

Core Loss:

What We Know and What We Don't Know

Prof. Charles R. Sullivan

chrs@dartmouth.edu



Dartmouth Magnetics and Power
Electronics Research Group



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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

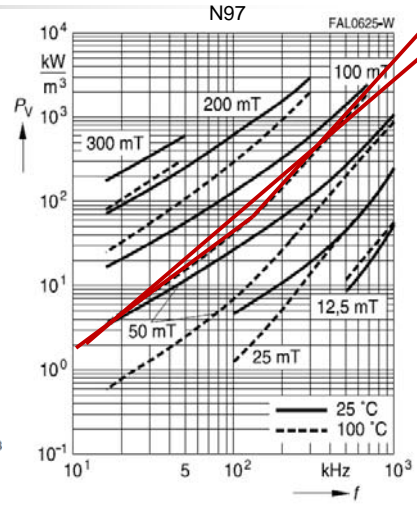
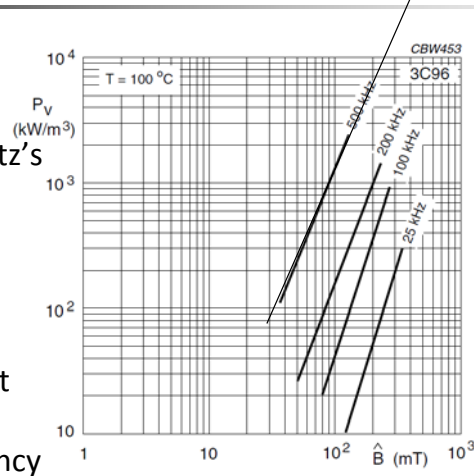
Later comments: differences in powder and tape-wound/laminated materials

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Some data and the Steinmetz model D M

- 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.

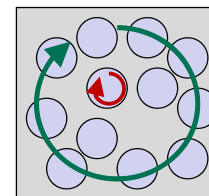


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Standard loss mechanisms D M

- Static hysteresis loss: loop area that's independent of frequency
→ $P \propto f$, or $P = k \cdot f \cdot B^\beta$
- 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: $P \propto f^{1.5} B^{1.5}$





Summing standard loss mechanisms



- $P = P_{hyst} + P_{excess} + P_{eddy}$
- True by definition if $P_{excess} \equiv P - P_{hyst} - P_{eddy}$
- But if $P_{anomalous}$ is defined as loss from impeded domain wall motion, P_{hyst} and $P_{anomalous}$ are not truly independent.
- Possible model:
 - $P = P_{hyst+} + P_{eddy}$, where P_{hyst+} is the loss associated with domain wall motion, and may be rate-dependent, e.g., $P = k_1 f^\alpha \cdot B^\beta + k_2 f^\gamma \cdot B^\zeta$
 - 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.

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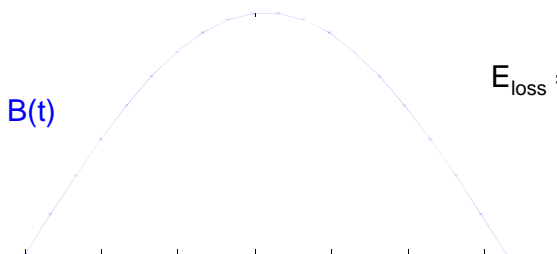
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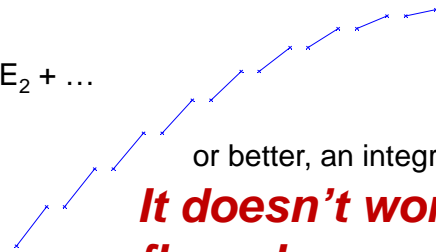
Waveform effect on core loss: Concepts, rather than how-to



- 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:



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



or better, an integral...

