Precision Power Magnetics Engineering: A Key Step toward High Performance Power Electronics

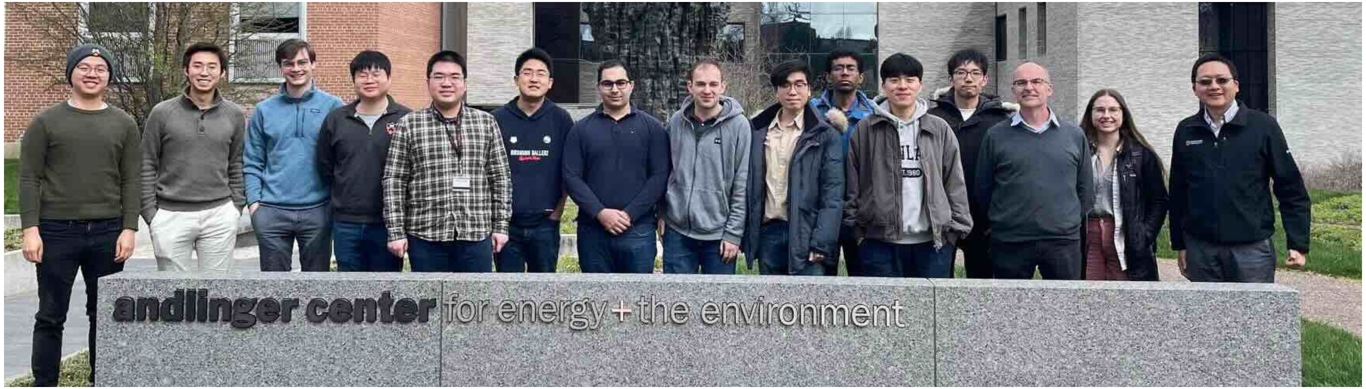
Minjie Chen

Princeton University

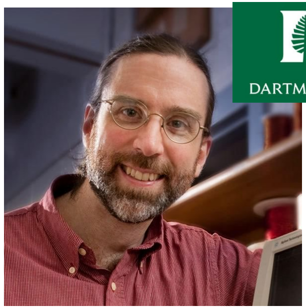
PRINCETON UNIVERSITY

pels IEEE POWER ELECTRONICS SOCIETY Powering a Sustainable Future

Princeton Power Electronics Research Team



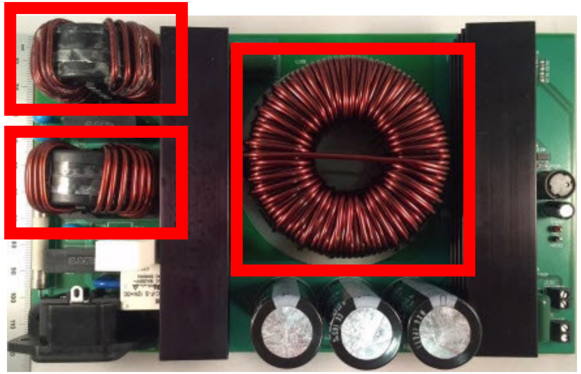
Prof. David Perreault

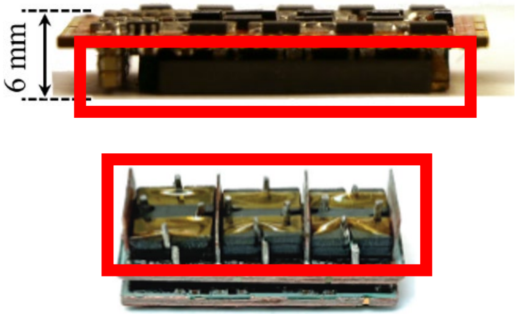


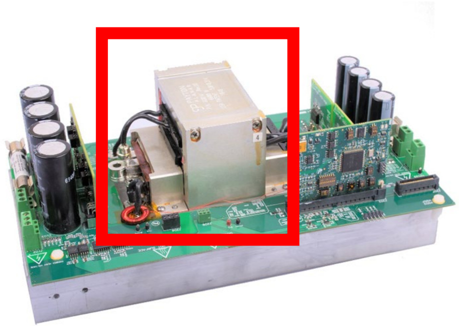
Prof. Charles Sullivan

Magnetics as the main performance/size limiter …

- **Magnetics design is interesting** (inductors, transformers, coupled inductors, EMI filters, etc.)
- **Magnetics design is complicated** (material, geometry, winding, loss, thermal, etc.)
- **Magnetics design is imprecise** (core loss, saturation, B-H loop, temperature) -> sub-optimal





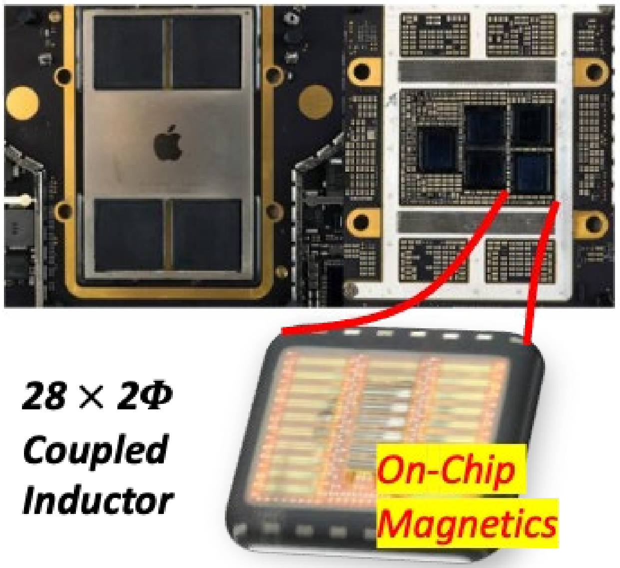


- Source: Princeton University, Texas Instruments

Every mm³ of magnetics is cost and performance …

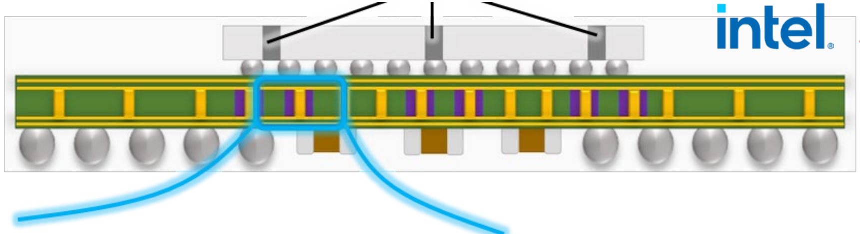
On-Chip Magnetics

Apple – October 2021 – Mac M1 Pro / M1 Max

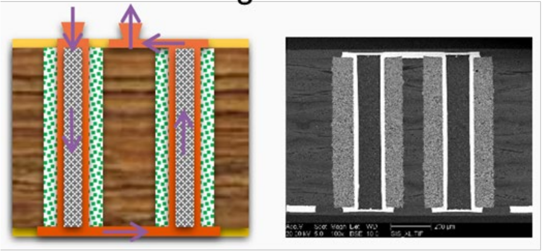


28 × 2Φ Coupled Inductor

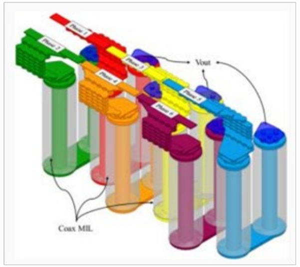
Vertical Power Delivery and Vertical Magnetics



Coaxial Magnetic Inductors



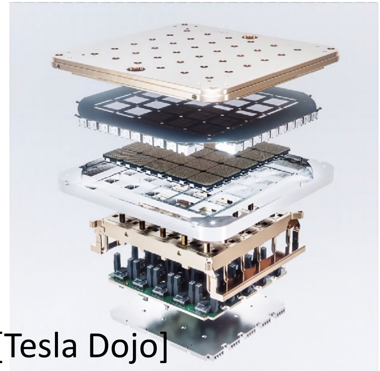
3D Implementation



- M. Chen and C. R. Sullivan, "Unified Models for Coupled Inductors Applied to Multiphase PWM Converters," in *IEEE Transactions on Power Electronics*, vol. 36, no. 12, pp. 14155-14174, Dec. 2021.

Other emerging applications need precision …

Future Computing



[Tesla Dojo]

Vertical power delivery

Electric Vehicles

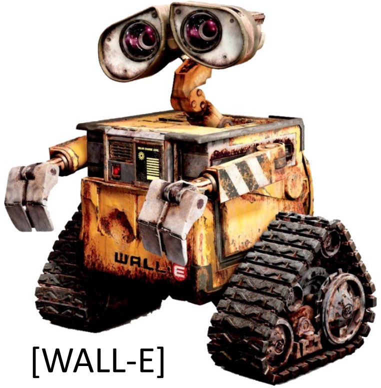
[Tesla]

Wide temperature range

Renewable Energy

High reliability

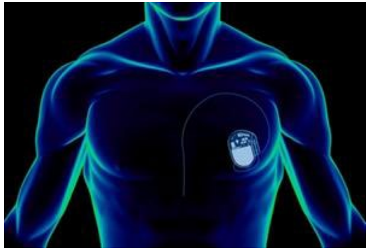
Robotics



[WALL-E]

High efficiency

Biomedical



Miniaturization

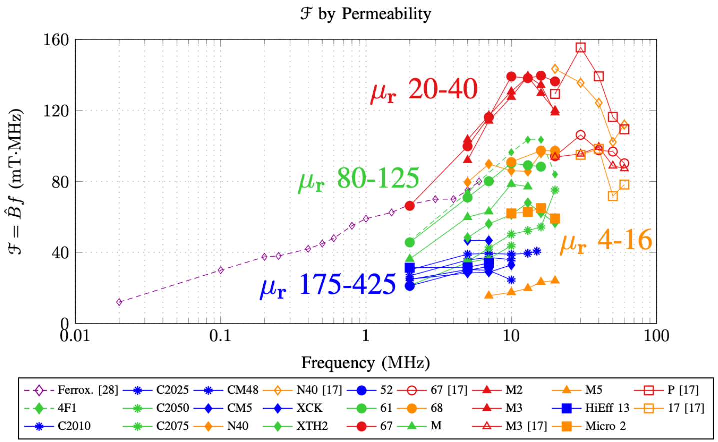
More Electric Aircraft

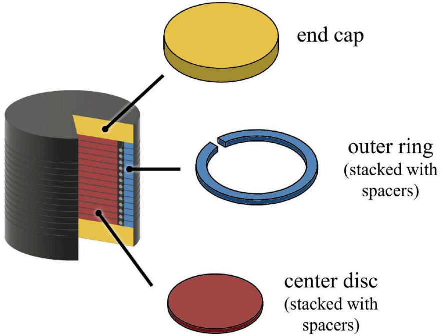
Light weight

High frequency power magnetics

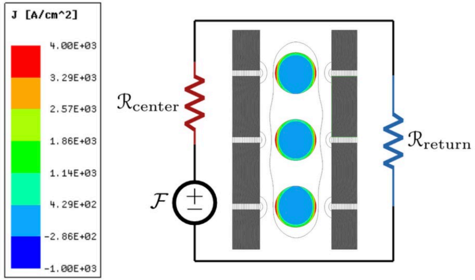
Option #1: Increasing the switching frequency

