

High-Frequency Passive Components: a critical challenge for power electronics

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Electronics Research Group



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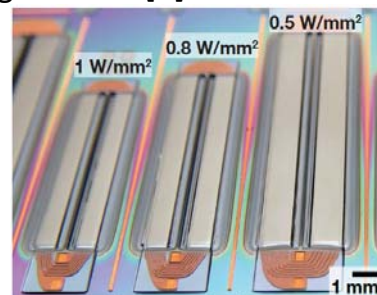
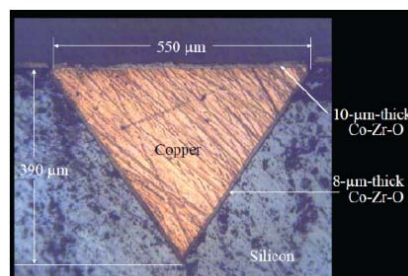
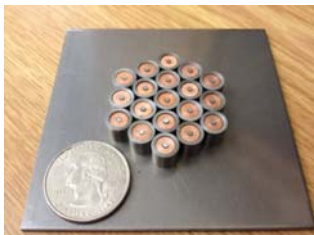
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Power Electronics Research at Dartmouth: 2 groups



- Prof. Jason Stauth: Power integrated circuits.
 - Resonant switched capacitor integrated converters.
 - Applications in PV, battery systems, RF communications, power delivery for digital systems.
- Prof. Charles Sullivan: ~~Magnetics, circuits and systems~~
 - Modeling and optimization of “macro” magnetics: 50 W to 250 kW.
 - Fabrication, materials, design and modeling of microfabricated magnetics: 1 W to 25 W, on-chip or co-packaged. Ref [1]

Today



Magnetics in power electronics



- Increasingly critical bottleneck
- Responsible for much of the
 - Size (volume and weight)
 - Power loss
 - Cost
 - Difficulty in design (long development cycles)



Solantro 350 W PV microinverter:
Miniaturized control chips are great but passives are still huge.



Two goals for magnetics research



- Models:
 - Accurate, capturing effect that are usually ignored.
 - Fast, for use in optimization.
 - Simple and easy, for engineers who usually don't bother.
- Innovative designs and technologies for higher performance.
 - Identify limitations of present technology and overcome them.
 - Start from fundamental goals and explore ways to accomplish them.

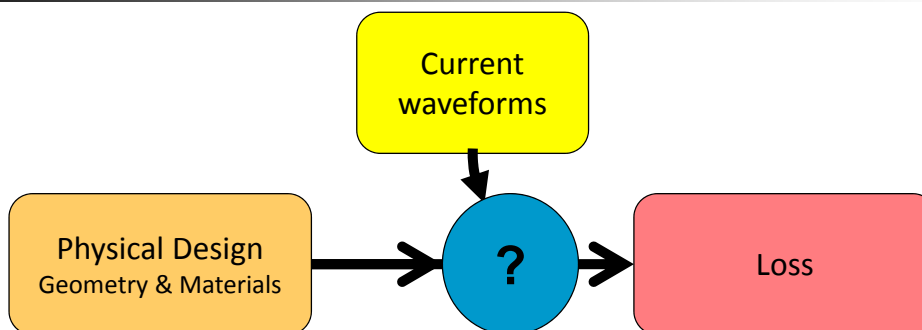


Winding models vs. Core models



- Linear, well known material properties.
- Behavior is a solution to Maxwell's equations.
- Numerical, analytical, or mixed solutions.
- Often complex geometries
- Nonlinear material properties, known only through measurements.
- Models are behavioral, based on measurements.
 - Physics-based micromagnetic models exist, but can't address ferrite loss yet.
- Usually simple geometries.

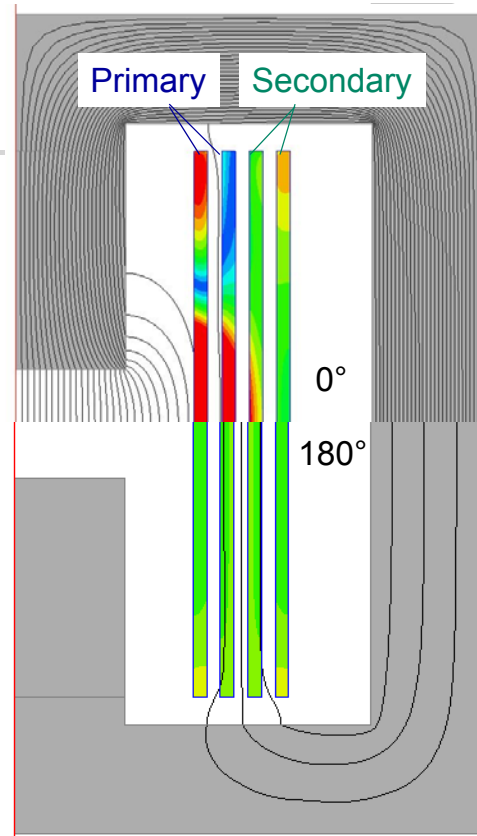
High-frequency winding loss models



- Winding ac resistances?

Loss calculated from currents

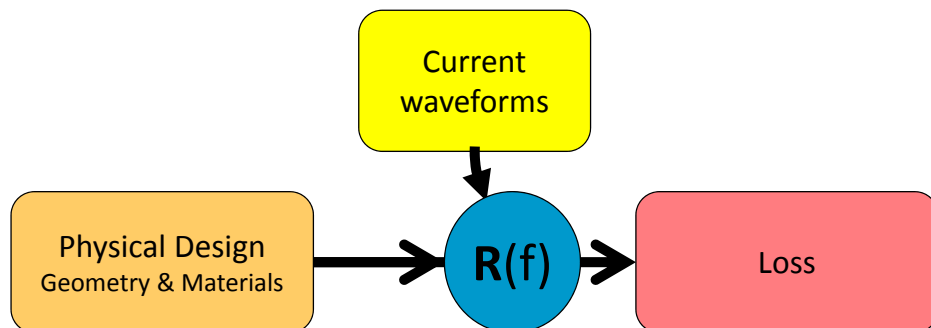
- Conventional, incorrect, model for transformer winding loss (assume sine waves for now).
 - $P_{\text{winding}} = I_1^2 R_1 + I_2^2 R_2$
 - Problem: Loss varies drastically depending on relative phase/polarity.
 - Factor of 4 error in this case.
- Correct model options:
 - R_1 and R_2 that are only for specific phase relationship.
 - **Resistance matrix.**



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Winding models

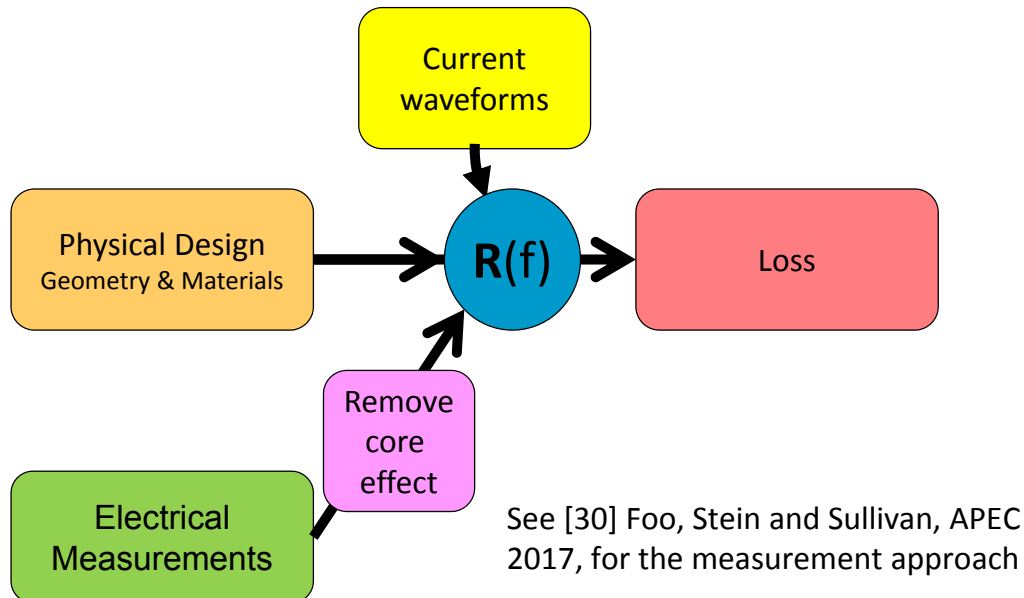


- ~~Winding ac resistances?~~
 - Frequency-dependent resistance matrix $\mathbf{R}(f)$.
 - Captures interactions between windings.
- Ref:[32, 2, 27]

