

Fringing effects

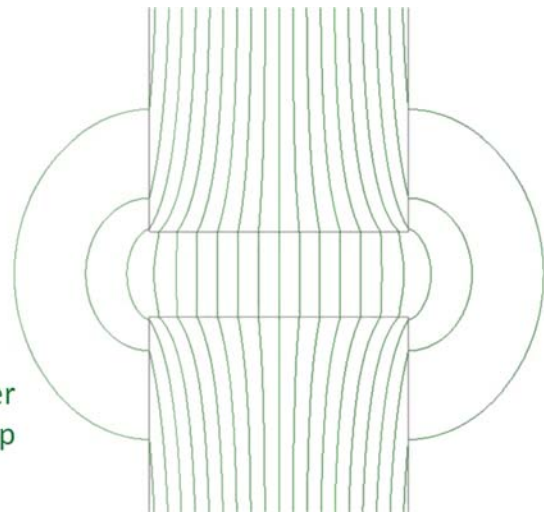
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Dartmouth Magnetism and Power
Electronics Research Group



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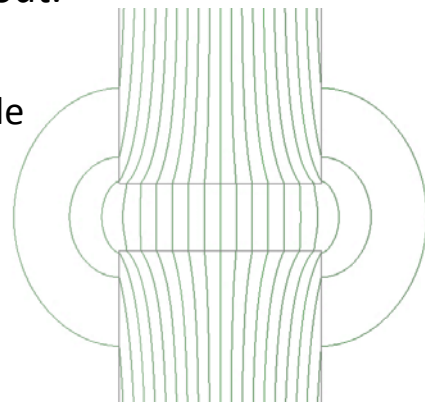
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What's a fringing effect?



- Flux near a core air-gap that bends out.
- Fringing causes:
 - Lower air-gap reluctance than simple predictions.
 - Extra winding loss.
 - Extra core loss in laminated/tape wound cores: eddy currents.



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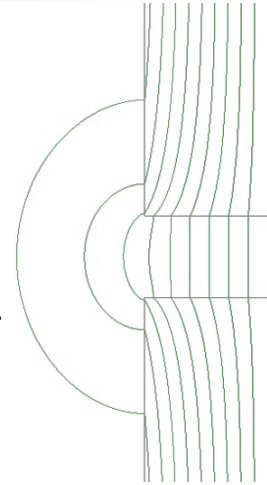


Fringing effect on air-gap reluctance



$\mathcal{R} < \frac{\ell_g}{\mu_0 A_{core}}$ because effective area $> A_{core}$

- 2D: exact model by conformal mapping.
- 3D effects include corners and curvature of a round centerpost.
 - Usually significant; for simple model see [1] or appendix.
- Non-issue for design calculations:
 - Design based on reluctance \mathcal{R} , not gap length ℓ_g .
 - Find necessary gap length experimentally.



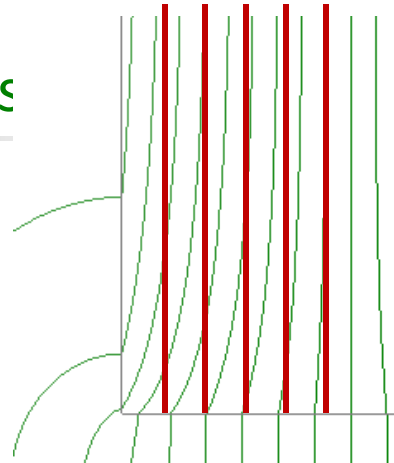
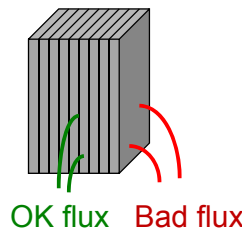
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[1] Hoke & Sullivan. "An improved two-dimensional ..." APEC 2002. 3



Fringing effect on core loss

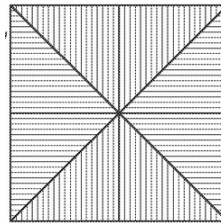
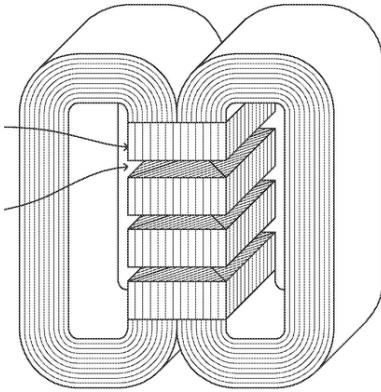
- Flux crosses perpendicular to laminations, inducing loss.
- The "out-of-plane flux" (OOPF) causes excess power loss P_{OOPF} .
- Only a problem on two sides of a post.



