Transformer Leakage Inductance Design Methodology

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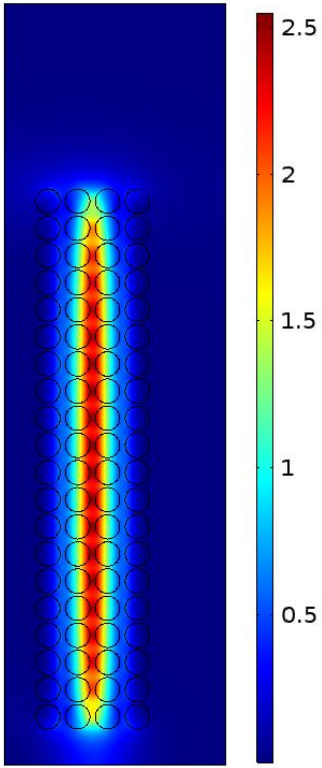
Outline

- Transformer leakage inductance
- Magnetically-integrated transformers
- Motivation
- Design specifications
- General transformer design
- Leakage inductance design
- Results and discussion
- Conclusion

Transformer Leakage Inductance (L_{lk})

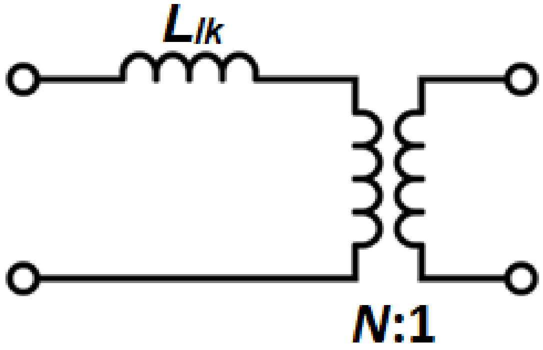
- Byproduct of stored magnetic energy
- Depends on the winding geometry
  - *winding structure*
    - number of layers, number of turns per layer
  - *interleaving configuration*
    - PPSS, PSSP, PSPS for 4 layers
  - *key design parameters:*
    1) inter-winding gap
    2) inter-layer gap
    3) inter-turn gap
    4) overlapping height of the two windings
- Infinite design possibilities



Magnetic energy density (J/m^3)

Magnetically-integrated Transformers

- L_{lk} can replace the series inductor in power converters
- Scope to reduce cost and footprint
- Requires precise L_{lk} design and tuning



Two-step design process

Step 1	General transformer design	Outputs the required core size, number of turns, and wire gauge
Step 2	Leakage inductance design	Outputs the right winding structure, interleaving configuration and key design parameters

Motivation

- Several methods exist for general transformer design, like Area Product Method, K_g (core geometry) method, etc.
- No emphasis on leakage inductance design
- Leads to inefficient design process—requires numerous trial-and-error iterations
- Only a handful of experienced magnetic engineers/designers know the tricks to tune the L_{lk}

This paper attempts to make the design process of magnetically-integrated transformers simpler and more efficient.

Design Specifications

Target: Naturally air-cooled 2-winding transformer for an isolated resonant dc-dc converter

Output power	1 kVA
Input voltage (rms)	340 V
Turns ratio	1:1
Operating frequency	220 kHz
Duty cycle	0.5
Maximum flux density	0.1 T
Maximum temperature rise	50º C

