High-Frequency Core and Winding Loss Modeling

This is a special web edition of a plenary talk from IEMDC 2013, with references added. References for winding loss are throughout; for core loss, they are collected at the end.

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Motivation

- High electrical frequency because of high pole count and/or high mechanical speed, for
  - High power/weight (power/cost) ratio
  - Wide speed range
- Switching frequency ripple.
- High frequency loss models and optimization techniques have been developed extensively in the field of static power conversion.
- Survey known techniques and outstanding issues, with an eye towards applications in machines.

Core losses vs. winding losses

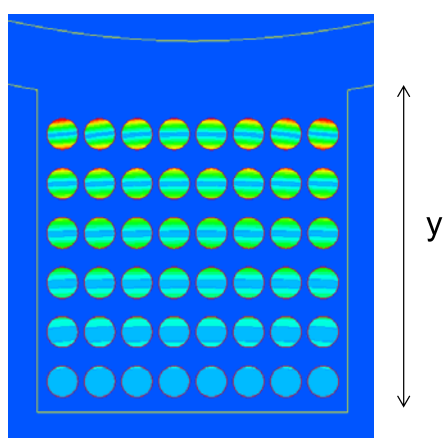
- High-frequency **winding** losses:
  - Material properties: Linear and well known.
  - Loss prediction: analytical or FEA solutions.
  - Size/frequency equivalence.
- High-frequency **core** losses:
  - Material properties: nonlinear; not well understood.
  - Loss prediction: generalization of empirical measurements.
  - Different considerations with different materials and in different frequency ranges.

High-frequency winding losses

- What counts as high frequency?
  - When (slot depth y) >> (skin depth δ)

f	60 Hz	200 Hz	500 Hz	1 kHz	2 kHz
δ in Cu at room temperature	8.5 mm	4.7 mm	3 mm	2 mm	1.5 mm

  - 2 cm slot at 2000 Hz is like an 11 cm slot at 60 Hz.
  - Example: AC winding losses 4.6x worse than I^2R_{dc}



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Myth:
no issues with wire diameter < 2δ

- Example shown:
  - AC winding losses 4.6x worse than I^2R_{dc} (i.e., $F_R = 4.6$)
  - $\delta = 1.5$ mm (f = 2 kHz)
  - $d = 2$ mm
- Real criterion: less than 10% effect when

$$d < \frac{1.12}{\sqrt{p}}\delta$$

  where p is the number of layers (6 in this case).
- Diameter less than 0.67 mm.

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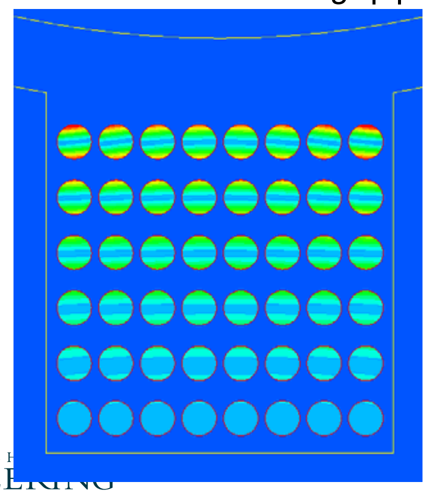
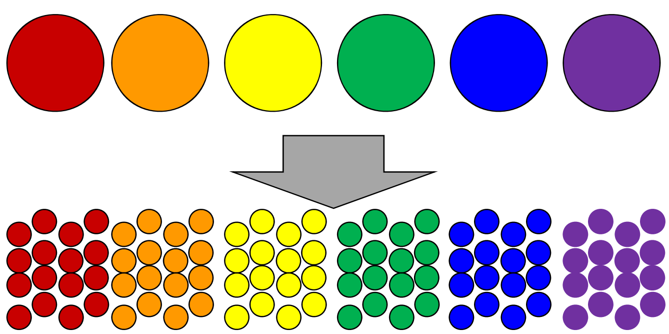


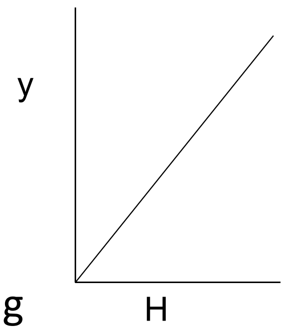
Change from d = 2 mm to d = 0.5 mm

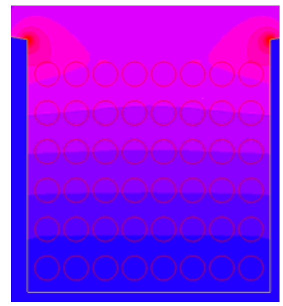


- 16 parallel wires—same dc resistance.
- But now the number of layers has changed—about 24 layers, so the diameter should really be 0.35 mm…
- But layers aren't clearly defined anyway….

