Core Loss:
What We Know and What We Don't Know

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What we know and what we don’t know

We know:
- How to measure core loss.
  (Other talks)
- Data for some situations.
- Approximate models, and their limitations.
- A list of loss mechanisms that contribute to loss.

We don’t know:
- The physics and physical parameters well enough to make accurate first-principles loss predictions.
- Practical methods to predicting all the relevant loss effects.
- Expected variability between material batches.

Initial focus: ferrite materials
Later comments: differences in powder and tape-wound/laminated materials
Some data and the Steinmetz model

- For sinusoidal excitation.
- Charles Steinmetz’s model: $P = k\hat{B}^\beta$
- Typical modern model: $P = kf^\alpha \hat{B}^\beta$
- Can use different parameters for different frequency ranges.

Standard loss mechanisms

- Static hysteresis loss: loop area that’s independent of frequency
  $\rightarrow P \propto f$, or $P = k f B^\beta$
- Eddy-current loss. Expect $P \propto B^2$
  - Scale: individual particle vs. overall core leg.
  - Simple theory: $P \propto f^2$, but,
    - That’s for sizes small compared to skin depth.
    - Resistivity can be frequency-dependent
- Anomalous loss, defined as either:
  - Any and all other loss mechanisms—also called “excess loss”
  - Local eddy-current loss induced by rapid domain-wall motion: $P \propto f^{1.5}B^{1.5}$

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Summing standard loss mechanisms:

- \( P = P_{\text{hyst}} + P_{\text{excess}} + P_{\text{eddy}} \)
- True by definition if \( P_{\text{excess}} \equiv P - P_{\text{hyst}} - P_{\text{eddy}} \)
- But if \( P_{\text{anomalous}} \) is defined as loss from impeded domain wall motion, 
  \( P_{\text{hyst}} \) and \( P_{\text{anomalous}} \) are not truly independent.
- Possible model:
  - \( P = P_{\text{hyst}} + P_{\text{eddy}} \), where \( P_{\text{hyst}} \) is the loss associated with domain wall motion, and may be rate-dependent, e.g., \( P = k_1 f^{\alpha} B^{\beta} + k_2 f^{\gamma} B^{\zeta} \)
  - The same model can be formulated in terms of voltage per turn and period.

Omitted in all of the above:

Behaviors:
- Effect of DC bias
- Effects of non-sinusoidal waveforms.
- Effect of core size and shape.

Phenomena:
- Wave propagation and dimensional resonance.
- Mechanical resonance.
- Flux crowding as affected by core shapes.
Behaviors: DC Bias

- Can be expected to affect hysteresis.
- Strong effect on magnetostriction and mechanical resonance.
- Affects permeability and thus skin depth and wavelength.
- Extensive data collection needed.

Waveform effect on core loss:
Concepts, rather than how-to

- Initial hope in GSE model: instantaneous loss depends on B and dB/dt: \( p(t) = p(B(t), dB/dt) \)
  - If this worked, you could add up loss for incremental time segments:

\[ E_{\text{loss}} = E_1 + E_2 + \ldots \]

or better, an integral…

*It doesn’t work: flawed concept*
Improvement that enabled iGSE

- Loss depends on segment dB/dt and on overall $\Delta B$.
- Still $E_{\text{loss}} = E_1 + E_2 + \ldots$, but $E_1$ depends on a global parameter as well as a local parameter.

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Composite waveform method

- Same concept as GSE: add up independent loss for each segment.

$$E_{\text{loss}} = E_1 + E_2$$

- Unlike the GSE, this works pretty well in simple cases:
  - Waveforms where $\Delta B$ is the same for the segment and the whole waveform!
  - It reduces to the same assumptions as the iGSE [3].
What we know how to do for non-sinusoidal waveforms:

- For simple waveforms, add up the loss in each segment.

- For waveforms with varying slope, add up the loss for each segment, considering overall $\Delta B$ and segment $\delta B$.

- See iGSE paper for how those factor in [3].

- For waveforms with minor loops, separate loops before calculating loss ([3] again).

