Design Methodologies for High Frequency Multiwinding Magnetics: from Fundamental Principles to Design Tools

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Design Methodology Webinar Series, 2021

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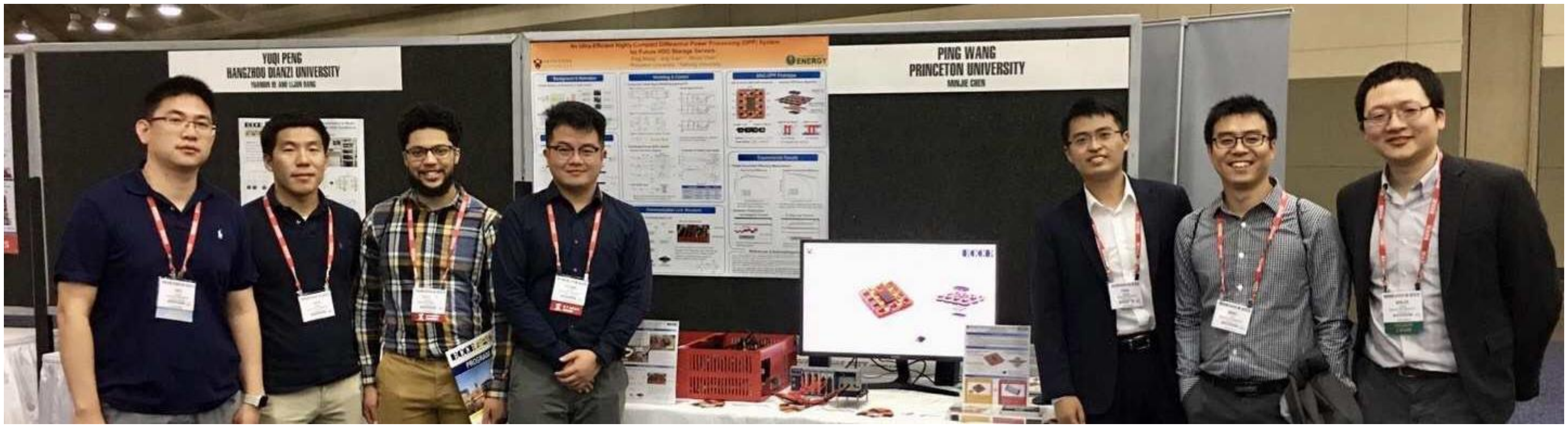
Princeton Power Electronics Research Group



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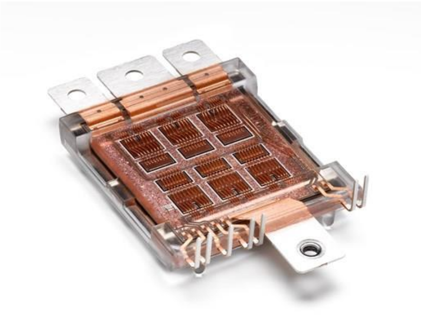
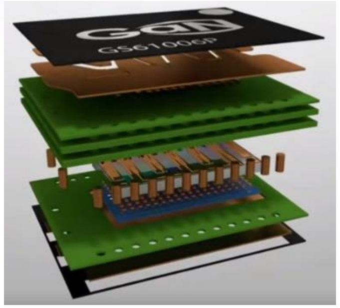
We Need Better Magnetics

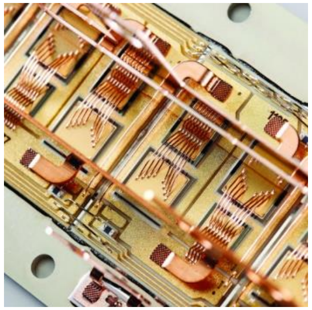
- Major breakthroughs in power semiconductor devices



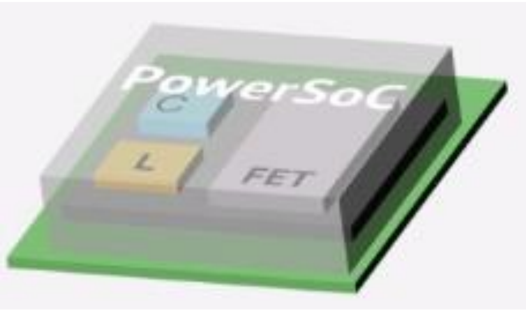
SiC modules



GaN switches

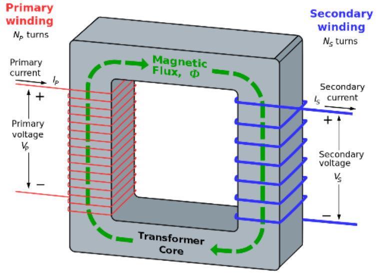


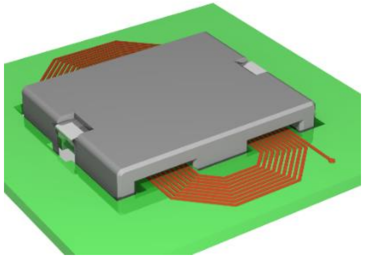
IGBT modules

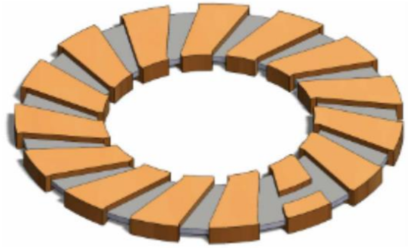


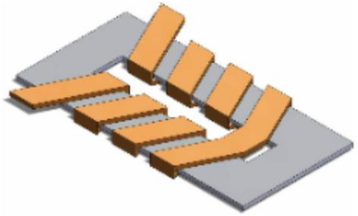
Packaging & cooling

- Magnetics are lagging behind (both discrete and integrated)