Better analysis approach for wire with d < δ, without using *p* (number of layers)

- Loss is due to field impinging on a wire.
- Field strength is linearly increasing with height in slot.
- What matters is average square of field strength.
- Not affected by detailed positioning of wire.





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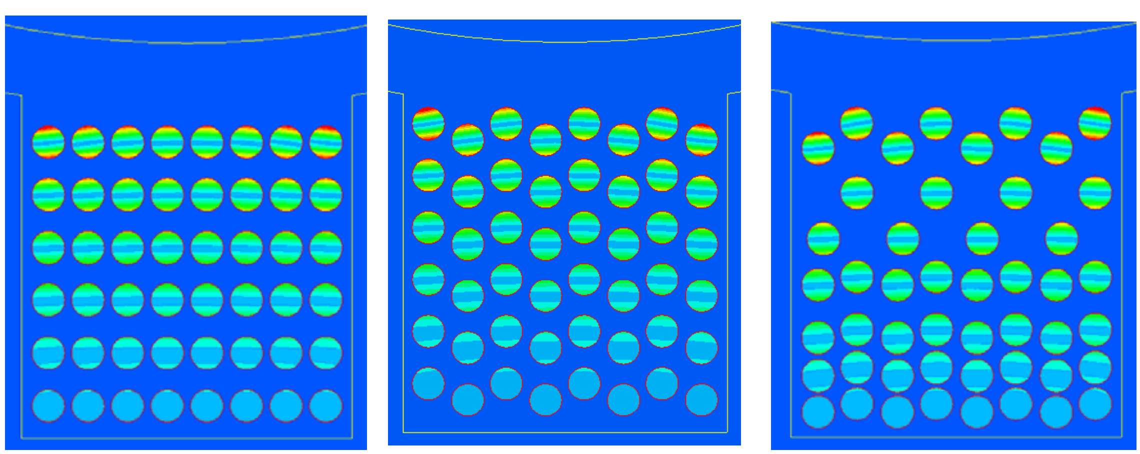
- Not affected by number of parallel strands.

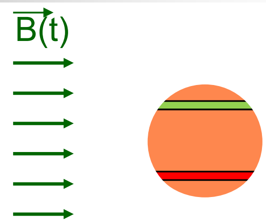
Same loss within 0.5%

- Key parameter is average of $|H|^2$ on the wire, not detailed layer structure.



Eddy-Current Loss in Strand

See page 11 for references



- Example current loop:
- Integrate to get total loss:

$$P(t) = \frac{\pi \cdot \ell \cdot d^4}{64 \cdot \rho_c}\left(\frac{dB}{dt}\right)^2$$

- Assumes *B* is not affected <=> $d < \delta$
- Average eddy-current power loss:

Time average

$$\overline{P(t)} = \frac{\pi \cdot \ell_t \cdot N \cdot d^4}{64 \cdot \rho_c}\left\langle \overline{\left(\frac{dB}{dt}\right)^2} \right\rangle = \frac{\pi \cdot \ell_t \cdot N \cdot d^4}{384 \cdot \rho_c} B_{\max}^2$$

Spatial average

For *B* sinusoidal with *t* linear with position.

One formulation…for 1D field shape

Number of parallel strands per turn

Number of turns per slot

$$\frac{R_{ac}}{R_{dc}} = F_R = 1 + \frac{\pi^2 n^2 N^2 d^6}{192 \cdot \delta^4 b_s^2}$$

Breadth of slot

- Criterion for less than 10% eddy-current loss:

$$d < 1.125 \frac{\delta^{2/3} b_s^{1/3}}{(nN)^{1/3}}$$

- Fixed total turn area, A_t $\quad d < 1.118 \dfrac{\delta^2 b_s}{A_t N}$
- For our example: d < 0.33 mm, 36 strands/turn