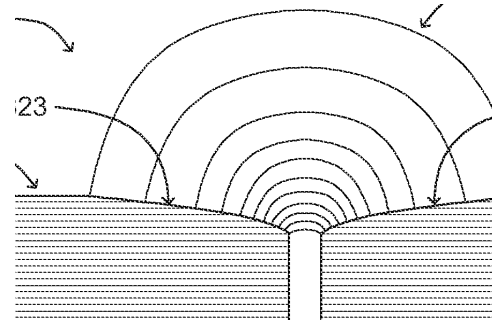
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Carsten patents to reduce fringing loss in laminated/tape-wound cores, 2013



US Pat. No.
9,123,461B2



US Pat. No. 8,466,766

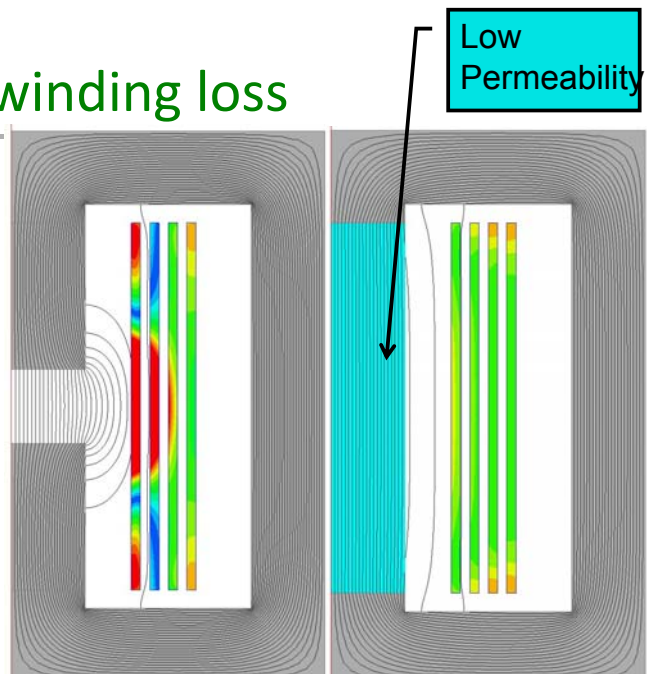
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Fringing effect on winding loss

- Strong field near the gap causes increased eddy-current winding loss.
- Curved field is bad for foil windings:



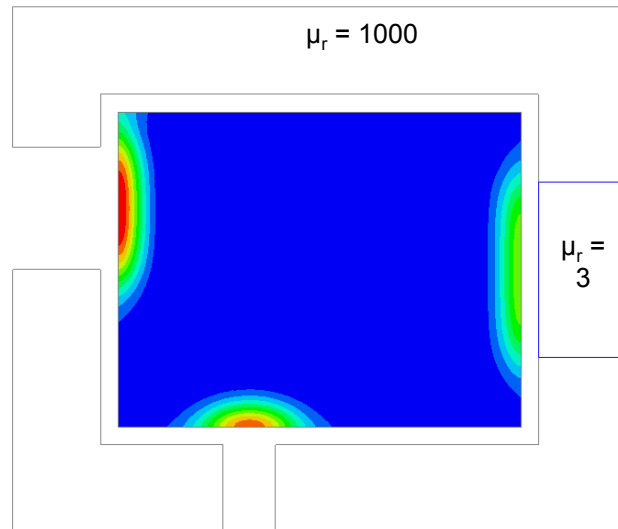
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One conceptual approach



- Solid winding.
- Current flow is attracted to gaps.
- Amount of current is proportional to gap reluctance.

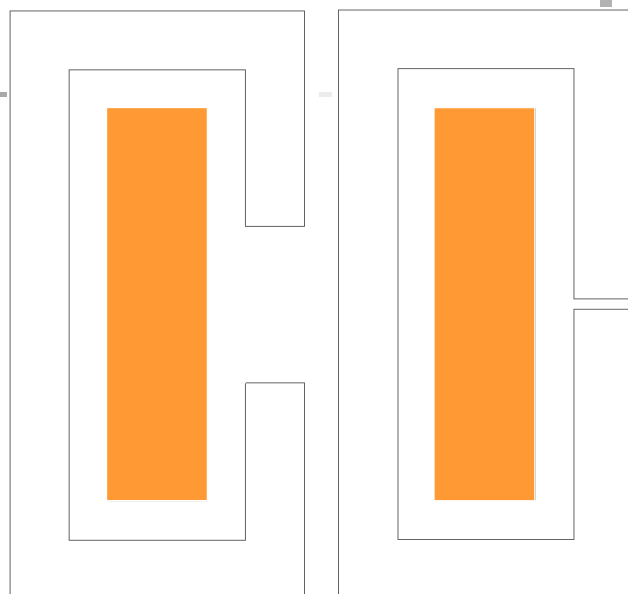


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Single gap

- Which winding has larger loss, with the same ac current in each winding?

