Rapid High-Frequency Transformer Simulation and Optimization

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Motivation

- Wide bandgap switches enable power converters to operate at HF
- Magnetics become limiting factor in converter performance
- Transformer design at high frequencies is difficult
- Current is not guaranteed to share evenly:
  - Between paralleled conductors
  - Within individual conductors
- Engineers rely on heuristics (e.g., interleaving) to design
- Verification is done with finite element analysis – slow!
- What if we could analyze the whole space of possible configurations?
  - *Enable true optimization*

Analysis Method (see [1])

- Assume high frequency operation
  - Current flows in skins – treat as surface current densities with units A/m
  - No B or H fields within conductors
- Assume negligible H field in core – relevant to many applications
- Maxwell's laws are reduced to a linear algebraic system of equations
- Solving gives information about layer currents, surface current densities, and H fields
- Easily solved using numeric computing toolkit (e.g. MATLAB, numpy)

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\begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 0 & 0 & 0 & 0 & 0 & b & b & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
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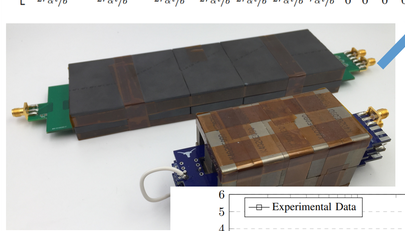
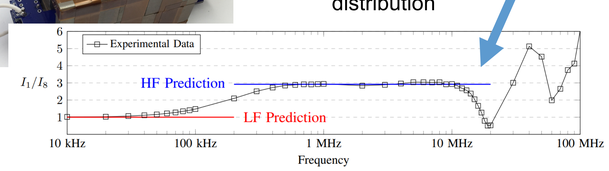
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
\frac{(3r_\alpha+r_\beta)l}{b} & \frac{(2r_\alpha+r_\beta)l}{b} & \frac{(r_\alpha+r_\beta)l}{b} & r_\alpha l/b & 0 & 0 & 0 & 0 & 0 & \frac{1}{2}\delta^2 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{2}\delta^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
r_\beta l/b & r_\beta l/b & r_\beta l/b & r_\beta l/b & r_\beta l/b & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{2}\delta^2 & -\frac{1}{2}\delta^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
2r_\alpha l/b & 2r_\alpha l/b & 2r_\alpha l/b & 2r_\alpha l/b & 2r_\alpha l/b & 2r_\alpha l/b & r_\alpha l/b & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{2}\delta^2 & 0 & 0 & -\frac{1}{2}\delta^2 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \\ I_7 \\ I_8 \\ K_{1T} \\ K_{1B} \\ K_{2T} \\ K_{2B} \\ K_{3T} \\ K_{3B} \\ K_{4T} \\ K_{4B} \\ K_{5T} \\ K_{5B} \\ K_{6T} \\ K_{6B} \\ K_{7T} \\ K_{7B} \\ K_{8T} \\ K_{8B}
\end{bmatrix}
=
\begin{bmatrix}
I_p \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0
\end{bmatrix}
$$



Obtain equations from physical geometry

Solve sparse matrix to get information about current distribution



- Method has been extensively validated by comparison with FEA, measurement of experimental transformers
- *Up to six orders of magnitude faster than FEA simulation!*

Implementation

- Must be able to specify & generate arbitrarily complex windings
- Accomplished through binary tree structure:
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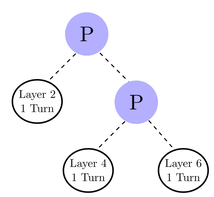
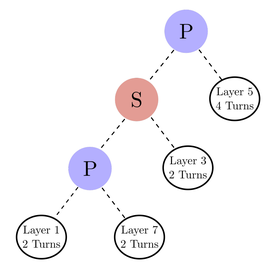
  - Layers identified by number and turn count
  - Connected via either series or parallel nodes
- Valid stackups have a primary and secondary tree, cumulatively identifying turn counts and interconnections for every layer.
- Can run analysis method on any valid stackup object, produce either a symbolic or numeric solution (if geometry is given)
- Can recursively generate stackups meeting certain turns ratio, layer count requirements

(P,[L2,1T],(P,[L4,1T],[L6,1T]))

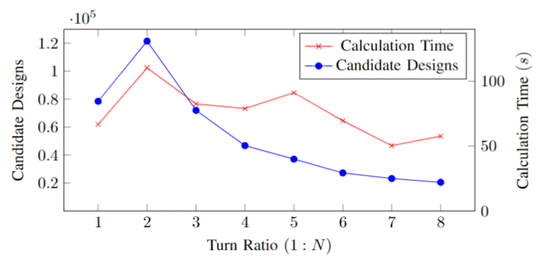


(P,(S,(P,[L1,2T],[L7,2T]),[L3,2T]),[L5,4T])



Software Tool

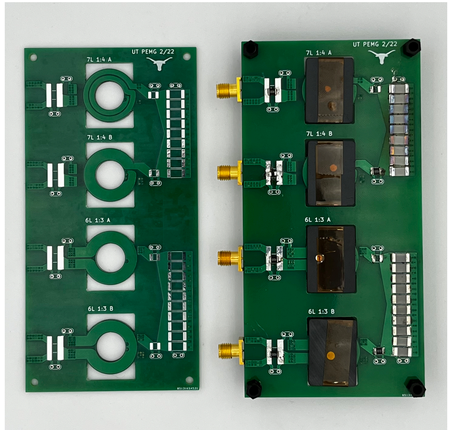
- Combination of two tools: Evaluator & Optimizer
- Evaluator – For given winding, calculate current distribution & loss
- Optimizer – For given number of layers & turns ratio, identify optimal designs



Tool can process thousands of designs per second!

Experimental Verification

- Constructed test transformers for experimental verification



References

- [1] M. Solomentsev and A. J. Hanson, "Modeling current distribution within conductors and between parallel conductors in high frequency transformers," in 2021 IEEE Applied Power Electronics Conference and Exposition (APEC), 2021, pp. 1701–1708.
- [2] Wei Chen, Yipeng Yan, Yuequan Hu, and Qing Lu, "Model and design of pcb parallel winding for planar transformer," IEEE Transactions on Magnetics, vol. 39, no. 5, pp. 3202–3204, 2003.
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- [4] M. Li, Z. Ouyang, and M. A. Andersen, "Discovery of the nearly zero flux between two parallel conductors in planar transformers," IEEE Transactions on Power Electronics, vol. 37, no. 1, pp. 714–723, 2022.
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- [6] D. Fu, F. C. Lee, and S. Wang, "Investigation on transformer design of high frequency high efficiency dc-dc converters," in2010 Twenty-FifthAnnual IEEE Applied Power Electronics Conference and Exposition (APEC), 2010, pp. 940–947.