References and notes for simple round-wire loss formulas

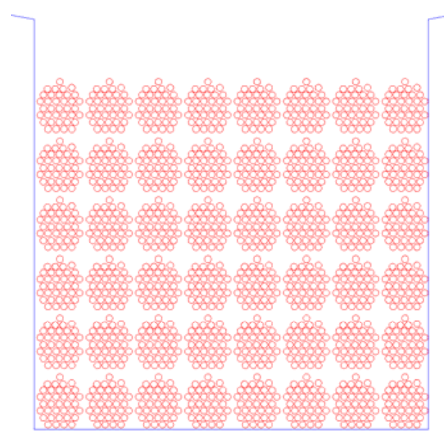
The formulations on the previous pages are only good for wire diameter smaller than about two skin depths. Good designs will use wire that small, except when the winding is optimized primarily for one frequency and you are interested in analyzing loss at a higher frequency.

References

1. E. C. Snelling, *Soft ferrites, properties and applications*, second ed. London U.K.: Butterworths, 1988. *Includes loss formulas equivalent the ones discussed here, although Snelling does not directly show the derivation for the round-wire case. Also discusses optimization extensively.*
2. C.R. Sullivan "Computationally Efficient Winding Loss Calculation with Multiple Windings, Arbitrary Waveforms, and Two- or Three-Dimensional Field Geometry." *IEEE Transactions on Power Electronics* 16(1), January 2001, pp. 142 -150. *Includes a derivation of the formulation written in terms of dB/dt.*
3. C.R. Sullivan. "Optimal Choice for Number of Strands in a Litz-Wire Transformer Winding." *IEEE Transactions on Power Electronics,* 14(2), March 1999, pp. 283-291. *The formula for F_R given here is based on the formulas in this reference, but is re-written in terms of skin depth.*
4. C.R. Sullivan. "Cost-Constrained Selection of Strand Size and Number in a Litz-Wire Transformer Winding." *IEEE Transactions on Power Electronics,* 16(2), March 2001, pp. 281-288. *The optimization in reference 3. leads to expensive designs. This work includes costs considerations and shows how to find Pareto-optimal designs for cost and loss.*

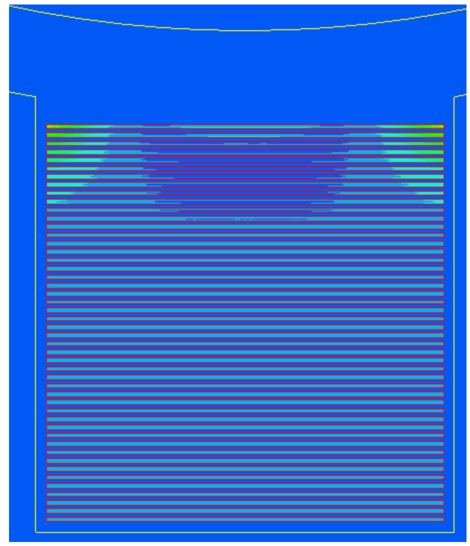
Simulation to test 36-strand wire

- $F_R = 1.104$
  (Eddy-current loss is 10.4% of the resistive loss, vs. 10% target)
- Strand diameter in this case is 22% of skin depth.
- Stranded wire vs. litz wire:
  - Individually insulated strands: always helps, sometime not essential.
  - Litz construction vs. simple twisting: Necessary for skin effect; not important for proximity effect.



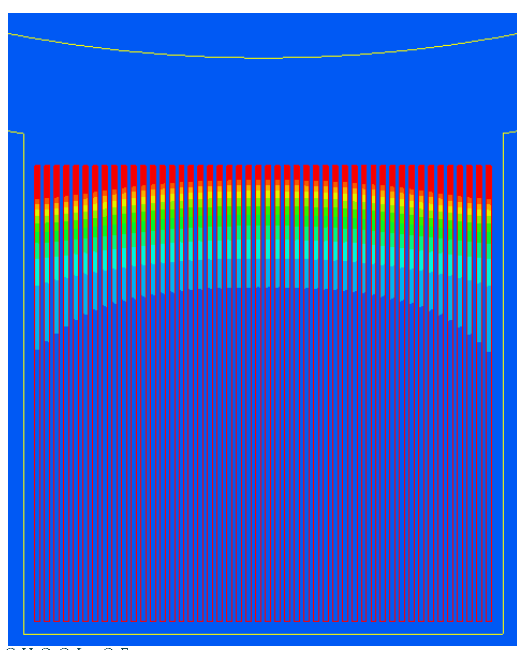
Alternative approach: strip or foil

- $F_R = 1.4$
  - Thickness = 0.22 mm = 0.15δ
  - 1D effect: $F_r = 1.1$
  - Remainder: lateral distribution at the top.

