Calculation and Measurement of Winding Loss at High-Frequency Pulsed Currents

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INTRODUCTION: Winding resistance increases manifold at high frequency (HF) mainly due to proximity effect. Available analyses, first for sine waves, have been extended to non-sine currents by summing losses from high harmonics, a high effort and low accuracy way for low duty cycle (DC). Accuracy of analytical approaches is compromised by core, external objects, and end effects. This paper makes use of an inductor with an open ferromagnetic core as a case difficult for analytical analysis. Simulations were performed both in the frequency domain (FD) and time domain (TD). They were validated experimentally, including adiabatic heating. TD simulations abolish drudge and inaccuracy of the harmonics' approximation in the case of periodic signals. TD simulations are a useful complement to analytical methods in the case of low duty cycle currents.

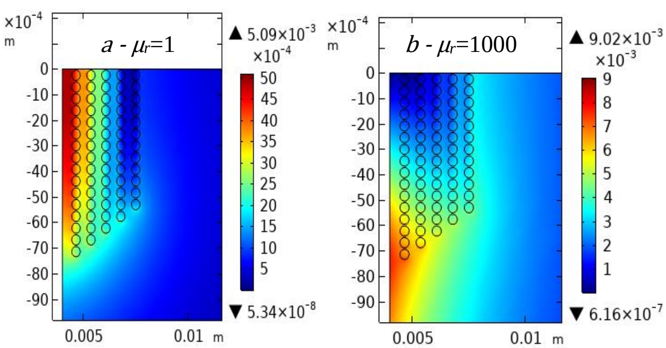

Figure 1. Magnetic flux density, T, in the winding for μ_r=1 and μ_r=1000 (60 kHz, peak current I_m=0.465 A).

COMPUTATIONAL METHODS: Magnetic Fields (mf) interface was used in conjunction with ODE, the latter for variables' integration.

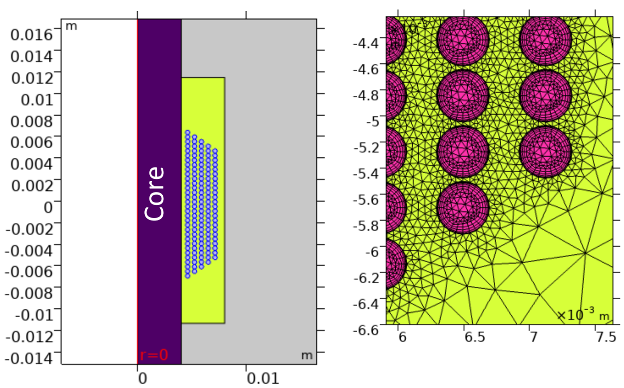

Figure 1. Modeled geometry (axisymmetric approximation) and mesh (adaptable to skin depth). Yellow shows winding encapsulation (was needed for calculation of parasitic capacitance and thermal simulations.

RESULTS: Winding was driven by pure sine and pulsed current waveforms, the latter with variable DC: sine, rectangular, triangular, and experimental waveforms.

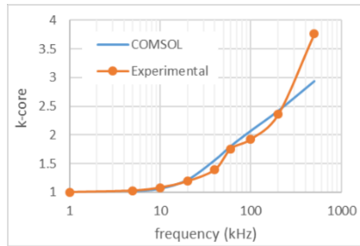

Figure 3. Core influence on losses in FD. R_{fer} is ac resistance of winding on ferrite, R_{ins} is that of winding on insulator former : k-core= R_{fer}/R_{ins}.

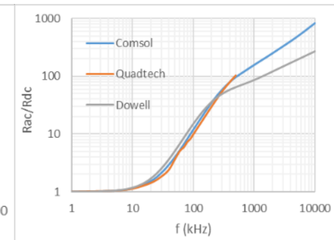

Figure 4. Frequency dependence of normalized inductor resistance.

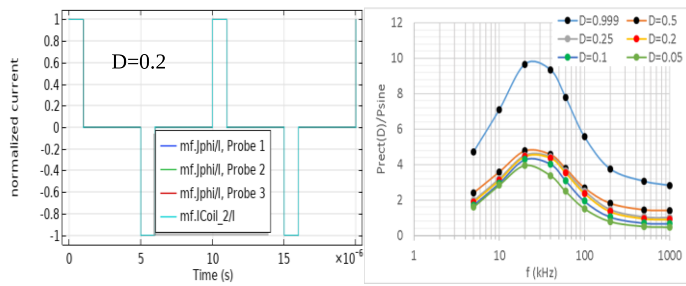

Figure 5. Drive current and frequency dependence of ratio of losses at pulsed excitation by a rectangular wave with duty cycle D<1, Prect(D), to those at pure sine wave, Psine.

I_m (A)	I_{rms} (A)	D	P_{exp} (au)	P_{coms} (au)
1.5	1.045	1	1	1
1.5	0.802	0.5	1.71	1.41
1.5	0.596	0.3	1.46	1.45
2	1.38	1	1	1
2	0.798	0.3	1.5	1.36

Table 1. Experimental data on inductor heating at 60 kHz compared with COMSOL simulations (in simulations, winding was driven by experimental waveforms).

CONCLUSIONS: TD simulations are both powerful and convenient in the case of pulsed currents at low D compared to summing losses for harmonics, especially if real current waveforms are known. At the same frequency and amplitude, pulsed currents induce much higher winding losses than sine currents.
Core has strong influence on the magnetic field, increasing the losses manifold compared to an air-core design. Experiments confirmed accuracy of field simulations. The developed methods were expanded to Litz-wound inductors (to be reported later).

REFERENCES:

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