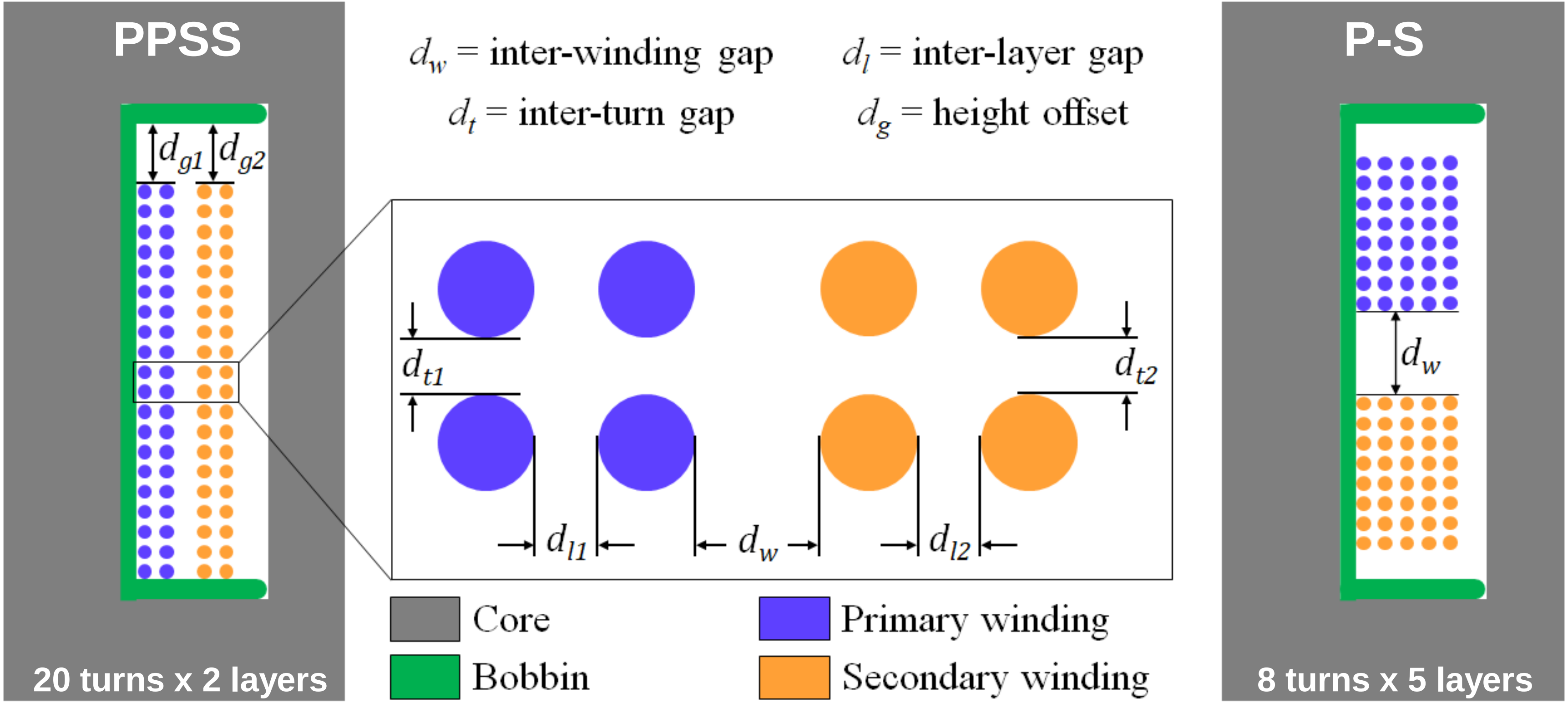
General Transformer Design (contd.)

Results of the *Area Product Method*

Minimum area product	1.65 cm^4
Selected core	**ETD 39** ($WaAc$ = 2.18 cm^4)
Peak current density	484 A/cm^2
Selected wire gauge	**AWG 19** (J = 450 A/cm^2)
Primary/secondary turns	**40/40**
Core loss	1.27 W
DC copper loss	1.24 W
Temperature rise	34.9º C
DC efficiency	99.75 %