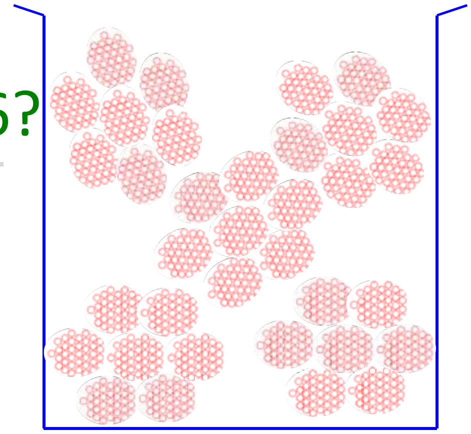


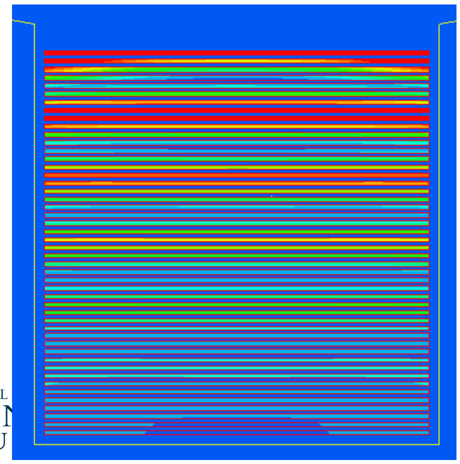
Foil oriented wrong

- $F_R = 9.3$
- Worse than the original wire winding.
- Current flow near high-reluctance region to minimize energy storage.



What if the number of turns is lower, e.g., 5 or 6?

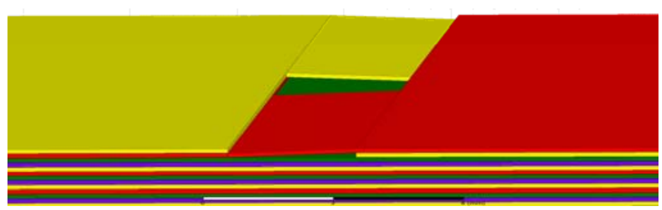




- Stranded or litz wire is straightforward.
  - Poor packing factor.
  - Poor thermal conductivity.
  - Sometimes expensive.
- Achieving current sharing in parallel foil layers is hard.
  - Example: F_R = 19.6: worst yet!

Options to force current sharing in parallel foil layers

- Transposition (interchanging foil layers)
  - Use bent strips, slit foil, or PCB vias.
  - Effective, expensive.



5. J.D. Pollock, W. Lundquist, and C.R. Sullivan “The Design of Barrel-Wound Foil Windings with Multiple Layers Interchanged to Balance Layer Currents,” IEEE Applied Power Electronics Conference, March, 2011.

- Other approaches under development.

Windings with multiple frequencies

References on next page

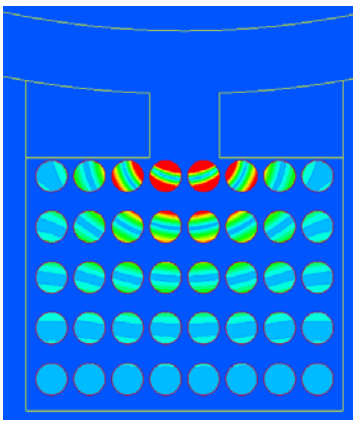
- Optimization for fundamental electrical frequency may result in high losses at switching frequency.
- Modeling:
  - For foil: Dowell's analysis, e.g. as formulated by Spreen (1990).
  - For round or litz wire: Semi-empirical models are better than Dowell or Bessel methods (e.g. Nan, 2004)
- Design: Parallel windings are often good. HF winding can be litz (Schaef, 2012) or foil (Sullivan, ECCE 2013)