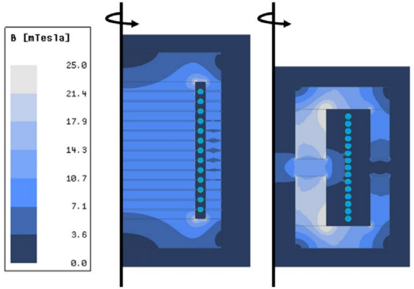
- Reduce the energy buffering requirement, reduce the B_{max}
- Better materials, better circuits, and better structural design





High Q inductors in the 5 MHz-10 MHz range





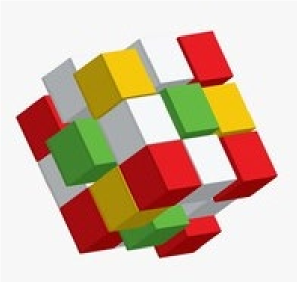
- A. J. Hanson, J. A. Belk, S. Lim, C. R. Sullivan and D. J. Perreault, “Measurements and Performance Factor Comparisons of Magnetic Materials at High Frequency,” in TPEL’16.
- R. S. Yang, A. J. Hanson, C. R. Sullivan and D. J. Perreault, “Design Flexibility of a Modular Low-Loss High-Frequency Inductor Structure,” in TPEL’21.

High precision power magnetics

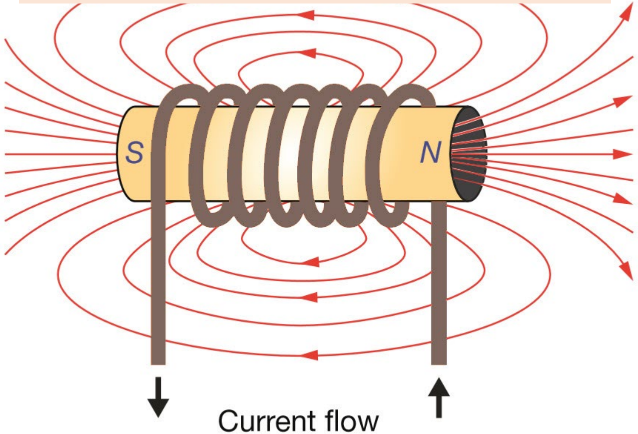
Option #2: Optimizing flux and current distribution

- Better magnetic flux …
- Better current distribution …

Magnetic Rubik

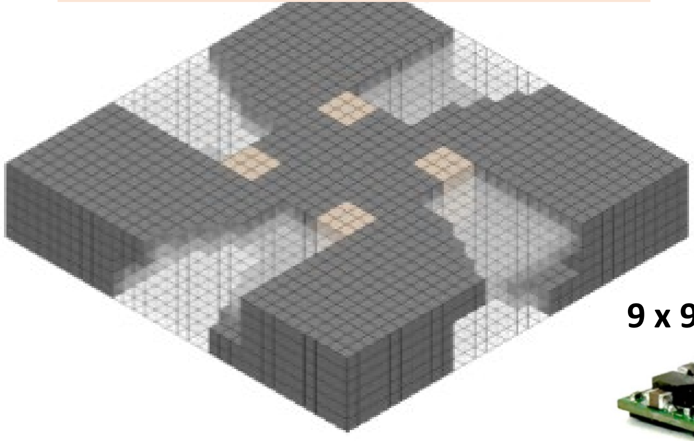


Approximate Magnetics



Flux & current for discrete assembly

Precision Magnetics

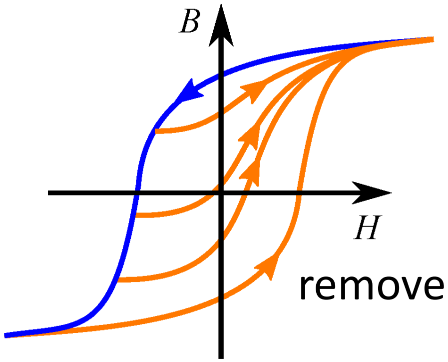


9 x 9 x 3.4 mm

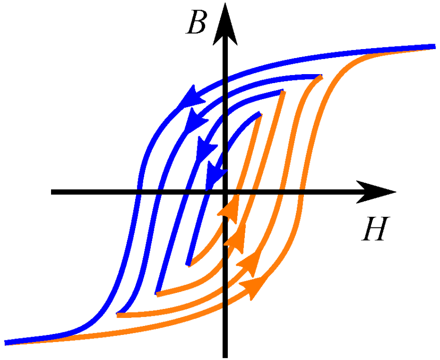
Flux & current co-optimization / co-design

Better utilization of magnetic materials and conductors

Optimal flux distribution

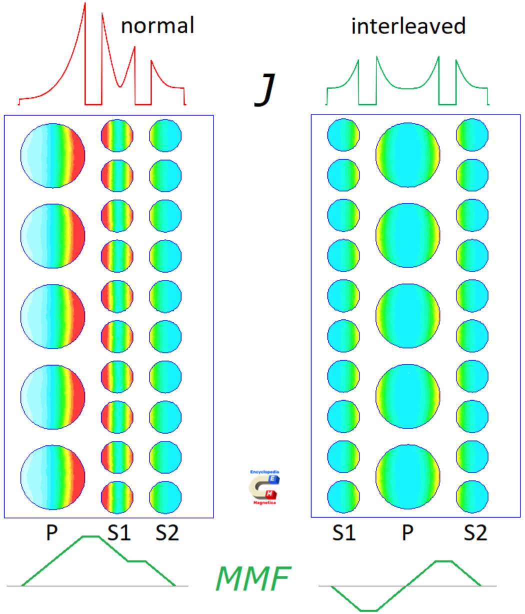


Deeper energy cycle



Material + freq + waveform mix

Optimal current distribution



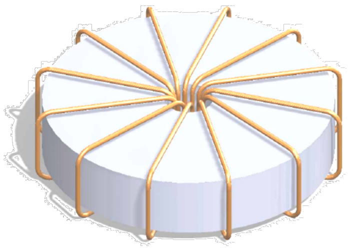
Precision of power magnetics design:

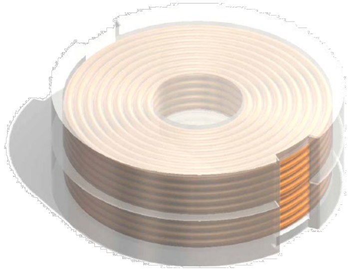
- Flux modeling & design (**imprecise**)
- Current distribution modeling & design (**precise**)
- Precise co-design of flux and current for complex structures (**opportunities**)

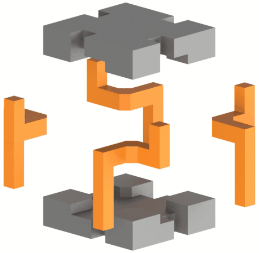
Optimizing flux and current distribution

PRINCETON UNIVERSITY

- **Current wrap around Flux**, or **Flux wrap around Current**

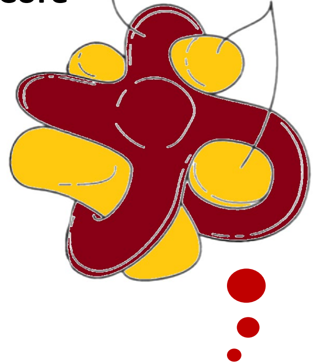


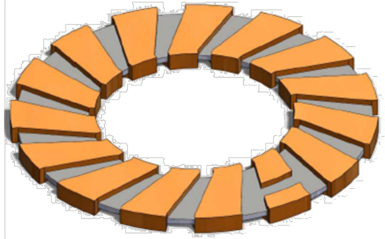


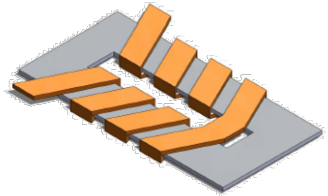


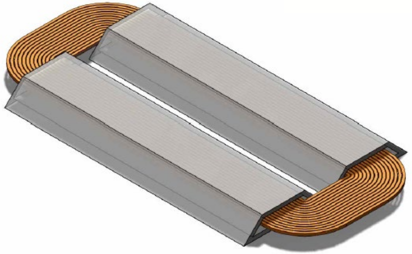
Twisted Core

Twisted Winding









Google

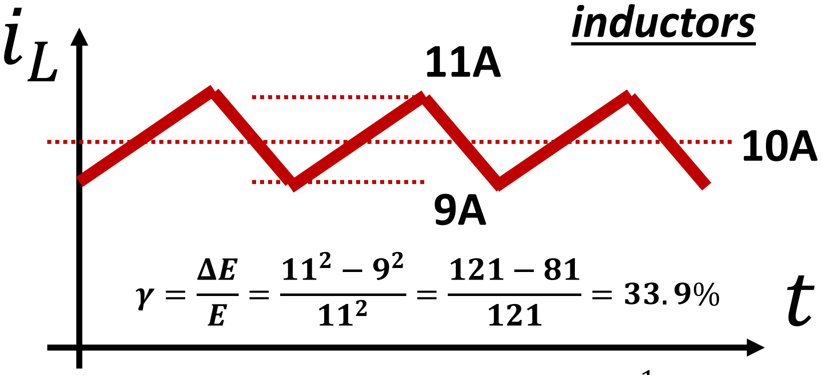
intel

Prof. Charles Sullivan
Dartmouth College

- C. R. Sullivan and M. Chen, "Coupled Inductors for Fast-Response High-Density Power Delivery: Discrete and Integrated," 2021 IEEE Custom Integrated Circuits Conference (CICC), Austin, TX, USA, 2021, pp. 1-8.