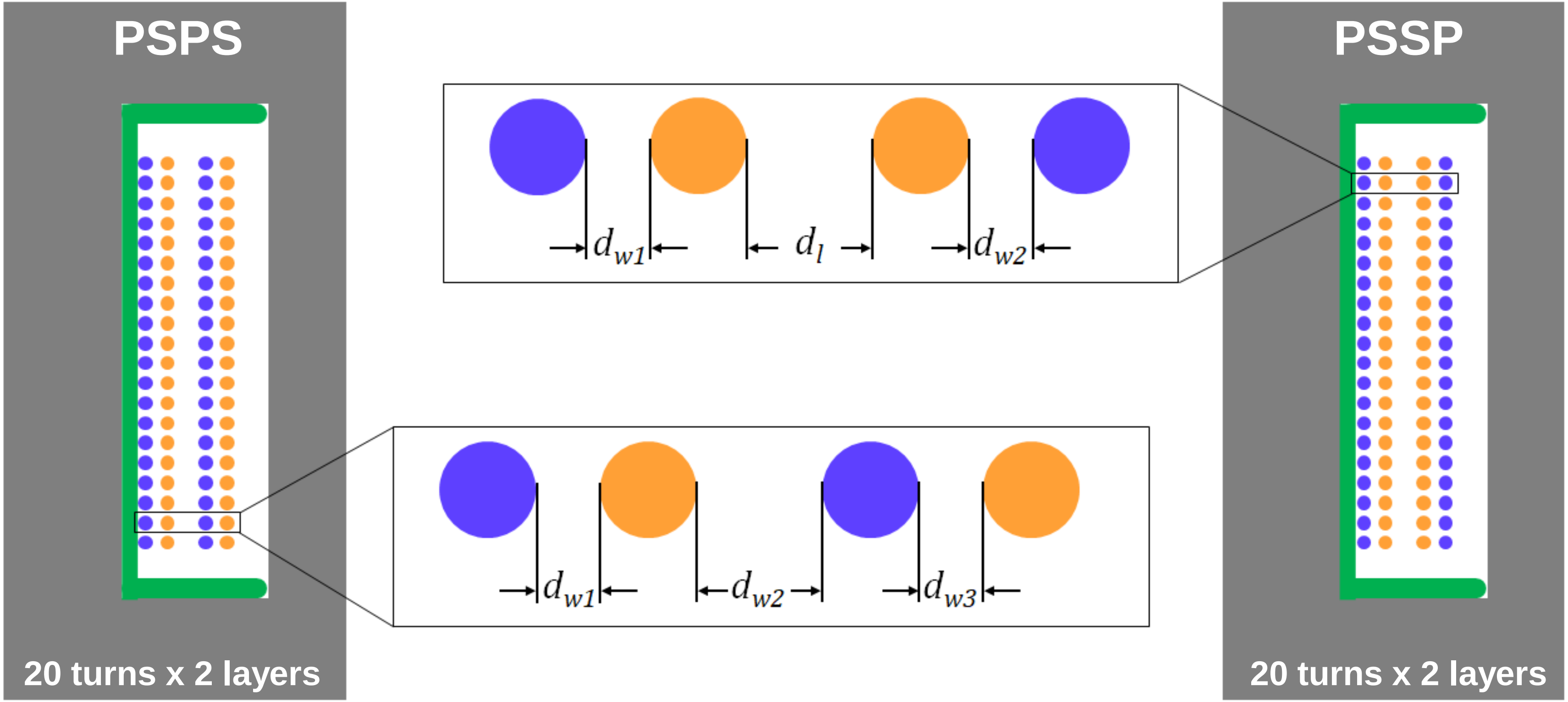
Leakage Inductance Design

2 winding structures: **PPSS** and **P-S**



Leakage Inductance Design (contd.)

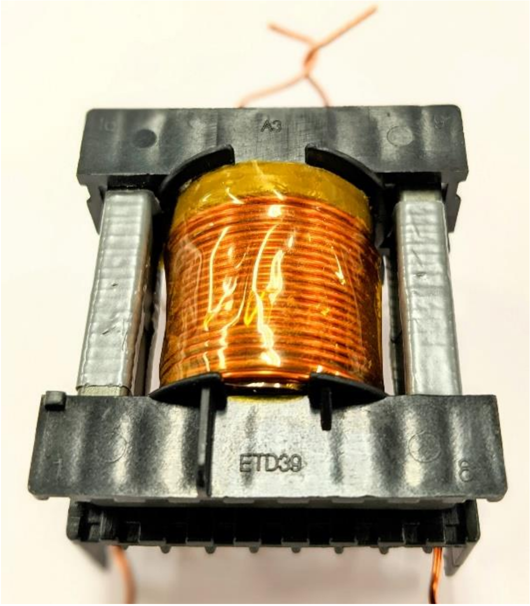
3 possible interleaving configurations: PPSS, **PSPS** and **PSSP**



Results

Ideal values of different parameters
and corresponding L_{lk}

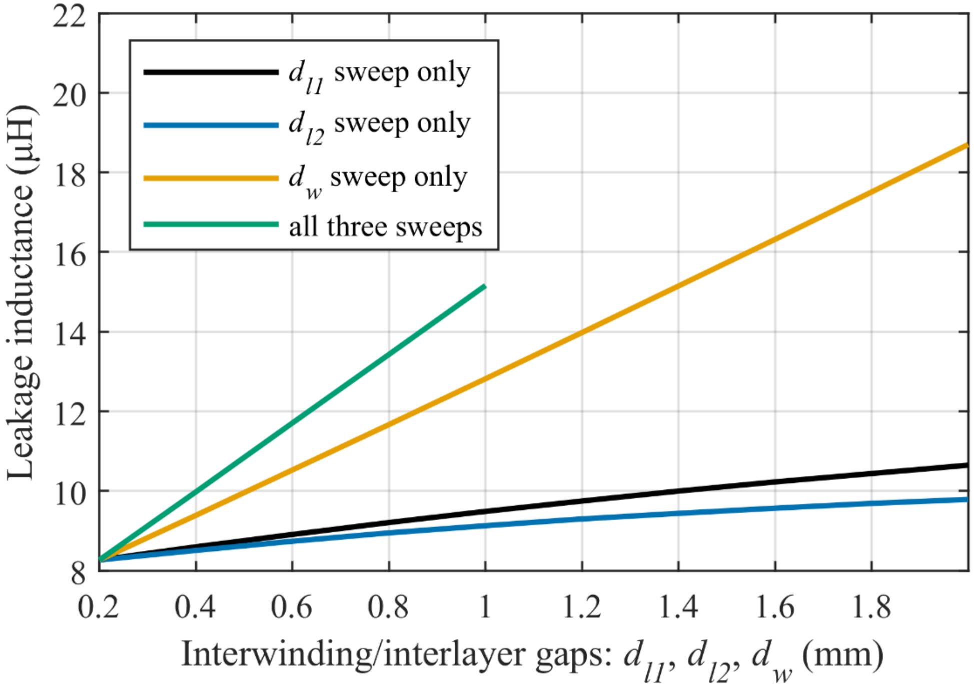
Parameter	**Value**			
	PPSS	**PSPS**	**PSSP**	**P-S**
d_l **(mm)**	0.2	0.2	0.2	0.2
d_w **(mm)**	0.2	0.2	0.2	0.3
d_t **(mm)**	0.1	0.2	0.2	0.2
d_g **(mm)**	0	1.8	1.8	0
L_{lk} **(μH)**	**8.27**	**1.92**	**2.29**	**45.84**