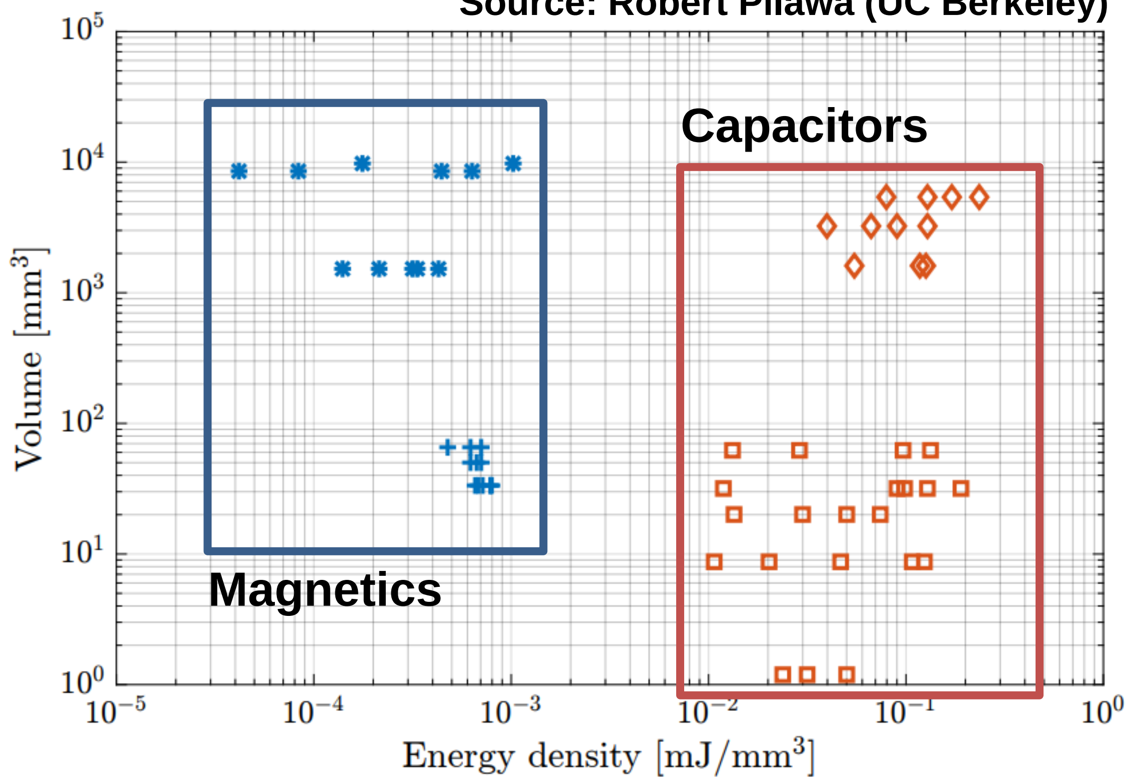




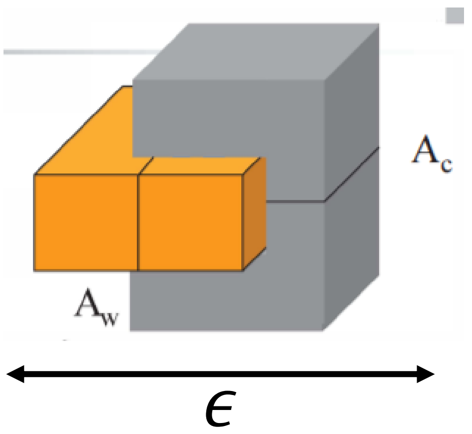
- C. R. Sullivan, M. Chen, "Coupled Inductors for Fast-Response High-Density Power Delivery: Discrete and Integrated," IEEE Custom Integrated Circuits Conference (CICC), 2021 (accepted).

Energy Density vs. Functionality

Source: Robert Pilawa (UC Berkeley)



Source: Charles Sullivan (Dartmouth)



$V \propto \epsilon^2$ core area

$I \propto \epsilon^2$ copper area

$$P = VI \propto \epsilon^4$$

scaling factor

- Capacitors win in **energy / power density**
- Magnetic components win in **functionality / flexibility**
- Larger magnetics offer higher power density
- **Small & multifunctional magnetics → high frequency & multiwinding**

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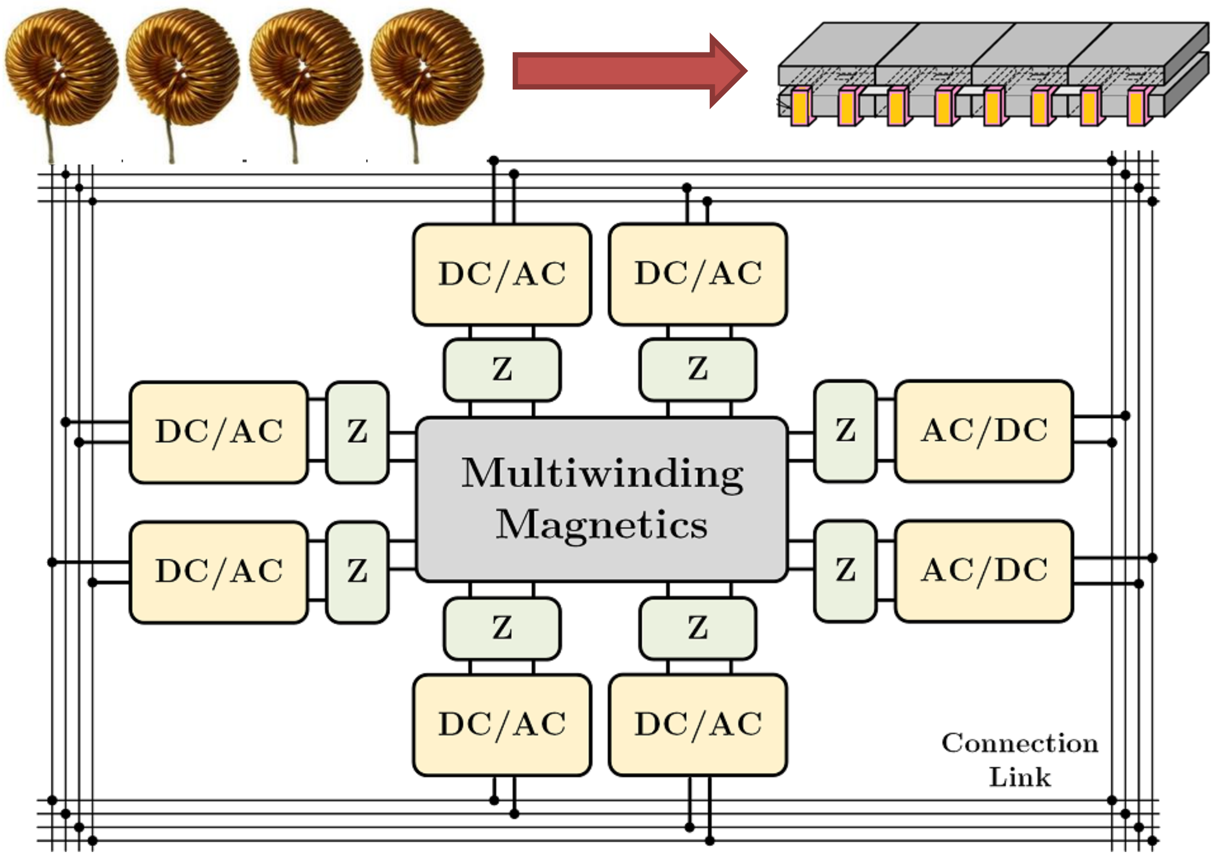
The "integrated magnetic" concept is not new…