Circuit techniques for optimizing magnetics utilization

Deep cycling of magnetics

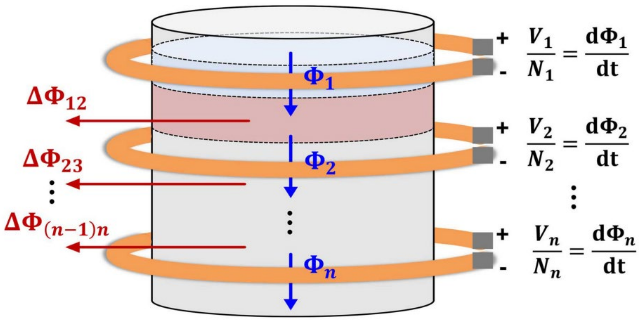


Inductive Energy Utilization Ratio ($\frac{1}{2}LI^2$)

Energy Utilization

Energy Storage

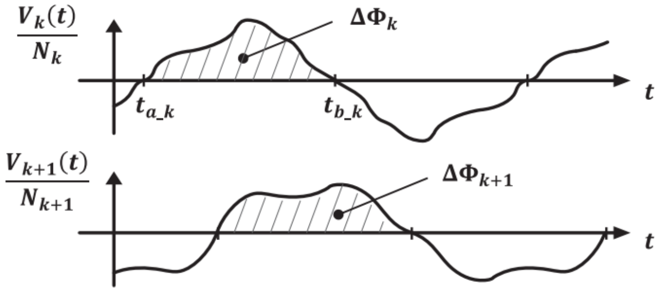
Share magnetics for different purposes



transformers

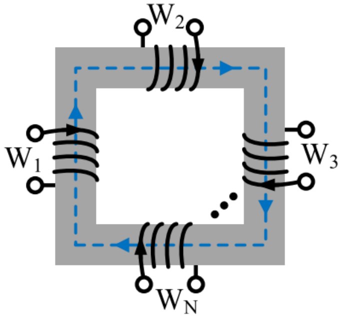
Sharing

$$v = N\frac{d\Phi}{dt}$$

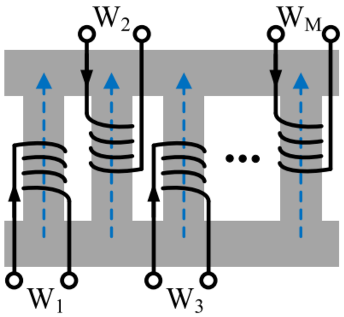


Series coupling, parallel coupling, and matrix coupling …

Series Coupled

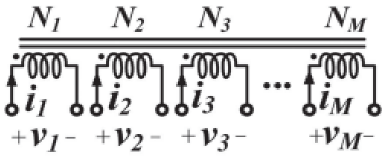


Parallel Coupled



Series Coupled

Voltage Equalizing Xformer

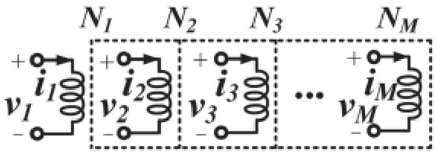


KCL: $N_1 i_1 + N_2 i_2 + \cdots + N_M i_M = 0$

KVL: $\frac{v_1}{N_1} = \frac{v_2}{N_2} = \cdots = \frac{v_M}{N_M}$

Parallel Coupled

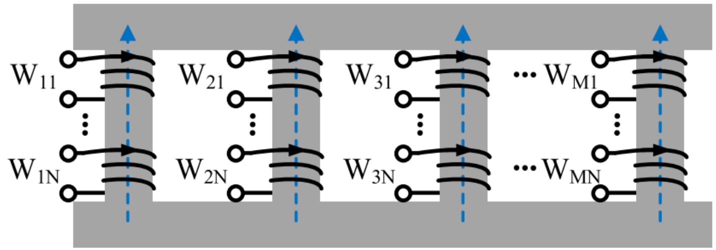
Current Equalizing Xformer

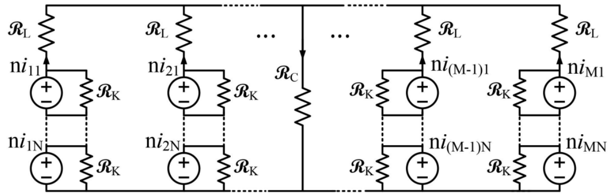


KVL: $N_1 i_1 = N_2 i_2 = \cdots = N_M i_M$

KCL: $\frac{v_1}{N_1} + \frac{v_2}{N_2} + \cdots + \frac{v_M}{N_M} = 0$

Matrix Coupled



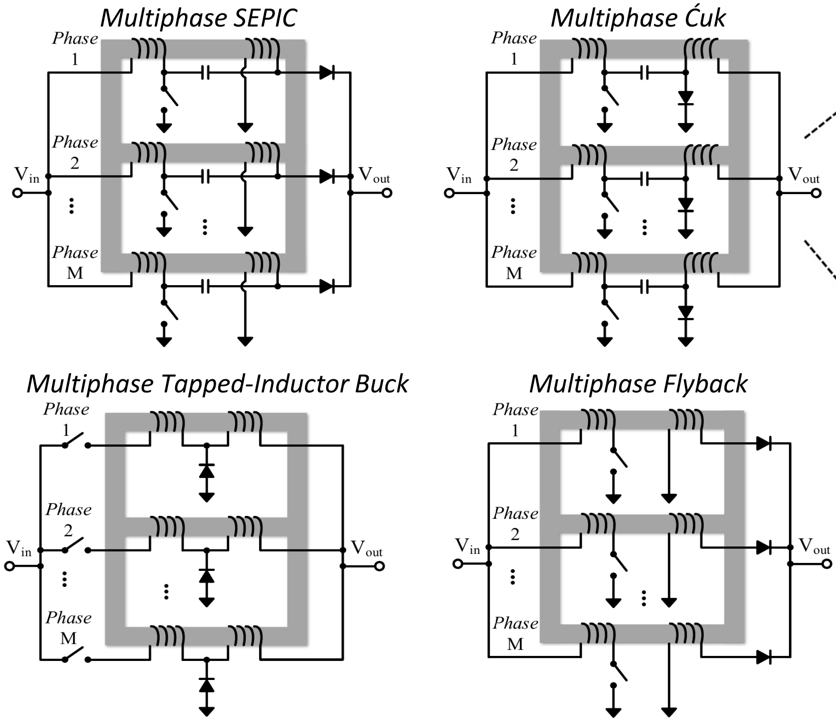


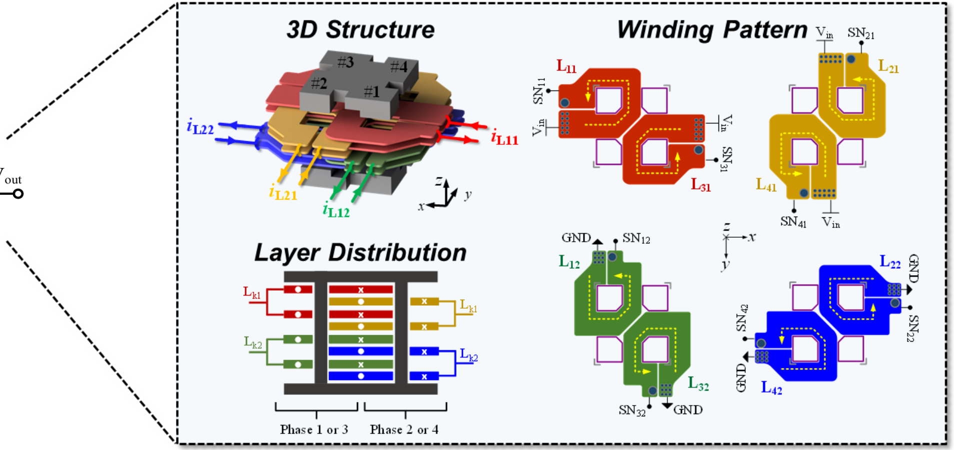
… more

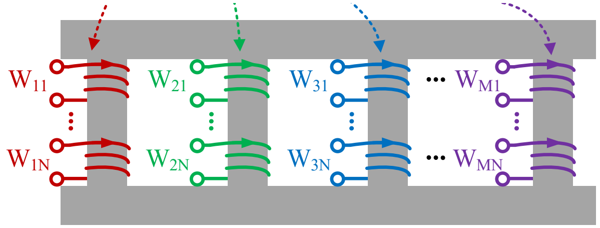
- M. Chen and C. R. Sullivan, "Unified Models for Coupled Inductors Applied to Multiphase PWM Converters," in IEEE Transactions on Power Electronics, vol. 36, no. 12, pp. 14155-14174, Dec. 2021.

PRINCETON UNIVERSITY

All-in-One Magnetics for higher order PWM converters







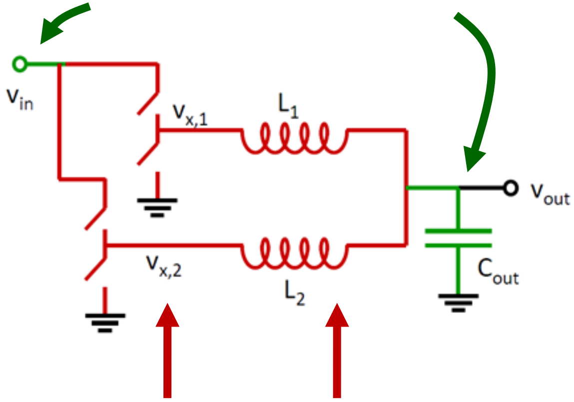
Dr. Ping Wang
Princeton PhD'23

- P. Wang, D. H. Zhou, Y. Elasser, J. Baek and M. Chen, "Matrix Coupled All-in-One Magnetics for PWM Power Conversion," in IEEE Transactions on Power Electronics, vol. 37, no. 12, pp. 15035-15050, Dec. 2022.

