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Design, Modeling, and Testing of a Novel Inductor for Electric Vehicles

Sydney Fultz-Waters, Jacob Krynock
Materials Engineering Department
California Polytechnic State University, San Luis Obispo

Sponsored by Sandia National Laboratories

Overview

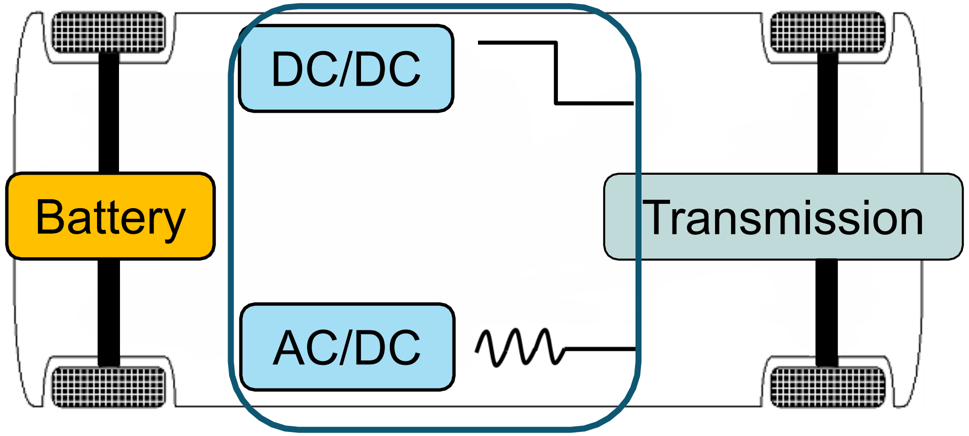
- Background
- Problem Statement
- Methods and Materials
- Results
- Discussion and Analysis of Results
- Conclusions
- Acknowledgements

Background

Inductors in Electric Vehicles

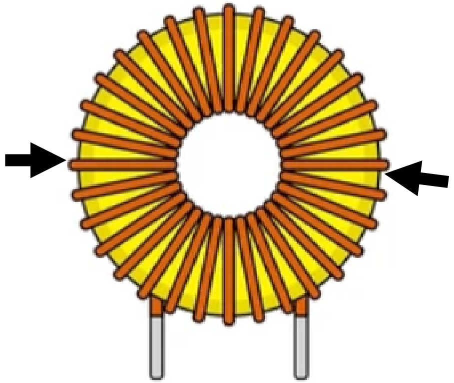
New EV technology emphasizes improved power system components at low prices

- Inductors control or convert current in EV systems
- Must withstand high operating temperatures and frequencies



