Design Considerations and Multi-Objective Optimization for Magnetic Components in High-Power, Medium-to-High-Frequency Power Electronics

Todd Marzec, Ph.D. Student, Mohendro Kumar Ghosh, Postdoctoral Research Associate, Maurice Sturdivant, M.S. Student

Advisors: Paul R. Ohodnicki, Ph.D. & Brandon Grainger, Ph.D.

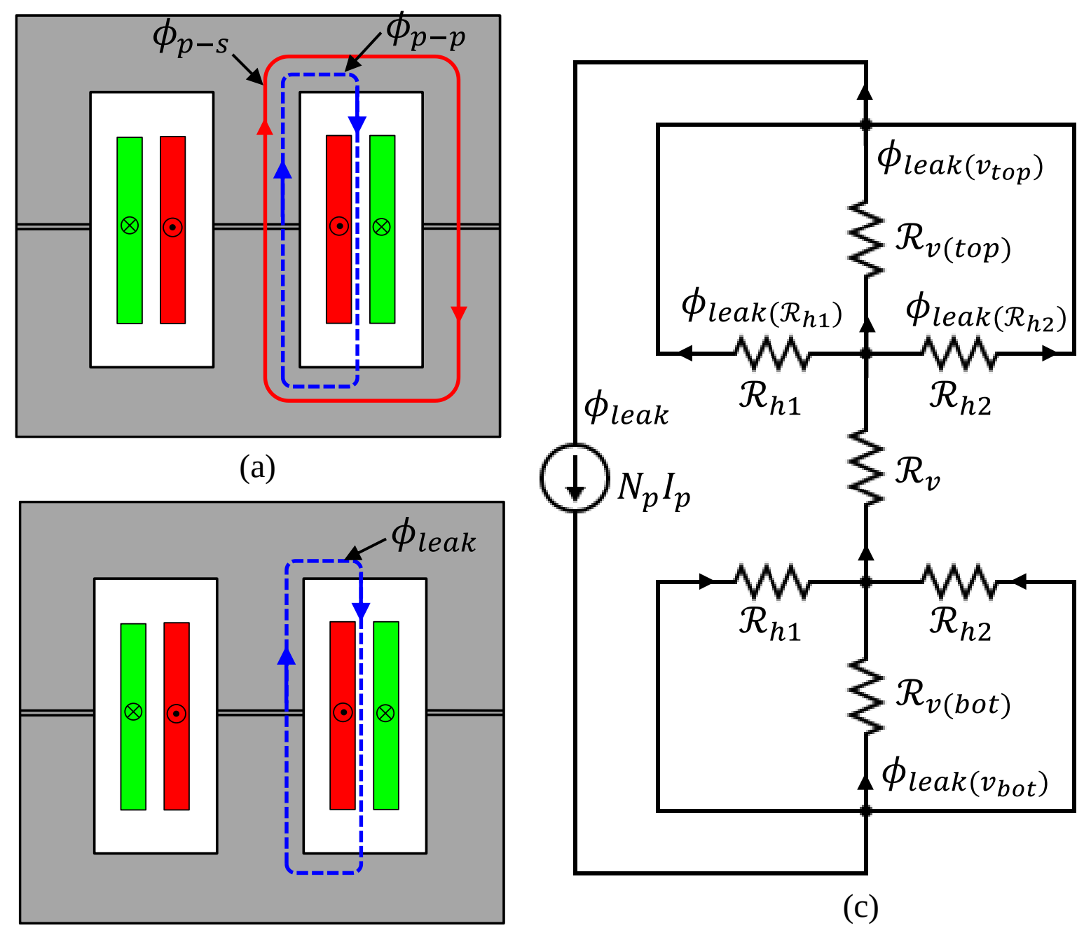
University of Pittsburgh – Magnetic, Electronic, and Photonic Materials and Devices Lab & Electric Power Technologies Lab

1. Trade Study: MF/MV Transformer Isolation Requirements and Core Selection

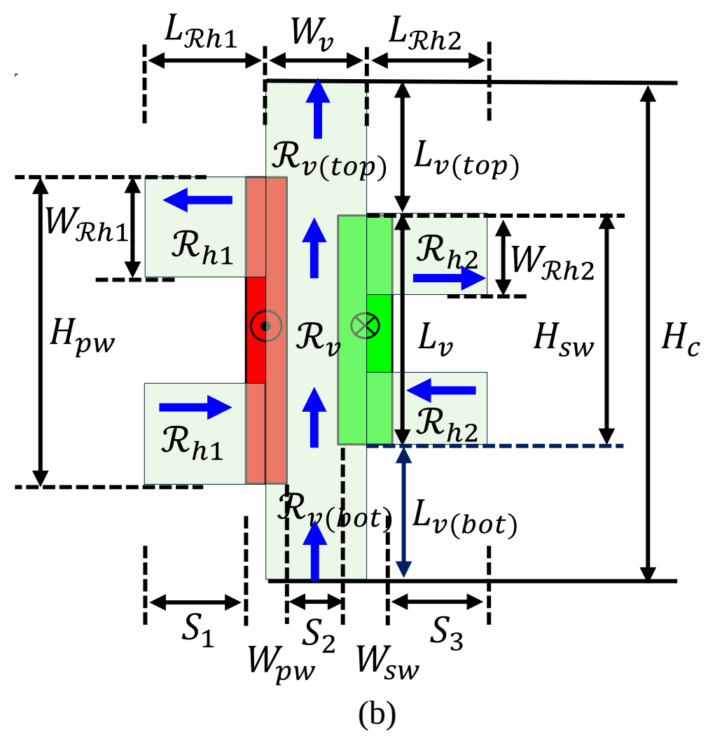
➢ Effectiveness of using Soft Magnetic Alloys