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Winding models

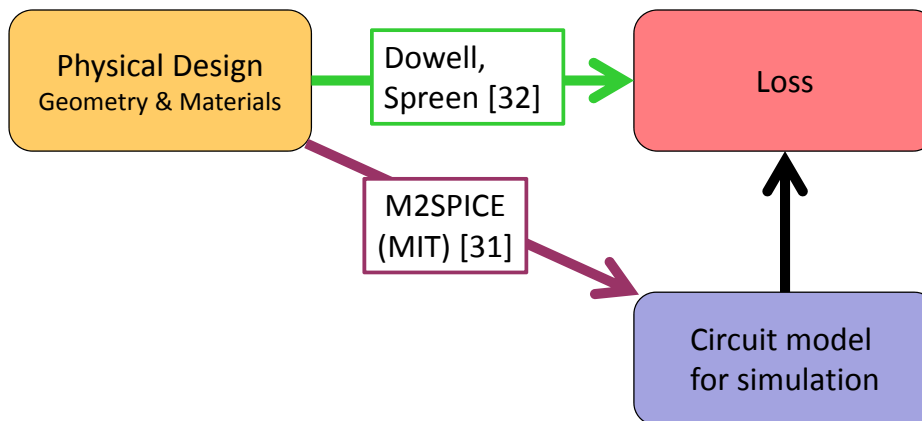


Predictions from physical structure

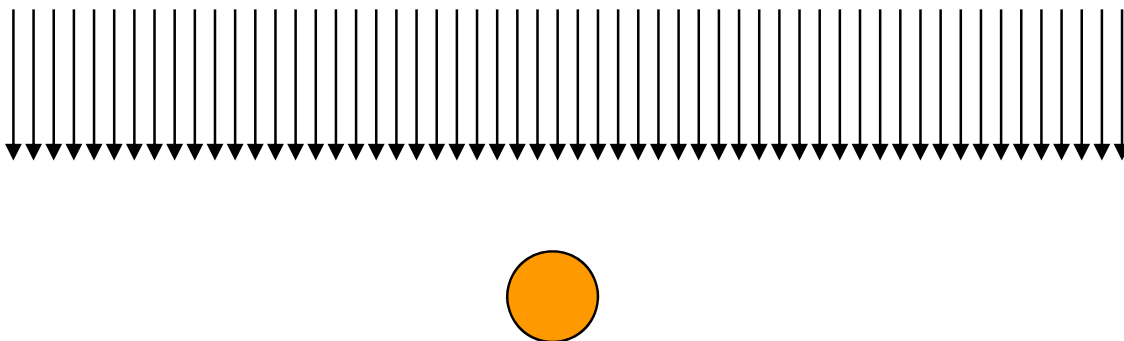


	1-D fields	2-D or 3-D fields
Rectangular conductors (e.g. foil and PCB)	Analytical 	Numerical (Finite Element, PEEC, etc.)
Round-wire conductors (including litz): State of the art before work at G2Elab.	Simulation-tuned physical model 	Simulation-tuned physical model + dc field simulation

Winding models: 1D, rectangular conductors



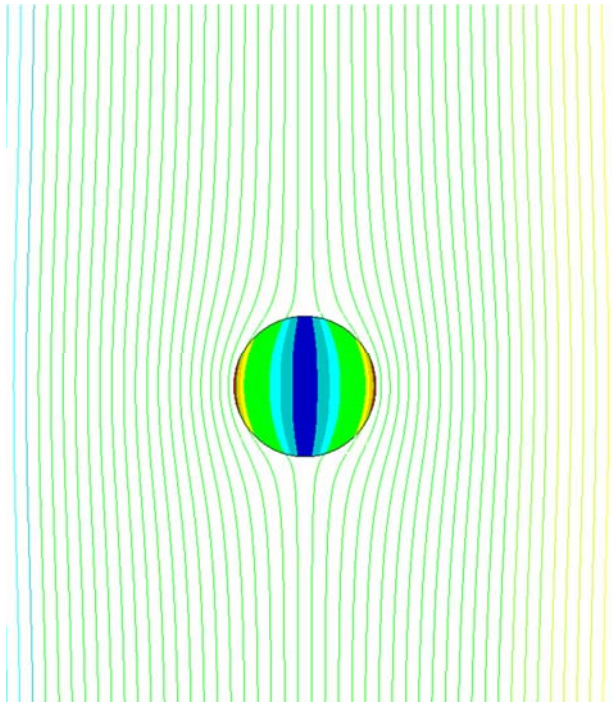
Round conductor: Textbook problem



- Cylinder subjected to uniform field
- Dowell's model is a crude approximation.



Textbook solution

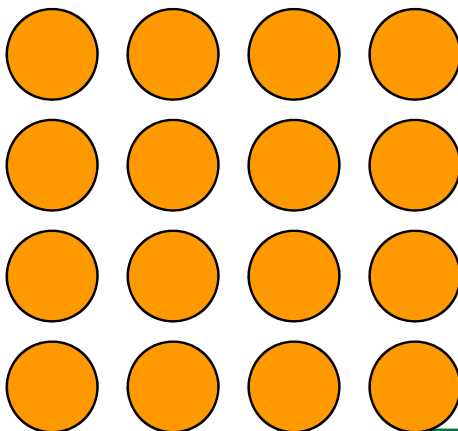
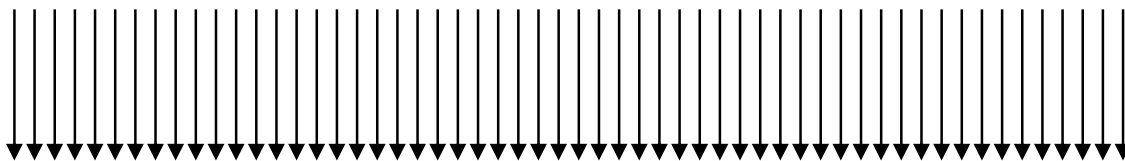


- Exact solution, described by Bessel functions.
- Use for winding loss analysis pioneered by Ferreira.

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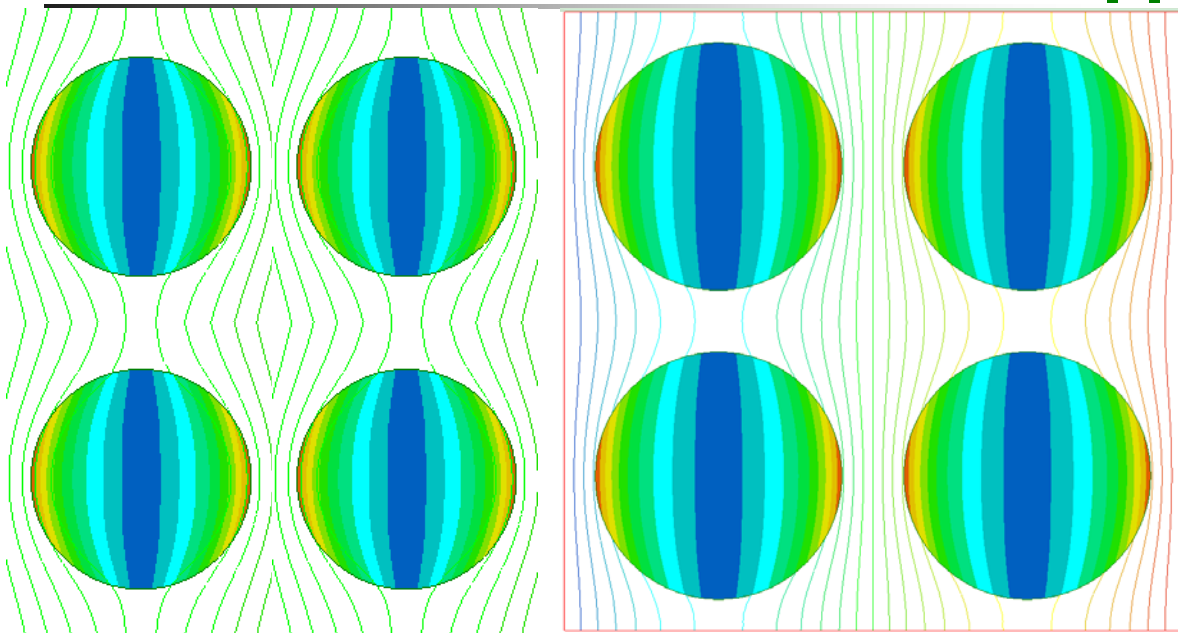
Actual problem



- *Array of* cylinders subjected to uniform field
- Several solution approaches ...
- But first, does it matter?