EV power system schematic

Electrically conductive windings



Magnetic core

An example of a toroidal inductor

Power Loss in Inductors

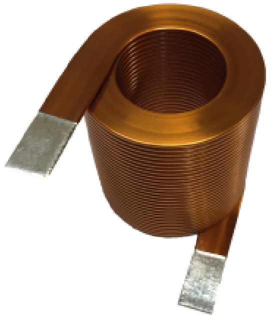
Inductor Power Loss

Winding Loss

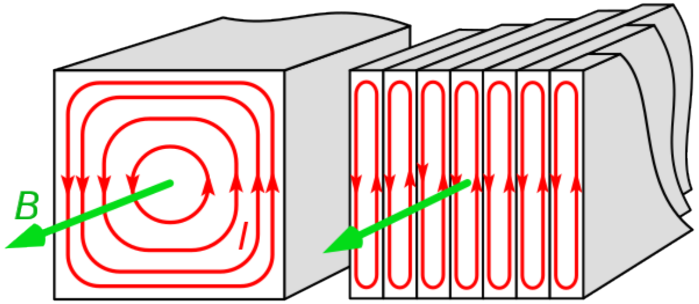
Core Loss

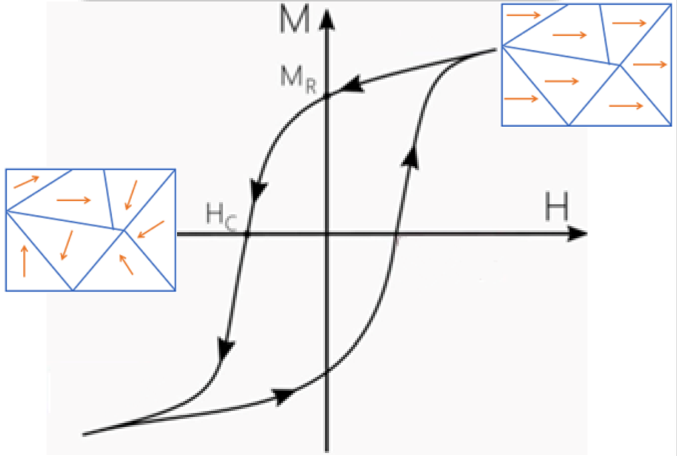
Eddy Currents

Hysteresis Loss



$$P = I^2 R_{wire}$$



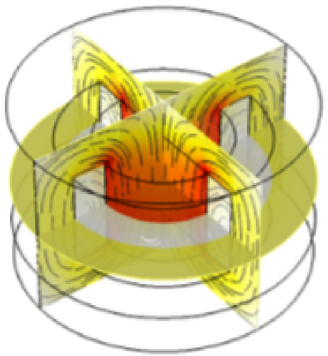


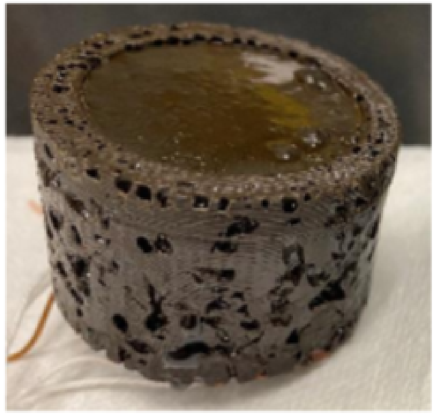
How to minimize?	↓ Resistivity (ρ_{wire}) ↓ Length (l_{wire}) ↑ Cross-sectional Area (A_{wire})	↑ Resistivity (ρ_{core}) ↓ Cross-sect Area (A_{core})	↑ Permeability (μ_r) ↑ Saturation Magnetization (M_s)

Iron Nitride Inductors

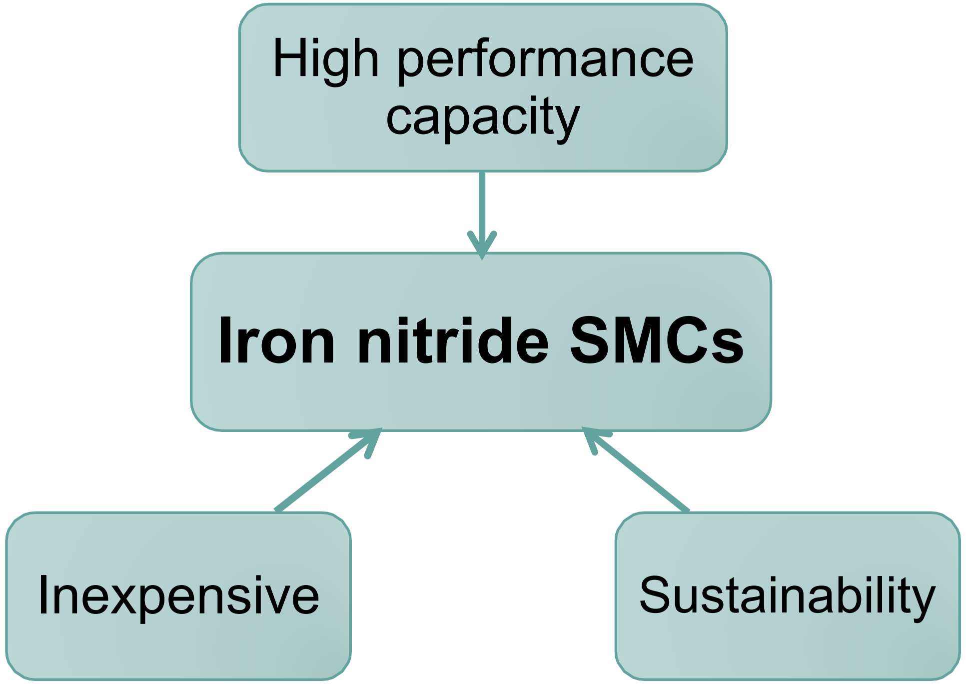
Power system components must operate at high temperatures and high frequencies

- Development of iron nitride (IN) soft magnetic composite (SMC) at Sandia National Labs





Left: COMSOL model of toroidal inductor.
Right: Previous bobbin inductor prototype.