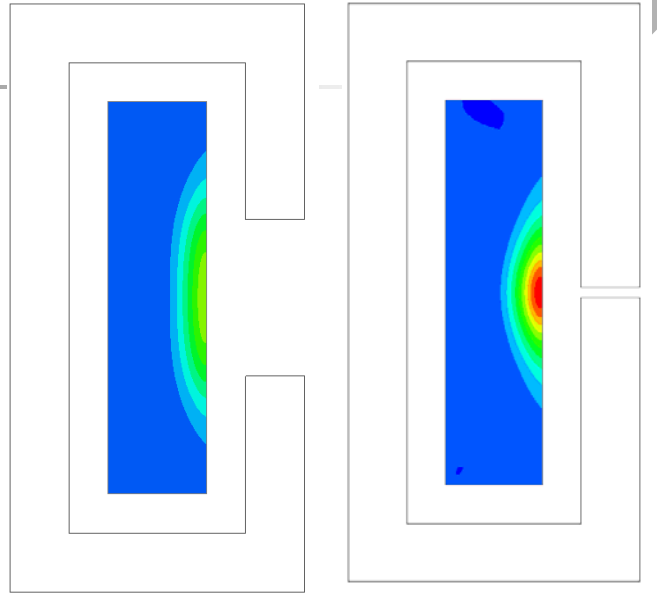


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Single gap

- All current flows near the gap.
- Longer gap → Current is spread over a larger area → lower loss.
- Current with small gap is spread wider than gap.



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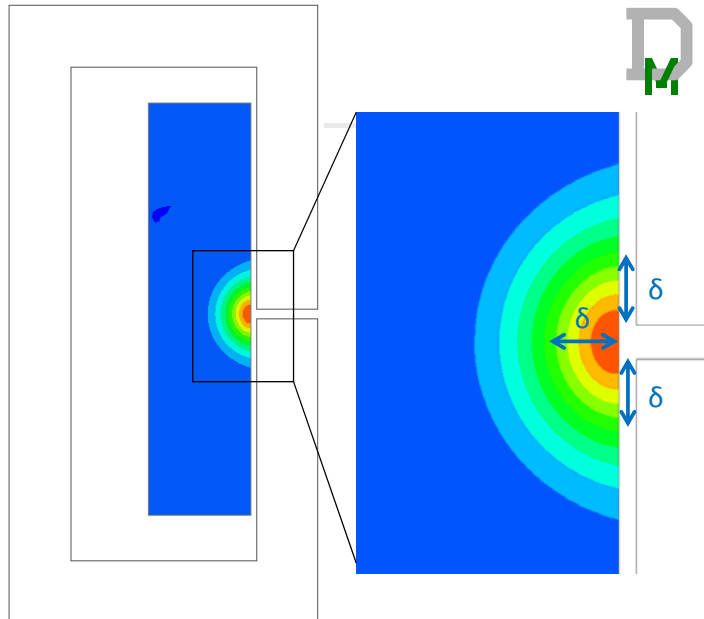
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Spread of current near a small gap

Case 1:
Winding close to gap.

- Current spreads beyond the edges of the gap according to the skin depth δ



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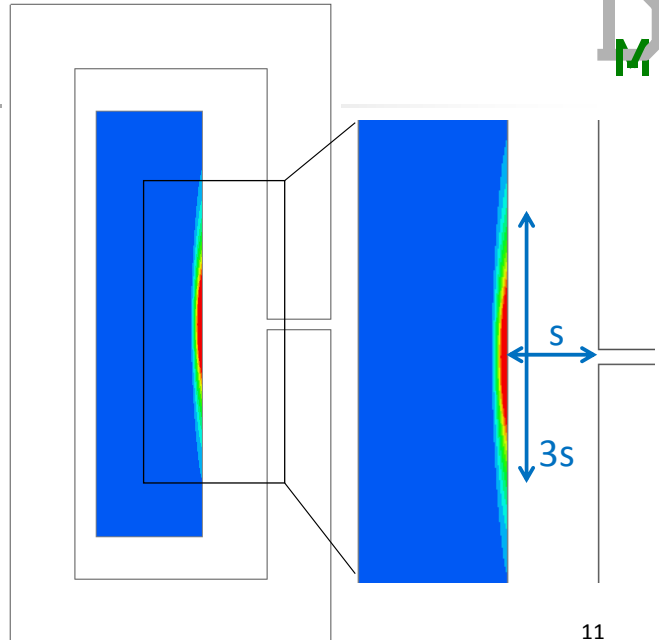
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Spread of current near a small gap