References for windings with multiple frequencies

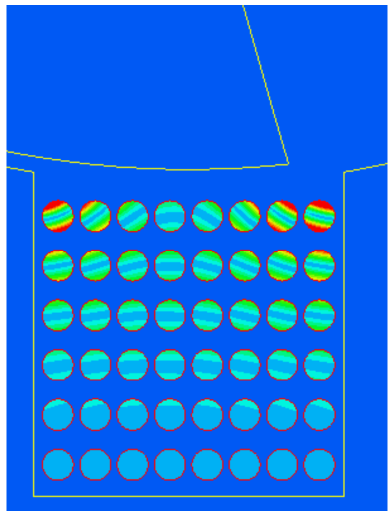
6. Spreen, J.H.; , "Electrical terminal representation of conductor loss in transformers," Power Electronics, IEEE Transactions on , vol.5, no.4, pp.424-429, Oct 1990. doi: 10.1109/63.60685.
7. Xi Nan and C. R. Sullivan, "Simplified High-Accuracy Calculation of Eddy-Current Losses in Round-Wire Windings." IEEE Power Electronics Specialists Conference, June 2004, pp. 873 - 879.
8. Christopher Schaef and C.R. Sullivan, "Inductor Design for Low Loss with Complex Waveforms," IEEE Applied Power Electronics Conference, Feb. 2012.
9. C.R. Sullivan, Hamza Bouayad and Yue Song, "Inductor Design for Low Loss with Dual Foil Windings and Quasi-Distributed Gap" ECCE 2013 (Forthcoming).
10. M.E. Dale and C.R. Sullivan. "Comparison of Single-Layer and Multi-Layer Windings with Physical Constraints or Strong Harmonics." IEEE International Symposium on Industrial Electronics, July 2006.
11. M.E. Dale and C.R. Sullivan "Comparison of Loss in Single-Layer and Multi-Layer Windings with a DC Component." IEEE Industry Applications Society Annual Meeting, Oct. 2006. *The discussion in in terms of a switching frequency plus dc, but it could equally well be a fundamental electrical frequency for a machine plus a switching frequency.*

2D geometries

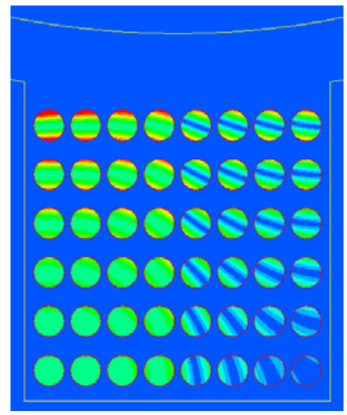
E.g., with wider teeth $F_R = 6.9$ (vs. 4.6 for open slot)



Time varying field shape.



Multiple windings per slot.



Solution for 2D geometries

- Situations of interest include wider teeth, time varying field shapes with rotor saliencies, and multiple windings per slot, as shown on the previous slide.

For all the cases above, the "squared field derivative" (SFD) method works.

- Separates winding design from field simulation.

Time average

$$\overline{P(t)} = \frac{\pi \cdot \ell_t \cdot N \cdot d^4}{64 \cdot \rho_c} \left\langle \overline{\left(\frac{dB}{dt}\right)^2} \right\rangle$$

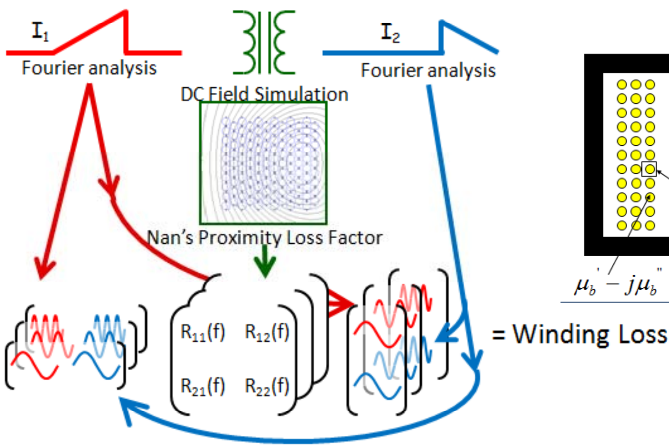
Spatial average

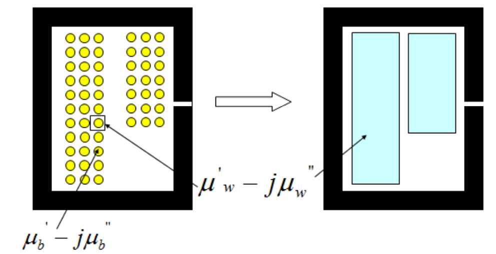
2. C.R. Sullivan "Computationally Efficient Winding Loss Calculation with Multiple Windings, Arbitrary Waveforms, and Two- or Three-Dimensional Field Geometry." *IEEE Transactions on Power Electronics* 16(1), January 2001, pp. 142 -150.