Inductor Core Materials

Magnetic Material	Saturation Magnetization, M_s (T)	Resistivity, ρ (μΩ·m)	Description
Si Steel	**1.87**	0.05	• Laminated Si steel sheets • Most common core material
Ferrite	0.52	**5×10^6**	• Powdered Fe_2O_3 pressed with small amounts of Ni, Zn, and/or Mn
Iron nitride SMC	**1**	$\rightarrow \infty$	• Composite lowers M_S from 1.89 T to 1 T but increases resistivity • High temperature stability

MATERIALS ENGINEERING California Polytechnic State University

CAL POLY College of Engineering

Sandia National Laboratories

Problem Statement

What is the optimal size, number of windings, vol% loading of iron nitride, and wire gauge to meet the 600 μH inductance requirement of the inductor?

Size → height (h), inner radius (a), outer radius (b)

Number of windings → number of turns (N)

Vol% loading of iron nitride → affects permeability (μ)

Wire gauge → diameter of wire

$$L = \frac{\mu N^2 h}{2\pi} \ln\left(\frac{b}{a}\right)$$

Equation to calculate the inductance (L) of a toroidal inductor

Optimize design of inductor

- COMSOL Multiphysics software (Finite Element Analysis)
- Experimental data to validate scaled model to reach 296 μH

Methods and Materials

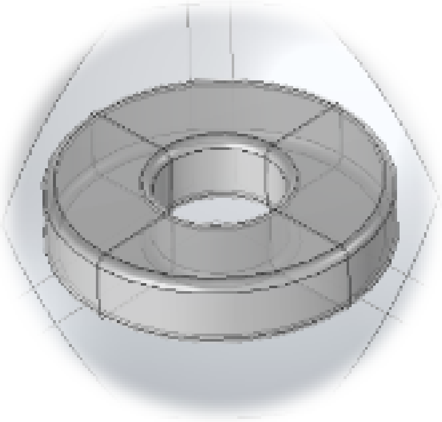
Experiment Design

Modeling and Simulation

- Numerical model
- Finite element analysis (FEA)
  - COMSOL Multiphysics software

$$L = \frac{\mu N^2 h}{2\pi} \ln\left(\frac{b}{a}\right)$$

Inductance equation used in modeling



Toroidal inductor in COMSOL

Experimental Validation

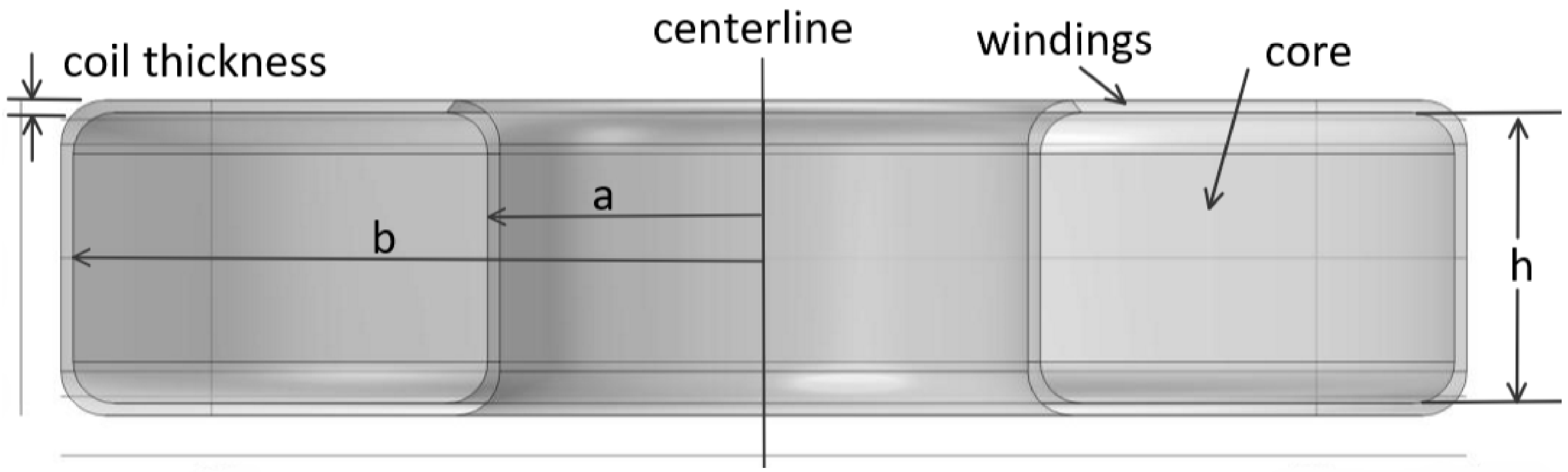
- Inductor fabrication
  - 2^2 = four total inductors
  - Reduced scope to conserve resources