- ✓ Soft Magnetic Alloys enable compact, low-loss transformers for medium (1–50 kHz) and high (>50 kHz) frequencies.
- ✓ Laminated steel cores are unsuitable due to high eddy current losses.
- ✓ Nanocrystalline materials excel at lower medium frequencies, while ferrites perform better at higher frequencies. A crossover region exists where both materials perform similarly.
- ✓ Isolation space affects leakage flux, loss, and size [1]; standards (IEC-60947-1 [2], UL-508 [3]) guide design for insulation safety and efficiency.

➢ Reluctance-based Magnetic Equivalent Circuit Model



Magnetic flux paths for (a) full load condition, (b) shorted secondary condition, and (c) reluctance-based equivalent magnetic circuit.)



Schematic diagram showing reluctances.

Transformer Matrixx	*Design Values* [in]
Window height, *Hc*	5.51
Window width, *Wc*	3.15
Core depth, *Dc*	1.15
Eddy path depth, *t*	0.025
Primary winding height, *Hpw*	4.201
Primary winding width, *Wpw*	0.35
Secondary winding Height, *Hsw*	2.801
Secondary winding Width, *Wsw*	0.7
Isolation space, S2	0.321

Flux Paths	*Leakage Reluctances* [AT/Wb]	*Leakage Flux* [Wb]	*Leakage Core Loss* [W]
in vertical flux path	2.10E+07	1.12E-06	0.19
in horizontal flux paths	3.32E+06	8.83E-06	14.92
	2.35E+07	8.31E-07	0.11
Total	9.51E+07	1.08E-05	60.86

➢ Prototype Design and Results

- ✓ Open Secondary Test: Full primary voltage (1131 V-pk), zero secondary current, max core flux, zero leakage flux, primary current = 1.3 A-pk.
- ✓ Shorted Secondary Test: Reduced primary voltage (85.6 V-pk), full-load primary (89.1 A-pk) & secondary (71.2 A-pk) currents, full-load leakage flux.

10 kHz Shell Type Transformer Prototype [5]

Design Specifications

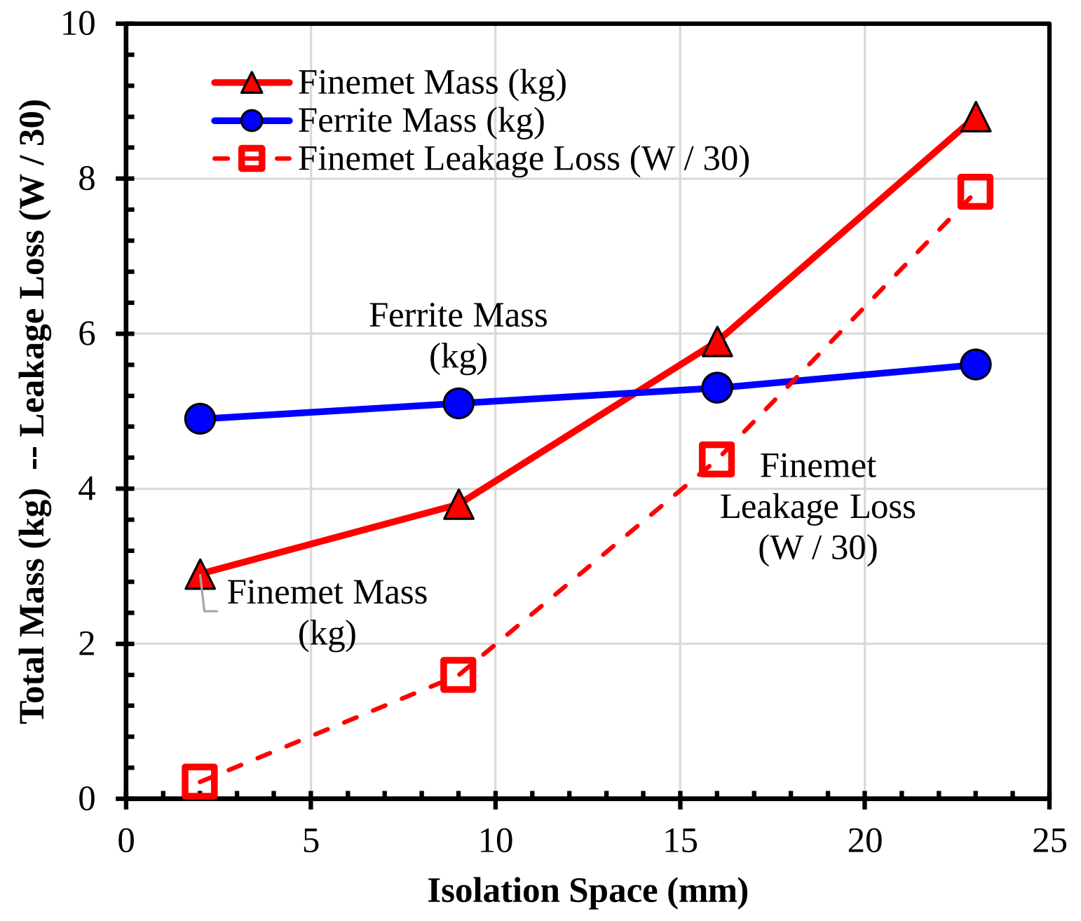
Parameters	*Design Values*
Base Material	Nanocrystalline (Finemet FT-3TL)
Frequency [kHz]	10
Peak Flux Density [T]	0.630
Core Mass [kg]	10.32
Primary Voltage [V-pk]	1131.4
Primary Current [A-pk]	89.1
Secondary Current [A-pk]	71.2
Output Power [kW]	50
Primary and Secondary Turns	12 and 15