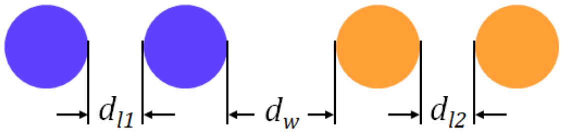


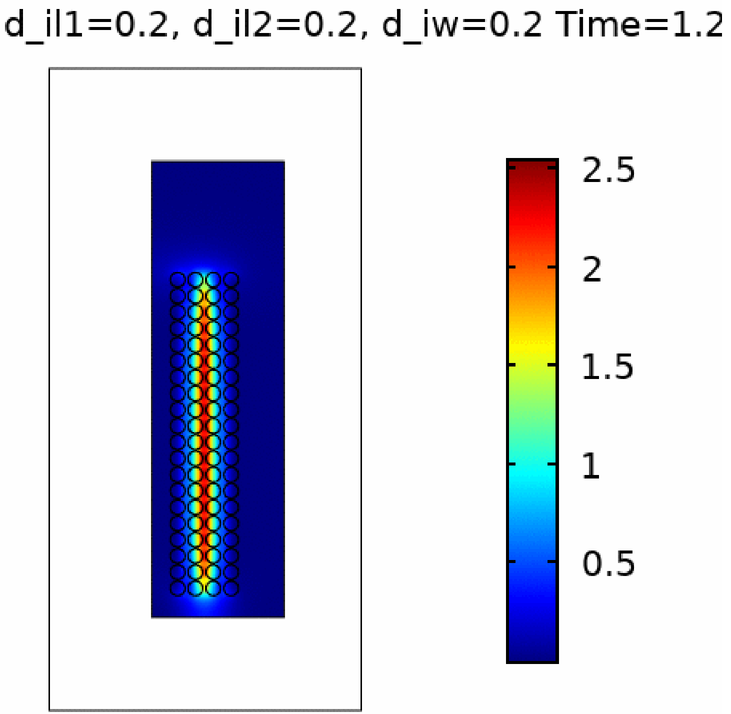
PPSS Structure
Measured leakage inductance = 8.3 μH

Results: PPSS structure

Parametric sweep of inter-winding and inter-layer gaps

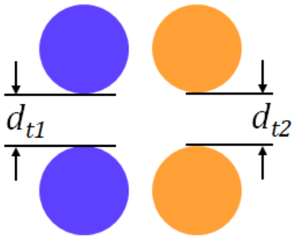




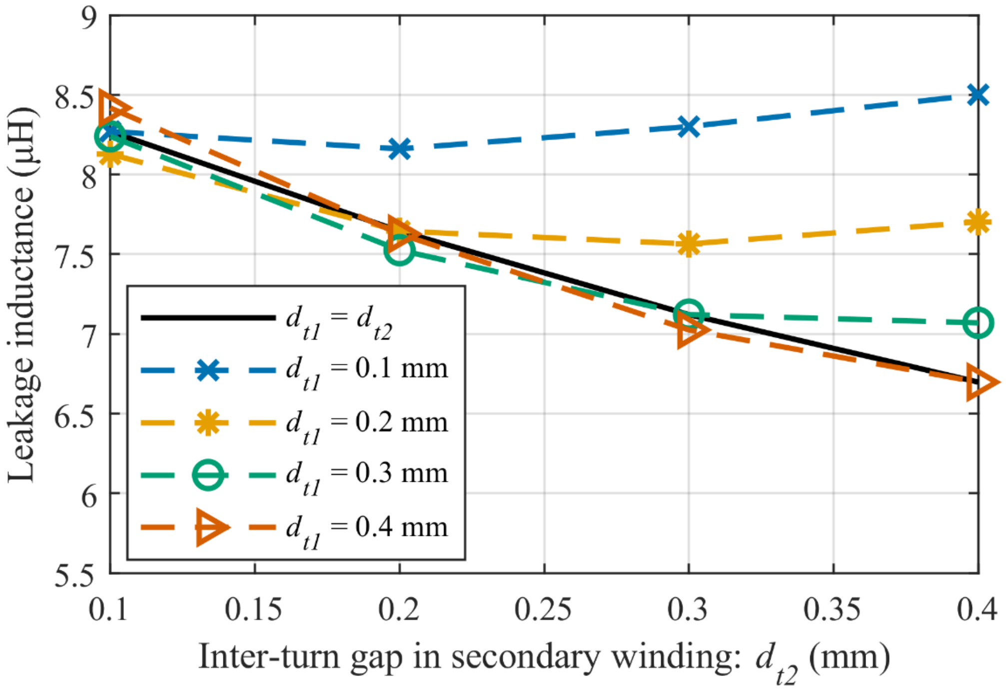


Magnetic energy density (J/m^3)

