Core Loss Initiative: Technical

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Saturday workshop summary

- Morning topic: Core loss
- Afternoon topic: Fringing
- My impossible task: Summarize both sessions.
Core loss

- Behaviors to capture in models, measurements and data sheets.
  - Nonlinearity
  - Different behavior at different frequencies.
  - Effect of complex waveforms.
  - Impact of physical dimensions.

- Measurement Accuracy Issues (Stefan Ehrlich, Fraunhofer Institute)
  - Precision needed and how to achieve it.
Nonlinearity and frequency dependence

- Steinmetz model
  \[ P = kf^{\alpha} \hat{B}^{\beta} \]
  would mean straight, parallel lines on both plots.
- Linear model would mean \( \beta = 2 \).
- Behavior is more complex.

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How to capture nonlinear frequency dependent loss data?

- Just collect the data and interpolate.
- Better curve fits.
  - Example: \( P = k_1 \cdot f^\alpha \cdot B^\beta + k_2 \cdot f^\gamma \cdot B^\zeta \)
- Dynamic models that inherently have the right dependence on \( f \) and \( B \).
  - Example of a first attempt at this from Ray Ridley—work in progress.
<table>
<thead>
<tr>
<th>Issue</th>
<th>Implication</th>
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<tbody>
<tr>
<td>DC bias effect</td>
<td>Data collection needed</td>
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<td>Variety of waveforms</td>
<td>Options include</td>
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<td></td>
<td>• Extrapolation from limited data (e.g., iGSE method)</td>
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<td>• Comprehensive “loss map” data collection for waveforms of interest.</td>
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<td>• e.g., Byron Beddingfield’s DAB tester for “dual slope” waveforms.</td>
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<td>Effect of core size and shape</td>
<td>Effects to study:</td>
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<td></td>
<td>• Skin effect</td>
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<td>• Wave propagation/dimensional resonance</td>
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<td>• Mechanical resonance</td>
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<td>• Simple flux crowding as affected by shape</td>
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</table>
Dimensional Effects

- Straightforward to model and analyze:
  - Flux crowding at corners.
  - Cross section variation.
  - See blog post for more on examples at right.

- Complex, known physics; uncertain parameters:
  - Skin effect and wave propagation
  - Mechanical vibration: See ref [5]*.

- Poorly understood:
  - Higher loss on surfaces than in bulk.

*Slides in on the memory stick are only a placeholder. Find these, with references, at sites.dartmouth.edu/power-magnetics/*
Surface losses in MnZn ferrite confirmed

- A prototype with NiZn ferrite does not have this problem.

Talk Wed. 09:45, “A Low-Loss Inductor ....”, Session T12, Magnetics, paper 1487, Yang, Hanson, Perreault and Sullivan.
Skin effect, affected by
μ and σ
(permeability and conductivity)

Wave propagation
(dimensional resonance)
affected by μ and ε
(ε = permittivity or dielectric const.)
Typ. ε_r = 10^5 for MnZn ferrite

Rough core leg size for these effects

- For low loss, skin effect may be important sooner than shown.
Drilled MnZn core to install sense windings.

Flux ratio: A/B (inner/outer)

Marcin Kacki, Myrek Rylko, John Hayes, Ed Herbert
Dimensional effects: implications

- For large area core legs at high frequency:
  - Segmented, laminated, or “bundle of sticks” approach.
  - Measurement data taken on a different core size may not be adequate.
- Very rough idea of size and frequency thresholds
  - ~ 1 cm at 1 MHz with MnZn ferrite.
  - ~ 1 cm at 10 MHz with NiZn ferrite.
- Data on $\varepsilon$ and $\rho$ combined with streamlined modeling could avoid the need for loss measurement of every core size.
- Caution: $\varepsilon$ and $\rho$ vary with frequency and temperature.
Afternoon: Fringing

- Changes air-gap reluctance.
  - Calculations rarely needed: design based on reluctance $R$, not gap length $\ell_g$, and find the gap experimentally.
  - If needed, calculations are in the appendix.
- Extra winding loss.
- Extra core loss in laminated/tape wound cores: eddy currents.
Fringing effect on core loss

- Flux crosses perpendicular to laminations, inducing loss.
- The “out-of-plane flux” (OOPF) causes excess power loss $P_{OOPF}$.
- Only a problem on two sides of a post.
- Solutions exist: patented shapes and configurations [9],[10].

OK flux  Bad flux
Fringing effect on winding loss

- Strong field near the gap causes increased eddy-current winding loss.
- Curved field is bad for foil windings:

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One conceptual approach

- Solid winding.
- Current flow is attracted to gaps.
- Amount of current is proportional to gap reluctance.

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Single gap

Which winding has larger loss, with the same ac current in each winding?
Single gap

- All current flows near the gap.
- Longer gap → Current is spread over a larger area → lower loss.
- Current with small gap is spread wider than gap.
One design approach:

- Spread several gaps evenly:
  - Spacing $x$ between gaps.
  - Distance $x/2$ from edge of winding.
- Choose spacing $s < x/3$.
- Current distribution is not perfect, but “pools” of current overlap and impact on loss is small.
- For details, see ref. [1]

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Are all equal spacings gaps equal?

- Current spreads to both sides of gap.
- Position accordingly: x/2 on edges.

25% worse

14% worse
Approaching distributed gap

Low Permeability
Winding shape optimization

- Shape winding configuration to work with curved gap field.
- Applies to round wire and litz wire, not foil.
- Can actually work better than a distributed gap!
- Ad-hoc approach common, but full optimization is available [2,3,4].
Fringing conclusions

- Current flows near the gaps.
- A wider gap lowers resistance.
- Spacing $s > x/3$ is a good rule.
- Not all equally spaced gaps are equal—first gap $x/2$ from edge.
- Shaped windings with a single gap.
Ways forward on core loss: Industry

**Magnetic material users**
- Ask suppliers for data.
- Estimate skin effect for MnZn ferrites; consider segmented core.
- For non-sinusoidal waveforms: Barg refinement of iGSE (different parameters for each segment).

**Magnetic material suppliers**
- Data with dc-bias.
- Data in electronic form.
- Data for different core sizes.
- Data on resistivity (and permittivity?).
- Tolerances: min and max loss
- Data for square-wave drive.

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Ways forward on core loss: research

- Integration of models for different loss effects.
  - Hope: effects considered separate maybe different aspects of the same effect.
  - Comprehensive, accurate, research models.
  - Practical, usable models for designers.
- Simple, nonlinear simulation models.
  - Linear models can’t match observed behavior.
References: Core loss


Fringing References


[10] US Pat. No. 8,466,766
Another example

- Both gaps are small enough that it doesn’t matter much.
- Shorter gap is worse.
Fringing reluctance calculation

\[ R_{\text{faces}} = \frac{\pi}{p \cdot \mu_0 \left(1 + \ln \frac{\pi \ell}{2 \ell_{\text{gap}}} \right)} \]

\[ R_{\text{corners}} = \frac{1}{\mu_0 k \ell} \]

where

\( p = \text{perimeter} = 2(w+d) \)

\( k = 1.23 \)

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