Case 2: Small skin depth; winding spaced from gap.

- Current spreads over a width $\sim 3s$.



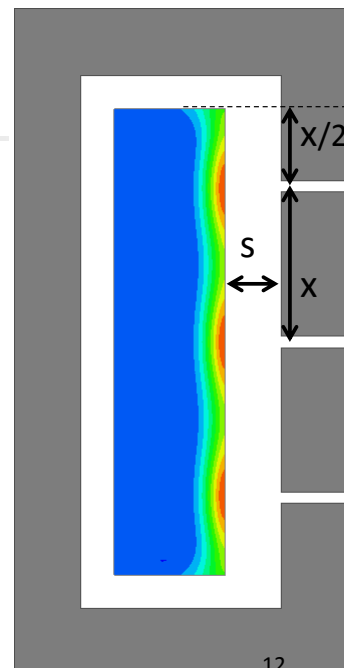
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One design approach:

- Spread several gaps evenly:
 - Spacing x between gaps.
 - Distance $x/2$ from edge of winding.
- Choose spacing $s < x/3$.
- Current distribution is not perfect, but “pools” of current overlap and impact on loss is small.
- For details, see [1] Jiankun Hu, C. R. Sullivan, “[AC Resistance of Planar Power Inductors and the Quasidistributed Gap Technique](https://engineering.dartmouth.edu/inductor/papers/qdgi.pdf)”, *IEEE Tran. on Power Electr.*, 16(4), pp. 558–567, 2001. <https://engineering.dartmouth.edu/inductor/papers/qdgi.pdf>



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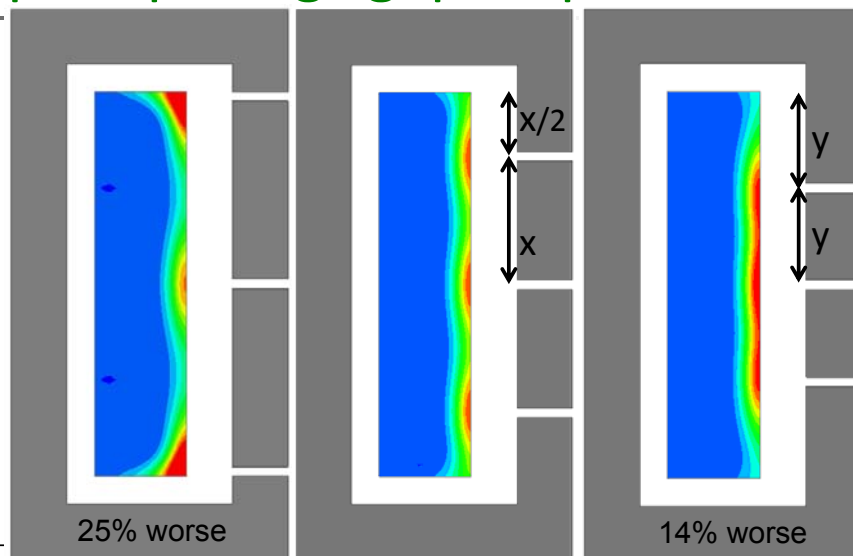


Are all equal spacings gaps equal?



- Current spreads to both sides of gap.
- Position accordingly: $x/2$ on edges.

