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.

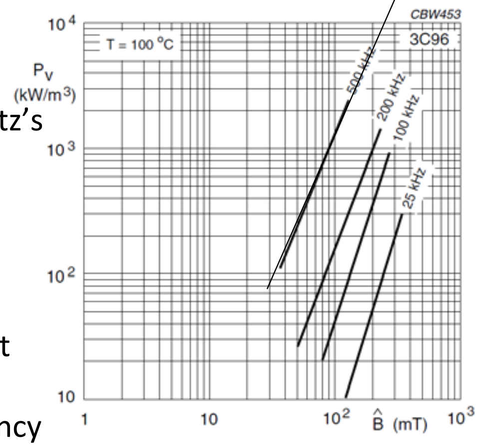
We don't know:

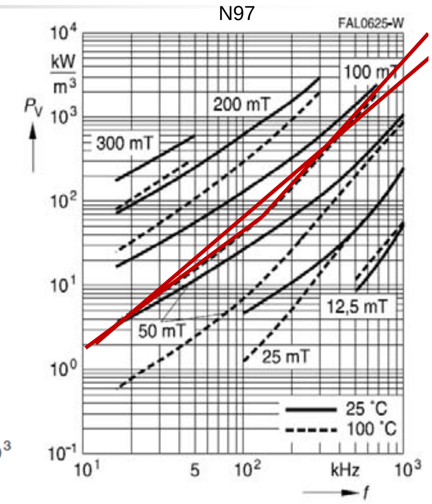
- The physics and physical parameters well enough to make accurate first-principles loss predictions.
- Practical methods to predicting all the relevant loss effects.
- Expected variability between material batches.

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

Some data and the Steinmetz model

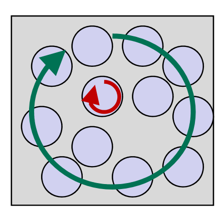
- For sinusoidal excitation.
- Charles Steinmetz's model: $P = k\hat{B}^{\beta}$
- Typical modern model:
  $P = kf^{\alpha}\hat{B}^{\beta}$
- Can use different parameters for different frequency ranges.





Standard loss mechanisms

- Static hysteresis loss: loop area that's independent of frequency
  $\rightarrow P \propto f$, or $P = k \cdot f \cdot B^{\beta}$
- 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., $P = k_1 \cdot f^{\alpha} \cdot B^{\beta} + k_2 \cdot f^{\gamma} \cdot B^{\zeta}$
  - 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

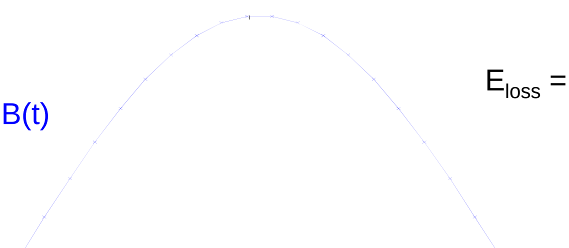
?

- 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.

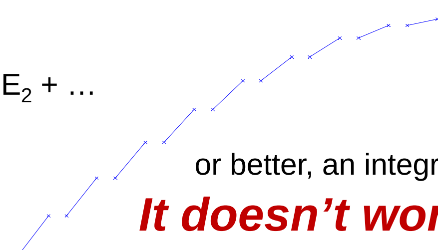
Waveform effect on core loss: Concepts, rather than how-to

- 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:

B(t)



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

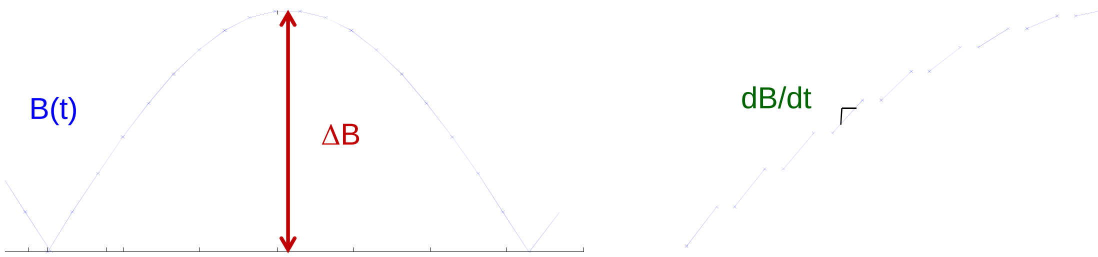


or better, an integral…

It doesn't work: flawed concept

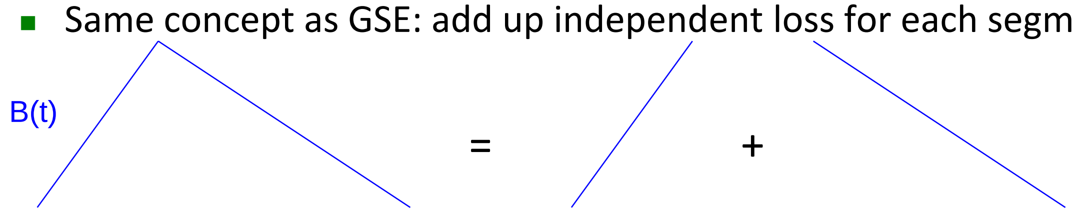
Improvement that enabled iGSE

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



Composite waveform method

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

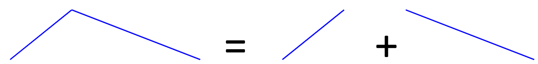


$$E_{loss} = E_1 + E_2$$

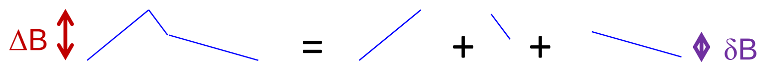
- Unlike the GSE, this works pretty well in simple cases:
  - Waveforms where ΔB is the same for the segment and the whole waveform!
  - It reduces to the same assumptions as the iGSE [3].