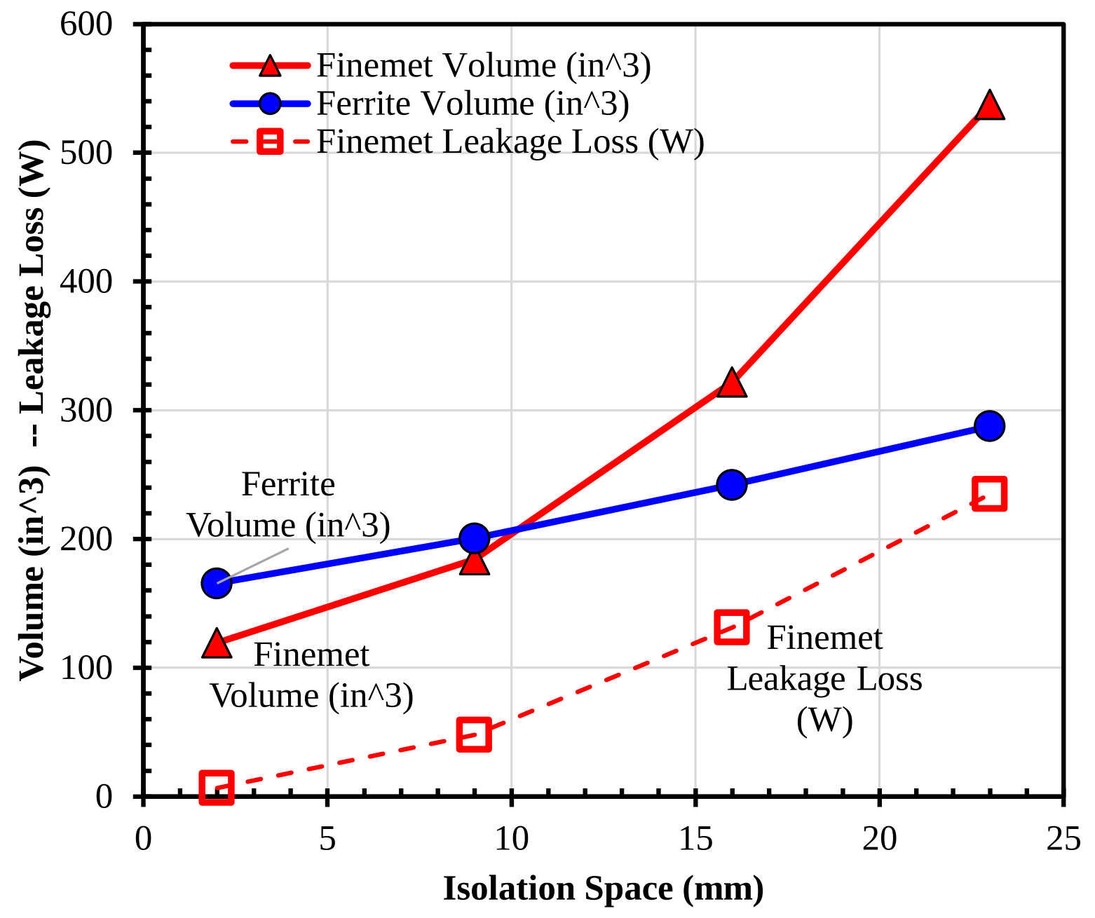
Prototype Transformer Performance

Parameters	*Measured Results*
Primary Flux Density [T]	0.63
Magnetizing Core Loss [W]	64.3
Leakage Flux Density [T]	0.047
Leakage Core Loss [W]	62.5
Relative Comparison in Leakage Core Loss	
Calculation Method	***Leakage Core Loss* [W]**
Measured	62.5
MEC Analytical	60.8