***It doesn't work:
flawed concept***

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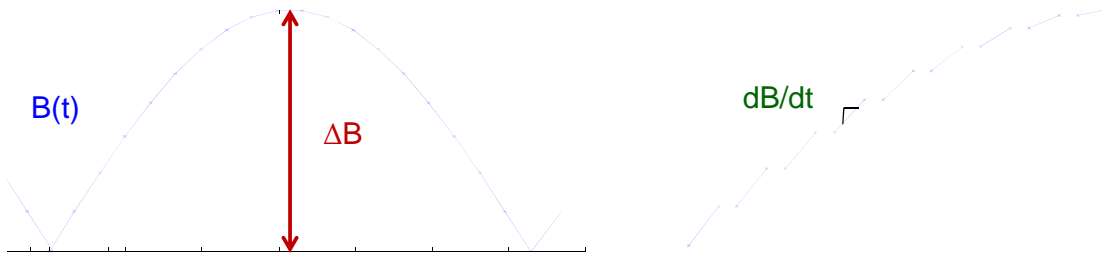
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Improvement that enabled iGSE



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



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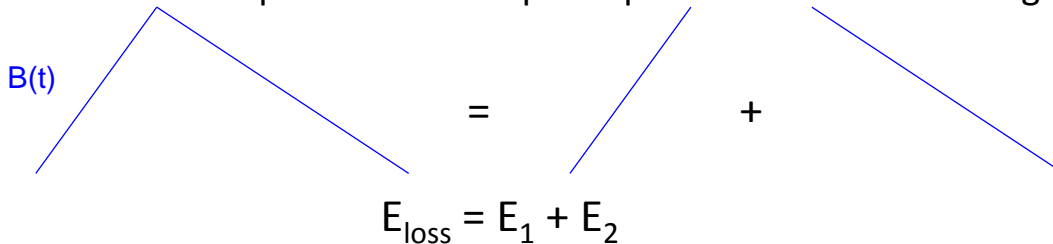
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Composite waveform method



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



- Unlike the GSE, this works pretty well in simple cases:
 - Waveforms where ΔB is the same for the segment and the whole waveform!
 - It reduces to the same assumptions as the iGSE [3].

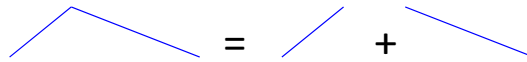
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What we know how to do for non-sinusoidal waveforms:



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



- For waveforms with varying slope, add up the loss for each segment, considering overall ΔB and segment δB .



- 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



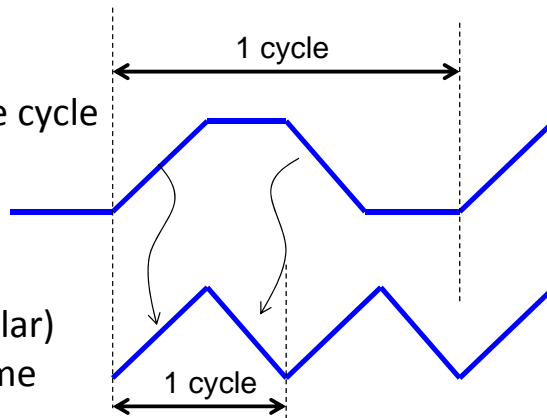
- iGSE derives them from a Steinmetz model
 - Limitation: Steinmetz model holds over a limited frequency range.
- Loss map model uses square-wave data directly for a wide frequency range.
 - Clearly better if you have the data.
 - Can also map with different dc bias levels.
- Sobhi Barg ([1] Trans. Pow. 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^2GSE (J. Mühlethaler and J. Kolar) captures this but is cumbersome and requires extensive data.



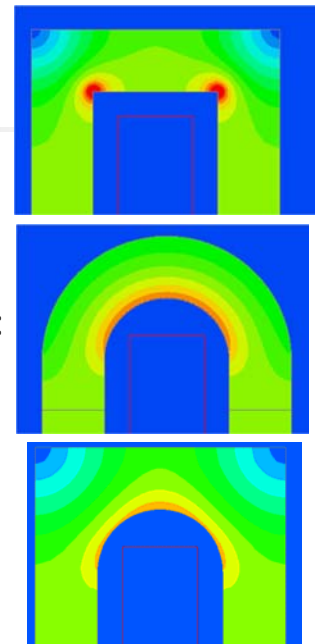
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Dimensional Effects