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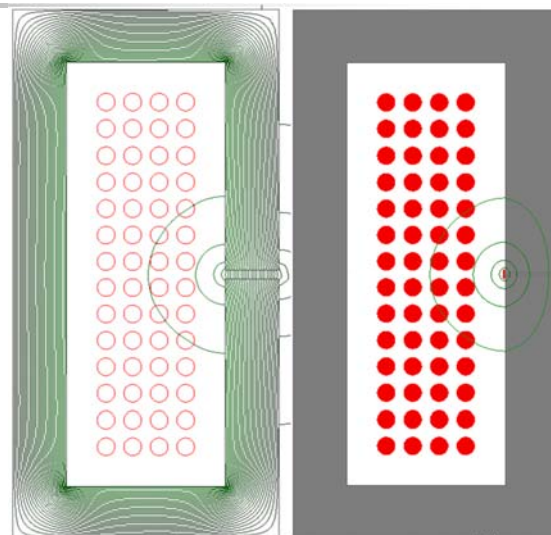


A second conceptual approach



- MMF across gap = MMF generated by the winding.
- Replace gap with a single-turn ribbon carrying a current NI .
- The field is identical.

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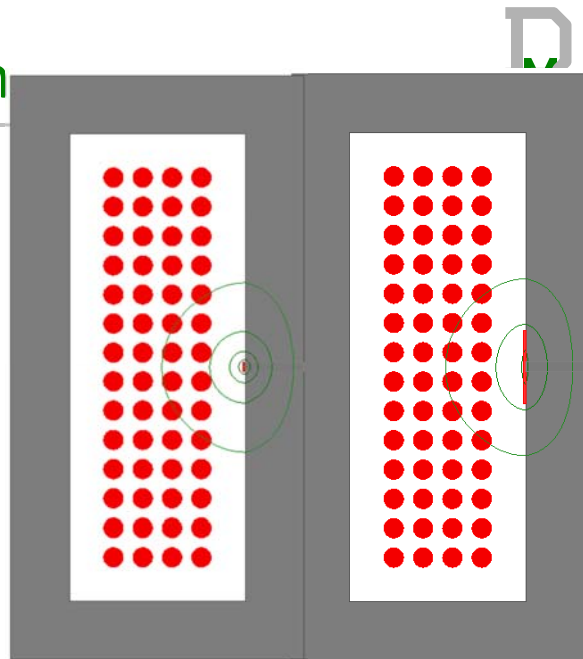




Effect of gap length

- Same NI in ribbon representing the gap—more concentrated vs. more widely spread out.
- Easy to see that the longer gap will have a less intense fringing field near the gap.
- Far from the gap, the two are identical.

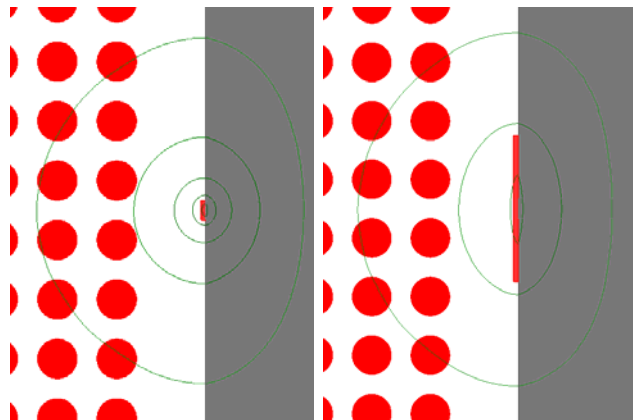
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Effect of gap length