before 1970s

Coupled inductor buck

1990s

Multiphase buck

2000s

Isolated dc-dc

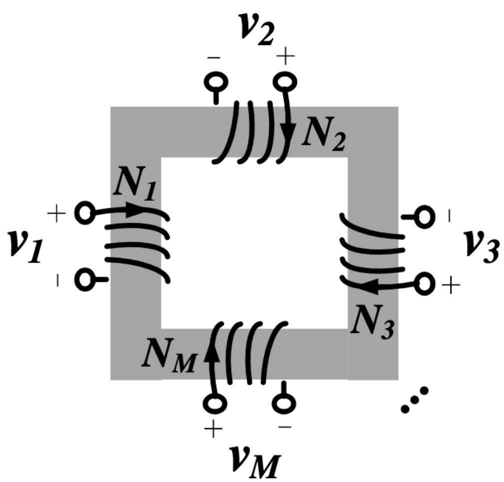
2010s

Solid state xformer

Need design methods and tools for "integrated" magnetics at HF

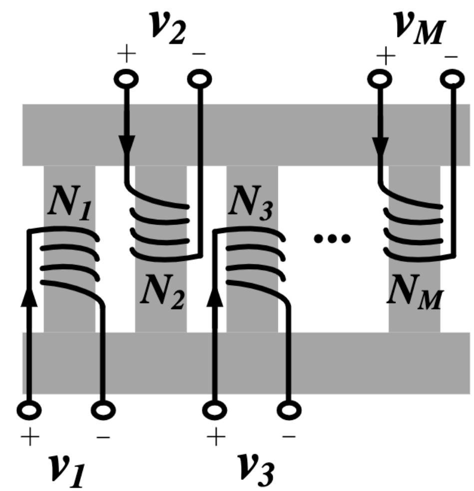
Two Types of "Integrated" Magnetics

Series Coupled Structure
single flux multi linkage

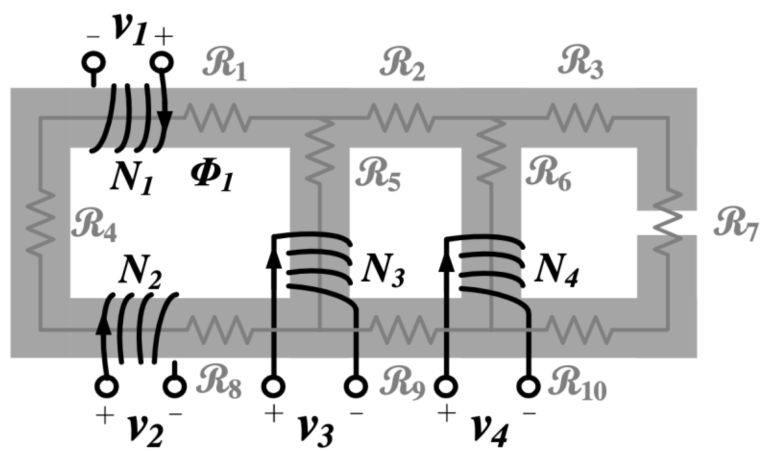


Geometrical Dual

Parallel Coupled Structure
multi flux single linkage



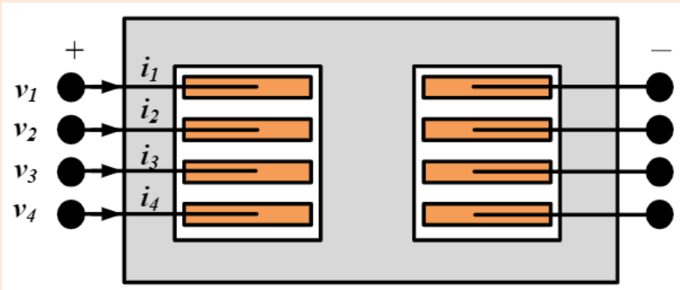
All multiwinding magnetics are combinations of series and parallel coupled structures

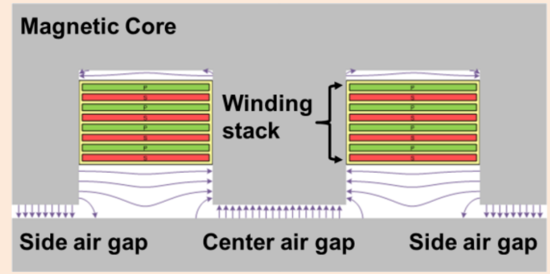


[M. Chen and C. R. Sullivan, TechRxiv'20]

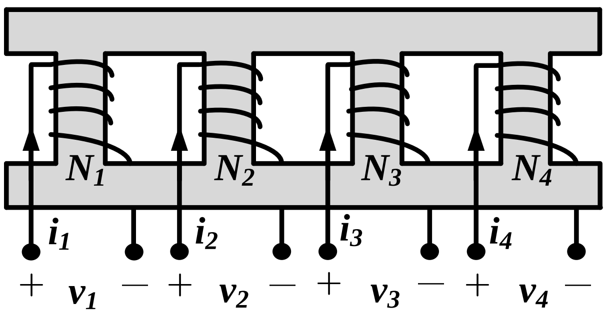
Outline

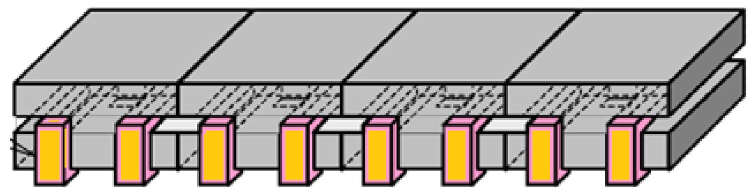
- Design methodologies for series coupled structure (planar core)