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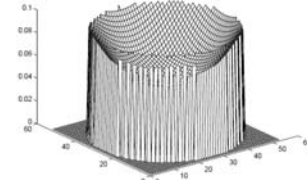
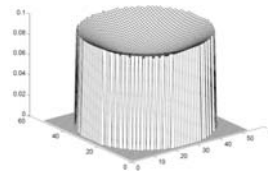
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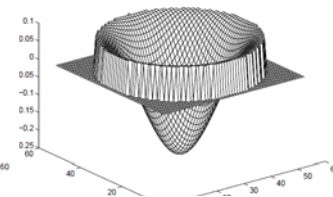
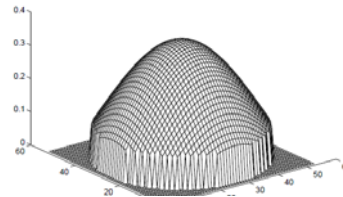
Dimensional Effects: plots of $|B|$ in a round centerpost



- Skin effect, affected by μ and σ (permeability and conductivity)



- Wave propagation (dimensional resonance) affected by μ and ϵ (permeability and dielectric const.)



- Figures from Glenn Skutt's excellent PhD thesis: "High-Frequency Dimensional Effects in Ferrite-Core Magnetic Devices," Virginia Tech, 1996.



Typical skin depths and wavelengths: 1st order calculation



Skin depth	100 kHz	1 MHz	10 MHz
MnZn Ferrite (3F46)	8.2 cm	1.3 cm	0.18 cm
NiZn Ferrite (67)	80 m	18 m	2.5 m

$\lambda/4$	100 kHz	1 MHz	10 MHz
MnZn Ferrite (3F46)	6.1 cm	0.87 cm	0.12 cm
NiZn Ferrite (67)	2 m	237 cm	30.6 cm

- Approximate values: based on typical resistivity and permeability 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.

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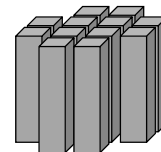
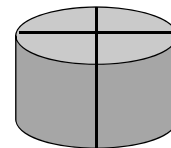
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Dimensional effects: implications



- 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
 - ~ 1 cm at 1 MHz with MnZn ferrite.
 - ~ 1 cm at 10 MHz with NiZn ferrite.
- More data and streamlined modeling could help avoid the need for full loss measurement of every core size.



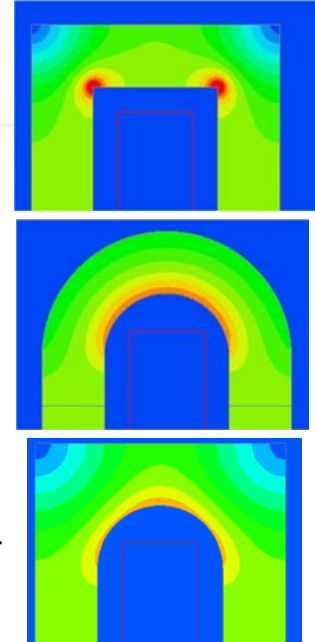
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Other dimensional effects

- Flux corner crowding
 - Can be predicted by magnetostatic simulations.
 - Sharp corners aren't terrible.
- Surface losses
 - Concern for multi-gap designs—discussed this afternoon.
- Our experience: not a problem in NiZn ferrite: See APEC paper 1484, Wed. 09:45, "A Low-Loss Inductor Structure ...", Session T12, Magnetics.



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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.

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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).

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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: 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.

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References

- [1] Sobhi Barg, K. Ammous, H. Mejbri, and A. Ammous, "An Improved Empirical Formulation for Magnetic Core Losses Estimation Under Nonsinusoidal Induction," *IEEE Trans. Pow. Electr.* 32(3), March 2017
- [2] Benedict Foo, A. Stein, C. Sullivan, "A Step-by-Step Guide to Extracting Winding Resistance from an Impedance Measurement", APEC 2017.
- [3] K. Venkatachalam, C. R. Sullivan, T. Abdallah, and H. Tacca, "Accurate prediction of ferrite core loss with nonsinusoidal waveforms using only Steinmetz parameters," in *IEEE Workshop on Computers in Pow. Electr.*, 2002.
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- [4] Glenn Skutt's , "High-Frequency Dimensional Effects in Ferrite-Core Magnetic Devices," Virginia Tech, PhD thesis 1996. Available for download from Virginia Tech.
- [5] C. A. Baguley, U. K. Madawala, B. Carsten and M. Nymand, "The Impact of Magnetomechanical Effects on Ferrite B–H Loop Shapes," in *IEEE Transactions on Magnetics*, vol. 48, no. 8, pp. 2284-2292, Aug. 2012. doi: 10.1109/TMAG.2012.2191297