Results: PPSS structure



Parametric sweep of inter-turn gap



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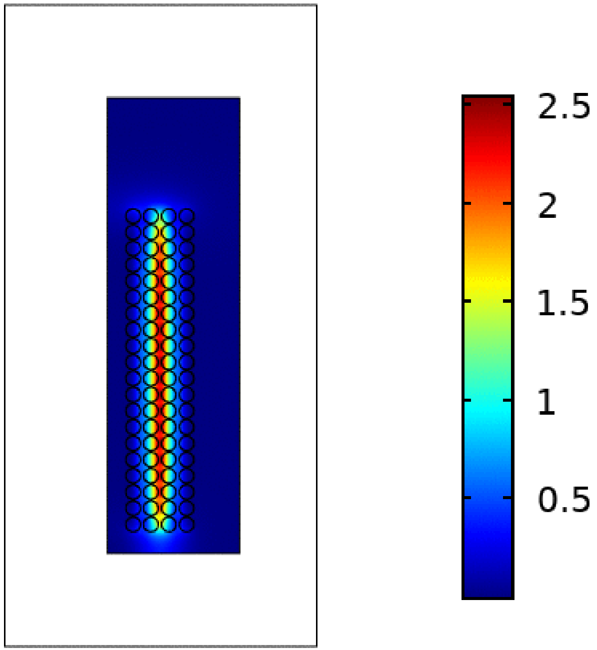
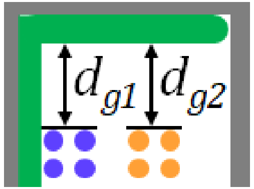
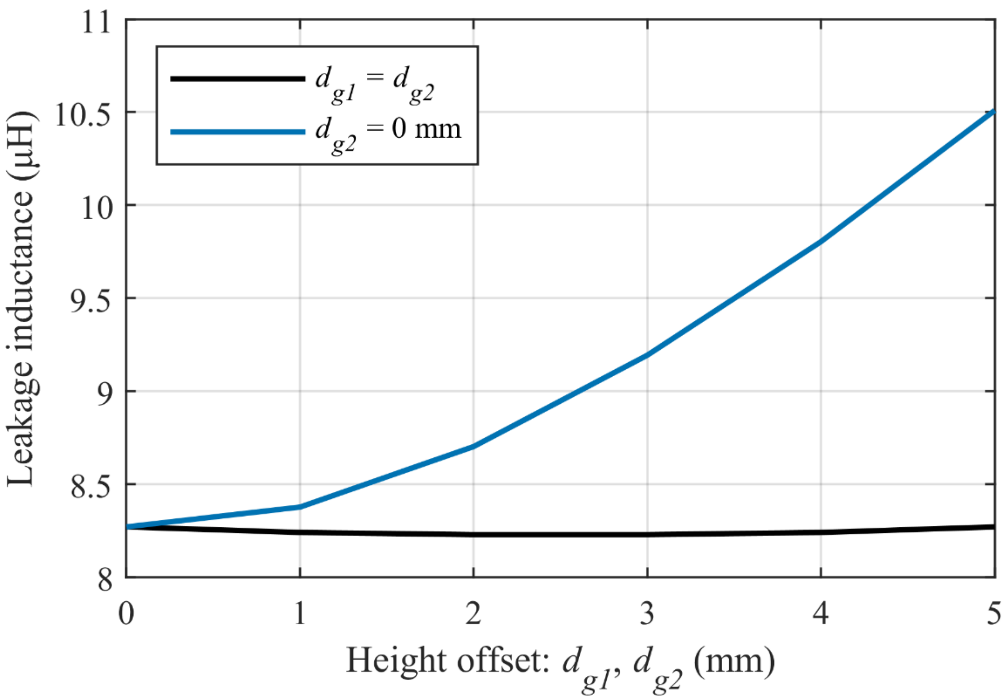


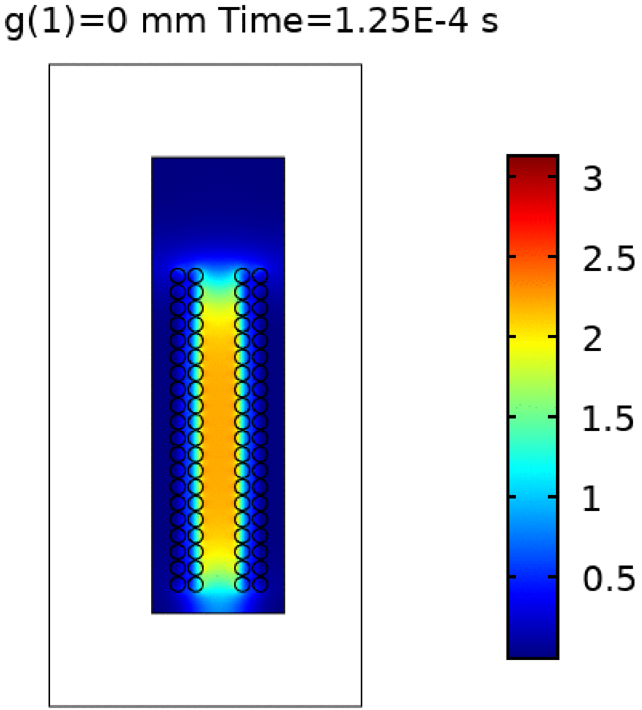
Magnetic energy density (J/m^3)