The benefits of parallel coupling come from interleaving …

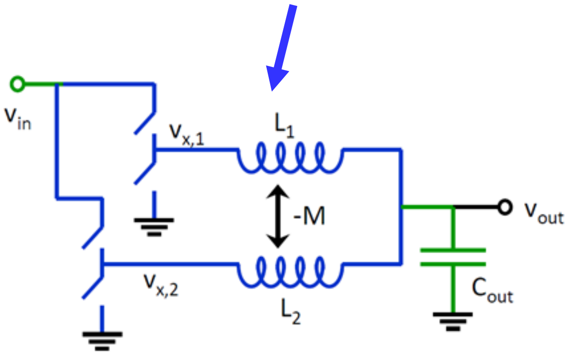
PRINCETON UNIVERSITY

Benefits at input/output

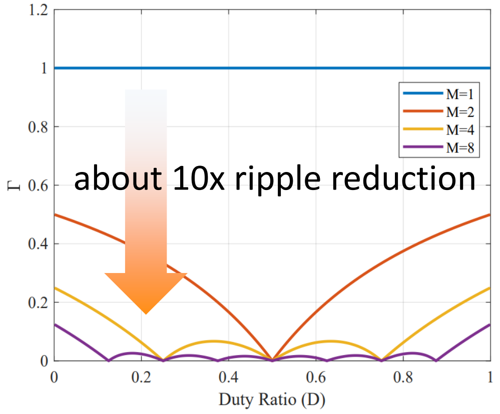


Uncoupled, Same Phase Ripple

Benefits within each phase



Quantify the benefits of coupling



- Coupling Coefficient (β)
- Interleaving Benefit (Γ)
- Coupling Benefit (γ)

$$\beta = \frac{M\mathbb{R}_C}{\mathbb{R}_L}$$

$$\Gamma = \frac{(k+1-DM)(DM-k)}{(1-D)DM^2}$$

$$\gamma = \frac{1+\beta\Gamma}{1+\beta}$$

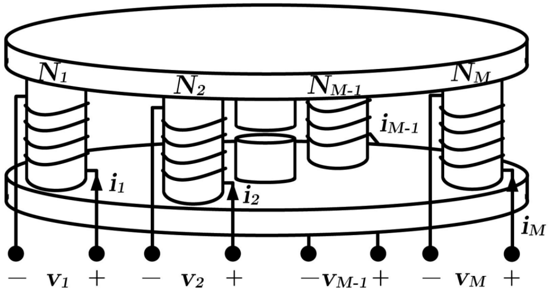
uncoupled $\boldsymbol{\gamma}\big|_{\boldsymbol{\beta}\to\mathbf{0}} = \mathbf{1}$

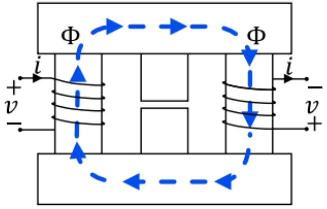
fully coupled $\boldsymbol{\gamma}\big|_{\boldsymbol{\beta}\to\infty} = \boldsymbol{\Gamma}$

- M. Chen and C. R. Sullivan, “Unified Models for Coupled Inductors Applied to Multiphase PWM Converters,” TPEL’21.

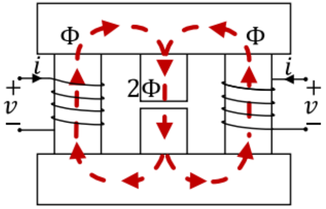
Unified models for multiphase coupled magnetics

PRINCETON UNIVERSITY



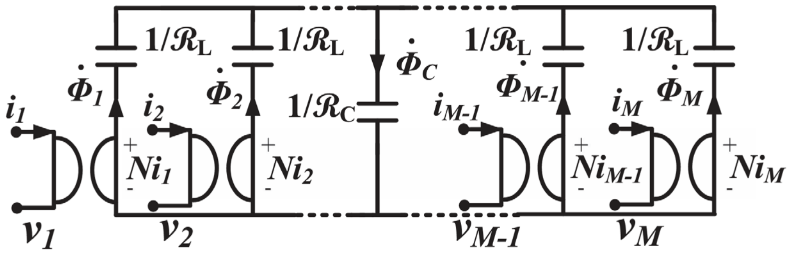


Differential Path
(Small Ripple)

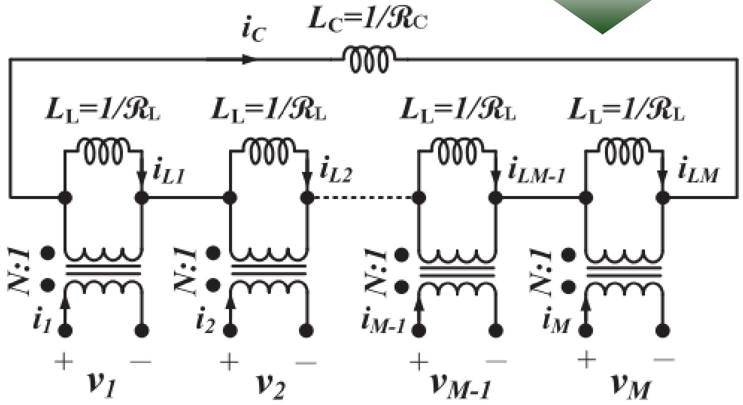


Common Path
(Fast Transient)

Gyrator-Capacitor Model

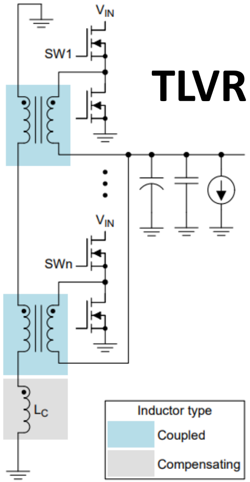


Inductance Dual Model



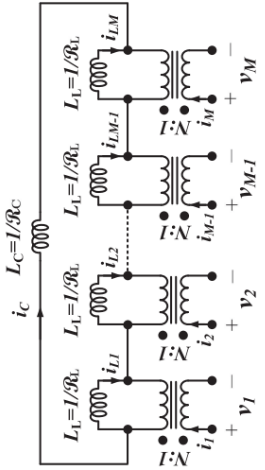
- M. Chen and C. R. Sullivan, “Unified Models for Coupled Inductors Applied to Multiphase PWM Converters,” TPEL’21.

Trans-Inductor Voltage Regulator (TLVR)



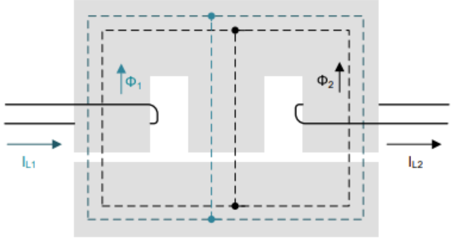
dual

TLVR = CoupL



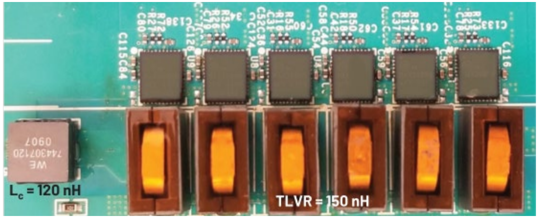
Better Scalability

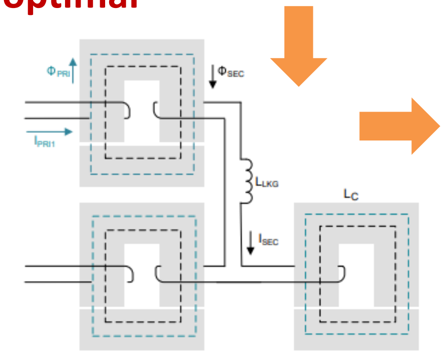
Better Core/Winding Utilization

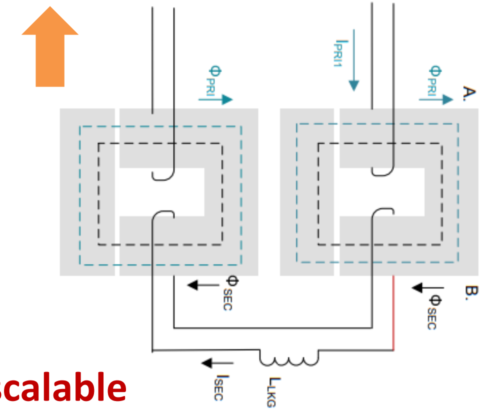


optimal

Image source: TI & ADI







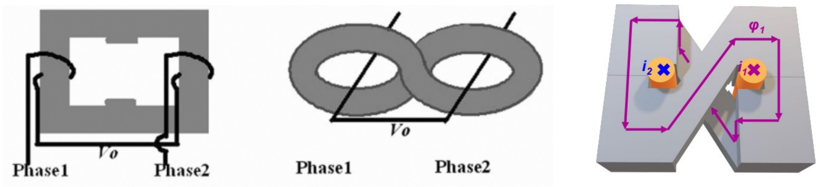
sub-optimal but highly scalable

- M. Chen and C. R. Sullivan, “Unified Models for Coupled Inductors Applied to Multiphase PWM Converters,” TPEL’21.
- S. Jiang, X. Li, M. Yazdani, and C. Chung. “Driving 48V Technology Innovations Forward – Hybrid Converters and Trans-Inductor Voltage Regulator (TLVR),” APEC’20.
- M. Schurmann and M. Ahmed (Texas Instruments) *Introduction to the Trans-Inductor Voltage Regulator*.

TLVR and Coupled Inductors are Topological Duals

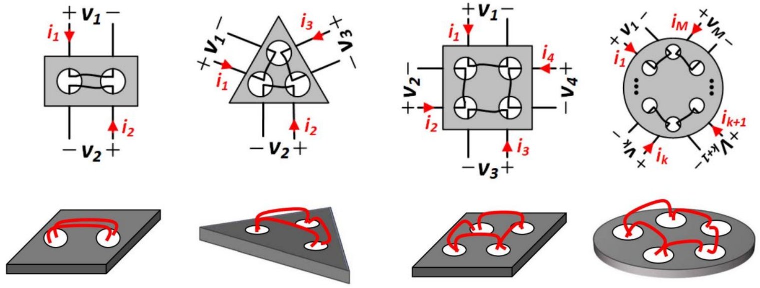
Lateral-flux twisted-core coupled inductors

- **CPES Twisted Core Structure**



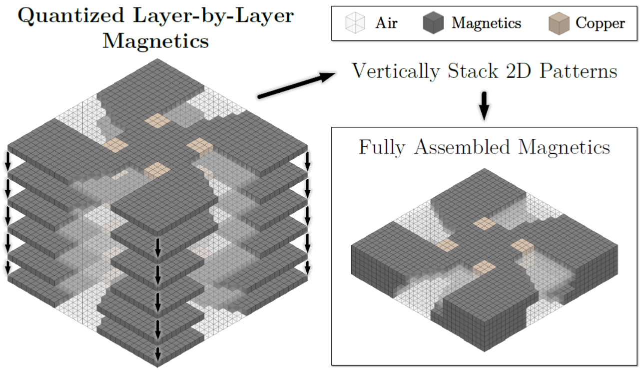
limited to 2-phases

- **Princeton Magnetic Via Structure**



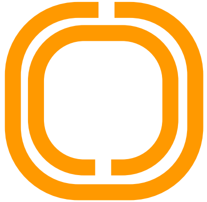
2-Phase **3-Phase** **4-Phase** ***M*-Phase**

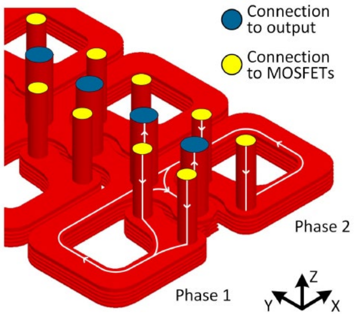
- Y. Dong, J. Zhou, F. C. Lee, M. Xu and S. Wang, "Twisted Core Coupled Inductors for Microprocessor Voltage Regulators," TPEL'08.
- A. M. Naradhipa, F. Zhu and Q. Li, "Ultra-Low-Profile Twisted Core Inductor for Vertical Power Delivery Voltage Regulator," APEC'24.
- J. Baek, Y. Elasser and M. Chen, "MIPS: Multiphase Integrated Planar Symmetric Coupled Inductor for Ultrathin VRM," TPEL'23.