➢ Leakage Flux Core Loss Vs. Isolation Spacing

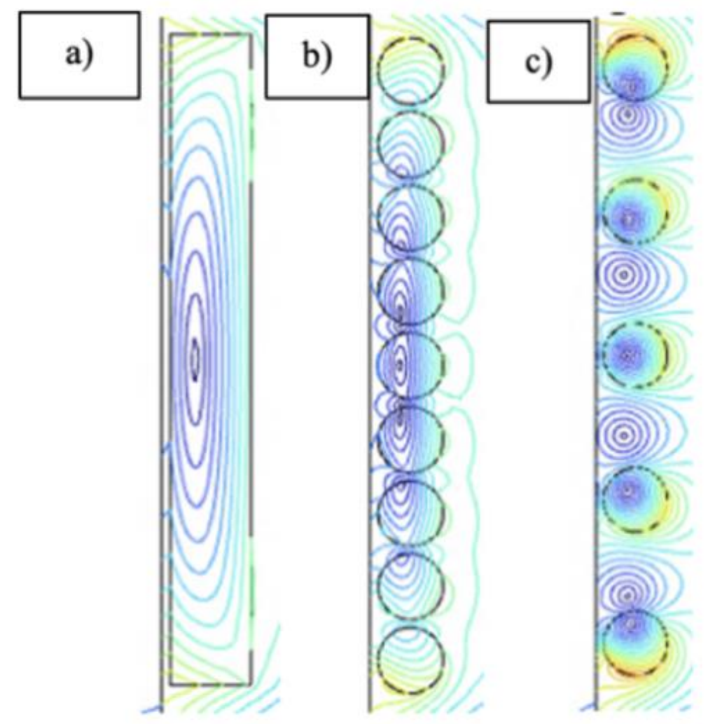
- ✓ 20 kHz, 25 kW transformer, 800 V-rms, 60°C limit, tested isolation spaces (2–23 mm) for nanocrystalline & ferrite cores.
- ✓ Larger isolation increases leakage loss, size, and mass in nanocrystalline, while ferrite shows minimal impact.





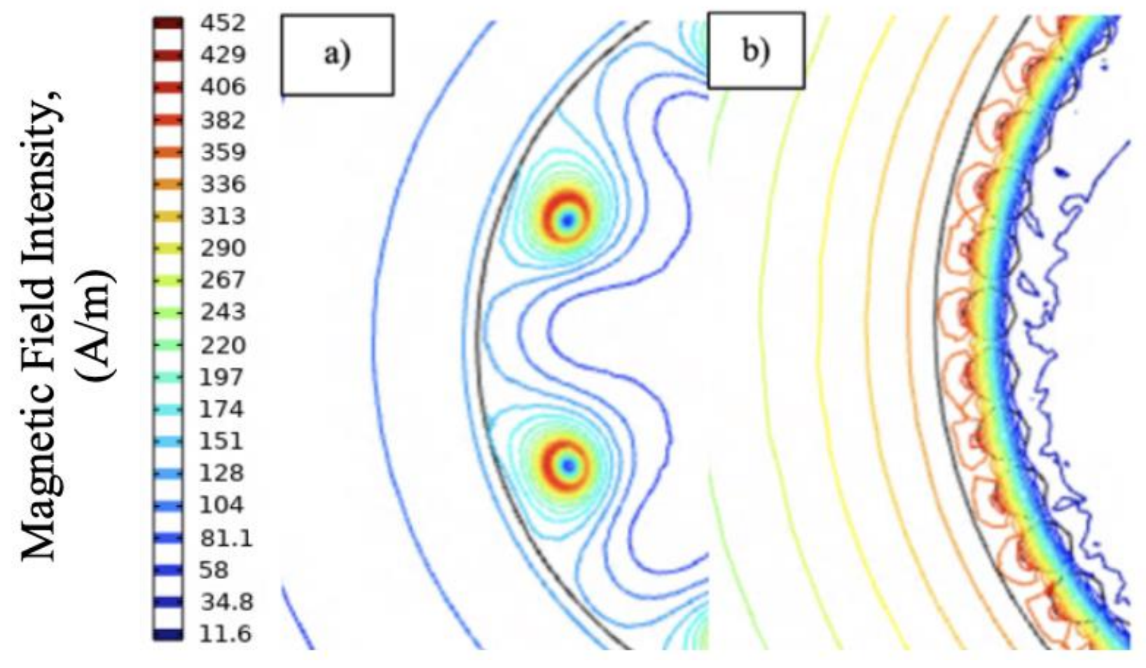
2. High Frequency Winding Design Considering AC Losses and Parasitics

- ✓ High-Frequency Inductors (0.1–10 MHz): Offer higher power density, benefiting Navy power systems with SiC-based wide-bandgap semiconductors enabling faster switching and smaller inductors.
- ✓ Challenges and Solutions: High-frequency operation adds inefficiencies/parasitics; optimizing accurate modeling for multi-objective design holds potential efficiency enhancements for next-gen applications [4].