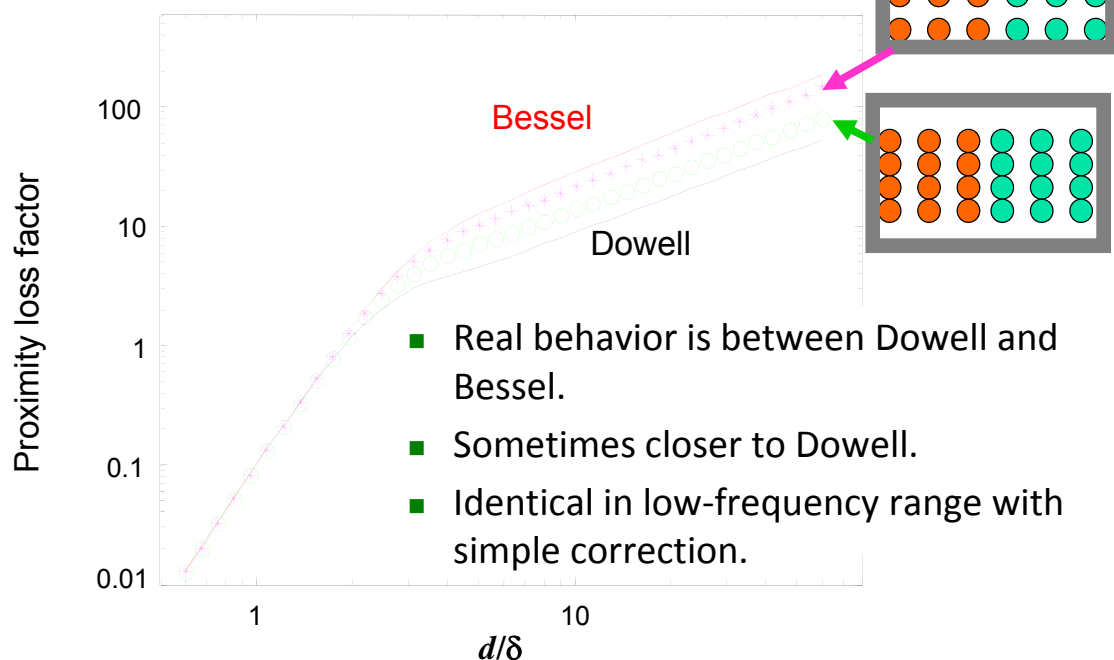
Using the Bessel solution for the real problem



Not a valid solution!

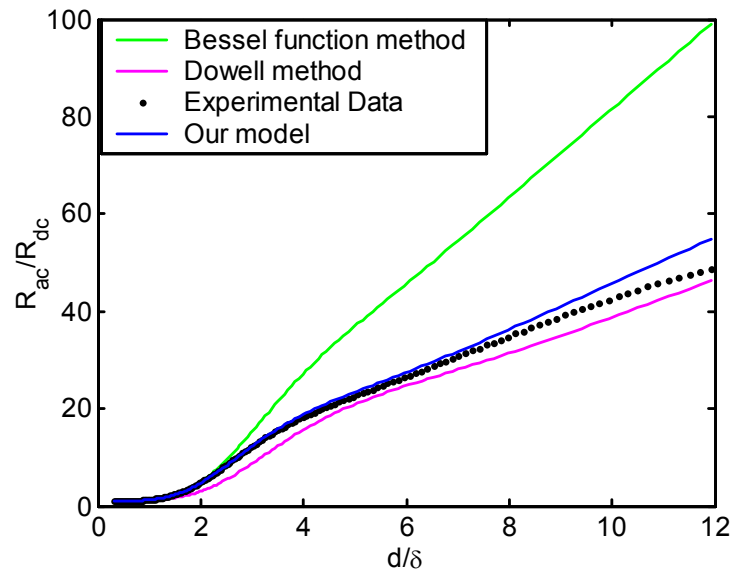
Real Solution (FEA)

Simulation Results



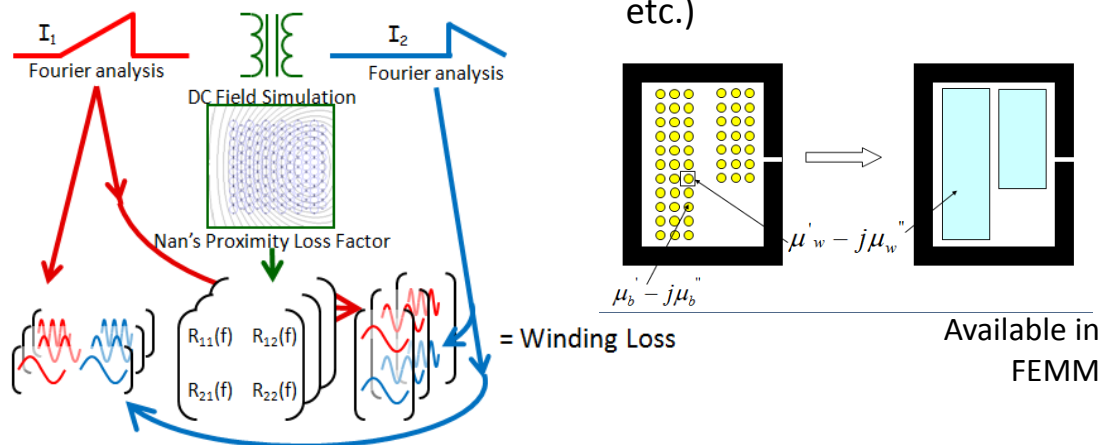
Xi Nan's model [ref 26]

- Weighted average of Dowell-like and Bessel-like behavior: "Simulation tuned physical model"
- Fits experimental results better than Dowell or Bessel.
- Can be applied to 2D or 3D field configurations ...

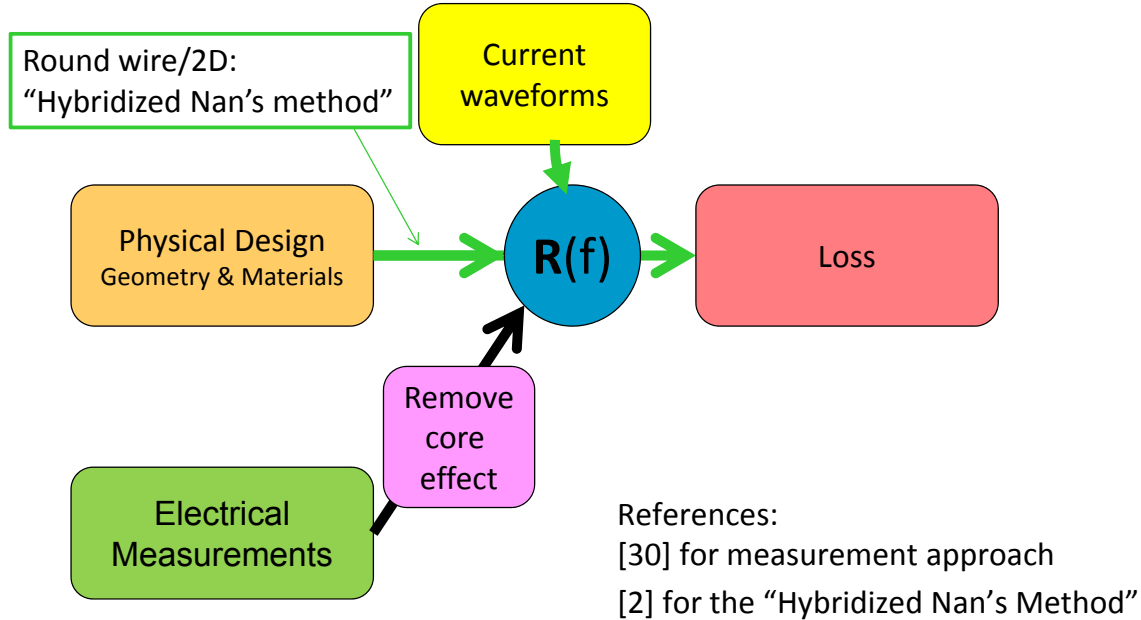


Full winding loss model: 2-D, full frequency range, multi-winding interactions

- Hybridized Nan's method ([2] Zimmanck, 2010)
- Homogenization with complex permeability (Nan 2009, Meeker, 2012 [28], etc.)