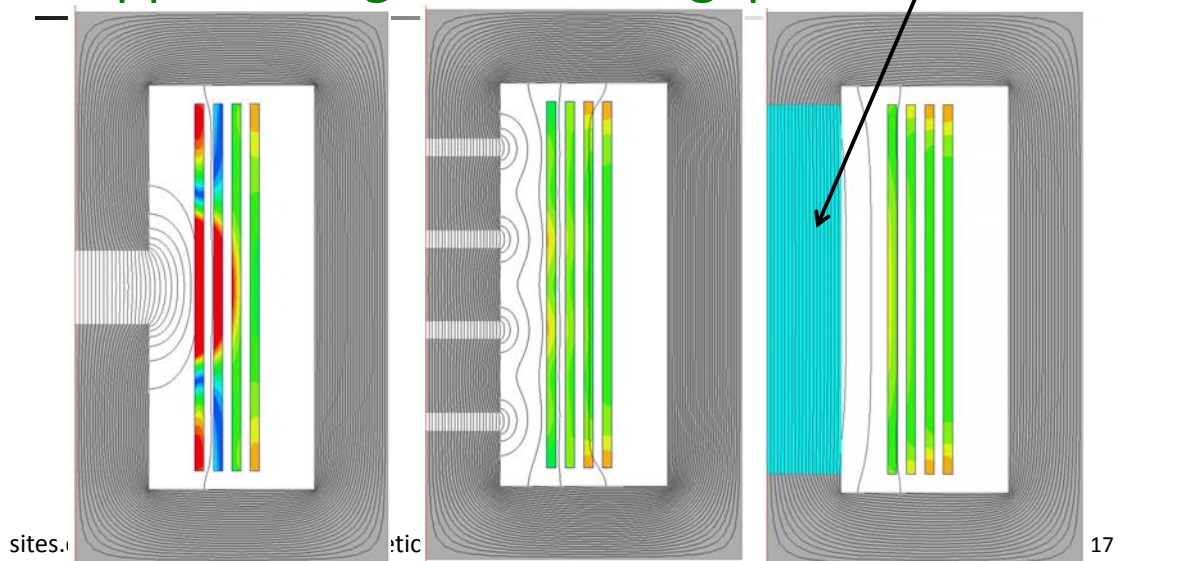
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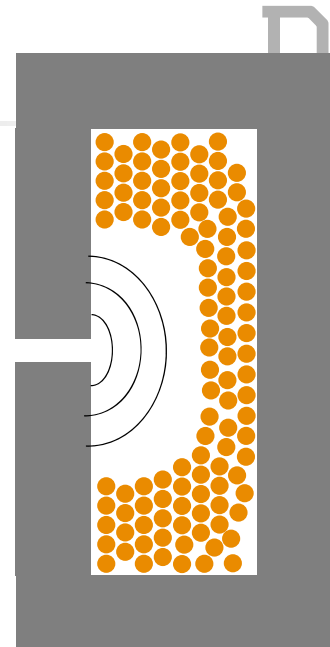


Approaching distributed gap



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.

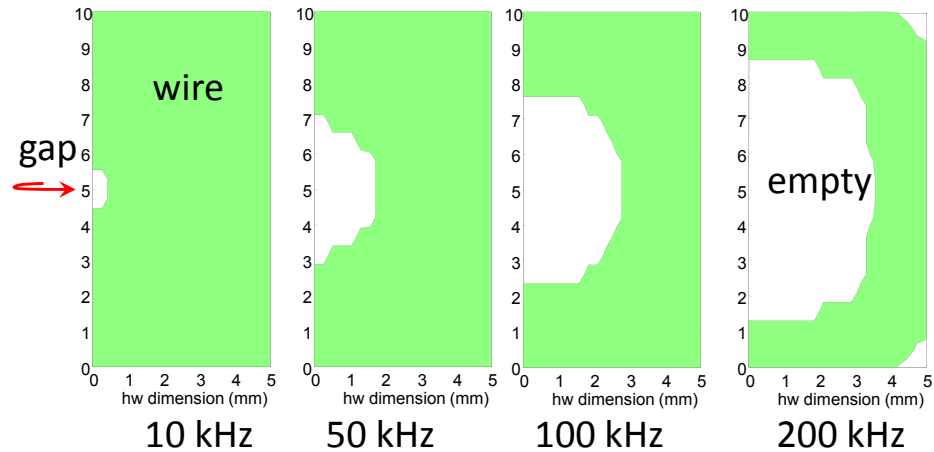




Examples of optimized shapes



Dartmouth
"shapeopt"
software,
available free
on our web
site.



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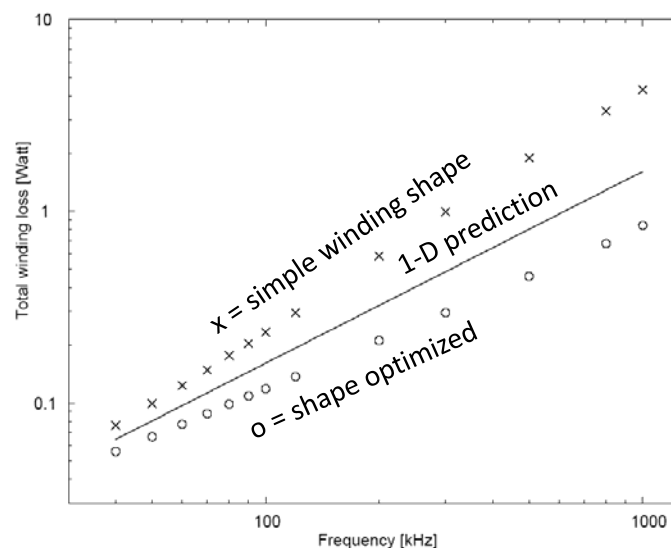
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How much benefit from shape optimization?