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

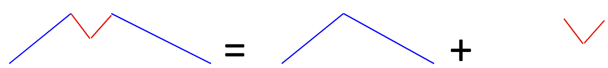
- For simple waveforms, add up the loss in each segment.



- 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).

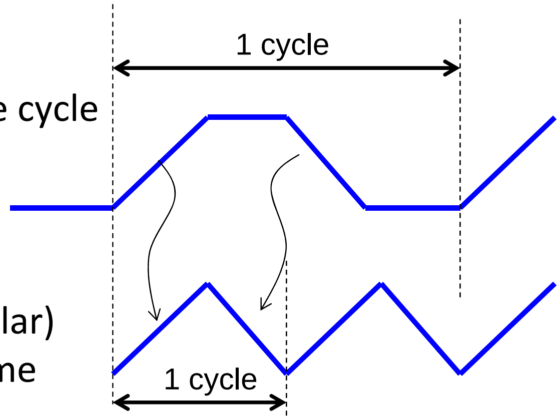


Loss models for each segment

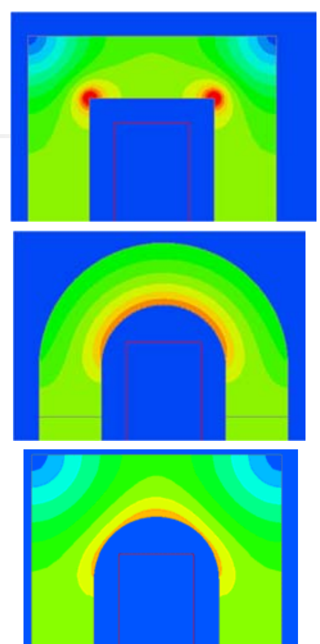
- iGSE derives them from a Steinmetz model
  - Limitation: Steinmetz model holds over a limited frequency range.
- Loss map model uses square-wave data directly for a wide frequency range.
  - Clearly better if you have the data.
  - Can also map with different dc bias levels.
- Sobhi Barg ([1] Trans. 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.
- i²GSE (J. Mühlethaler and J. Kolar) captures this but is cumbersome and requires extensive data.



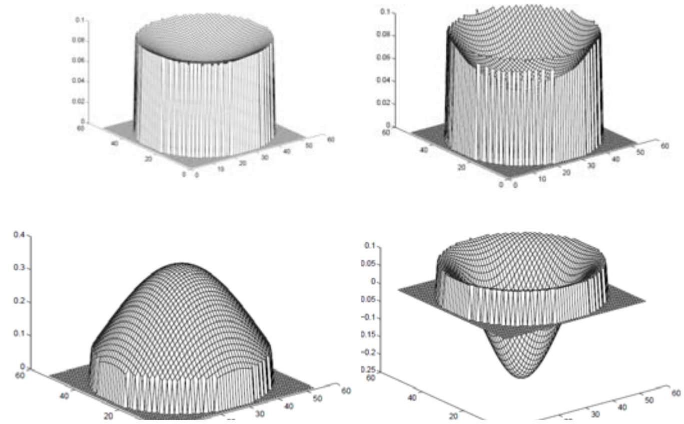
Dimensional Effects



- 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.

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
  (permittivity 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

λ/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

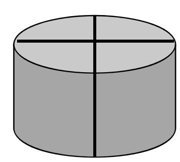
- Approximate values: based on typical resistivity and permittivity vs. frequency from Ferroxcube catalog: not for these specific materials.
- Rough cross sections (e.g., centerpost diameters) where effects start.
- MnZn: skin effect and wave propagation start at similar points—skin effect may dominate.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

Dimensional effects: loss prediction

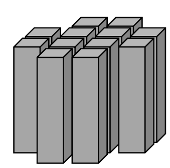
- MnZn:
  - May be adequate to consider skin effect only.
  - Essential data: resistivity vs. frequency.
    - Available on request from some ferrite companies.
  - A 2-D finite-element simulation can give an accurate prediction: Talk from Myrek Rylko, 9:20.
- NiZn:
  - Wave propagation and dimensional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



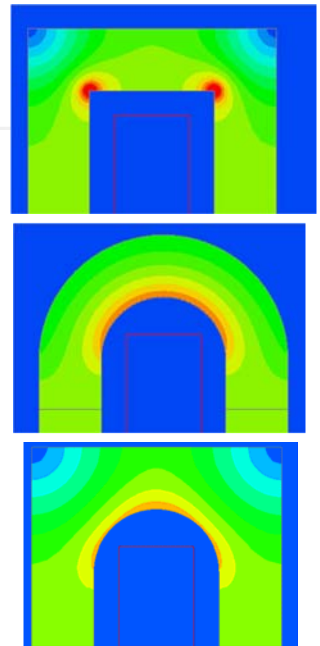
- Very rough idea of size and frequency thresholds
  - ~ 1 cm at 1 MHz with MnZn ferrite.
  - ~ 1 cm at 10 MHz with NiZn ferrite.



- More data and streamlined modeling could help avoid the need for full loss measurement of every core size.

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.



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

[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. *https://engineering.dartmouth.edu/inductor/papers/IGSE.pdf*

[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