Results: PPSS structure



Parametric sweep of the height offset

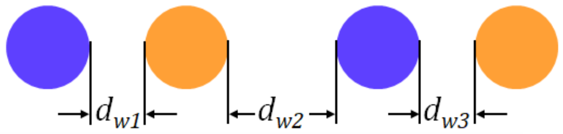




Magnetic energy density (J/m^3)

Results: PSPS structure

Parametric sweep of inter-winding and inter-layer gaps



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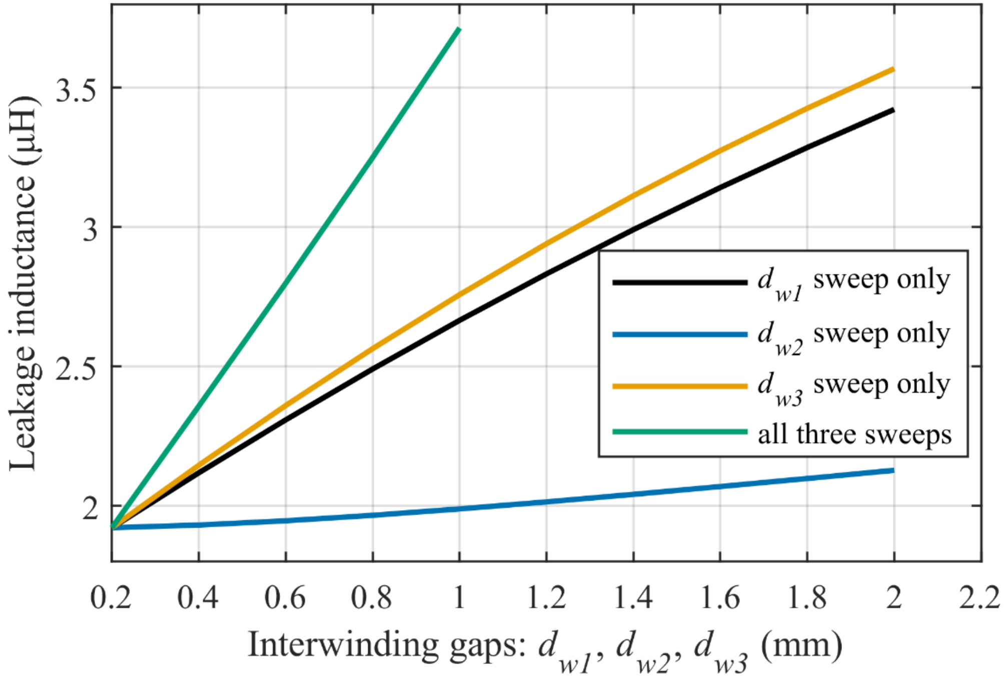
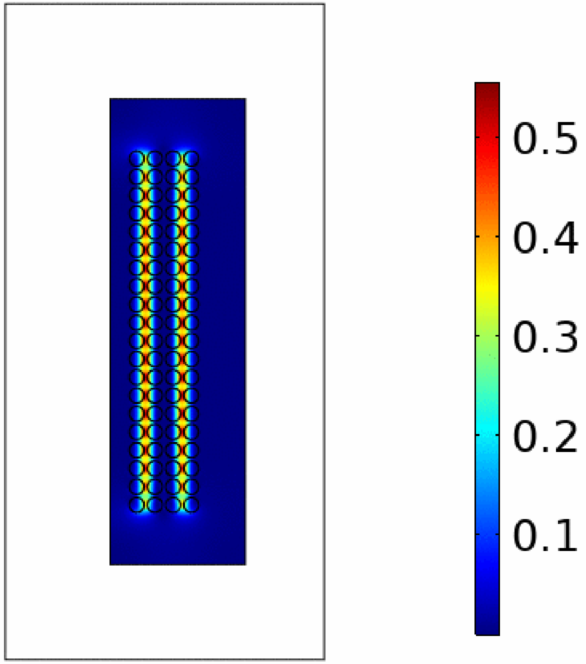
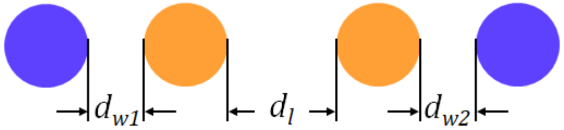




