{\beta-\alpha} \frac{k_N}{T}\int_0^T \left|\frac{dB}{dt}\right|^{\alpha} dt \qquad (4)$$

The above equation is consistent with the Steinmetz equation (1) for sine waves, if k_N is defined as:

$$k_N = \frac{k}{(2\pi)^{\alpha-1}\int_0^{2\pi} \left|\cos\theta\right|^{\alpha} d\vartheta} \qquad (5)$$

where k comes form the equation (1). The value k_N/k is a constant, once α is known.

For a square wave voltage with duty ratio δ, the equation (5) can be simplified to:

$$P_{NEW} = k_N\ f^{\alpha}\,(\Delta B)^{\beta}\left(\left(\frac{2}{\delta}\right)^{\alpha} + \left(\frac{2}{1-\delta}\right)^{\alpha}(1-\delta)\right) \qquad (6)$$

and then to:

$$P_{NEW} = k_N\ (2f)^{\alpha}\,(\Delta B)^{\beta}\left(\delta^{1-\alpha} + (1-\delta)^{1-\alpha}\right) \qquad (7)$$

where f is the operating frequency;
$\Delta B/2$ is the peak induction;
δ is the duty ratio of the square wave voltage.

Note: The second and third harmonics are dominant at the usual values of duty ratio δ. For extreme values of δ (95%), a higher value of α could give better matching to the actual losses.

3. EXPERIMENTAL MEASUREMENTS OF THE LOSSES

3.1 Measuring approach and equipment

To carry out the measurements a half bridge test platform was used. The average power is computed by the multiplying capability of channel 1 and channel 2 of a digital oscilloscope (Yokohawa DL1540). Exactly two periods are displayed, triggering at the zero crossing of the current. An averaging factor of 32 is used in the acquisition. The duty ratio is changed to obtain a variable waveform, while maintaining a constant peak-to-peak flux.

To have an independent check of the power loss measurement, a calorimeter (20W size) test is done for δ=50%. The comparison shows a 2% overestimation of the proposed measuring method to the calorimetric measurements, and for δ=95%, with a 5% underestimation. These differences are low considering the operating frequency and the special waveforms.

3.2 Measuring data and comparison with model

Two different material are measured: 3F3 material and EE42 N67 material, an ETD 44 core. A peak induction of 0.1T is maintained. The results are shown in Table II. The same current waveform (a separate inductor is put in series) is applied to the coil without ferrite to measure the copper loss. In this case, the transverse field through the litz wire is similar to the case with ferrite, and the eddy current losses have the same order of magnitude.

TABLE II
POWER LOSS MEASUREMENTS AT 0.1T, 100KHZ, 100°C
SQUARE WAVE VOLTAGE

δ, [%]	P_{meas} [W]	P_{cu}, [mW]	P_{fe} [W]	V, [V]	I, [m]	I, [A] p-p
50	0.983	3.332	**0.979**	35.02	350	1.208
60	1.015	3.35	**1.012**	35.68	349.6	1.208
70	1.113	3.453	**1.110**	38.5	349.4	1.208
80	1.332	3.55	**1.328**	44.09	348.9	1.208
90	2.154	3.944	**2.150**	57.49	349.5	1.232
95	4.144	4.483	**4.140**	77.64	368.1	1.328

The specific loss predictions (P_V, losses per unit volume) calculated by the proposed model, the equation (7), are shown in Fig.1, Fig.2 and Fig.3 for the ferrite grades 3F3 and N67 at 100kHz and 25KHz, 0.1 T. The same graphs show the experimental measurements for square voltage waveforms with δ=50%–95%. The classical Steinmetz Equation (1) with corresponding α and β for sine wave, are also shown in the same graphs. The experiments were made with an ETD 44 core, 3F3 material grade and an EE42 core, N67 material grade.

The matching of the proposed model and the experimental results is within 5% for duty ratio δ up to 90%. The small difference for δ=95% can be explained by the high frequency content at that point and the fact that material characteristics show a higher α at higher frequencies.