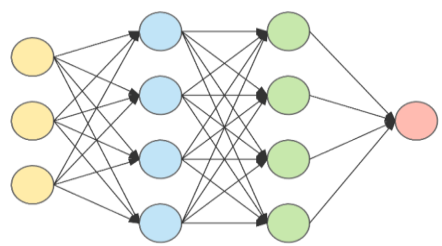


- Design methodologies for parallel coupled structure (ladder core)





- Machine learning based magnetic core loss modeling methods



Princeton MagNet

Design Multiwinding Planar Magnetics

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1. What is the optimal way to interleave many layers?

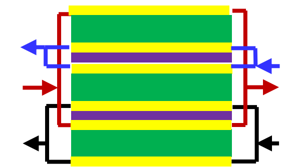
Alternating interleave

1 & 3 as primary
2 & 4 as secondary

Symmetric interleave

1 & 4 as primary
2 & 3 as secondary

More complicated?



……?

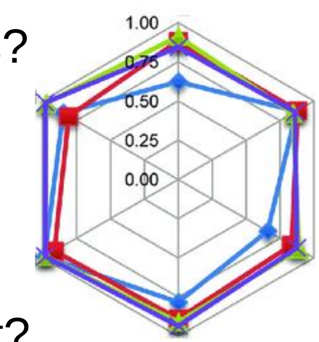
2. What are the optimal winding stack and winding spacing?

Thin Middle Spacing

Thick Middle Spacing

3. Multi-object optimization space

1) Interleaving options?
2) Materials?
3) Geometry?
4) Size?
5) Efficiency?
6) Coupling coefficient?



[M. Chen et al., TPEL'16]

Two Commonly Shared Assumptions

Every model starts from assumptions …

(1) MQS assumption

- Assume $\frac{\partial E}{\partial t} = 0$.
- Applicable when the wavelength is much longer than the device size (usually lower than ~100 MHz).

Magneto-Quasi-Static Maxwell's equations

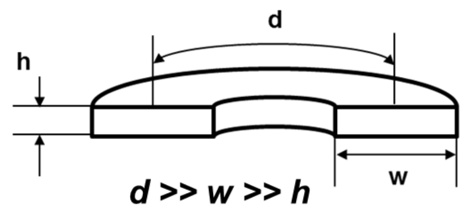
$$\begin{cases} \nabla E = \frac{\rho}{\varepsilon_0} \\ \nabla B = 0 \\ \nabla \times E = -\frac{\partial B}{\partial t} \\ \nabla \times B = \mu_0 (J + \cancel{\varepsilon_0 \frac{\partial E}{\partial t}}) \end{cases}$$

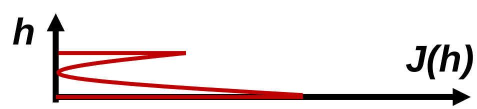
Ignore the time evolution of the electric field

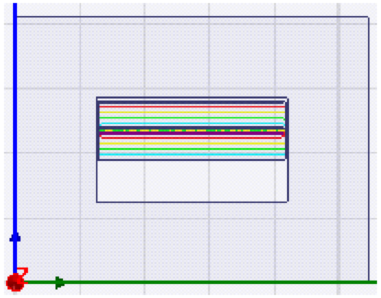
(2) 1-D assumption

- Fields vary only along the thickness direction.
- Applicable when the flux is guided by the magnetic core.