Winding models

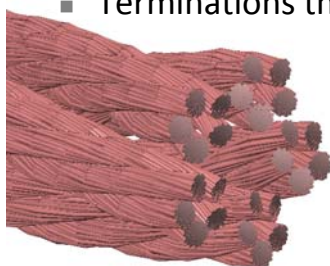


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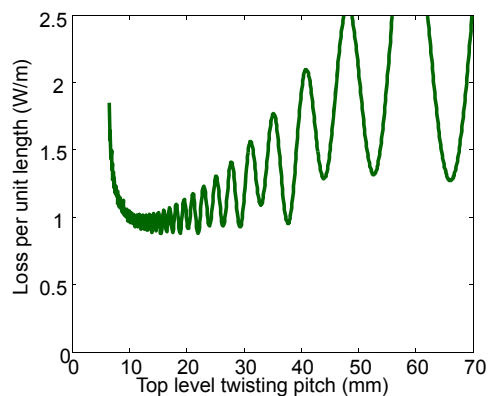
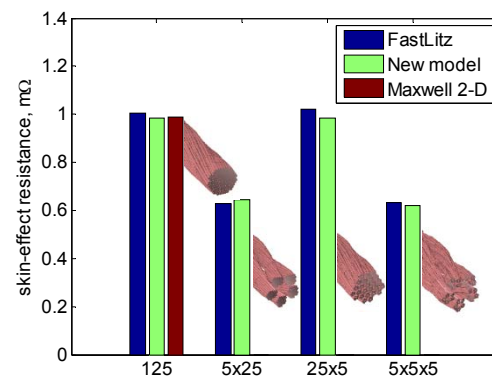
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Advanced litz wire models including construction details

- Important for large number of strands and/or small number of turns.
- Our recent research results:
 - Basic guidelines [10]
 - Detailed model [11]
- Research needs:
 - Optimization, verification and economics.
 - Terminations that preserve litz behavior.



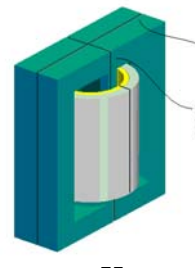
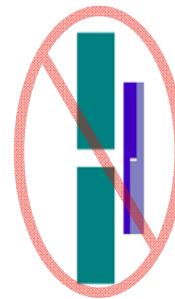
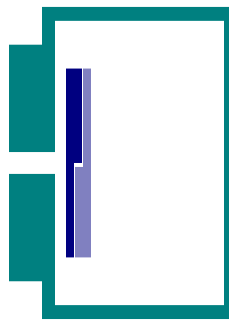
1050 strands of AWG 44,
constructed as 5x5x42



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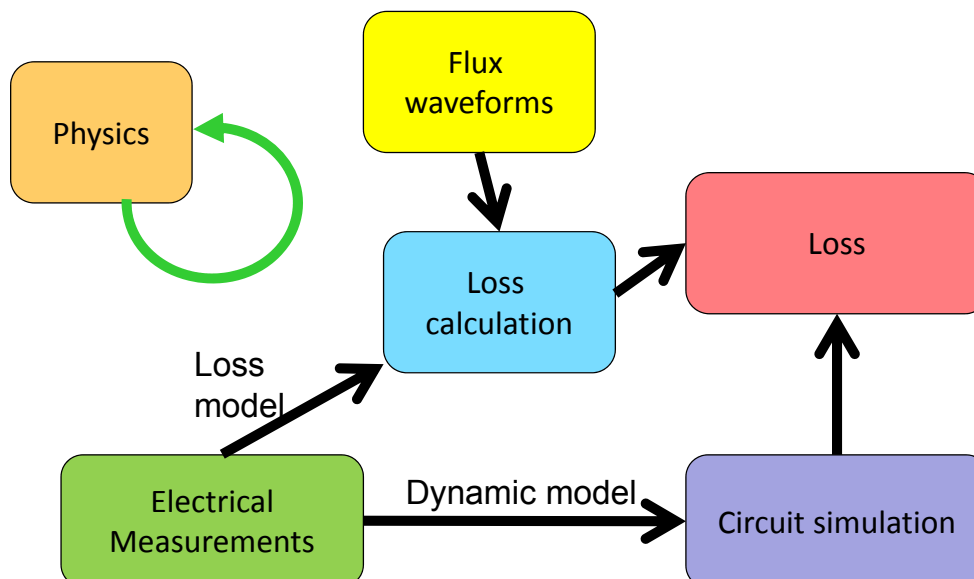
1D, 2D and 3D modeling approaches

- 1D: can use analytical models.
 - For Xfrmers and good (quasi-) distributed gap Ls.
 - Dowell isn't precise but we know how to do better.
- 2D: Fast, easy, low-cost simulations.
 - Naïve sections for E-cores can be misleading.
 - Mimic return path for to reduce error 5X [Ref 25]
- 3D: Use for verification, not design.



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Core models



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Core Loss Calculation Models

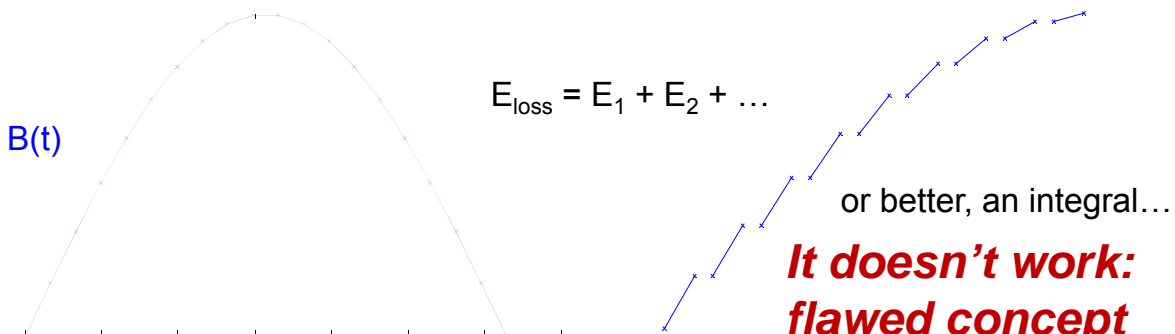


- Steinmetz equation:
 - Sinusoidal waveforms only
- Various types of modified/generalized/etc. Steinmetz equations.
 - Extend to non-sinusoidal waveforms.
 - Most common:
improved Generalized Steinmetz Equation (iGSE) [4]
- Loss Map/Composite Waveform Method [5]

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



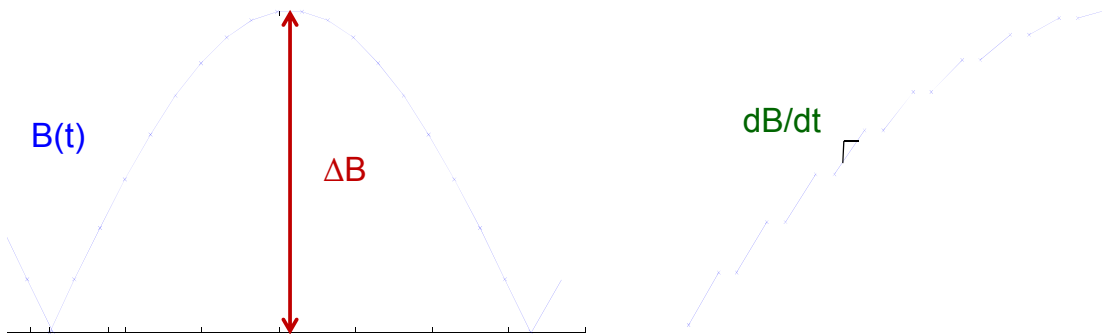
- Initial hope in GSE model: instantaneous loss depends on B and dB/dt: $p(t) = p(B(t), dB/dt)$
 - If this worked, you could add up loss for incremental time segments:



Improvement that enabled iGSE [4]



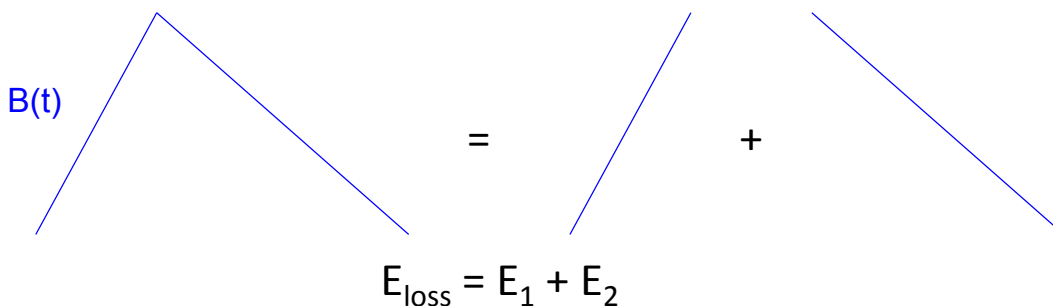
- Loss depends on segment dB/dt and on **overall** ΔB
- Still $E_{\text{loss}} = E_1 + E_2 + \dots$, but E_1 depends on a global parameter as well as a local parameter.