Multiple frequencies and 2D fields

See references on next page.

- Hybridized Nan's method (Zimmanck, 2010)
- Homogenization with complex permeability (Nan 2009, Meeker, 2012)





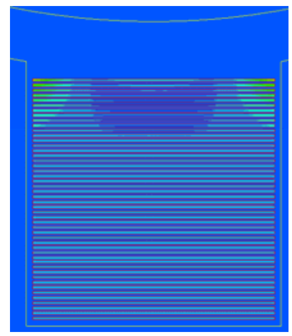
References for windings with multiple frequencies and 2D fields

12. D. R. Zimmanck and C.R. Sullivan, "Efficient Calculation of Winding Loss Resistance Matrices for Magnetic Components," Twelfth IEEE Workshop on Control and Modeling for Power Electronics (COMPEL), June, 2010. *In some cases this is slightly less accurate than the following two, but the FEA computation is dramatically less: rather than using one FEA simulation at each frequency of interest, it uses one dc (static) simulation and can then predict losses for any frequency.*

12. Xi Nan and C. R. Sullivan "An Equivalent Complex Permeability Model for Litz-Wire Windings." *IEEE Transactions on Industry Applications*. 45(2), March-April 2009, pp. 854–860.
13. Meeker, D.C., "An improved continuum skin and proximity effect model for hexagonally packed wires," *J. of Computational and Appl. Mathematics,* 236(18), 2012, pp. 4635–4644.

Summary: High Frequency Winding Loss

- Linear behavior: complete solutions possible (analytical or FEA).
- Well understood (not always).
- To avoid proximity effect, need dimensions << δ
  - Specifically: $d < \frac{1.1}{\sqrt{p}}\delta$
- Options:
  - Foil parallel to field lines.
  - Stranded/litz wire.



Core loss

- Static applications don't include rotation, as in machines.
- Classical eddy-current loss.
  - Linear
  - Can be modeled analytically or using FEA.
  - Increasingly important at higher frequencies; mitigated by thinner laminations.
- Hysteresis and anomalous losses
  - Nonlinear
  - Cannot be predicted from fundamentals—only from measurements of loss.
  - **Resulting challenge: How can results from one set of measurements apply to a different situation?**

Hysteresis and anomalous loss

- Definition: ***hysteresis*** loss is the component of loss that would be predicted assuming the BH loop shape was independent of frequency.
- Definition: ***anomalous*** loss is anything in addition to classical eddy current loss and hysteresis loss.
  - By definition, anomalous loss is rate-dependent.
  - A primary mechanism for anomalous loss in many materials is local eddy currents near moving domain walls.

Physically motivated models: Hysteresis models

- Detailed and accurate hysteresis models include Preisach and Jiles-Atherton.
- Standard methods are only static; do not predict anomalous losses.
- Addition of linear dynamics is sometimes used, but doesn’t capture nonlinearity in anomalous loss.
- **Usefulness:**
  - Prediction of minor-loop behavior.
  - Only useful when anomalous losses are negligible:
    - Frequencies below where anomalous loss is important.
    - Some powder materials with low anomalous loss.
    - Thin-film anisotropic materials with low anomalous loss.

Physically-motivated models: Anomalous loss

- Models based on local eddy-current loss induced by domain wall motion:
  - $P_{anom} \alpha (Bf)^{\gamma}$; $\gamma = 1.5$ (or 2) See core loss reference 1, at end.
  - Better evidence for usefulness in metallic materials than in ferrites.
  - Useful for machine design applications.
  - Can be used to develop models for non-sinusoidal waveforms.

Steinmetz equation

- Originally for one frequency: $P = k\hat{B}^{\beta}$
- Elaborated for frequency dependence: $P = kf^{\alpha}\hat{B}^{\beta}$
- Works amazingly well for
  - Limited frequency range
  - Fixed waveform shape (e.g. sinusoidal)
  - Constant or zero dc bias
- Challenge: how to generalize from sinusoidal measurements to other waveforms.
  - Or from square-wave measurement to other waveforms.