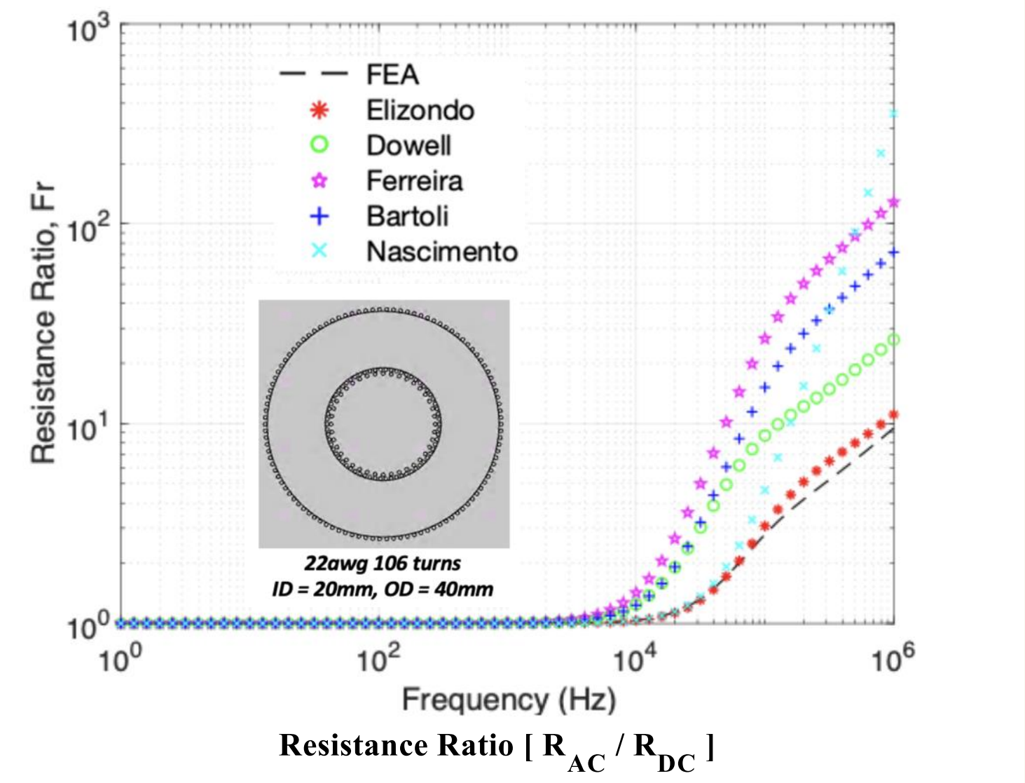


Standard windings and magnetic field distributions for (a) foil, (b) tightly packed and (c) loosely packed windings.

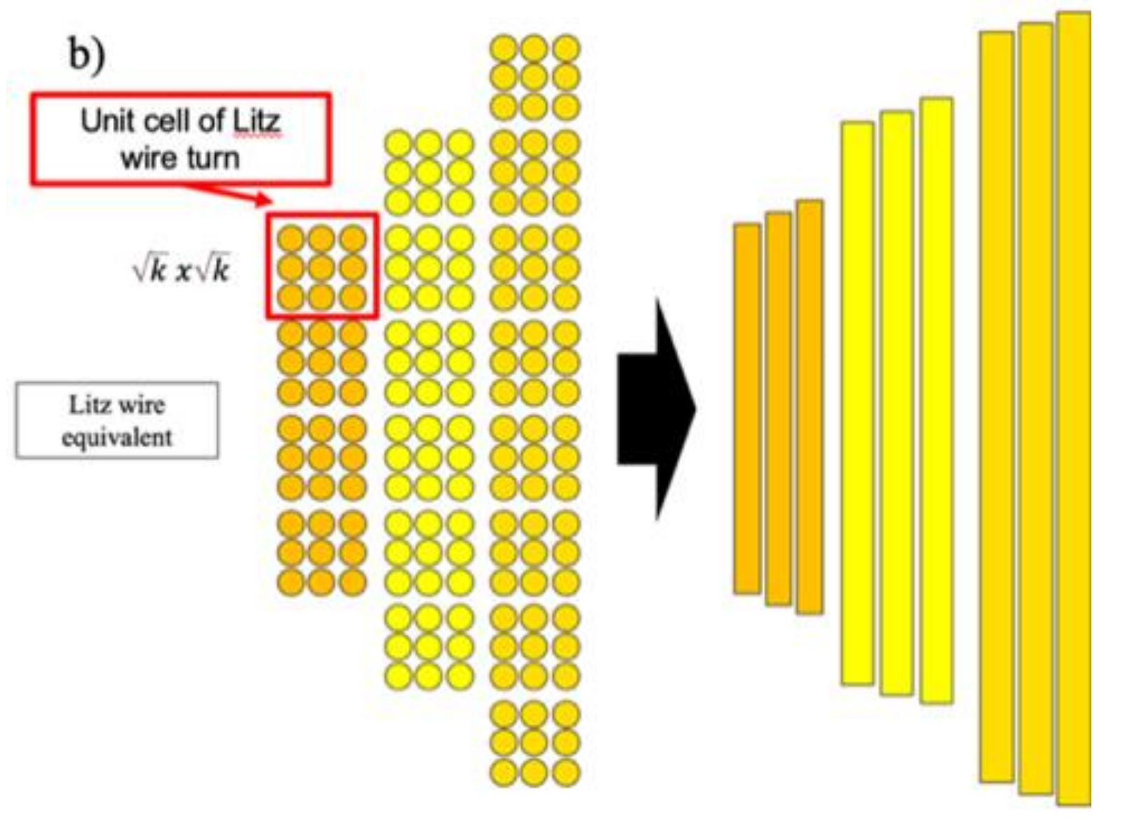
Toroidal Windings and magnetic field distributions for (a) loosely packed and (b) tightly packed windings.