Magnetic energy density (J/m^3)

Results: PSSP structure

Parametric sweep of inter-winding and inter-layer gaps



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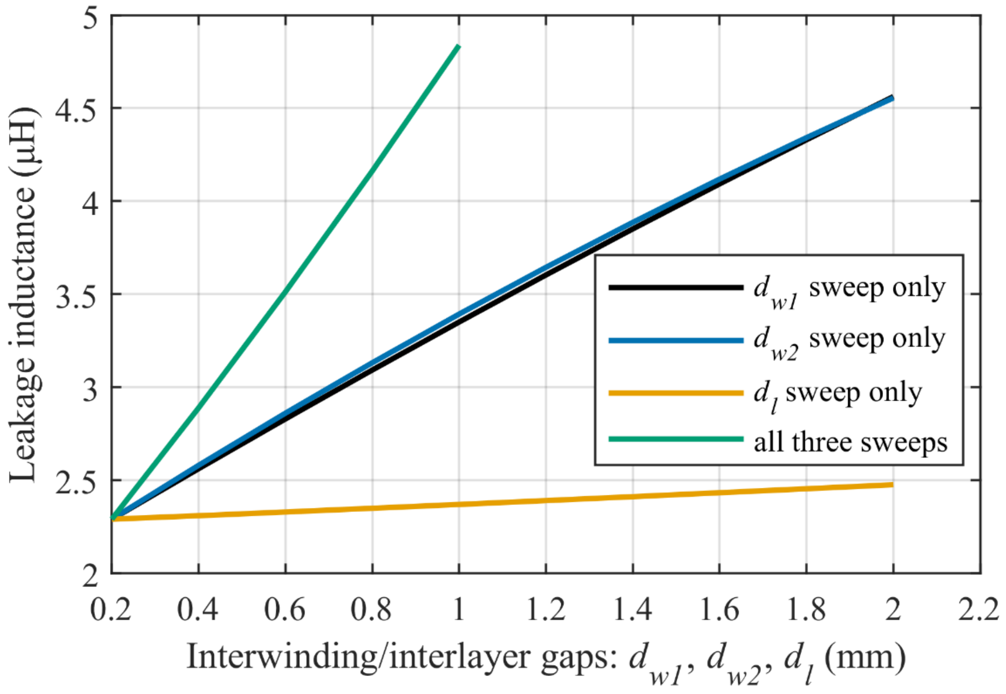
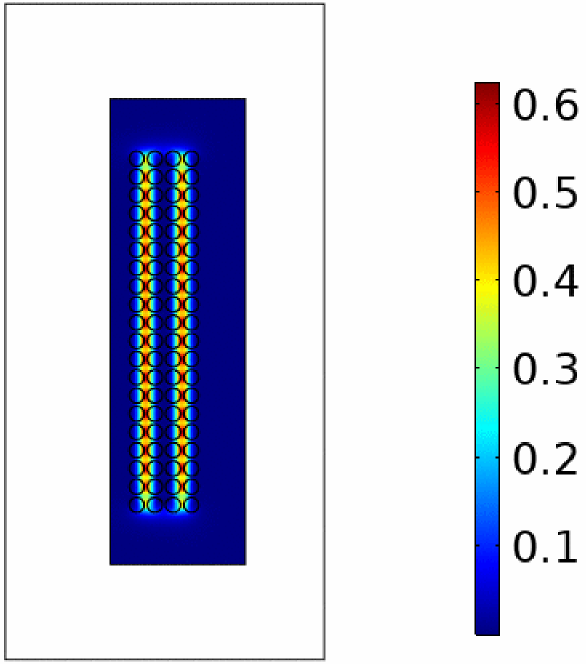
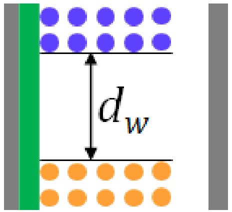