Factors	Levels	
Vol% of Iron Nitride	65 vol% IN	50 vol% IN
Wiring Size	20 AWG	26 AWG

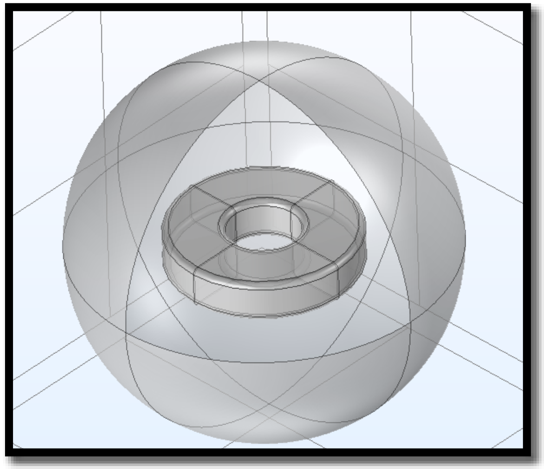
COMSOL Modeling

Assumes homogeneous conductor with *N* turns => single domain layered over core

- Includes insulative coating on windings to separate wires
- Air sphere generated around inductor to simulate realistic operating environment
- Fine meshing to increase accuracy of solution



Cross-section view


Toroidal inductor in COMSOL before solving for inductance

MATERIALS ENGINEERING

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Inductor Fabrication

1. Mold Development

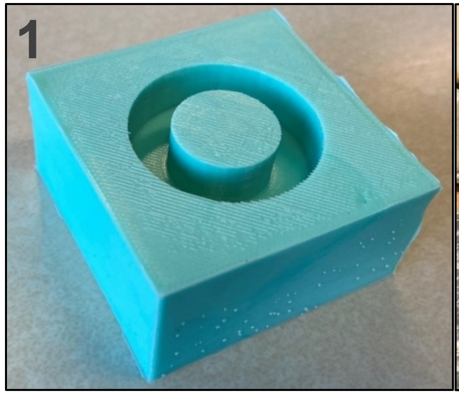
- Design antimold in SolidWorks for 3D printer
- Silicone rubber mold

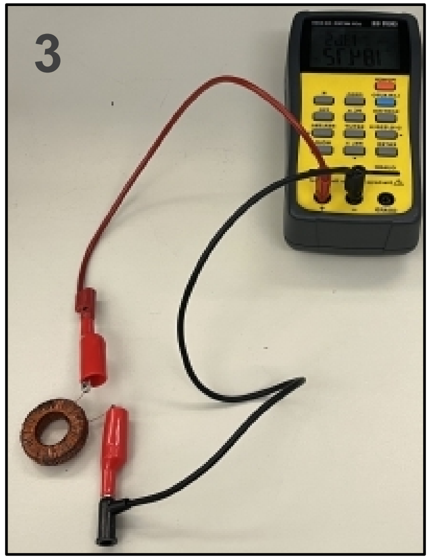
2. Composite Mixture and Cure

- Mix thermoset epoxy (4-AS and NND) and IN powder, then cure in mold at 180°C for 12 hours
- Grind to remove sharp edges and obtain level surfaces