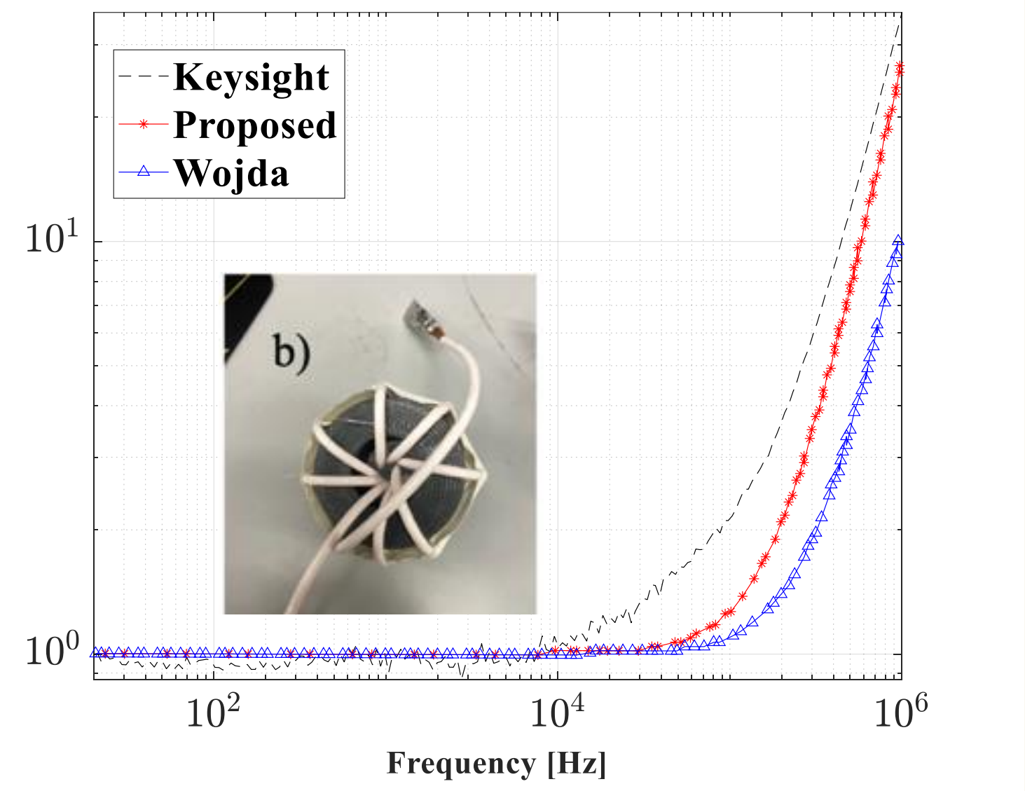


AC Winding Loss Model Survey and Benchmarking: (top) multi-layer solid copper winding, (bottom) Litz wire winding.



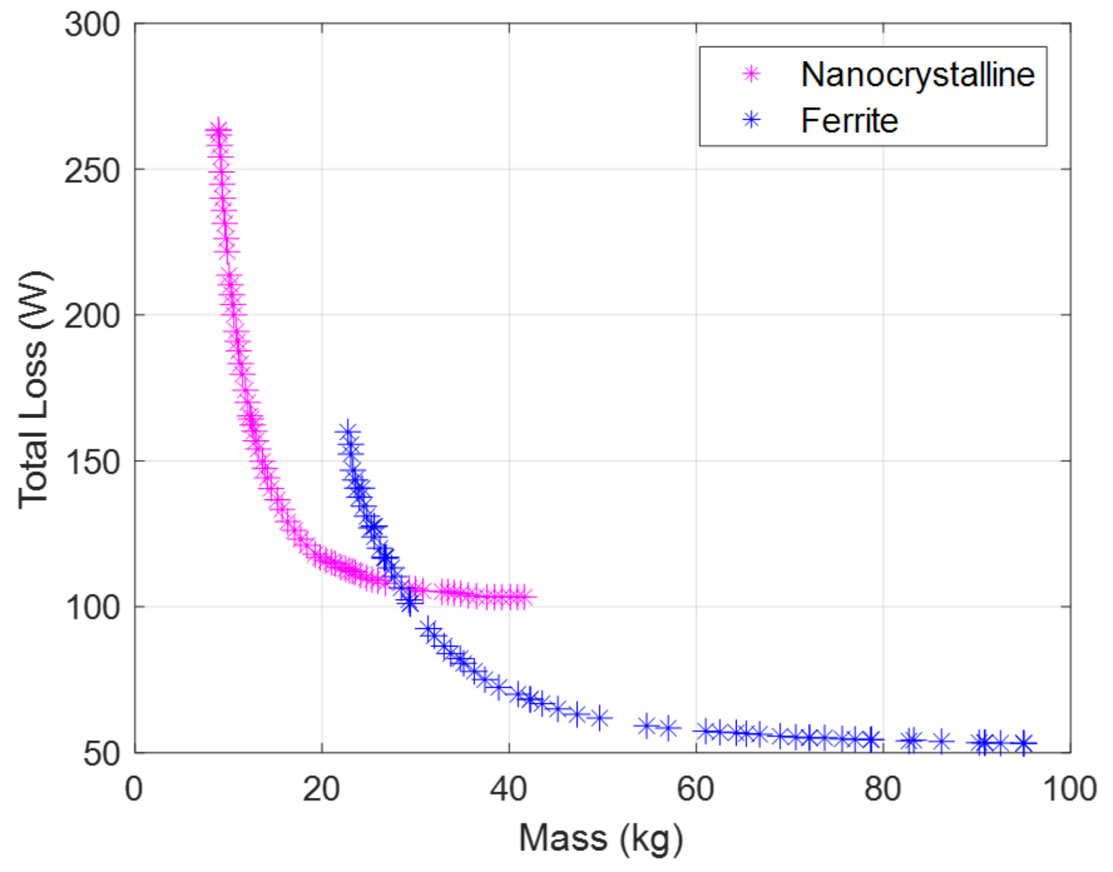
- ✓ Winding Spacing & AC Losses: Tight vs. loose windings significantly impact AC losses; Litz wire reduces skin & proximity effects for high-frequency, high-current applications. Particularly difficult when winding spacing is non-uniform like toroids.
- ✓ Modeling & Validation: Benchmarking analytical models with COMSOL & experimental data identified Elizondo et al.'s model as most accurate (DC–1 MHz), leading to an improved Litz wire loss model [5].