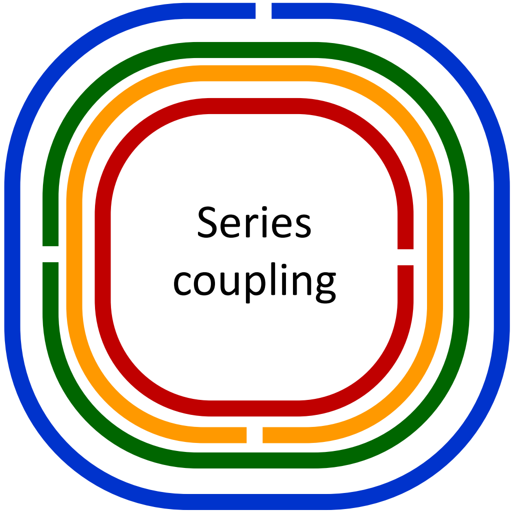
Dr. Youssef Elasser
Princeton PhD'24

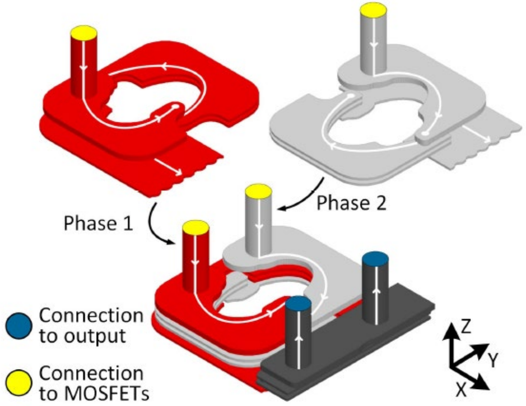
Air-core: opportunities and challenges …

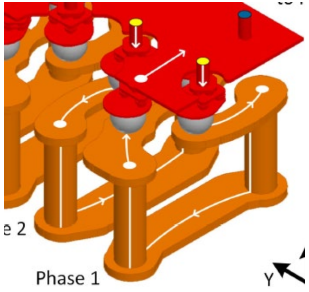


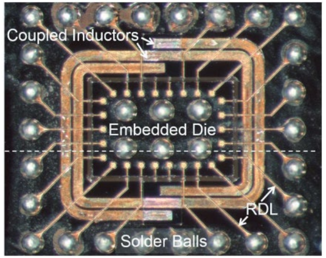


- Very low coupling coefficient
- Limited inductance density
- EMI concerns





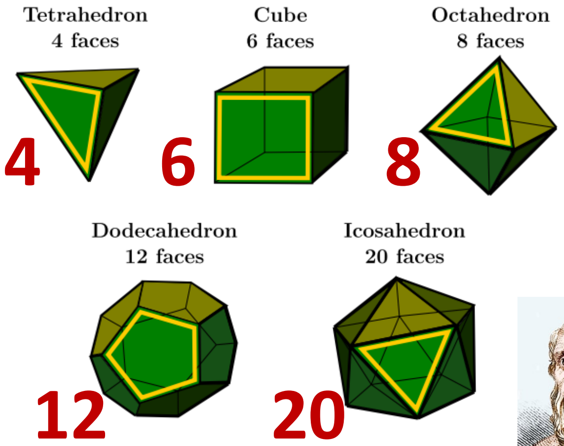


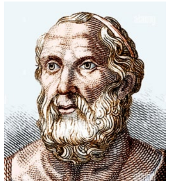


- Y. Ding, X. Fang, R. Wu and J. K. O. Sin, “Fan-Out-Package-Embedded Coupled Inductors …,” ISPSD, 2020, doi: 10.1109/ISPSD46842.2020.9170128.

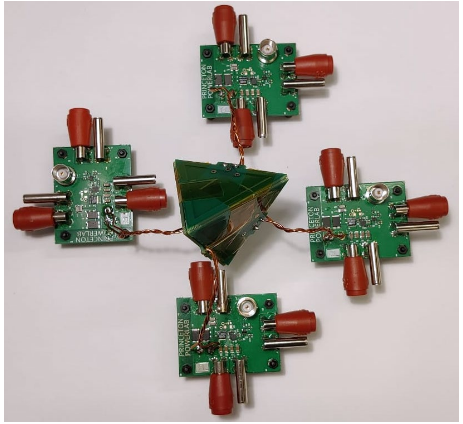
Multiphase air-core coupled magnetics exist …

- Fully symmetric Platonic structures (a total of 5)
- Limited design flexibility, ~2x smaller ripple, ~2x faster

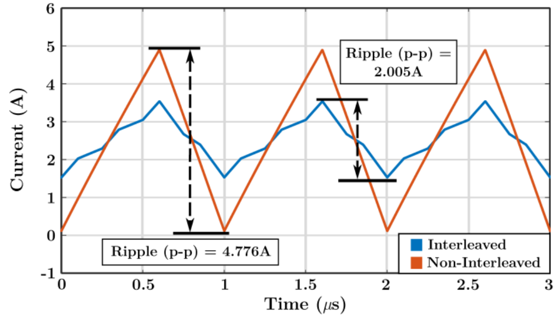


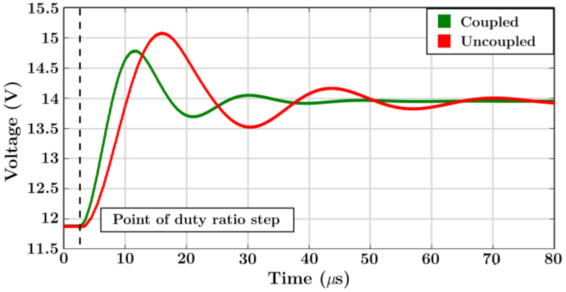


Plato



4-Phase Air-Coupled Class-E Dc-Dc Converter @ 10 MHz

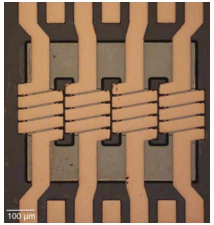




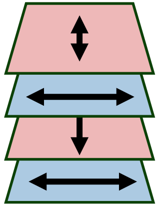
- T. Sen, Y. Elasser and M. Chen, "Origami Inductor: Foldable 3-D Polyhedron Multiphase Air-Coupled Inductors With Flux Cancellation and Faster Transient," TPEL'24.

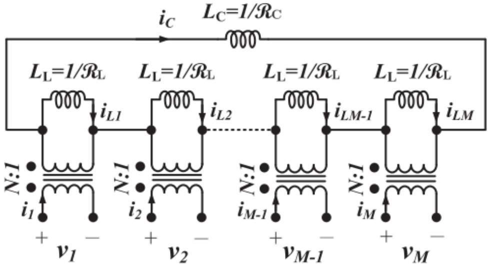
Tanuj Sen
Princeton PhD'26

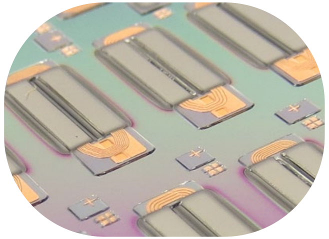
Planar integrated coupled inductor & TVLR designs

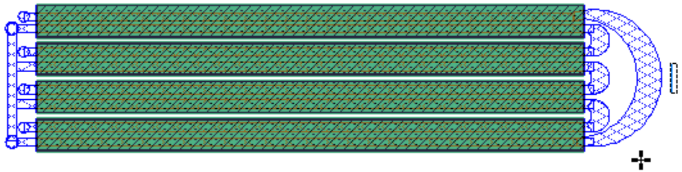


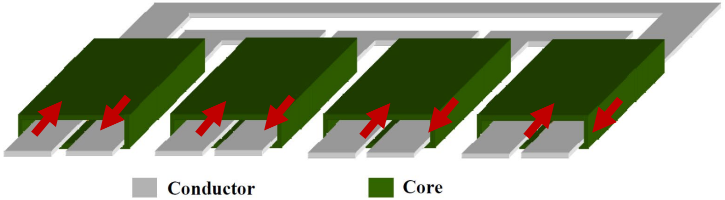
Multi-layer stack





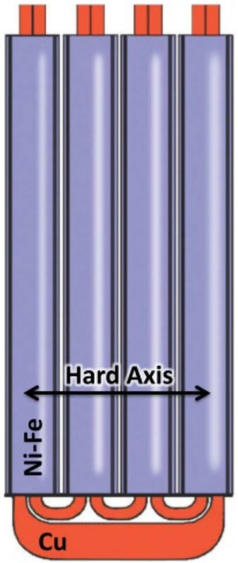






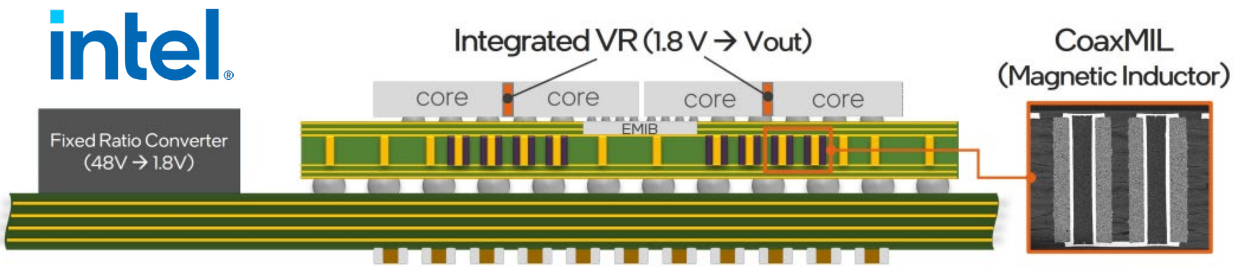
- Pair-wise coupled "tunnel" design.
- Each core has net-zero dc current: avoid saturation even with high permeability magnetic materials.
- Inductance density still not high enough (limited by lateral winding & flux and wafer thickness)

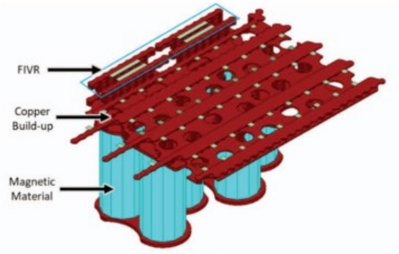
- *Dartmouth/Tyndall, 2004*
- *Intel (Dibene et al, 2010)*
- *Columbia/IBM (Sturken, 2013)*
- *Galway (Duffy, 2019)*