Loss models for each segment

- iGSE derives them from a Steinmetz model
  - Limitation: Steinmetz model holds over a limited frequency range.
  - Loss map model uses square-wave data directly for a wide frequency range.
    - Clearly better if you have the data.
    - Can also map with different dc bias levels.
  - Sobhi Barg ([1] Trans. Pow. Electr., March 2017) shows that the iGSE gets much more accurate if you use different Steinmetz parameters for each time segment in a triangle wave.
Limitation for all of the above: open research question.

- “Relaxation effect”
- Simple theory says loss for one cycle should be the same for both flux waveforms.
- In practice, it’s different.
- $i^2$GSE (J. Mühlethaler and J. Kolar) captures this but is cumbersome and requires extensive data.

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Dimensional Effects

- Straightforward to model and analyze:
  - Flux crowding at corners.
  - Cross section variation.
- Complex, known physics; uncertain parameters:
  - Skin effect in core
  - Electromagnetic waves
  - Mechanical vibration: See ref [5].
- Poorly understood:
  - Higher loss on surfaces than in bulk.

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Dimensional Effects: plots of $|B|$ in a round centerpost

- Skin effect, affected by $\mu$ and $\sigma$ (permeability and conductivity)
- Wave propagation (dimensional resonance) affected by $\mu$ and $\epsilon$ (permittivity and dielectric const.)


Typical skin depths and wavelengths: 1st order calculation

<table>
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<tr>
<th>Sample</th>
<th>Skin depth</th>
<th>$100 \text{ kHz}$</th>
<th>$1 \text{ MHz}$</th>
<th>$10 \text{ MHz}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MnZn Ferrite (3F46)</td>
<td>8.2 cm</td>
<td>1.3 cm</td>
<td>0.18 cm</td>
<td></td>
</tr>
<tr>
<td>NiZn Ferrite (67)</td>
<td>80 m</td>
<td>18 m</td>
<td>2.5 m</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\lambda/4$</th>
<th>$100 \text{ kHz}$</th>
<th>$1 \text{ MHz}$</th>
<th>$10 \text{ MHz}$</th>
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<tbody>
<tr>
<td>MnZn Ferrite (3F46)</td>
<td>6.1 cm</td>
<td>0.87 cm</td>
<td>0.12 cm</td>
<td></td>
</tr>
<tr>
<td>NiZn Ferrite (67)</td>
<td>2 m</td>
<td>237 cm</td>
<td>30.6 cm</td>
<td></td>
</tr>
</tbody>
</table>

- Approximate values: based on typical resistivity and permittivity vs. frequency from Ferroxcube catalog: not for these specific materials.
- Rough cross sections (e.g., centerpost diameters) where effects start.
- MnZn: skin effect and wave propagation start at similar points—skin effect may dominate.
- NiZn: wave propagation may be the limiting effect.
Dimensional effects: loss prediction

- MnZn:
  - May be adequate to consider skin effect only.
  - Essential data: resistivity vs. frequency.
    - Available on request from some ferrite companies.
  - A 2-D finite-element simulation can give an accurate prediction: Talk from Myrek Rylko, 9:20.

- NiZn:
  - Wave propagation and dimensional resonance dominate.
  - Fewer simulators are capable of including this effect.

Dimensional effects: implications

- For large area core legs at high frequency:
  - Segmented 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
    - \( \sim 1 \text{ cm at } 1 \text{ MHz with MnZn ferrite.} \)
    - \( \sim 1 \text{ cm at } 10 \text{ MHz with NiZn ferrite.} \)
  - More data and streamlined modeling could help avoid the need for full loss measurement of every core size.
Other dimensional effects

- Flux corner crowding
  - Can be predicted by magnetostatic simulations.
  - Sharp corners aren’t terrible.
- Surface losses
  - Concern for multi-gap designs—discussed this afternoon.

Other materials

- Powdered metal:
  - Simpler models work well:
    - Negligible anomalous loss and relaxation effect.
    - Low permittivity means negligible wave propagation effects.
    - Eddy current is within particles—little skin effect.
- Tape-wound/laminated materials:
  - Anomalous loss better understood.
  - Anisotropic eddy-current effects.
Ways forward: Industry

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).

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.

Ways forward: 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