3. Winding and Testing

- Hand wind with high temp copper wire before inductance and resistance testing with LCR meter
- Remove enamel through tinning process





Target Dimensions

h = 1.4 cm

a = 1 cm

b = 1.6 cm

N = 150 turns

Target Scaled Inductance

L = 296 μH

Results

Effective Vol%

Effective vol% differs from expected vol%

- Voids from curing process and packing into the mold
- Bigger issue for 65 vol% due to higher density

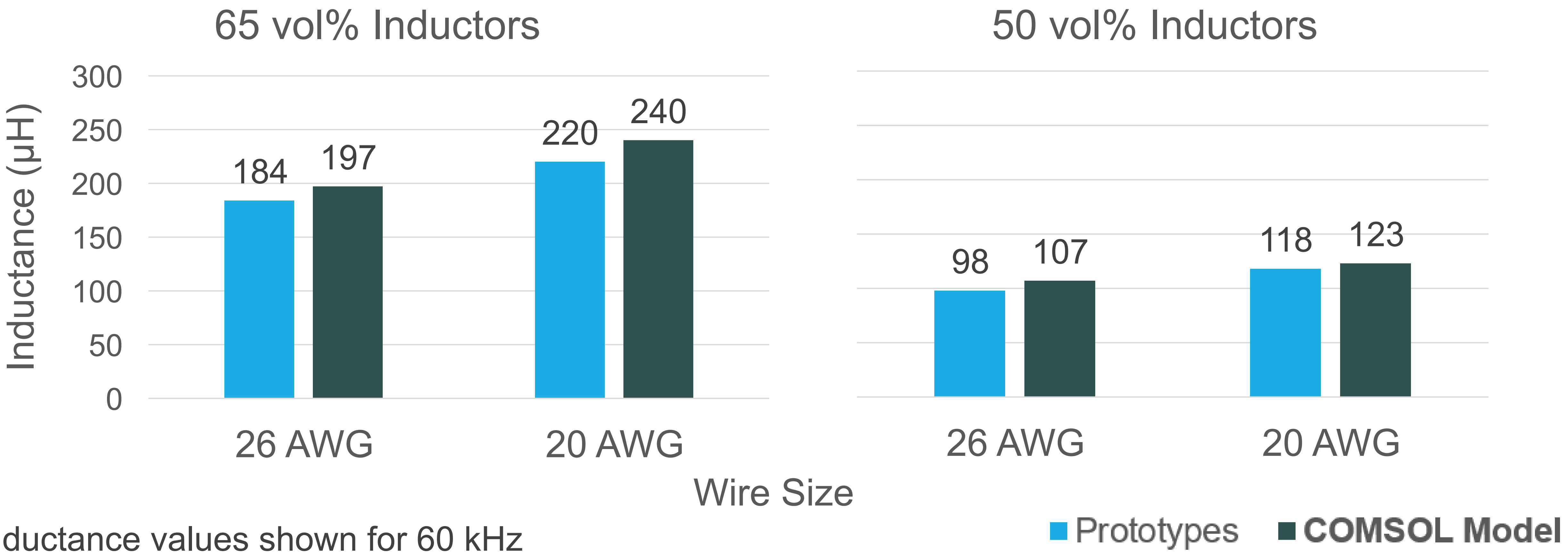
Decreasing permeability in model reflects effective vol% and reduced magnetization

- Given μ(65 vol%) = 13, Estimated μ(65 vol%) ≈ 8
- Given μ(50 vol%) = 7, Estimated μ(50 vol%) ≈ 6

Inductor Prototype	Porosity	Effective Vol%	Model μ_r
65 vol% IN, 26 AWG	12%	58	8
50 vol% IN, 26 AWG	5%	48	6
65 vol% IN, 20 AWG	6%	61	8.5
50 vol% IN, 20 AWG	3%	49	6

Effective vol% and corresponding permeability used in COMSOL model

Combining Model and Experiment



Inductance values shown for 60 kHz
(interpolated from measured inductance values at 1, 10, and 100 kHz)

Discussion and Analysis of Results

% Difference in Inductance Results

Inductance does not change significantly over 1-100 kHz

Current model accounts for magnetization effects and voids by lowering permeability