Magnetic core guides the flux





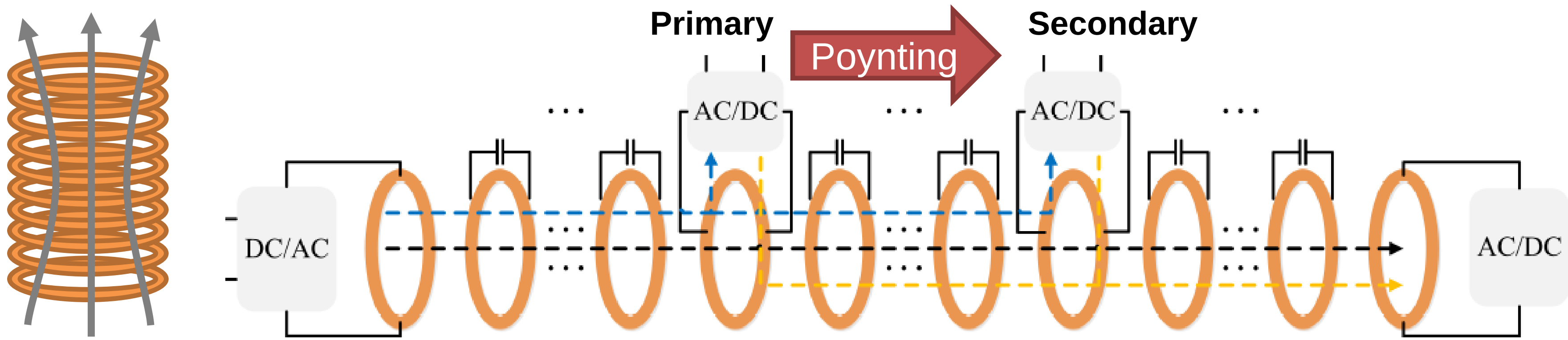


Skin and proximity effects change current distribution

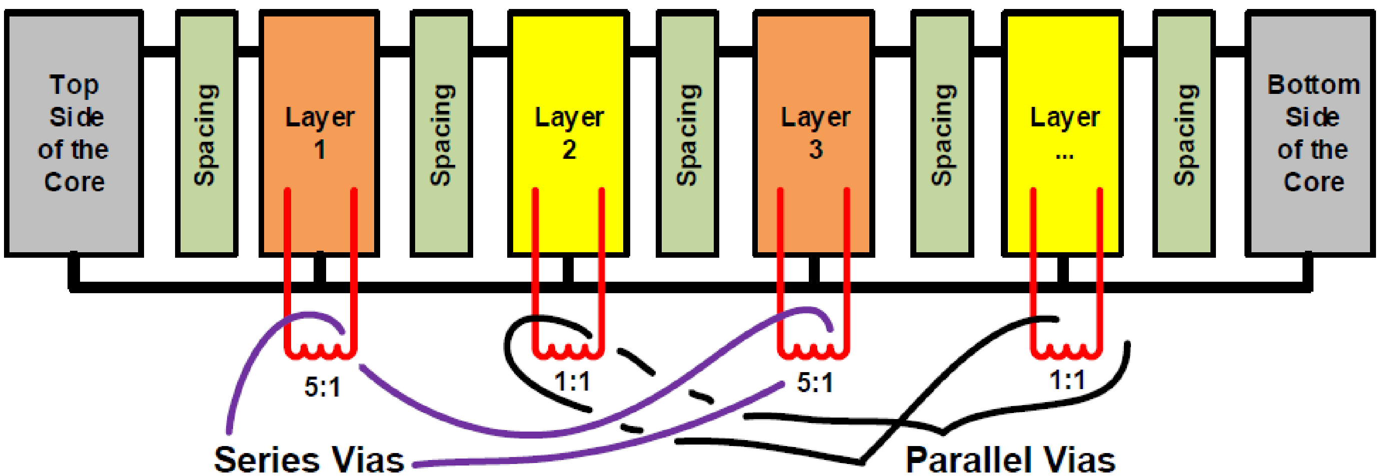
[M. Chen et al., TPEL'16]

Wave Propagation in Planar Windings

- ❑ 1-D energy wave propagation method (Poynting vector)



- ❑ Modular lumped circuit models for repeating building blocks



[M. Chen et al., TPEL'16]

Modeling a Single Conductor Layer

Field diffusion equations:

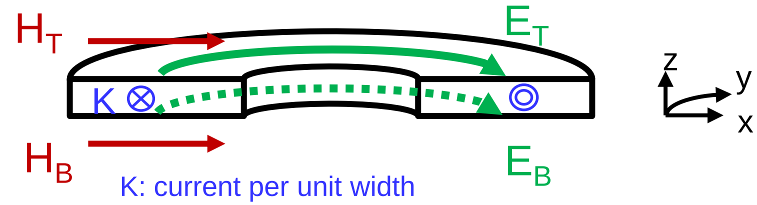
$$H_X(z) = \frac{H_T\, sinh(\Psi z) + H_B\, sinh(\Psi(h-z))}{sinh(\Psi h)}$$

Ampere's law:

$$\Psi = \frac{1+j}{\delta} \qquad \delta = \sqrt{\frac{2}{\mu\omega\sigma}}$$

$$\nabla \times H = J = \sigma E$$

Electromagnetic Fields



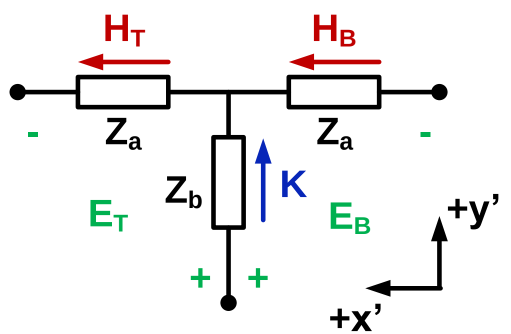
E field as a function of H and K:

$$\begin{cases} E_T = E_Y(h) = \frac{\Psi}{\sigma}\left(\frac{H_T e^{\Psi h} - H_B}{e^{\Psi h} - e^{-\Psi h}} - \frac{H_B - H_T e^{-\Psi h}}{e^{\Psi h} - e^{-\Psi h}}\right) \\ E_B = E_Y(0) = \frac{\Psi}{\sigma}\left(\frac{H_T - H_B e^{-\Psi h}}{e^{\Psi h} - e^{-\Psi h}} - \frac{H_B e^{\Psi h} - H_T}{e^{\Psi h} - e^{-\Psi h}}\right) \end{cases}$$

$$\boldsymbol{Z_a = \frac{\Psi(1 - e^{-\Psi h})}{\sigma(1 + e^{-\Psi h})}}$$

$$\boldsymbol{Z_b = \frac{2\Psi e^{-\Psi h}}{\sigma(1 - e^{-2\Psi h})}}$$

Modular Layer Model



KVL/KCL relationships:

V/m $\quad\Omega\quad$ A/m

$$\begin{cases} E_T = Z_a H_T + Z_b K & \textbf{KVL} \\ E_B = Z_b K - Z_a H_B & \textbf{KVL} \\ K = H_T - H_B & \textbf{KCL} \end{cases}$$

***H & K*:** through variables ~ unit (**A/m**)

***E*:** across variable ~ unit (**V/m**)

***Z_a, Z_b*:** impedances ~ unit (**Ω**)

Modeling Two Adjacent Layers

Intuition:

- *Two three-terminal networks*
- *Connected by the H field between them*

Faraday's Law and Field Continuity

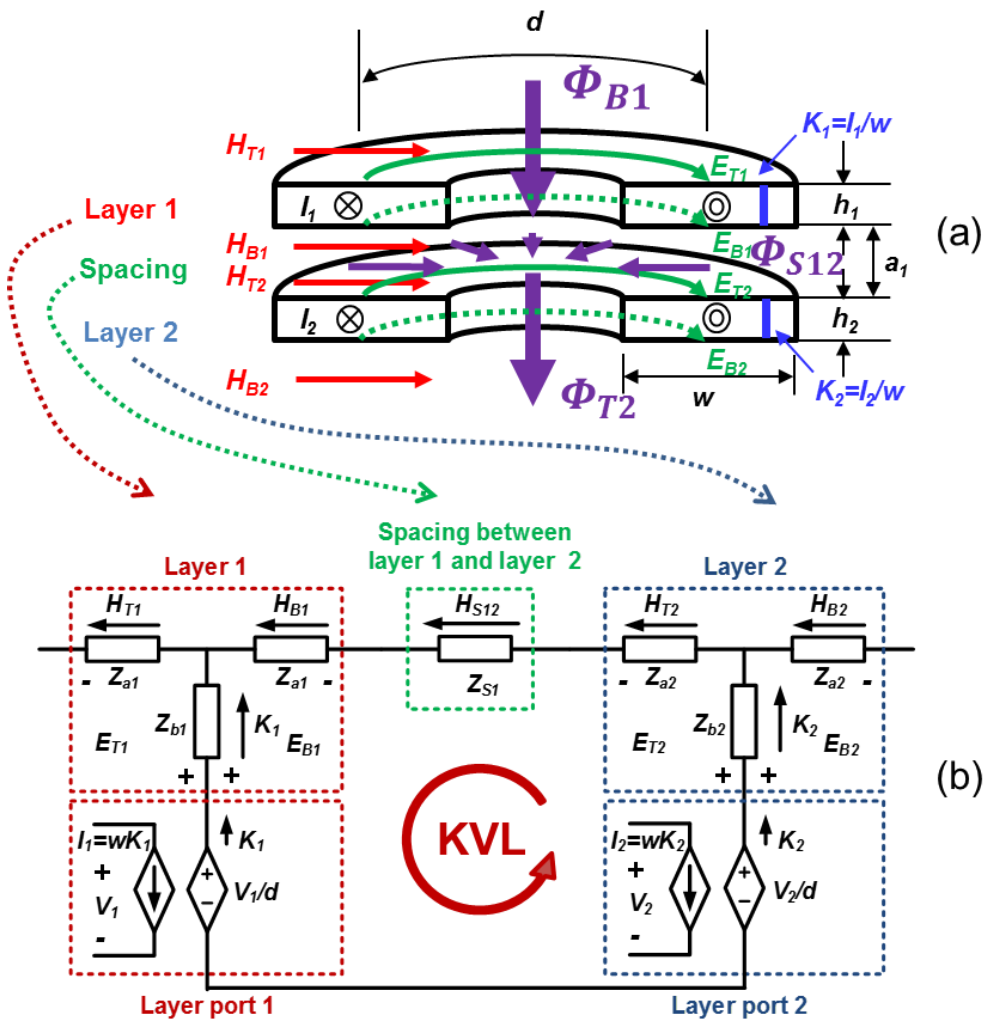
$$E_{B1}d - V_1 = -\frac{d\Phi_{B1}}{dt} \qquad E_{T2}d - V_2 = -\frac{d\Phi_{T2}}{dt}$$

$$\frac{d\Phi_{T2}}{dt} = \frac{d\Phi_{B1}}{dt} + \frac{d\Phi_A}{dt}$$

Flux Linking Two Layers:

An additional KVL equation

$$\underbrace{j\omega\mu_0 a_1}_{\Omega}\underbrace{H_{S12}}_{A/m} = \underbrace{\frac{V_2}{d} - E_{T2} - \frac{V_1}{d} + E_{B1}}_{V/m}$$



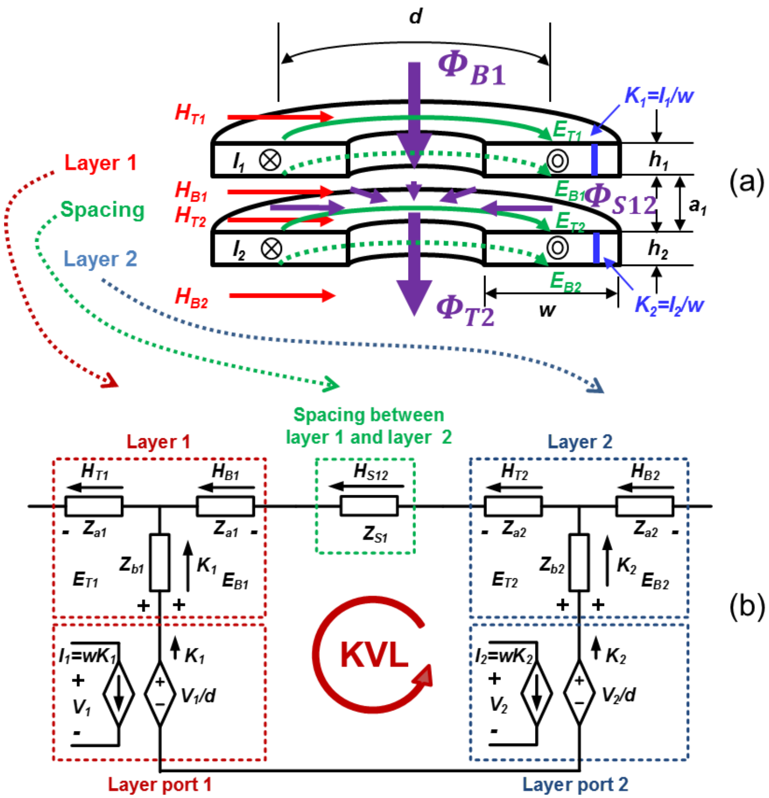
Circuit Domain ⟷ Electromagnetic Domain

[M. Chen et al., TPEL'16]

Modeling Layers with Multiple Turns

Fields distributions in multiple-turns layers are linearly related to those in single-turn layers