Composite waveform method [4]



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



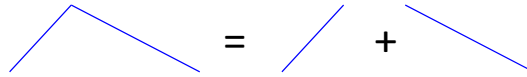
- Unlike the GSE, this works pretty well in simple cases:
 - Waveforms where ΔB is the same for the segment and the whole waveform!
 - It reduces to the same assumptions as the iGSE.



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 [4].
- For waveforms with minor loops, separate loops before calculating loss (see iGSE paper [4]).



Loss models for each segment



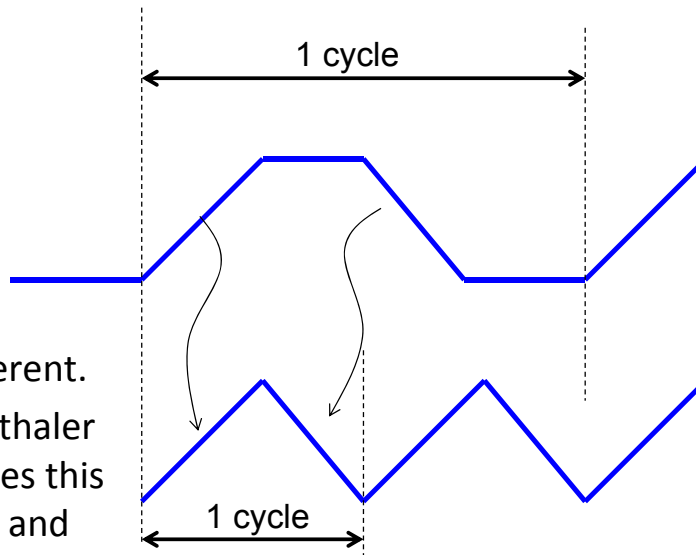
- iGSE derives them from a Steinmetz model
 - Limitation: Steinmetz model holds over a limited frequency range.
- Loss map model uses square-wave data directly for a wide frequency range.
 - Clearly better if you have the data.
 - Can also map with different dc bias levels.
- Sobhi Barg ([29] Trans. 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 (Jonas Mühlethaler and J. Kolar) captures this but is cumbersome and requires extensive data.



Modeling Conclusions



- Winding loss:
 - Complex but feasible to model accurately.
 - For 2 or more windings, need resistance **matrix**.
 - 1D rectangular conductors: analytical solutions.
 - 2D rectangular conductors: numerical simulations.
 - 1D or 2D round wire: Simulation-tuned physical models are better than Dowell or Bessel.
- Core loss
 - Nonlinear and can only be found experimentally.
 - Open questions on data needed and models.



Design



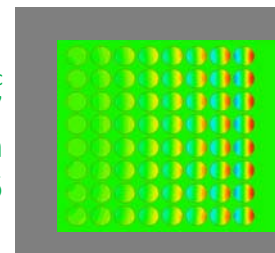
- Models (often) predict poor performance
- What can we do better?
 - Optimization and design innovation for kHz frequencies.
 - MHz frequency challenges and solutions.
 - Reconsideration of passive components.

High-frequency winding design



- Most critical is proximity effect: interaction of field and conductors.
- Not just diameter < skin depth:
need $d \ll \delta$ in a multilayer winding.
- How much improvement is possible
with many thin layers vs. a single layer?

$$\begin{aligned} R_{ac}/R_{dc} \\ &= 27.7 \\ &\text{with} \\ &d = 2\delta \end{aligned}$$



- With a number of layers, p , can improve by $1/\sqrt{p}$
- With a minimum thickness, t_{min} , can improve by $\frac{2t_{min}}{3\delta}$
- For 10X improvement: 100 layers, $t \approx \delta/7$ Ref:[6,7,8]
- **Need right combination—optimization is essential.**

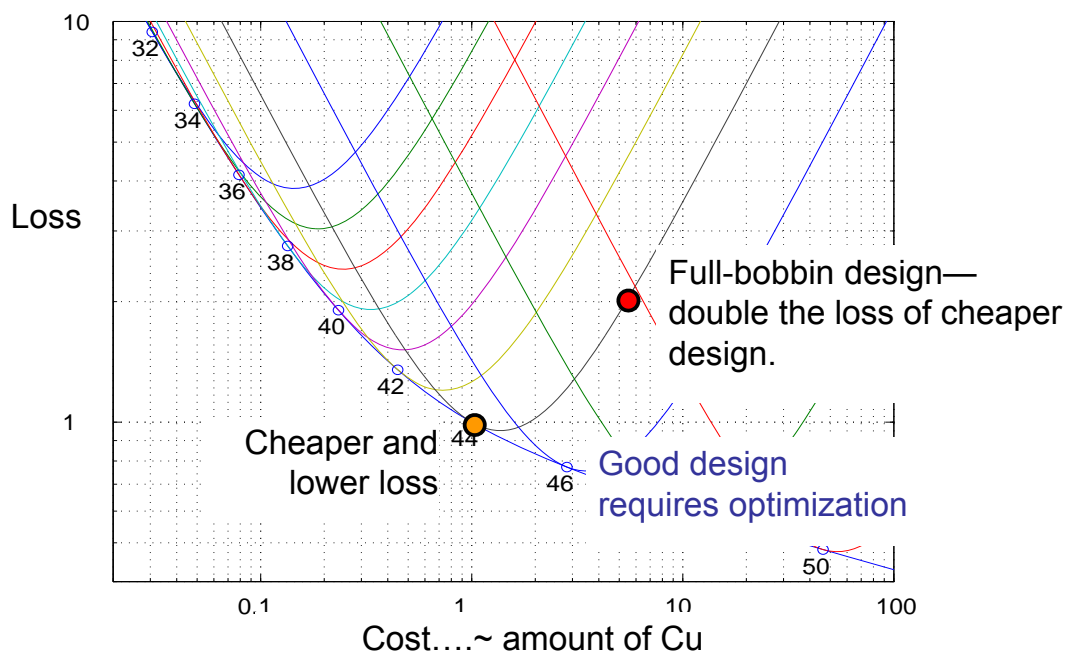
Litz wire

- Strands $d \ll \delta$.
- Invention: 1888, Sebastian de Ferranti.
- Analysis 1917 Howe; 1926 Butterworth.
- Conventional design options:
 - Papers with lots of complex math.
 - Catalog guidelines ... but these can lead to **higher loss than with solid wire at much higher cost.**



Image: Noah Technologies

Litz-wire design options



Litz wire

- Strands $d \ll \delta$.
- Invention: 1888, Sebastian de Ferranti.
- Analysis 1917 Howe; 1926 Butterworth.
- Conventional design options:
 - Papers with lots of complex math.
 - Catalog guidelines ... but these can lead to **higher loss than with solid wire at much higher cost.**
- One solution: single-formula design.