Generalizations of the Steinmetz Equation for nonsinusoidal waveforms.

- MSE (Modified Steinmetz Equation, 1996, 1999). Pioneering work, but with internal inconsistences. (Core loss references 2, 3)
- GSE (Generalized Steinmetz Equation, 2001). Internally consistent but not consistent with measurements. (Core loss reference 4)
- iGSE (improved Generalized Steinmetz Equation 2002). Internally consistent and has been shown to consistently match data reasonably well. (Core loss reference 5)
- Others
  - NSE (2004). Identical to iGSE. (Core loss reference 6)
  - WcSE (2008). Slightly simpler but less accurate. (Core loss reference 9)
  - EGSE, FHM (2009,2009). Don't capture waveform effect. (Core loss reference 11, 10)

iGSE (improved Generalized SE)

(Core loss reference 4)

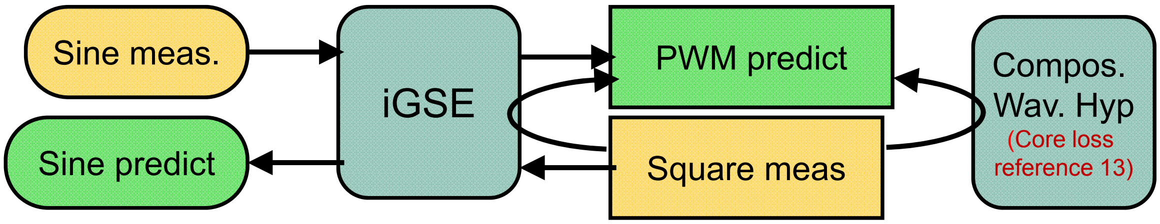
- Based on $\overline{P(t)} = k_i (\Delta B)^w \overline{\left|\frac{dB}{dt}\right|^z}$, plus compatibility with Steinmetz equation for sine waves.
- Result: $\overline{P(t)} = k_i (\Delta B)^{\beta-\alpha} \overline{\left|\frac{dB}{dt}\right|^\alpha}$
- Formula to get ki from sinsoidal data:

$$k_i \cong \frac{k}{2^{\beta+1}\pi^{\alpha-1}\left(0.2761+\frac{1.7061}{\alpha+1.354}\right)}$$

- Formula for PWL waveforms:

$$\overline{P_v} = \frac{k_i(\Delta B)^{\beta-\alpha}}{T}\sum_m \left|\frac{B_{m+1}-B_m}{t_{m+1}-t_m}\right|^\alpha (t_{m+1}-t_m)$$

Measuring with sine waves vs. measuring square-wave voltage?



- Predicting PWM loss with square-wave data: can use iGSE or the "composite waveform hypothesis" (Core loss reference 13). Both give exactly the same results.
- Making predictions with the same class of waveforms is more accurate. Because:
  - Steinmetz parameters are different for different frequencies.
  - Square wave includes harmonics—can span two ranges.