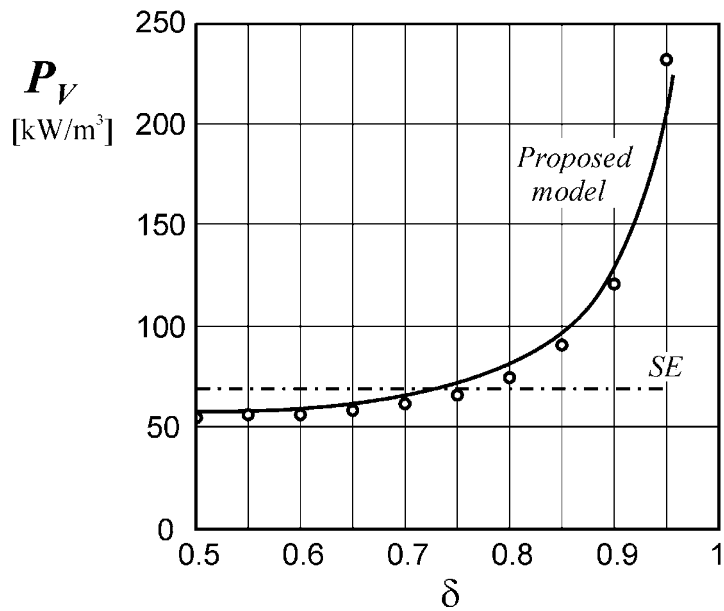

Fig.5 Specific ferrite core losses with square voltage waveforms for ferrite grade 3F3 at 100 kHz, 100°C, 0.1 T as a function of duty ratio δ; the experiments are the circles; the Proposed Model is the solid curve, for α=1.842; β=3.06; classical Steinmetz Equation (1) is dash-dot curve (*SE*).

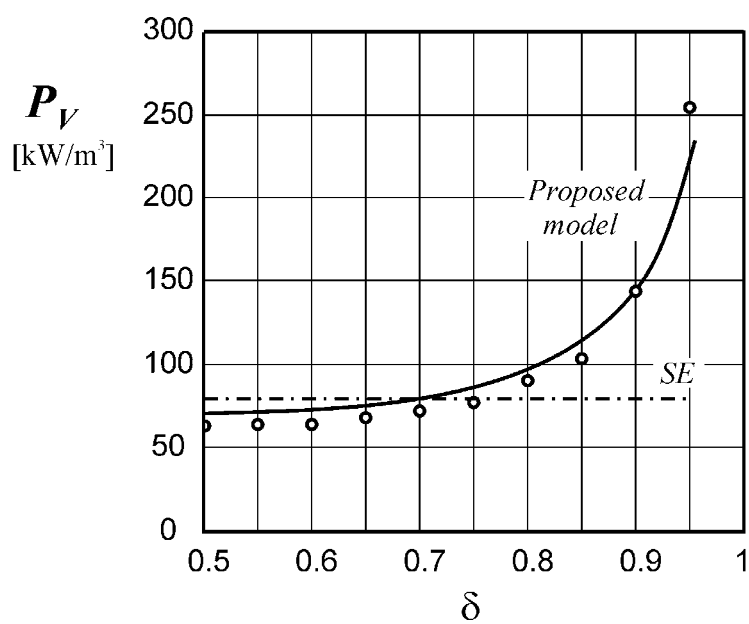

Fig.6 Specific ferrite core losses with square voltage waveforms for ferrite grade N67 at 100 kHz, 100°C, 0.1 T as a function of duty ratio δ; the experiments are the circles; the Proposed Model is the solid curve, for α=1.76; β=2.94; Steinmetz Equation (1) is dash-dot curve (*SE*).

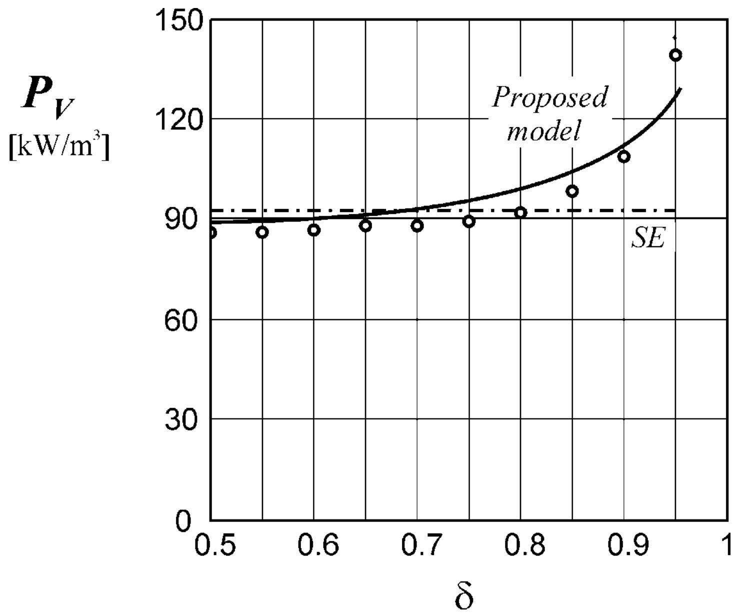

Fig.7 Specific ferrite core losses with square voltage waveforms for ferrite grade 3F3 at 25 kHz, 100°C, 0.2 T as a function of duty ratio δ; the experiments are the circles; the Proposed Model is the solid curve, for α=1.31; β=2.9; Steinmetz Equation (1) is dash-dot curve (*SE*).

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5. CONCLUSION

A new ferrite loss model is proposed. The model is checked with measurements on two different ferrite grades, with square waves with a large variation in duty ratio. The proposed model matches well the experiments of two quite different materials for all the values of the duty ratio δ=0,5÷0,95 and for two different temperatures.

The model is very useful for design of magnetic components for Power Electronics applications.

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