[Ref 10], <http://bit.do/simplitz>

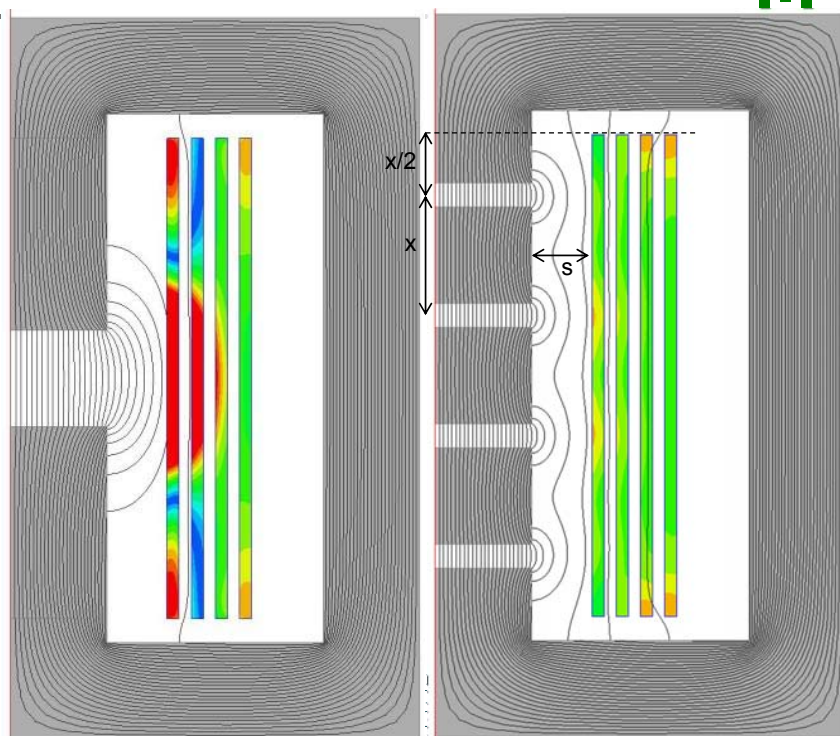
$$n_e = k \frac{\delta^2 b}{N_s}$$

Image: Noah Technologies



Inductors

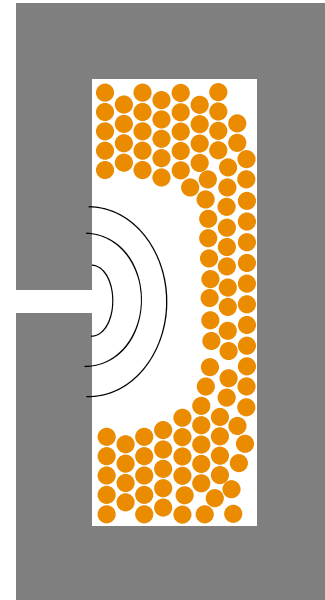
- Fringing field near gaps complicate design.
- Options to change:
 - Winding shape.
 - Gap configuration [Ref 15]



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 [Ref 16].



Costs: Cu vs. Al (as of 8 March 2016)



- Mass:
\$5.00/kg vs. \$1.6/kg (wrong metric)
- Volume basis:
4.42 ¢/cm³ vs. 0.43 ¢/cm³ 10X
- Resistance basis:
 $7.67 \frac{\$ \mu\Omega}{\text{m}^2}$ vs. $1.22 \frac{\$ \mu\Omega}{\text{m}^2}$ 7.3X
- >7X more cost effective ... dc or low frequency.
- What about high frequency?
 - Experiments and analysis show that the performance gap between Al and Cu is smaller at high frequency!

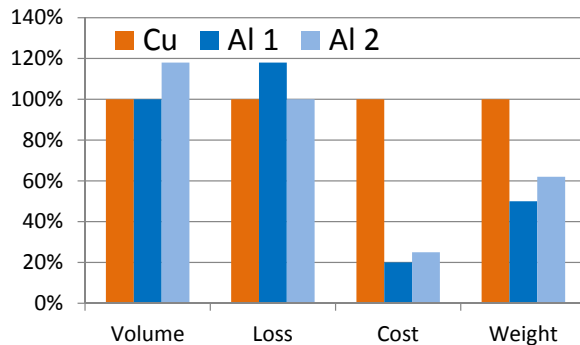


Real comparison of Al and Cu



■ Fair comparison of good designs: Compare

- a design optimized to use Al well, vs.
- a design optimized to use Cu well



Result: [Ref 22]

where to use Al:

- Most situations!

Where to use Cu:

- Where compact size is more important than efficiency, cost, temperature or weight.
- If termination cost difference exceeds wire cost difference.



Miniaturization with MHz frequencies?



■ We have good materials and design methods for 20 kHz to 300 kHz .

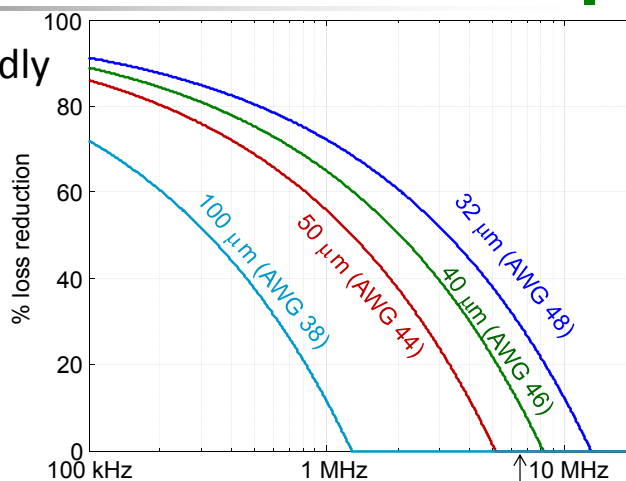
■ New semiconductors emerging

- GaN and SiC power devices: now commercially available, > 10X switching speed vs. Si.
- Theoretically allows smaller, more efficient magnetics.
- But can this be realized in practice?
 - Windings?
 - Core materials?



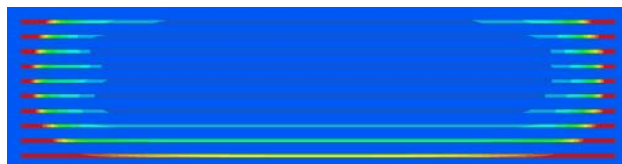
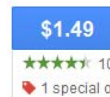
Windings at MHz frequencies ... Litz?

- Litz benefits drop off rapidly in the MHz range [36]
 - Barely better than a solid-wire winding.
- Huge room for improvement in theory:
 - A single-layer winding only has current in one skin depth: At 10 MHz, 21 μm .
 - 0.2% of a 1 cm winding window (0.23% with litz).
→ 400X improvement theoretically available.



Foil: < 20 μm at low cost

- Easy to get thickness \ll skin depth.
 - Freestanding foil down to $\sim 6 \mu\text{m}$.
 - On plastic-film substrates for ease of handling from 35 μm to $\ll 1 \mu\text{m}$.
- Thin layers have high dc resistance—need many in parallel.
- Challenges:
 - Achieving uniform current density—laterally and among layers.
 - High capacitance between layers.
 - Terminations

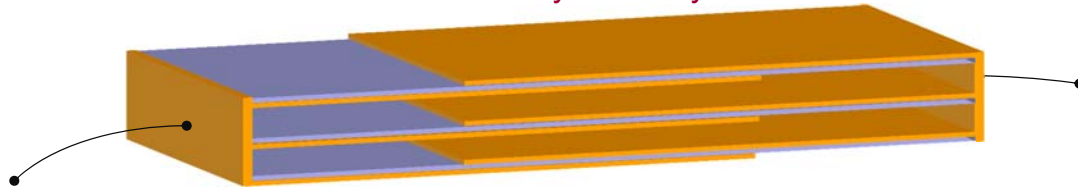


One concept for MHz foil windings: capacitive ballasting

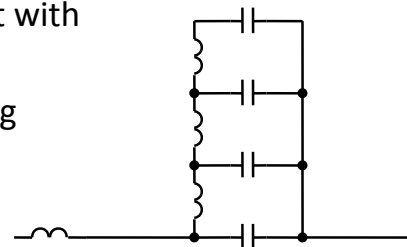


- Overlapping insulated layers create series capacitance for each layer.

Cartoon: real structures have many more layers



- Capacitive ballasting forces equal current sharing.
- Can create integrated LC structure, a concept with a long history.
- In addition to integration, solves MHz winding loss challenges.