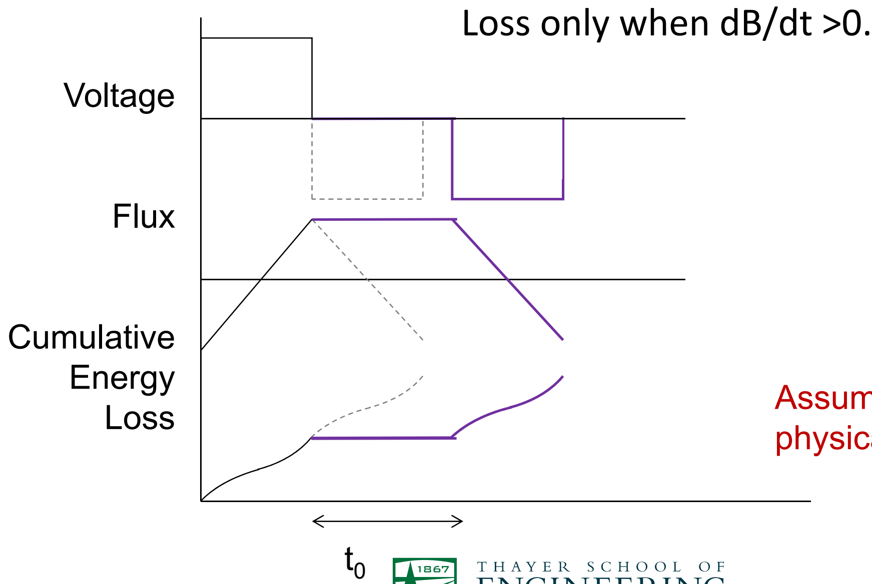
Recent work and frontiers

- Practical application of physically motivated anomalous loss models.
- Dual Natural SE (DNSE). (Van den Bossche, Core loss reference 15,16)
  - Uses iGSE (aka NSE) with the sum of two Steinmetz equations, one for pure hysteresis and one for anomalous losses.
- "Relaxation effect" shows a deviation from iGSE when PWM waveforms apply zero voltage.
  (See J. Muhlethaler IEEE TPE, 2012, and C. Sullivan, APEC 2010)
  (Core loss reference 7 Core loss reference 13)
- DC bias effects. (e.g., core loss reference 8)
- Dynamic model that intrinsically captures loss behavior.

Relaxation effect

(Core loss reference 7, 13)

Assumption: *Energy* loss per cycle doesn't change if waveform pauses.

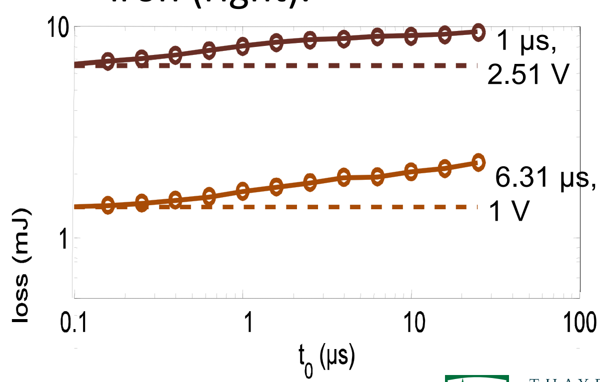


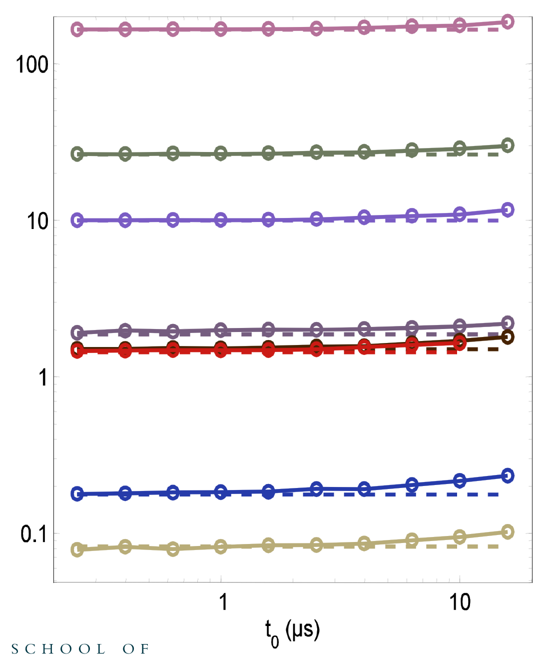
Assumed ***without*** physical basis

Measurements prove assumption wrong

(Core loss reference 7, 13)

- Increase in loss per cycle with increasing off-time (ferrite (below)).
- Not observed in powdered iron (right).





Conclusions

- Winding loss models are ready to use.
  - For low high-frequency loss, stranded/litz or foil parallel to field lines.
  - For dual-frequency applications, dual windings can sometimes work.
  - Challenge: parallel foil layers.
- Core loss is nonlinear and can only be found experimentally.
  - Challenge is generalization.
  - iGSE works well, but is not perfect (dc bias, relaxation…)
  - Rotation isn't considered in iGSE.

Core loss References (winding loss references are listed with the content)

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3. J. Reinert, A. Brockmeyer, and R.W. De Doncker, "Calculation of losses in ferro- and ferrimagnetic materials based on the modified Steinmetz equation", Annual Meeting of the IEEE Industry Applications Society, 1999.
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16. A.P. Van den Bossche, V.C. Valchev, D.M. Van de Sype, and L.P. Vandenbossche, "Ferrite losses of cores with square wave voltage and dc bias ," J. Appl. Phys. 99, 08M908 (2006), DOI:10.1063/1.2173955