- Compare designs optimized based on 1-D analysis to true shape-optimized designs.
- Up to 4X improvement.
- AWG 38 strand litz.
- Optimization tool available for download or on our site
<https://engineering.dartmouth.edu/inductor/shapeopt.shtml>
- References 2-4.

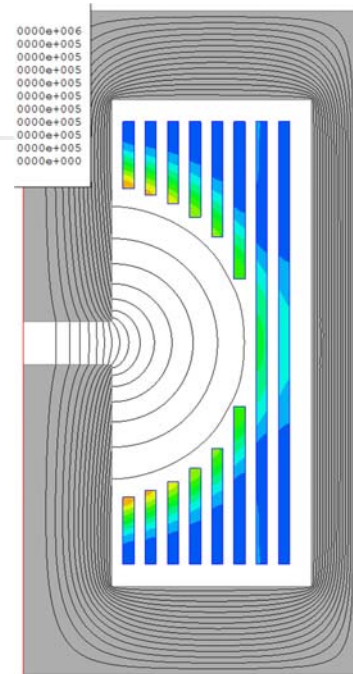


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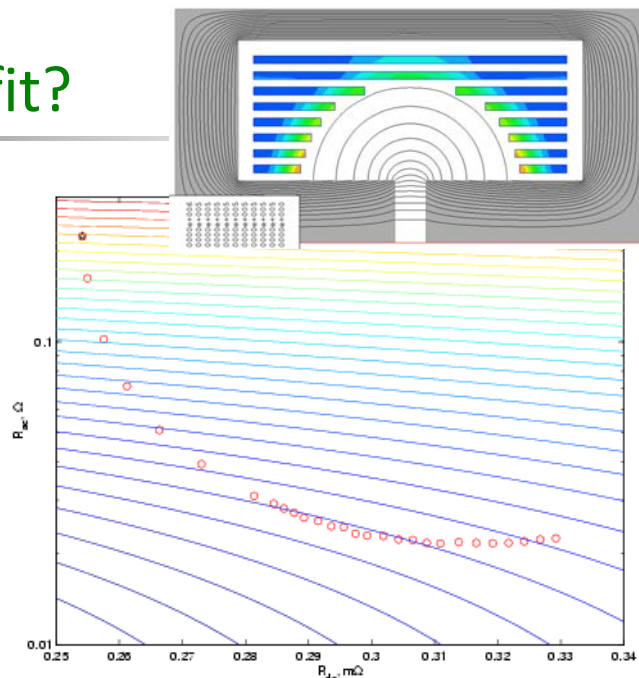
Shaped foil winding

- “Single layer” performance like helical winding—high-frequency current on tips on each turn.
- Size of cutout optimized for R_{ac} vs. R_{dc} tradeoff.
- Expensive to build, but there’s a commercial proprietary configuration with similar performance that’s cheaper to build.



How much benefit?

- Optimum cutout size depends on ripple ratio
- Contour lines of total power loss at 20% ripple
- The optimum circular cutout reduces loss by 63%.
- References 5.

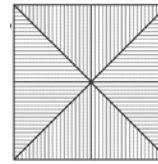
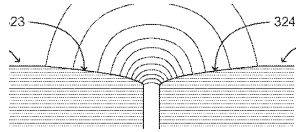




Conclusions I

- Lower air-gap reluctance than simple predictions.
 - Calculations are rarely needed.
 - If needed, the appendix has an accurate, simple calculation from [1].
- Extra core loss in laminated/tape wound cores: eddy currents.
 - Some mitigation options:

US Pat. No.
8,466,766



US Pat. No.
9,123,461B2

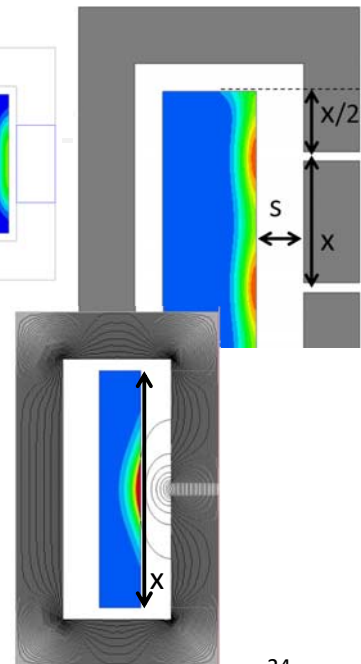
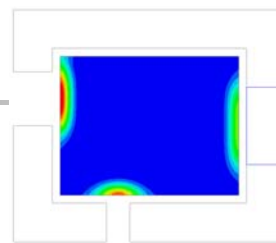
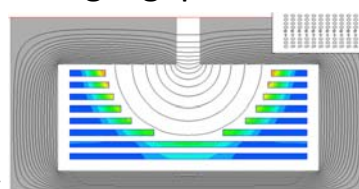
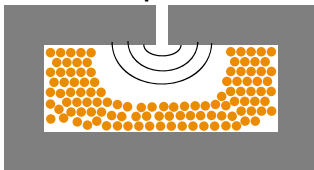
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Conclusions II