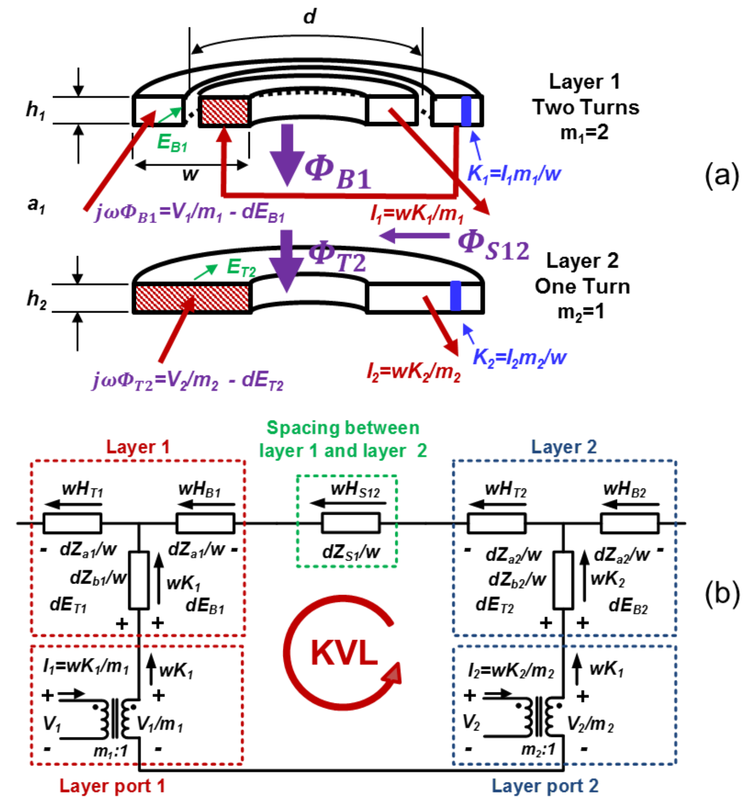
Multiple turns → Additional Linear Conversions



E&M Domain

Circuit Domain

Intuitive Ideal Transformers



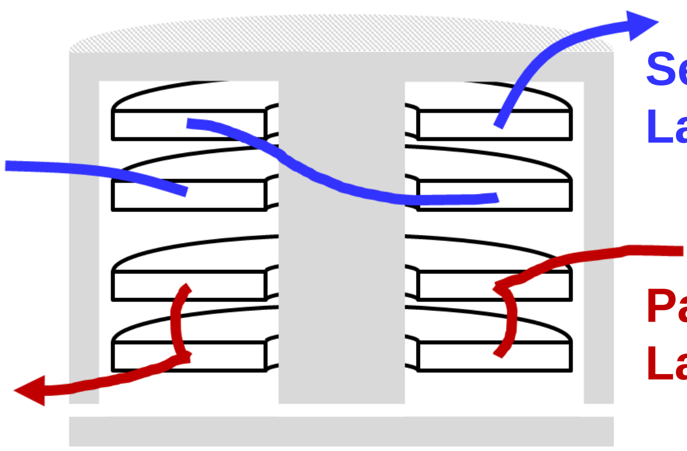
[M. Chen et al., TPEL'16]

Modeling Electrical Interconnects (Vias)

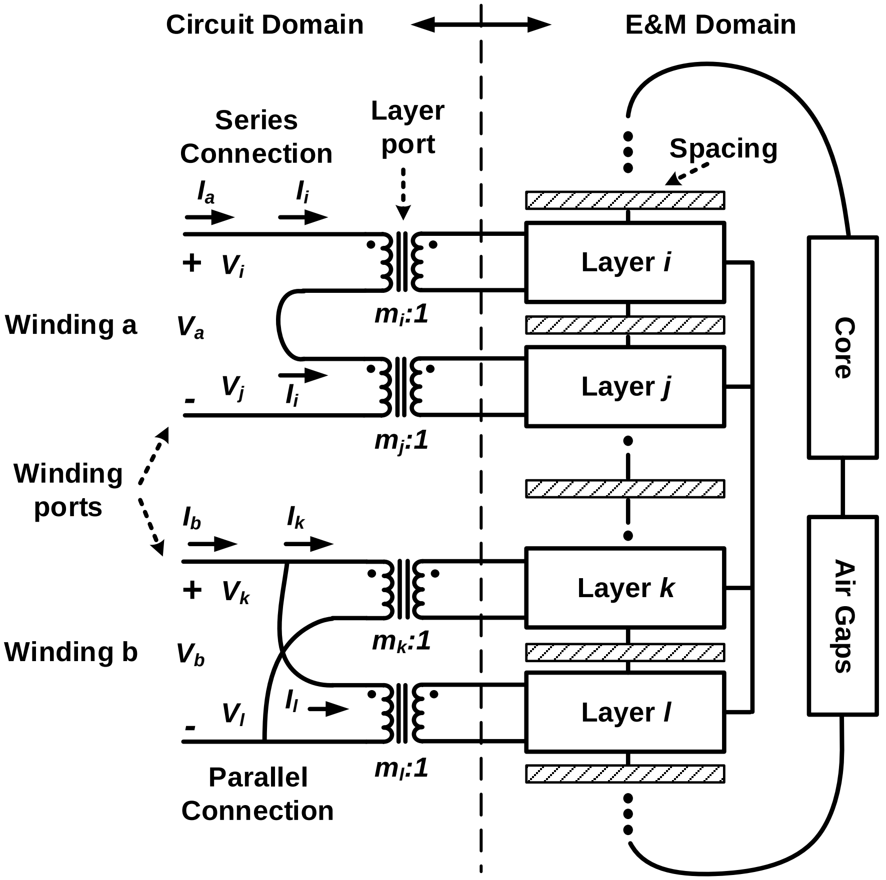
Modeling vias is equivalent to adding KVL, KCL constraints:

Layer i and Layer j in series
Layer k and Layer l in parallel

$$\begin{cases} V_i + V_j = V_a \\ V_k = V_l = V_b \end{cases} \qquad \begin{cases} I_i = I_j = I_a \\ I_k + I_l = I_b \end{cases}$$



Connect the layer ports in the same pattern as they are in the real circuit



[M. Chen et al., TPEL'16]