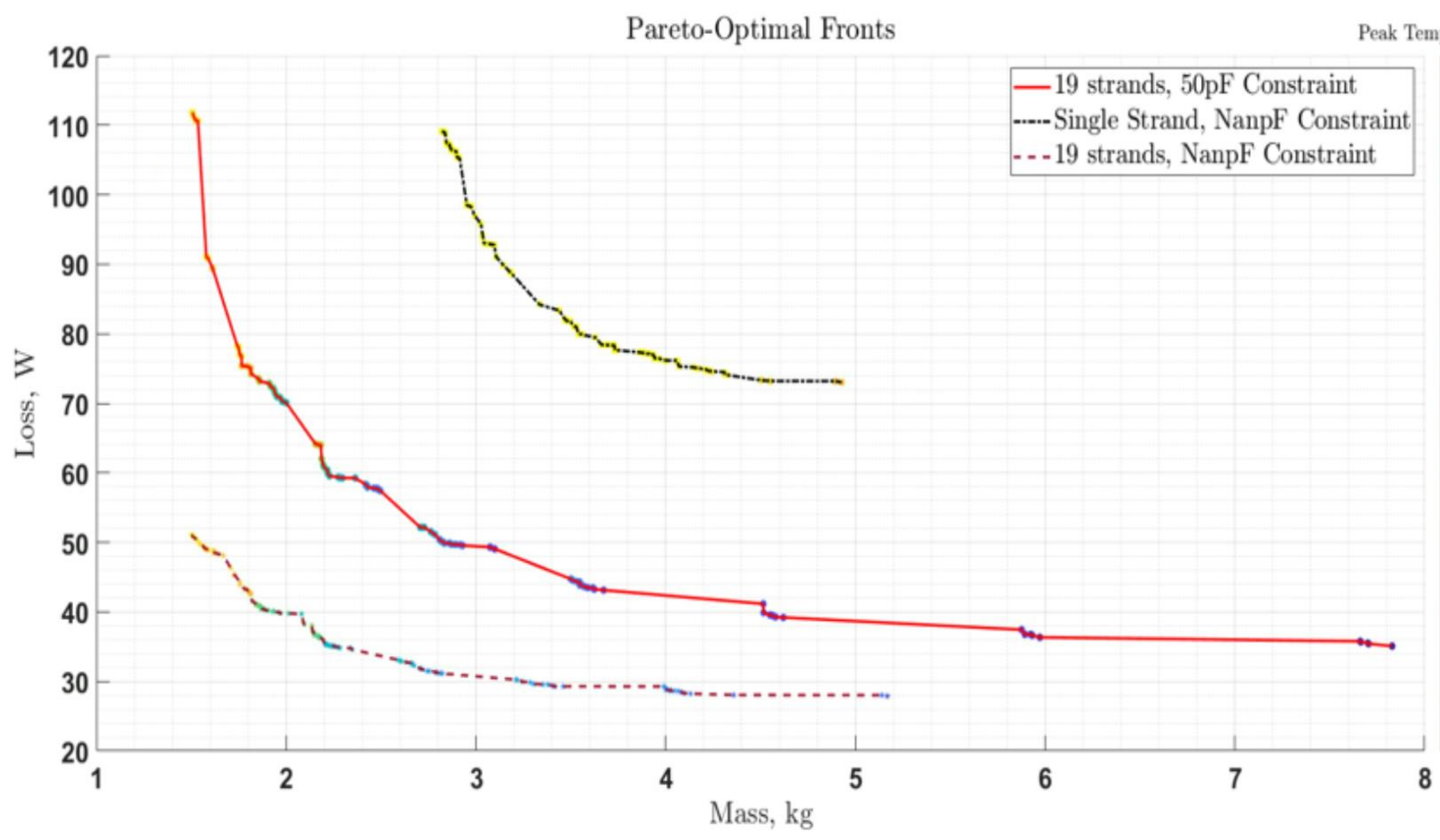


3. Multi-Objective Optimization Integration

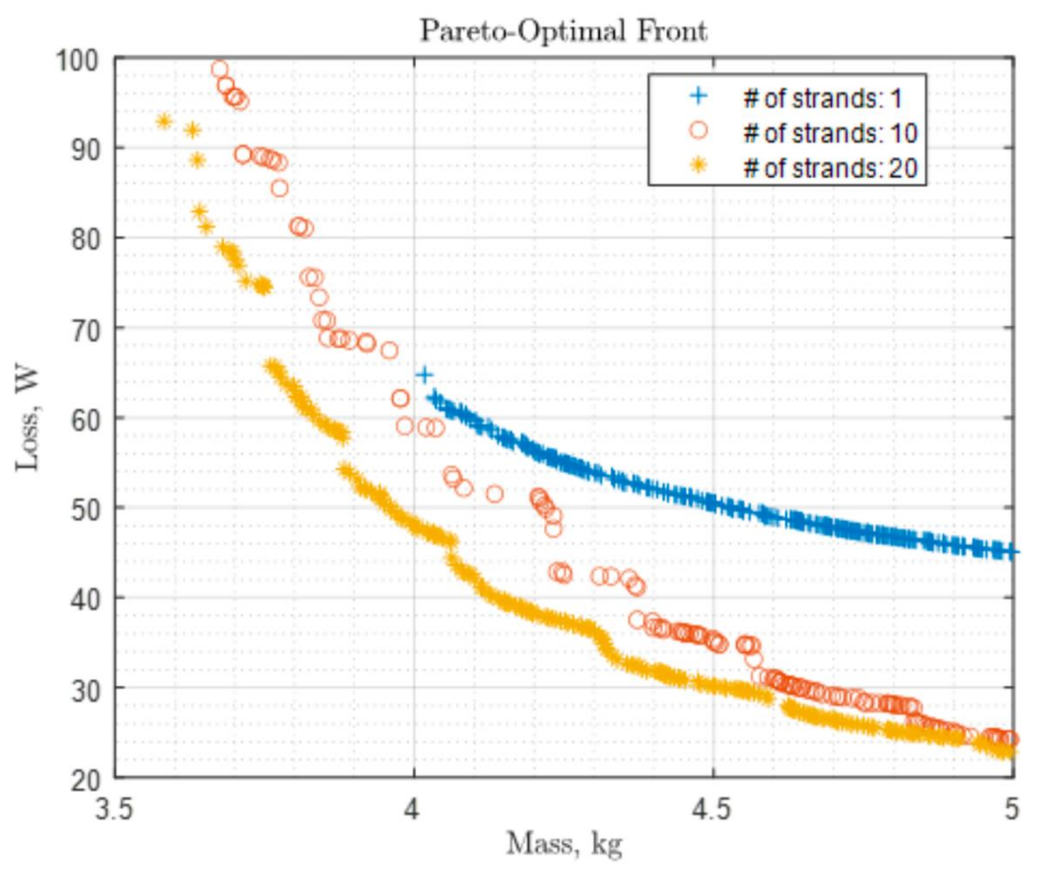
- ✓ In the case of magnetics design problems, it is normally the case that there are multiple objectives of interest [6]. In the 3 cases below, the inductors and transformers mass and loss are optimized at the same time.



MF/MV Transformer Isolation Trade-off Between Mass and Loss with Isolation Space of 9 mm.



Optimal Winding Designs with Combinations of Constraints on Conductor Strands and Parasitic Capacitance: Stranded and solid conductor windings are designed with parasitic capacitance in mind.



Skin Depth Effects and Influence on Efficient Designs: Windings constructed with 1 strand, 10 strands and 20 strands are compared.

References

[1] P. A. Dahono, et al., in IEEE Trans. On Pow. Elec., 2007.
[2] Industrial Control Equipment-UL 508.
[3] IEC 60947-1: Low Voltage Switchgear and Control–Part 1
[4] T. J. Marzec et al., "Analytical Methods for Determining High Frequency Winding Loss for Toroidal Inductors," 2023 IEEE Electric Ship Technologies Symposium (ESTS), Alexandria, VA, USA, 2023,
[5] T. J. Marzec et al., "Analytical Models for Solid and Litz Wire AC Winding Loss in Toroidal Inductors," in IEEE Transactions on Transportation Electrification, vol. 11,
[6] P. J. Dowell, "Effects of eddy currents in transformer winding,"
[7] J. A. Ferreira, "Improved analytical modeling of conductive losses in magnetic components,"
[8] D. Elizondo, et al., "Analytical Modeling of High-Frequency Winding Loss in Round-Wire Toroidal Inductors,"
[9] R. P. Wojda, "Winding Resistance and Power Loss of Inductors With Litz and Solid-Round Wires,"

Acknowledgments

A subset of this material is based upon the collaborative work between the U.S. Department of Energy (DoE), Eaton Corporation and the University of Pittsburgh.

Another subset is based on collaboration between the Office of Naval Research and the University of Pittsburgh.