- Current flows near the gaps.
- A wider gap lowers resistance.
- Spacing $s > x/3$ is a good rule.
- Not all equally spaced gaps are equal—first gap $x/2$ from edge.
- Shaped windings with a single gap.



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References



- [1] Jiankun Hu, C. R. Sullivan, "[AC Resistance of Planar Power Inductors and the Quasidistributed Gap Technique](https://engineering.dartmouth.edu/inductor/papers/qdgi.pdf)", *IEEE Tran. on Power Electr.*, 16(4), pp. 558–567, 2001. <https://engineering.dartmouth.edu/inductor/papers/qdgi.pdf>
- [2] Jiankun Hu, C. R. Sullivan, "[Analytical Method for Generalization of Numerically Optimized Inductor Winding Shapes](#)", *IEEE Power Electronics Specialists Conference*, pp. 568–573, June 1999.
- [3] Jiankun Hu, C. R. Sullivan, "[Optimization of Shapes for Round Wire, High Frequency Gapped Inductor Windings](#)", *IEEE Industry Applications Society Annual Meeting*, pp. 907–911, Oct. 1998.
- [4] C. R. Sullivan, J. D. McCurdy, R. A. Jensen, "[Analysis of Minimum Cost in Shape-Optimized Litz-Wire Inductor Windings](#)", *IEEE Power Electronics Specialists Conference*, June 2001.
- [5] J. D. Pollock, C. R. Sullivan, "[Loss Models for Shaped Foil Windings on Low-Permeability Cores](#)", *IEEE Power Electronics Specialists Conference*, pp. 3122–3128, June 2008.
- [6] J. D. Pollock, C. R. Sullivan, "[Modelling Foil Winding Configurations with Low AC and DC Resistance](#)", *IEEE Power Electronics Specialists Conference*, pp. 1507–1512, June 2005.
- [7] J. Pollock, C. R. Sullivan, "[Gapped-Inductor Foil Windings with Low AC and DC Resistance](#)", *IEEE Industry Applications Society Annual Meeting*, pp. 557–663, Oct. 2004.
- [8] Lundquist, Weyman, Vivien Yang, and Carl Castro. "Low AC resistance foil cut inductor." *Energy Conversion Congress and Exposition (ECCE), 2014 IEEE*. IEEE, 2014.

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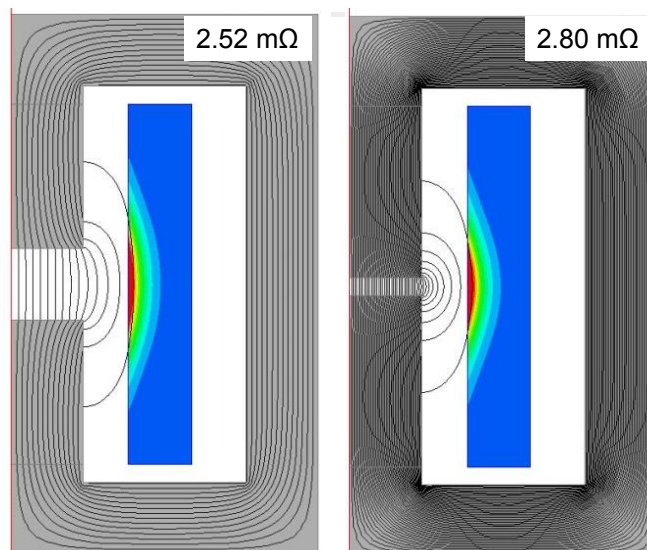
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Another example



- Both gaps are small enough that it doesn't matter much.
- Shorter gap is worse.



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Fringing reluctance calculation



$$\mathcal{R}_{faces} = \frac{\pi}{p \cdot \mu_0 \left(1 + \ln \frac{\pi \ell}{2 \ell_{gap}} \right)}$$
$$\mathcal{R}_{corners} = \frac{1}{\mu_0 k \ell}$$

where

p = perimeter = 2(w+d)

k = 1.23

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