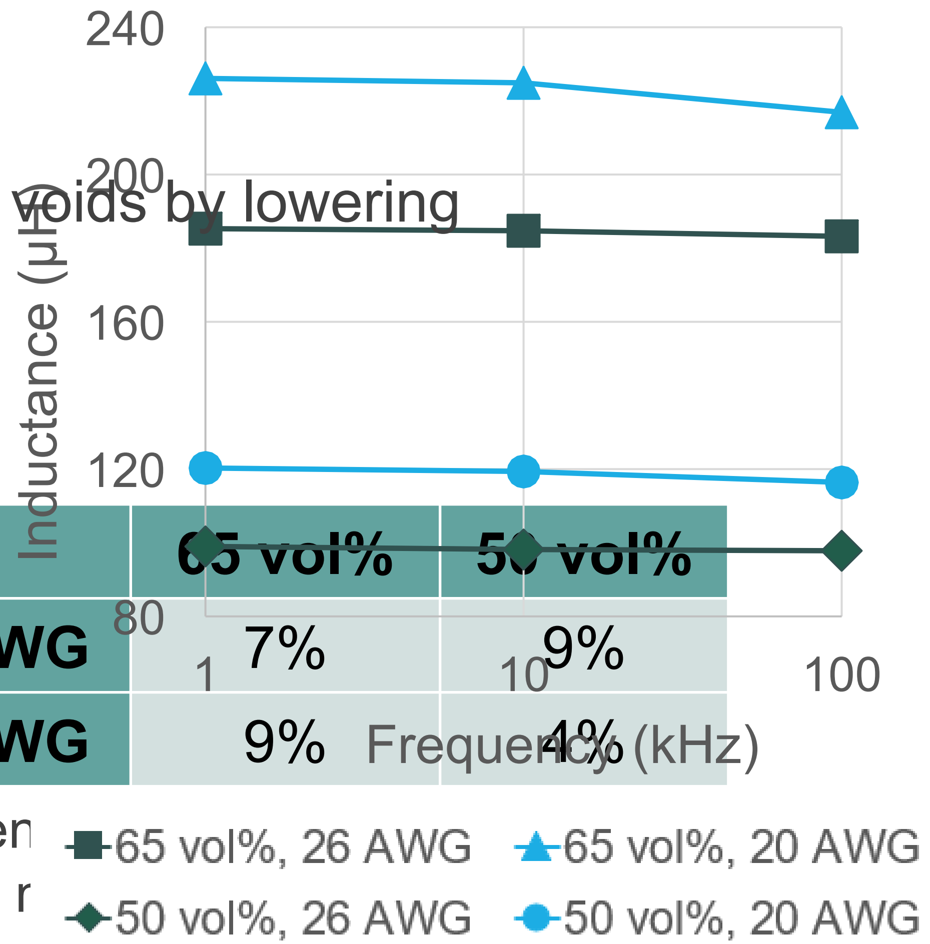
- Permeability of each vol% is different
- % difference < 10% accepted for this model

	65 vol%	50 vol%
26 AWG	8	6
20 AWG	8.5	6

Permeability values used in COMSOL model

	65 vol%	50 vol%
26 AWG	7%	9%
20 AWG	9%	4%

Percen
r



Conclusions

Conclusions

Larger wire size increases inductance due to lower AC resistance

- Investigate other types of conductors that do not increase AC resistance at high frequencies (e.g., Litz wire)

Model is better at predicting 50 vol% inductance likely due to the decreased vol% loading and corresponding decrease in voids

- COMSOL model shows better agreement for 50 vol% with a permeability of 7
- Current model does not account for core losses due to hysteresis or eddy currents

Greater hysteresis losses in 65 vol% inductors due to increased magnetic field

Revisiting Problem Statement

Project goal: a tunable model that is both precise and accurate

- ✓ **Precision:** the % difference between the model and experiment is similar for each set of inductor parameters
- x **Accuracy:** lowering the permeability is a temporary solution, does not accurately reflect core losses

296 μH → 600 μH Optimization:

- Optimal wire size and vol% loading based on results: 20 AWG, 65 vol%
- Size and number of turns determined from Excel Solver and verified with COMSOL
- Final results TBD until final model is finished that encompasses core losses

Acknowledgements

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