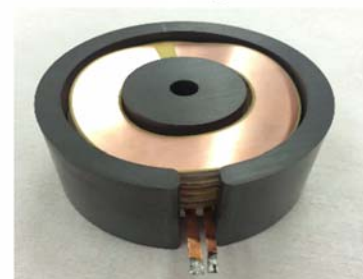
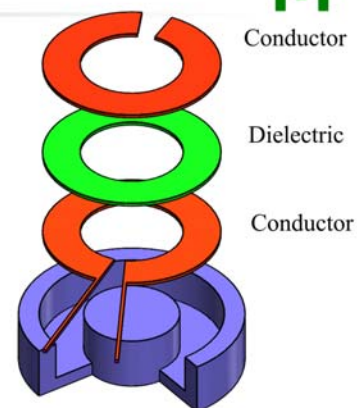
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Resonant structure for wireless power [34]



- Many stacked layers with no vias and no terminations.
- Current sharing between many thin layers enforced by same capacitance used for resonance.



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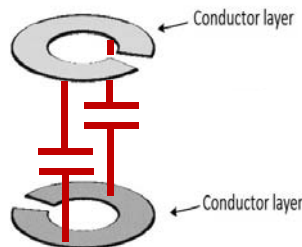
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Operation principle – single section

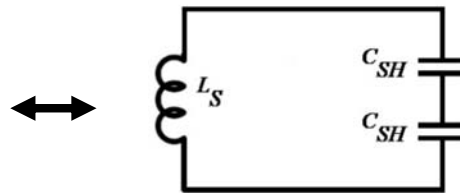


- Each section:

Side view



Equivalent circuit model



- Inductive current loop
- Capacitive connection between foil layers through dielectric



Operation principle – many sections

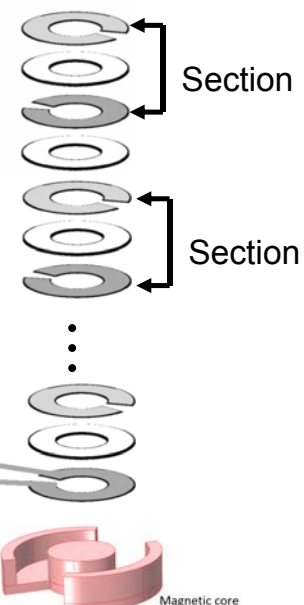
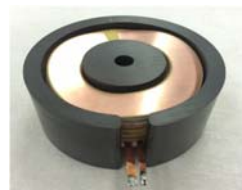


- Strong mutual coupling between all layers.

- Each section capacitance is coupled to form a parallel LC resonator.
- Coupled section capacitance forces equal current sharing in each layer.
- Integrated capacitance eliminates high current terminations.

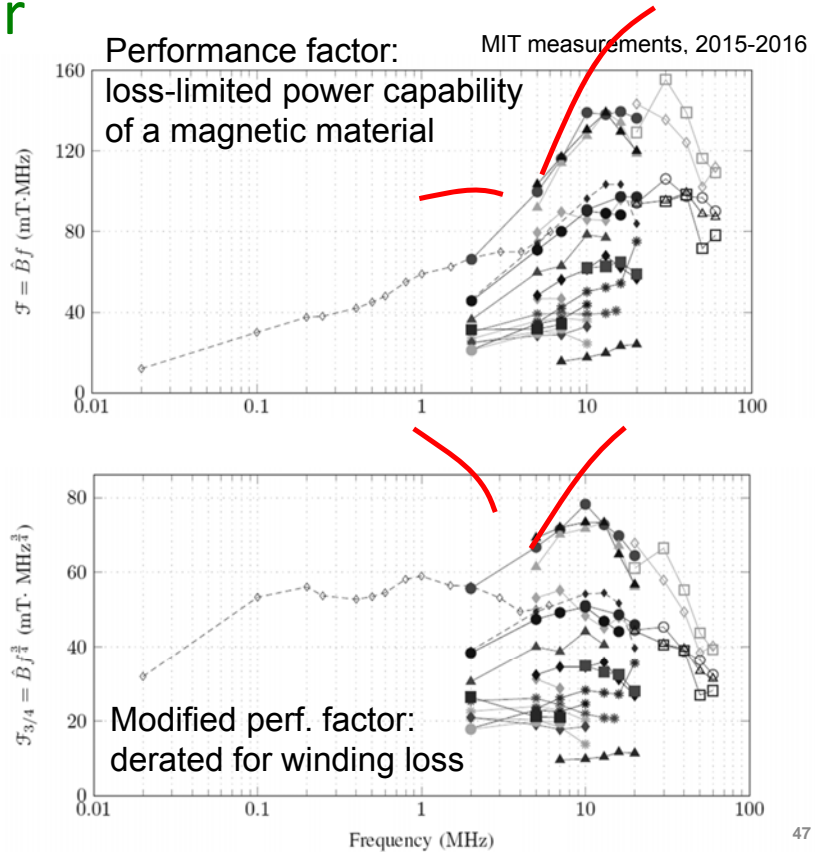
- Experimental $Q = 1180$ with 66 mm diameter.

- > 6X improvement over state of the art.
- Improves range and efficiency of WPT (improves from ~50% to ~90% at $d = D$)



Materials for MHz range

- MnZn and NiZn ferrites for MHz power.
- Significant improvements in last 1-2 years.
- More in development.
 - Thin-film materials prove this is possible.
- Winding approaches that overcome skin and proximity effect allow using top graph.



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Measurements and performance factor comparisons ...AJ Hanson, et al, IEEE Trans. on Pow. Electr. 31 (11), 2016

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Reconsideration of passive components [35]



- Start from fundamental function of passives and consider possible technologies.
 - Identify alternatives, and/or
 - Confirm value of standard approaches.
- These functions are:
 - Energy storage
 - Transformation (voltage/current ratio)
 - Isolation

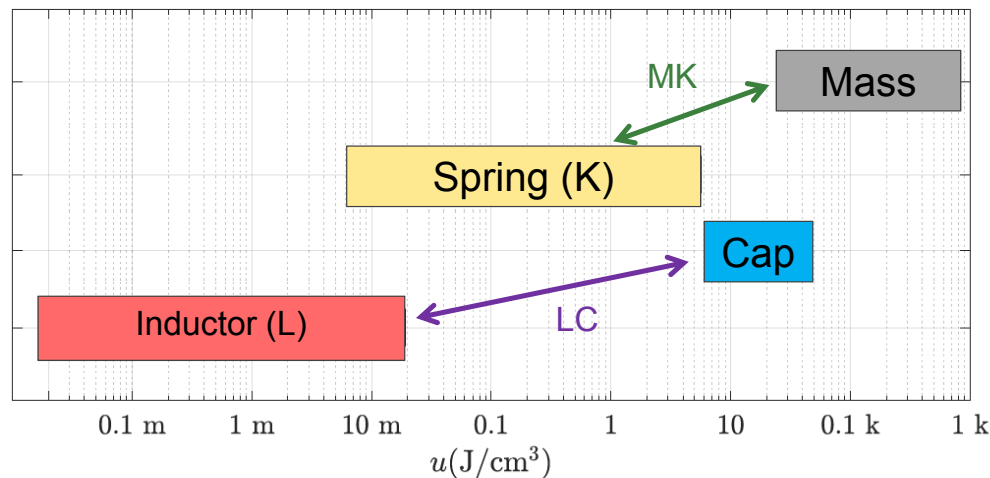


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Passive functions

- Energy storage
 - Magnetic (inductor)
 - Electrostatic (capacitor)
 - Kinetic energy (moving mass)
 - Elastic energy (spring)
 - Others considered but rejected (e.g., pneumatic).
- Transformation (voltage/current ratio)
- Isolation

Energy storage density limits



- Often want resonant pairs: LC or MK
- MK looks attractive, but requires transduction.
 - Electromagnetic: limitations similar to L.
 - Piezoelectric: candidate for further exploration.