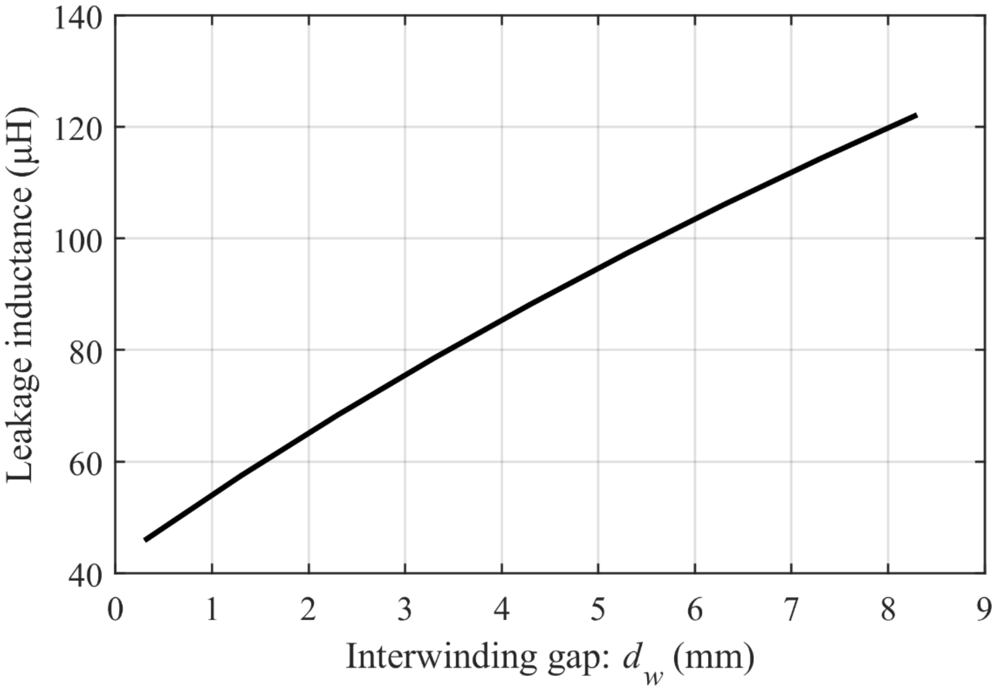


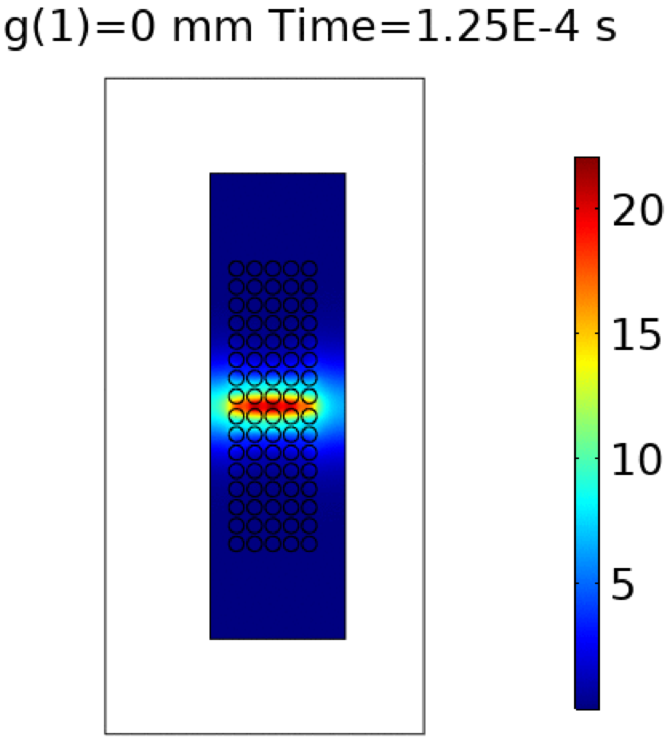
Magnetic energy density (J/m^3)

Results: P-S structure



Parametric sweep of inter-winding gap





Magnetic energy density (J/m^3)

Discussion

1) Interleaving of layers can reduce the effective L_{lk}
2) Alternately arranged P and S layers give the smallest L_{lk}
3) Most of the leakage energy is stored in d_w
4) Varying d_w can help in making large adjustments
5) Varying d_l can help in making small adjustments
6) Offsetting the height of one of the windings can increase L_{lk}

Conclusion

Using the Area Product Method, a 1 kVA, 340/340 V, 220 kHz, 2-winding transformer is designed with two ETD 39 ferrite cores and 40 turns of enameled AWG 19 wires per winding.

2 winding structures and 3 interleaving configurations of one of the 2 structures are investigated

Trends in L_{lk} due to various parametric sweeps are recorded and further discussed

Results show that L_{lk} between 1.9 and 122.1 μH is achievable

Observations made here can be helpful for future magnetic engineers/designers in realizing the desired L_{lk} with fewer trial-and-error iterations

Reference

1) C. W. T. McLyman, *Transformer and inductor design handbook*. CRC press, 2004.
2) **A. Sharma and J. W. Kimball**, "Evaluation of transformer leakage inductance using magnetic image method," *IEEE Transactions on Magnetics*, vol. 57, no. 11, pp. 1–12, 2021.
3) **A. Sharma and J. W. Kimball**, "Novel transformer with variable leakage and magnetizing inductances," in *2021 IEEE Energy Conversion Congress and Exposition (ECCE)*. IEEE, 2021, pp. 2155–2161.
4) Z. Ouyang, O. C. Thomsen, and M. A. Andersen, "The analysis and comparison of leakage inductance in different winding arrangements for planar transformer," in *2009 International Conference on Power Electronics and Drive Systems (PEDS)*. IEEE, 2009, pp. 1143–1148.

Thanks

for your attention!

Questions?

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