Vertical integrated magnetics design …

Power-Via-Magnetics (Microfabricated and Discrete)

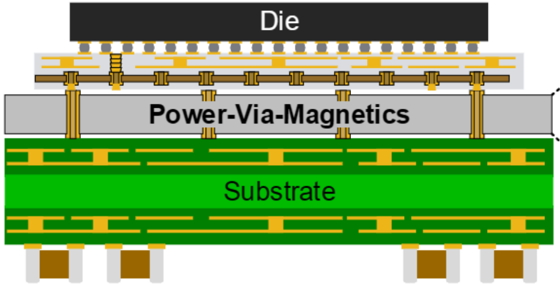


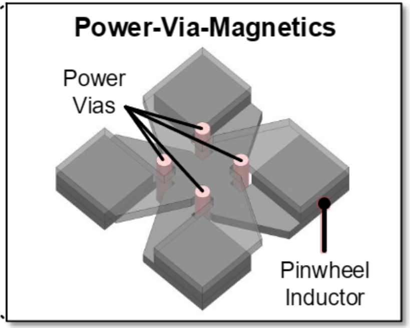


Dr. Jaeil Baek
Princeton Postdoc'21

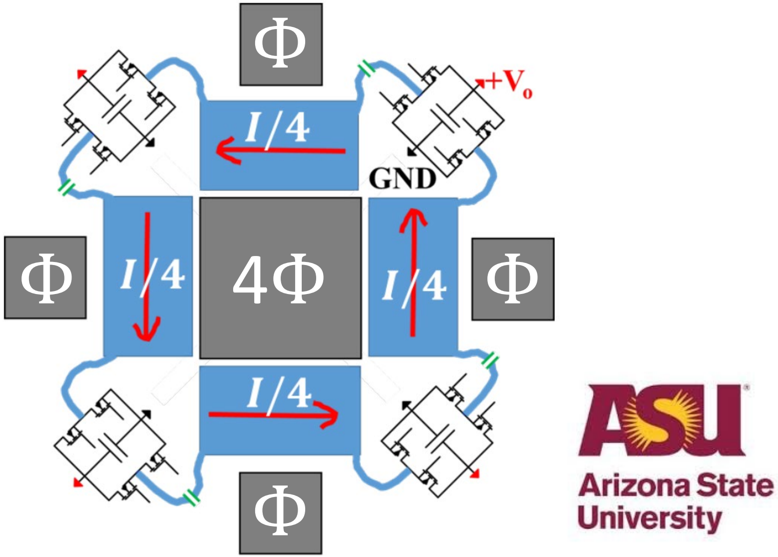
Prof. Mark Allen
UPenn

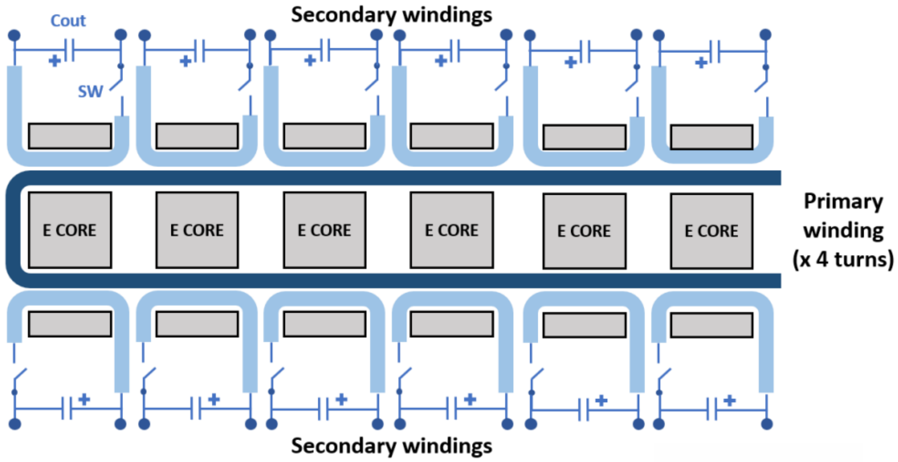
- J. Baek et al., "Vertical Stacked LEGO-PoL CPU Voltage Regulator," in IEEE Transactions on Power Electronics, vol. 37, no. 6, pp. 6305-6322, June 2022.
- B. Choi et al., "CoaxMIL 2.0 – Next Generation Coaxial Magnetic Integrated Inductors for Higher Efficiency Fully Integrated Voltage Regulator," 2024 IEEE 74th Electronic Components and Technology Conference (ECTC), Denver, CO, USA, 2024, pp. 1044-1047.





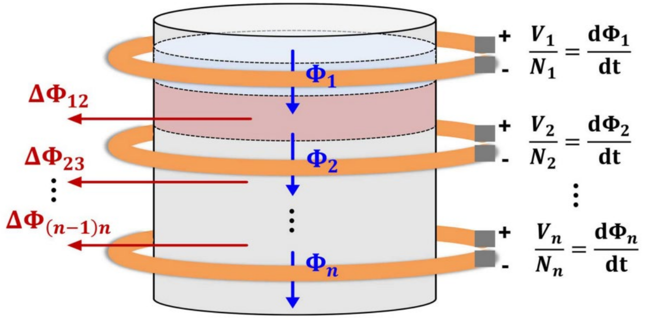
Flux splitting transformers for high/fractional turns ratios

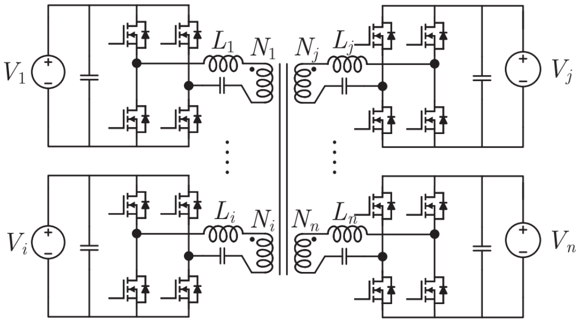


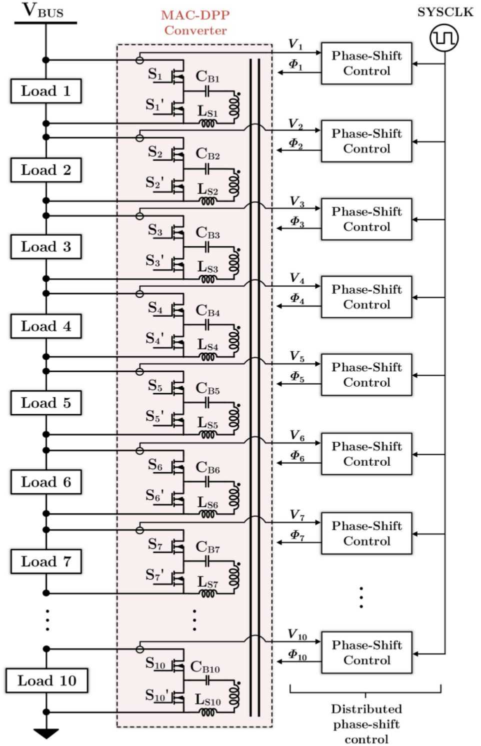


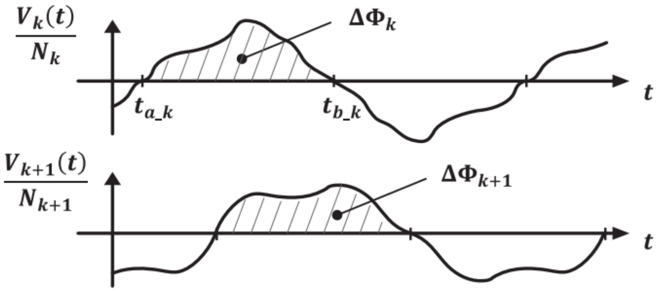
- M. K. Ranjram, et al., “Variable-Inverter-Rectifier-Transformer: A Hybrid Electronic and Magnetic Structure Enabling Adjustable High Step-Down Conversion Ratios,” TPEL’18.
- A. Figueroa, P. Mazariegos, J. Goicoechea, A. Castro and J. A. Cobos, “Low-Profile Direct Power Converter: 350A/48V-1V with Planar Matrix Transformer using standard PCB and commercial cores,” *APEC’24.*

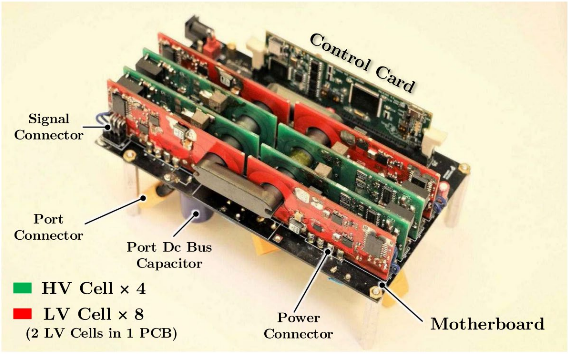
Series-coupled multi-winding magnetics







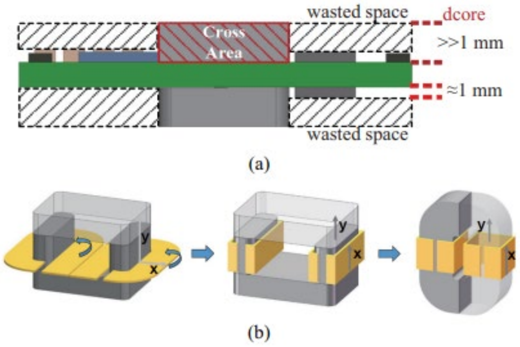


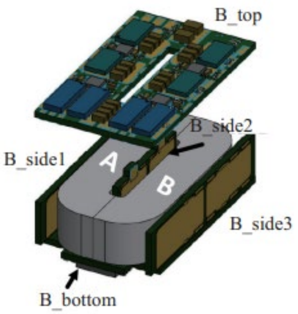


- Y. Chen, P. Wang, Y. Elasser and M. Chen, "Multicell Reconfigurable Multi-Input Multi-Output Energy Router Architecture," TPEL'20.
- P. Wang, Y. Chen, J. Yuan, R. C. N. Pilawa-Podgurski and M. Chen, "Differential Power Processing for Ultra-Efficient Data Storage," TPEL'21.