High-level analysis of potential

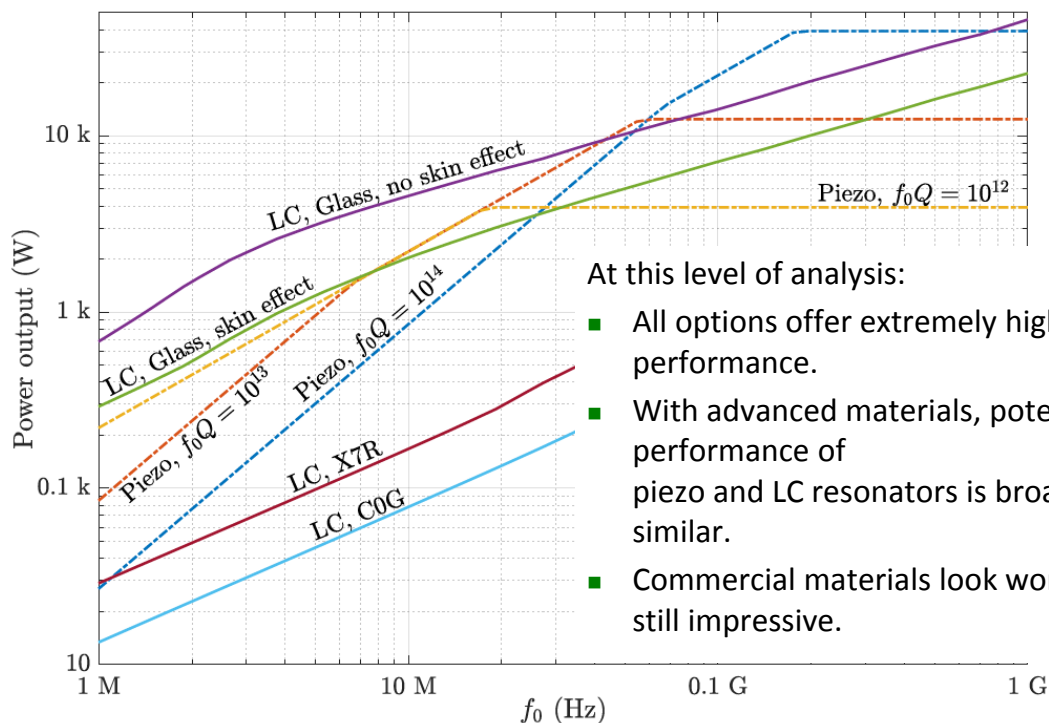


- Optimistic assumptions to examine future potential.
- Resonant switched capacitor (ReSC) circuit (aka switched tank converter, STC)
 - Limited but expanding application scope.
- Performance limited by
 - Dissipation and temperature rise.
 - Mechanical and electrical breakdown.

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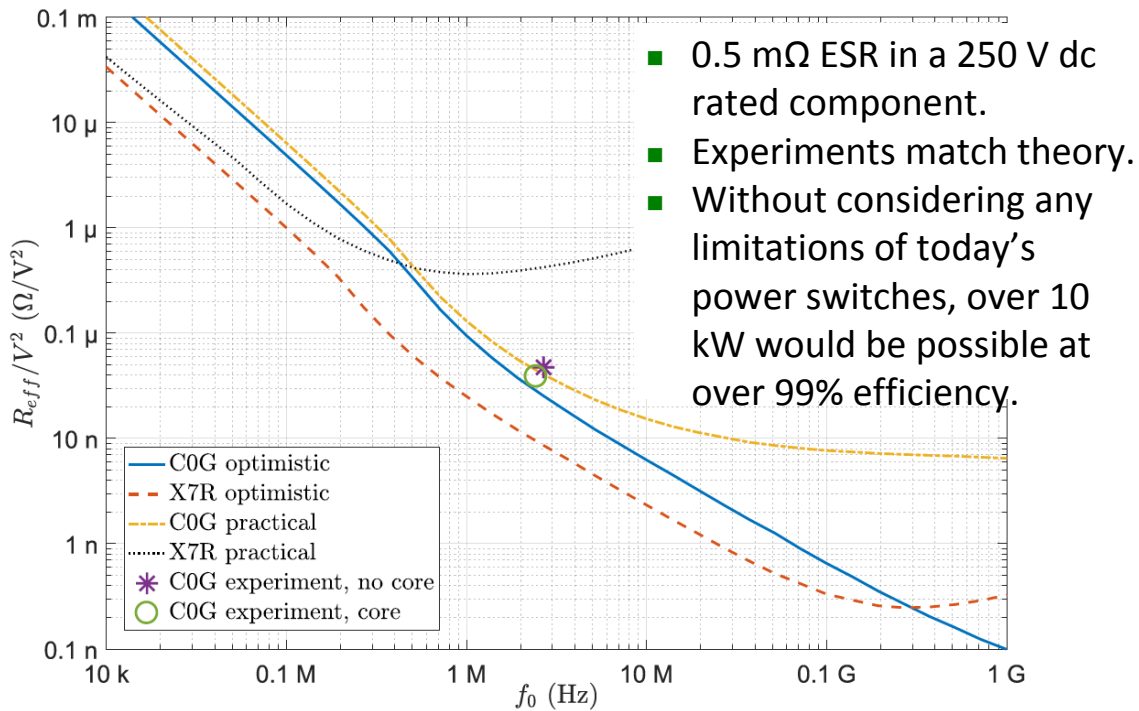


Approximate capability in 1 mm³



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Experimental results in $\sim 1 \text{ cm}^3$



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Conclusions from Fundamental Examination of Passives



- Piezo resonators: excellent potential, but much work needed to reach full capability.
- LC resonant structures: easier technology, experiments demonstrate good performance already.
- Scaling of piezo to small sizes is excellent whereas magnetics performance degrades.





Conclusions on Magnetics

- Proximity effect is the primary winding design consideration.
- Established winding loss reduction techniques include litz wire, interleaving, distributed gaps, quasi-distributed gaps, shaped windings, and parallel windings. Few designs use these to their maximum potential.
- Full models of twisting effects in litz are now available.
- Aluminum wire can achieve lower loss than copper wire in cost-limited designs. This is an under-utilized opportunity.
- For MHz frequencies, litz strands are too big. Ways of using thin foil effectively are under development, e.g. resonant designs, including WPT.
- Winding loss analysis methods are available if not always applied well; core loss modeling state of the art is less solid and new models are needed.
- New core materials are valuable if they have low enough loss to offer competitive performance factor at any frequency in the kHz or MHz range.

Description of key references

Key references in high-frequency power magnetics with an emphasis on publications from our group and a focus on discrete components rather than chip-scale microfabricated components; for our perspective on the latter see [1].

For windings, Zimmanck's method can efficiently generate frequency dependent winding loss matrices for any geometry, 1D, 2D, or 3D, and use them to predict loss for different nonsinusoidal waveforms in any number of [2]. This method applies very generally, including to coupled inductors, wireless power transfer coils, etc. References cited in [2] provide more detailed background, including [26,27]. See also [28]. A systematic approach to generating full models for loss and simulation for 1D geometry is provided in [3]. To use 2D models effectively for 3D geometries such as E-cores, the strategy in [25] can reduce the error involved by a factor of 5.

Although the Dowell model is reasonably accurate, see the appendix of [9] for a simple correction that can enhance the accuracy. Also useful in the appendix of [9] is a simple effective frequency approach to address winding loss with non-sinusoidal windings.

Strategies to reduce proximity effect loss, using multiple thin layers or avoiding multiple layers, are compared in [6, 7, 8], considering different types of optimization constraints. An overview of the most common implementation of thin layers to reduce proximity effect loss, litz wire, is provided in [9]. A practical guide to using it is provided in [10], and the most complete model including effects of details of twisting construction, is in [11]. Approaches for using thin foil layers beyond frequencies where litz is practical are discussed in [12]. An implementation of these concepts for a resonant coil for applications such as wireless power transfer is described in [13]. For other applications, thin foil layers can have capacitance issues; circuits designs that reduce the voltage swing on the windings (e.g., [14]) can help reduce the impact of the capacitance.

The impacts of gap fringing and the quasi-distributed gap technique for reducing these problems are discussed in [15]. This reference includes data showing that a small gap is not effective for reducing the impact of fringing. With round-wire or litz-wire windings, shaping the winding can allow excellent performance with a standard gap [16].

In inductors with substantial dc resistance, two windings in parallel can be a good choice for good dc and ac resistance [17]. It is possible to extend this approach to applications in which the inductor carries a combination of line frequency ac current and high-frequency switching ripple, using, if needed, a capacitor to prevent low-frequency current from flowing through the high-frequency winding [18]. A foil winding with a semi-circular cutout region near the gap [19, 20, 21] can also be used to achieve a favorable ac/dc resistance combination.

Although copper windings are most common, aluminum can offer advantages if cost or weight are important [22, 23].

Performance factor for magnetic materials is described and extended in [24], and data on performance factor is provided for many materials in the MHz range. For core loss with non-sinusoidal waveforms, the iGSE model remains the standard method [4], although some of its limitations are now known, as discussed in [5].

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