High Frequency Magnetics; Black Magic, Art or Science?

Magnetics Core Loss

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APEC Industry Session on Magnetics

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www.ridleyengineering.com
Introduction

Core loss calculations and measurements

New core material needs

Need for extensive data

Approximations to data

Different excitation waveforms

Temperature variations

Standardized data base proposals
Immediate Goals for Core Materials

Would be nice to at least extend saturation range further
B-H Loop and Core Losses

Core loss calculations and measurements
Core Loss MPP 200μ

Core Loss Density Curves - MPP 200μ, 300μ

5000 mW/cm³

300 kHz 0.1 T 5 W/cm³

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Core Loss PC95

300 kHz 0.1 T  **0.350 W/cm³** > 10 times better than MPP

350 mW/cm³
Core Loss Steinmetz Equation

\[ P_c = k f^x \Delta B^y \]

Steinmetz equation can be used to approximate the actual loss measurements

Three coefficients define the loss for a given material
Steinmetz Equation Limitations

$$P_c = kf^x \Delta B^y$$

Equation assumes curves are

1) Equally spaced with frequency
2) Equal slopes at different frequencies
Modifying the Steinmetz Equation

\[ P_c = k f^x \Delta B^y \]

Discrete step changes in coefficients from Mag Inc.

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>a</th>
<th>c</th>
<th>d</th>
</tr>
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<tbody>
<tr>
<td>&lt;100 kHz</td>
<td>0.074</td>
<td>1.43</td>
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<td>100-500 kHz</td>
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Steinmetz Equation Changing Coefficients

\[ P_c = k f^x \Delta B^y \]

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Ridley-Nace Variable Steinmetz Equation

Continuously-variable coefficients with Ridley-Nace formula

\[ P_c = (a \ln f + b)f^cB^{(df+e)} \]

Five coefficients needed to describe materials

Example for Magnetics R material:

\[ P_c = (-3.626 \ln f + 28.32)f^{1.729}\Delta B^{-0.00076 f+2.8332} \]
Continuously Variable $k$ Term

Magnetics R Material Measured Core Loss

$$k = -3.626 \ln f + 28.32$$

$$P_c = (a \ln f + b) f^c B^{(df+e)}$$

$a = -3.626 \quad b = 28.32$
Continuously Variable y Term

Magnetetics R Material Measured Core Loss

\[ P_c = (a \ln f + b) f^c B^{(df + e)} \]

\[ d = -0.00076 \quad e = 2.8332 \]
Oliver Variable Steinmetz Equation
(Powdered Iron Core Material)

\[ P_{\text{core}} = \frac{f}{a} + \frac{b}{B^3} + \frac{c}{B^{2.3}} + \frac{d}{B^{1.65}}f^2B^2 \]

Continuously-variable coefficients with Oliver formula

Four coefficients needed to describe materials, plus 2.3 and 1.65 exponents subject to change with different materials

www.micrometals.com/appnotes/appnotedownloads/coreloss update.pdf
Six coefficients needed to describe temperature variation
Every material has a different curve
Does the curve also change with frequency and flux level?
Different Core Excitations

Need to modify equations to suit each of these waveforms
General Triangular Flux Waveform

\[ P_c(D) = D_1 P_c \left[ \frac{f}{2D_1} \right] + D_2 P_c \left[ \frac{f}{2D_2} \right] \]

\[ P_c = (a \ln f + b) f^c B^{(df+e)} \]
Duty Cycle Core Loss Multiplier

\[ P_c(D) = D_1P_c \left[ \frac{f}{2D_1} \right] + D_2P_c \left[ \frac{f}{2D_2} \right] \]

- **DCM**: \( D' = D \)
- **CCM**: \( D' = 1 - D \)

\( B = 0.15 \, \text{T} \)
Putting it All Together
What We Need from the Manufacturers

1) Raw core loss sinewave test data over wide range of frequency, $B$, temperature

2) Who is going to fund the modeling into a standard format database?
Magnetics Forecast

High-ripple current inductor designs will dominate the practical high-performance market

Practical “high performance” means converters up to 5 MHz

Core material improvements will be just incremental (unless some breakthrough material emerges)

**Insufficient funding** is going into fundamental magnetic material research to give a good chance of any breakthroughs.

Data Standardization is badly needed from the core manufacturers to ease confusion

Core loss raw data is needed, not just curves.

Creative core geometries need to be applied to POL inductors and other high-ripple parts

Magnetic core will not go away (however much it is wished for)

Isolation transformers will creep back into PoL applications to boost efficiency – **More magnetics!**

Multi-converter processing will continue to proliferate.
Some References


Ed Herbert: http://www.pisma.com/technical-forums/magnetics/core-loss-studies

Christopher Oliver: www.micrometals.com/appnotes/appnotedownloads/coreloss update.pdf

Power Supply Design Center Articles http://www.ridleyengineering.com/design-center.html

[89] Core Loss Modeling
[90] Core Loss Modeling with Non-Sinusoidal Waveforms - Part II
[91] Core Loss Modelling - Sinewave Versus Triangle Wave - Part III

Ray Ridley and Art Nace
[A03] Modeling Ferrite Core Losses

Christopher Oliver
[A06] Core Loss Modeling & Measurement