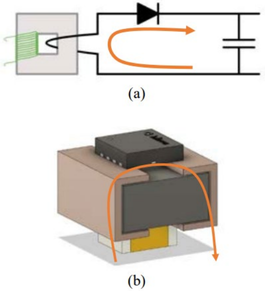
From wire-windings to planar embedded windings …

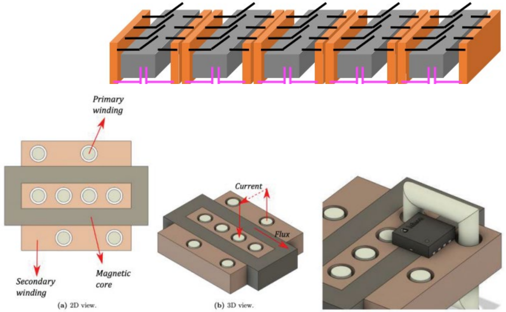
Vertical PCB Windings



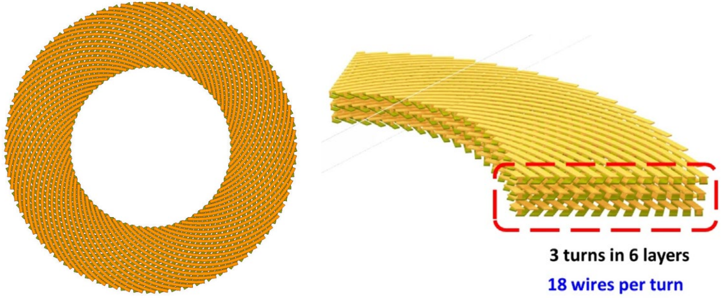


Single-Turn 3D Windings





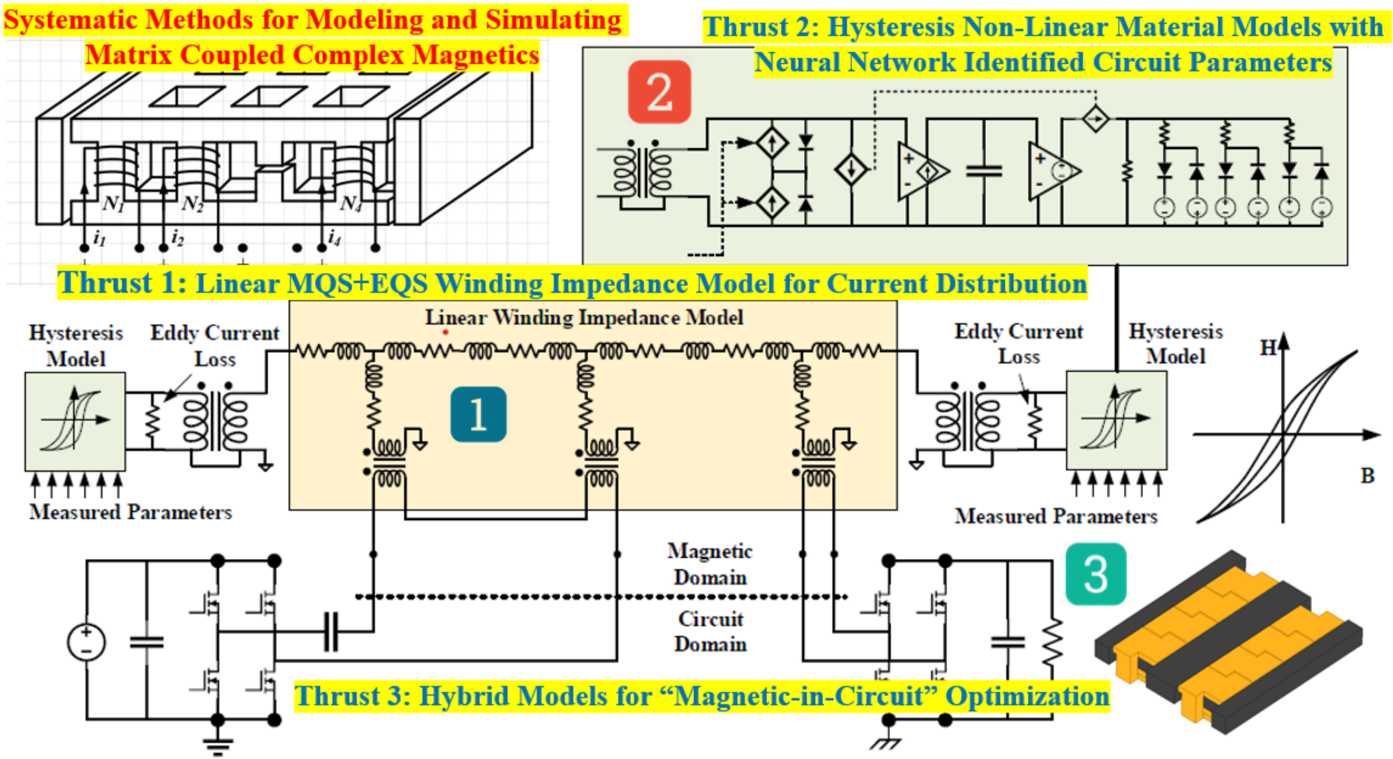
Planar Litz Windings



- G. Li and X. Wu, “A high power density 48 V-12 V DCX with 3-D PCB winding transformer,” in APEC’20.
- J. A. Cobos, A. Castro, Ó. García-Lorenz, J. Cruz and Á. Cobos, “Direct Power Converter – DPx – for High Gain and High Current Applications,” APEC’22.
- Z. Li, F. Jin, X. Lou, Y. -H. H. Qiang Li and F. C. Lee, “Design and Optimization with Litz Wire Version of PCB in Solid-State Transformer,” APEC’24.

Hybrid multi-physics models for magnetics simulation …

- Non-linear core models
- Linear winding models
- SPICE simulations



Modeling material non-linearity with neural networks

Princeton MagNet

Princeton Power Electronics Research Lab

http://mag-net.princeton.edu

IMAGENET

*Joseph Henry's **Magnet** in 1832 at Princeton*

Website Development

Magnetics Simulation

plexim
electrical engineering software

Automatic Data Acquisition

MagNet Database

Machine Learning Methods

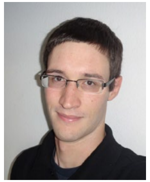
Data Quality Control

Equation-based Models

MagNet Core Team Members:

Haoran Li

Shukai Wang



T. Guillod

Hyukjae Kwon

- M. Chen et al., "MagNet Challenge for Data-Driven Power Magnetics Modeling," in IEEE Open Journal of Power Electronics, 2024.

MagNet Challenge 1: Steady State Modeling

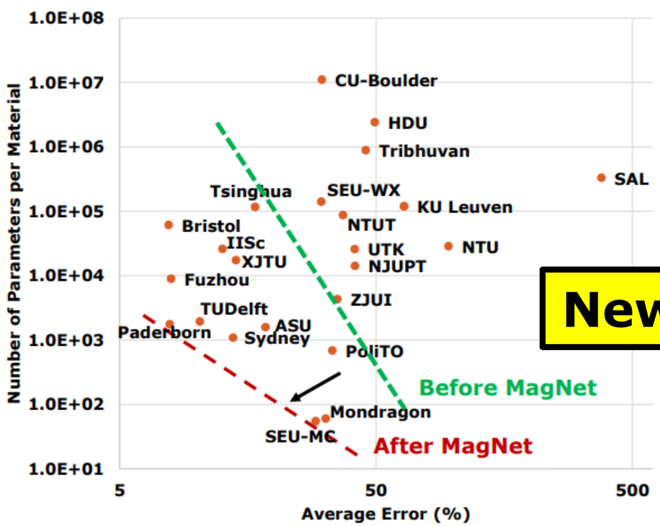
PRINCETON UNIVERSITY

Charles Steinmetz (1865-1923)

MagNet Challenge for Data-Driven Power Magnetics Modeling

Minjie Chen[1], Haoran Li[1], Shukai Wang[1], Thomas Guillod[2], Diego Serrano[1], Nikolas Förster[3], Wilhelm
Kirchgässner[3], Till Piepenbrock[3], Oliver Schweins[3], Oliver Wallscheid[3], Qiujie Huang[4], Yang Li[20], Yu Dou[21],
Bo Li[21], Sinan Li[4], Emmanuel Havugimana[5], Vivek Thomas Chacko[5], Sritharini Radhakrishnan[5], Mike
Ranjram[5], Bailey Sauter[6], Skye Reese[6], Shivangi Sinha[7], Lizhong Zhang[7], Tom McKeague[7], Binyu Cui[7],
Navid Rase ... [9], Gaoyuan
Wu[9], Hao ... Himanshu
Bhusan S ... ao Tian[12],
Qingcher ... ote[13], Iosu
Aizpuru[13], Minmin Zhang[14], Xia Chen[14], Yuchen Dong[14], Duo Wang[14], Tianming Shen[14], Yan Zhou[14],
Yaohua Li[15], Sicheng Wang[15], Yue Wu[15], Yongbin Jiang[15], Ziheng Xiao[15], Yi Tang[15], Yun-Shan Hsieh[16],
... [16], Chen Chen[16], Alessio
... quale[17], Luigi Solimene[17],
... ei Qin[19], Xiang Ma[19], Boyu
... , Jing Xu[19], Zhongqi Shi[19],
... n[22], Bowen Su[20], Yunhao
... u[23], Lu Wang[23], Tianming
... li Meerza[24], Kody Froehle[24],
... ongliang Dang[25], Yukun
... [6], Tianxiang Hu[26], Lumeng
... nacher[28],
AND Charles R. Sullivan[2]

133 co-authors



New SOTA

- Arizona, USA
- Fuzhou, China
- Hangzhou, China
- Bangalore, India
- Leuven, Belgium
- Hernani, Spain
- Nanjing, China
- Cambridge, USA
- Singapore, Singapore
- Taipei, Taiwan
- Hong Kong, China
- Paderborn, Germany
- Princeton, USA
- Hanover, USA
- Piscataway, USA
- Torino, ...
- Graz, A...
- Lalitpu...
- Beijing...
- Fremont, USA
- D...
- Br...
- Zu...
- Bo...
- Santa Clara, USA
- Manchester, UK
- Sydney, Australia
- Knoxville, USA
- Xi'an, China
- Mountain View, USA

24 teams

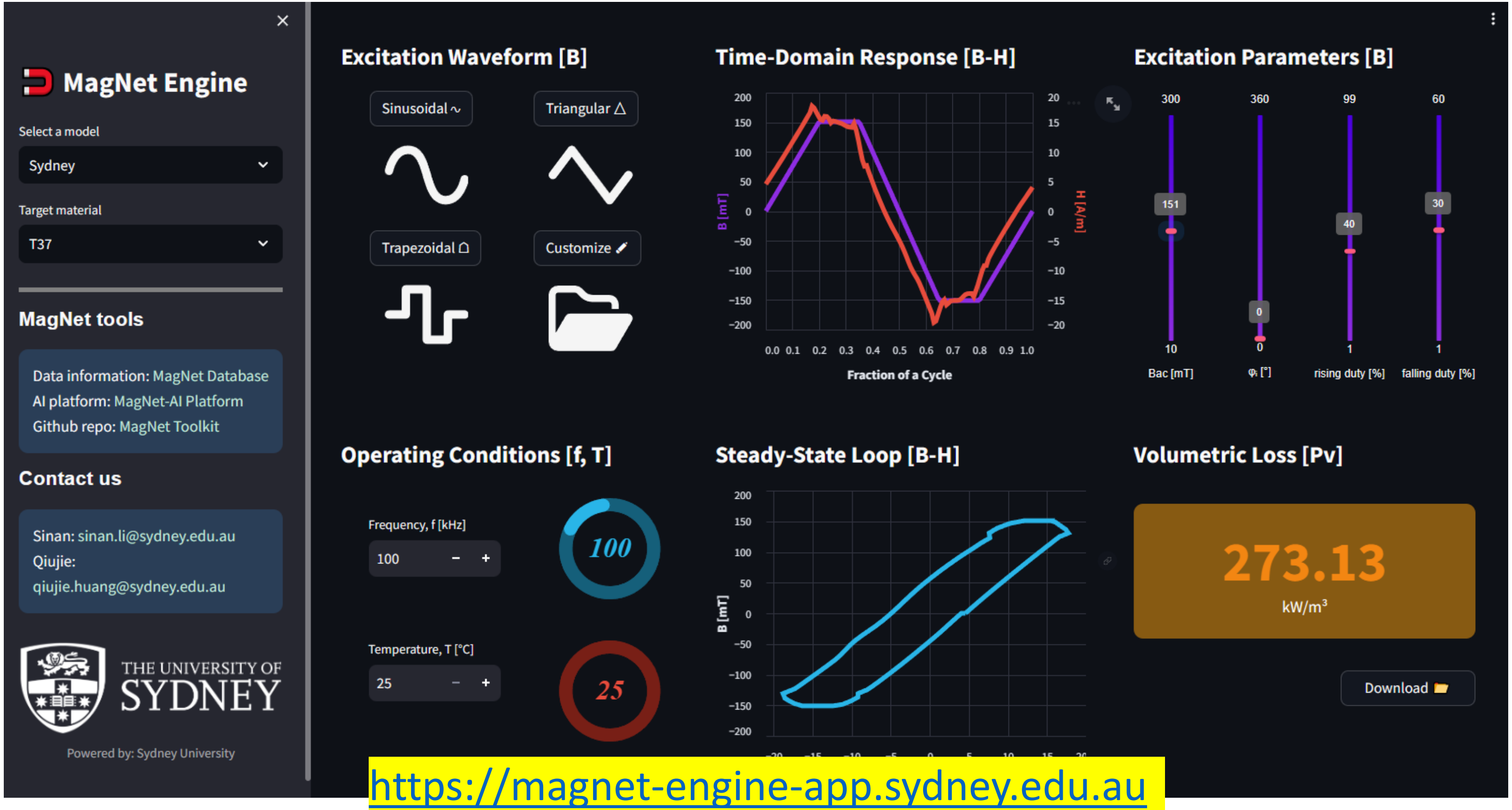
Many theses

MagNet 2023 - IEEE International Challenge in Design Methods for Power Electronics

pels MagNet challenge

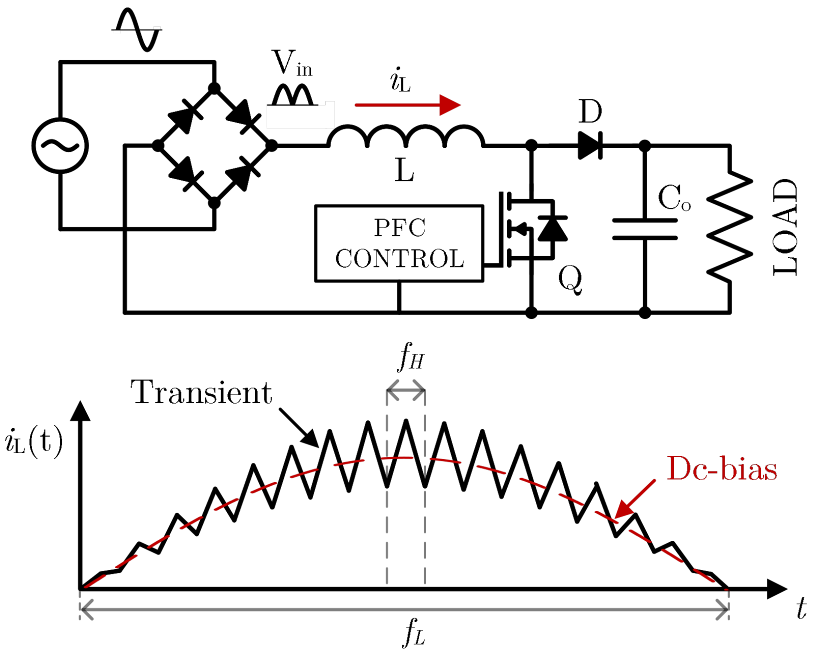
MagNet Engine: a Platform by University of Sydney …

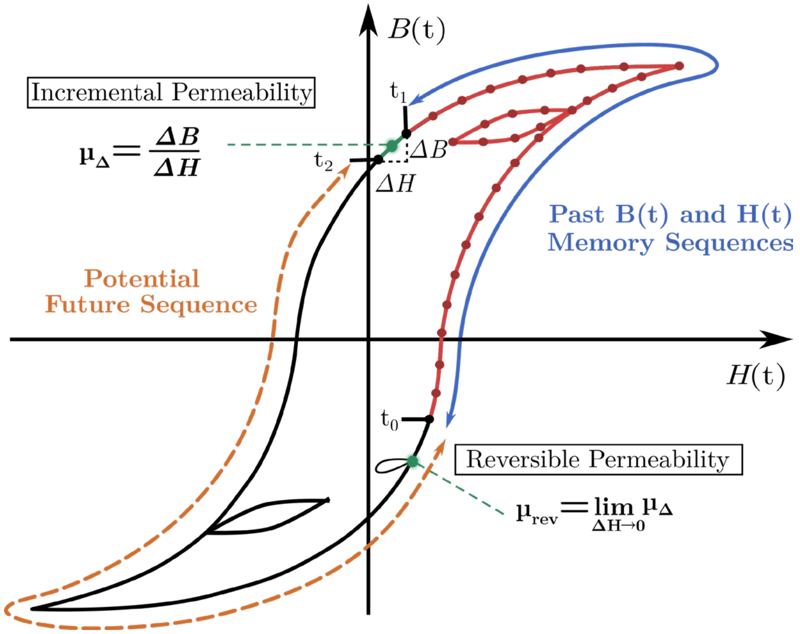
PRINCETON UNIVERSITY



https://magnet-engine-app.sydney.edu.au

MagNet Challenge 2: from steady-state to transient



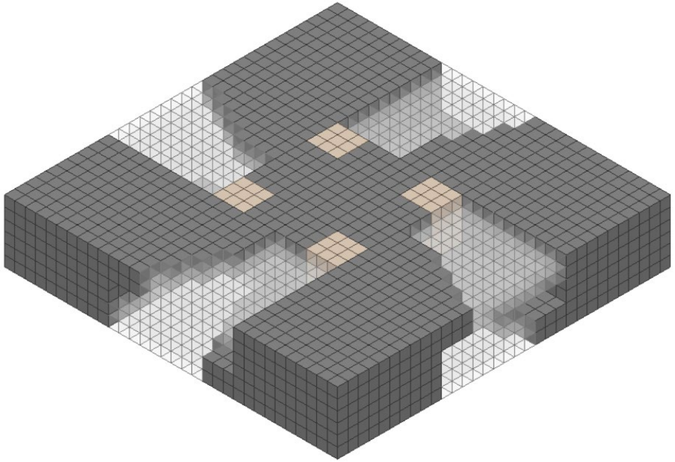


- **MagNet 2 Launch:** Wed 2:00 PM, Omni Hotel, Room Grand A
- **Oral Presentation:** Wed 9:50 AM, GWCC Level Three, A301

Non-linear hybrid models for power magnetics

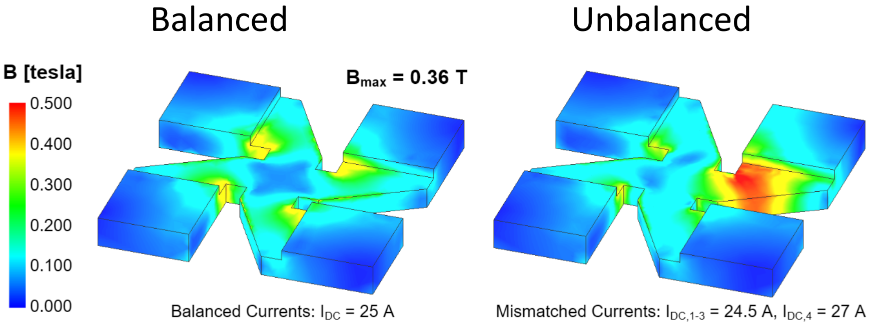
Precise Model for Pinwheel Inductor

- Models for material hysteresis and losses
- Models for non-linear circuit behaviors of complex magnetic components

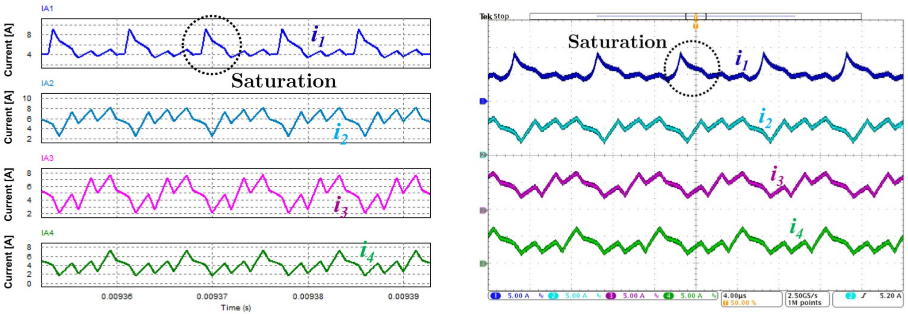


Pixelized Magnetics Design and Simulation

Flux distribution change with operating conditions



Material saturation influence circuit behaviors



DARTMOUTH

ARPAE™

NSF

tsmc

pSemi®
A Murata Company

ITG
Trusted Innovation
Magnetics & EMI Filters