An Open-Source SPICE Modeling Tool

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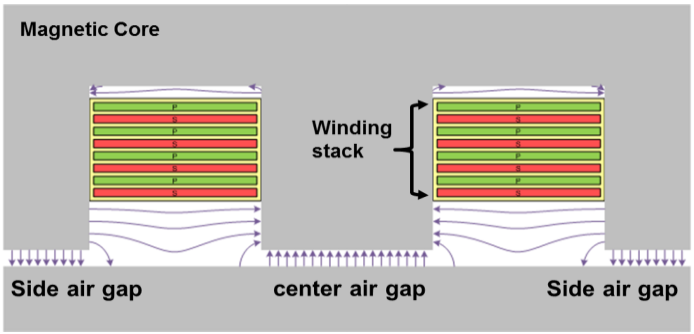
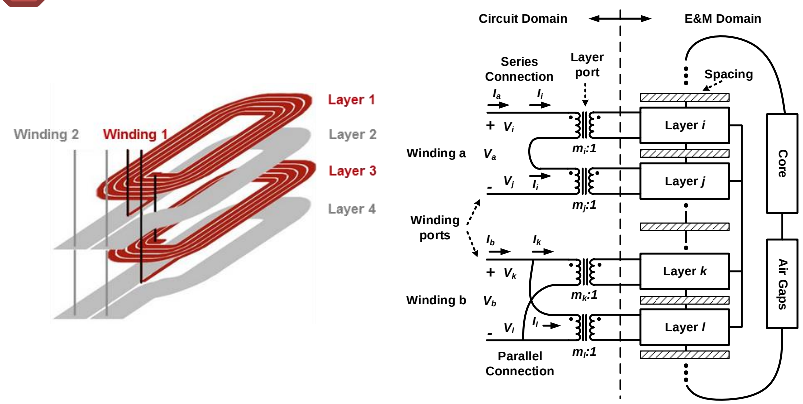
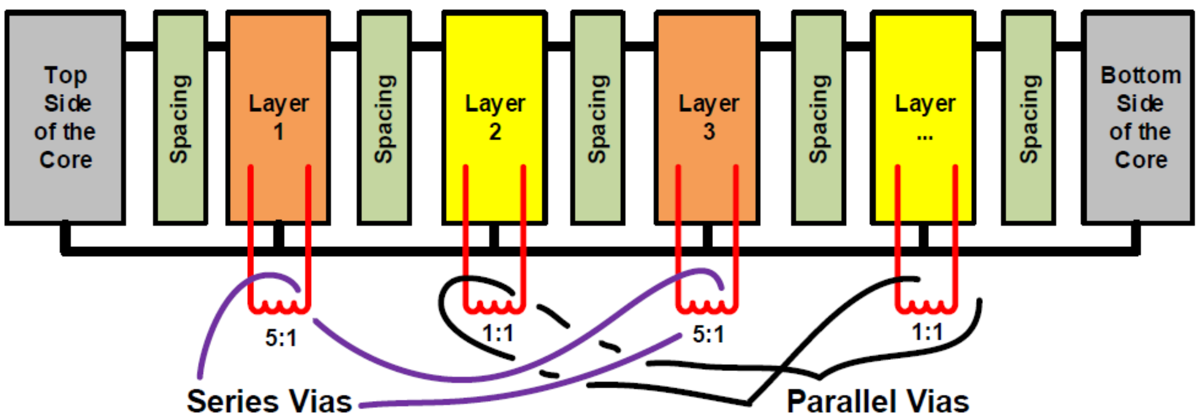
1 Geometry Information



3 SPICE Netlist



2 Modular Layer Model



Simulations!

GitHub

Search: M2SPICE

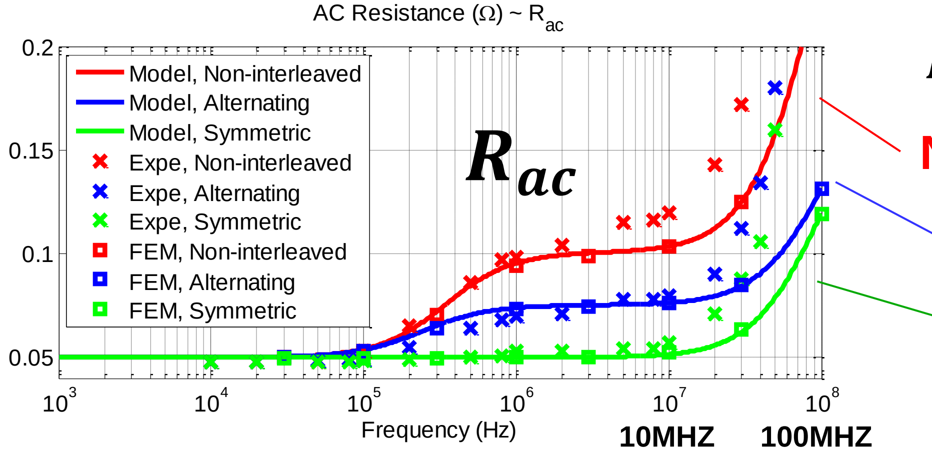
Impacts of Interleaving Patterns

Comparing the P_{ac} and E_{ac} of three 1: 1 transformers with three different interleaving patterns

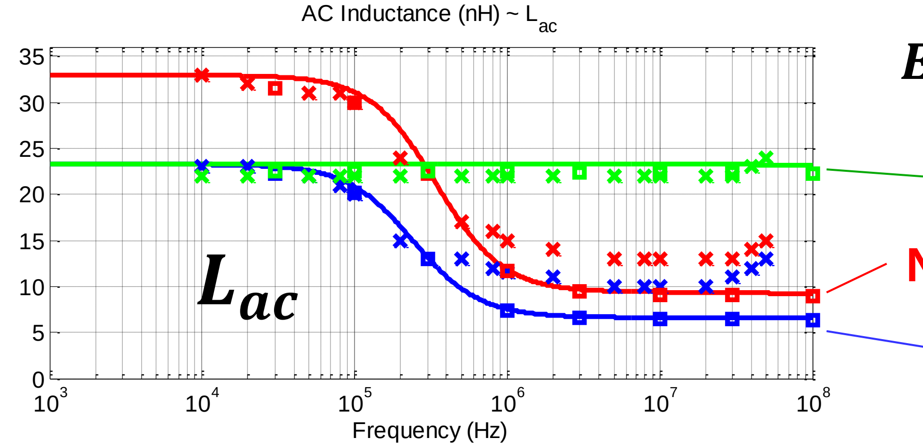
Non interleaved

Alternating

Symmetric



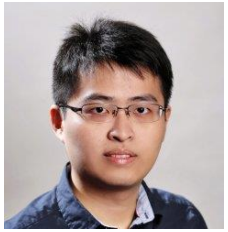
$$P_{ac} = \sum I^2 R_{ac}$$



$$E_{ac} = \frac{1}{2}\sum I^2 L_{ac}$$

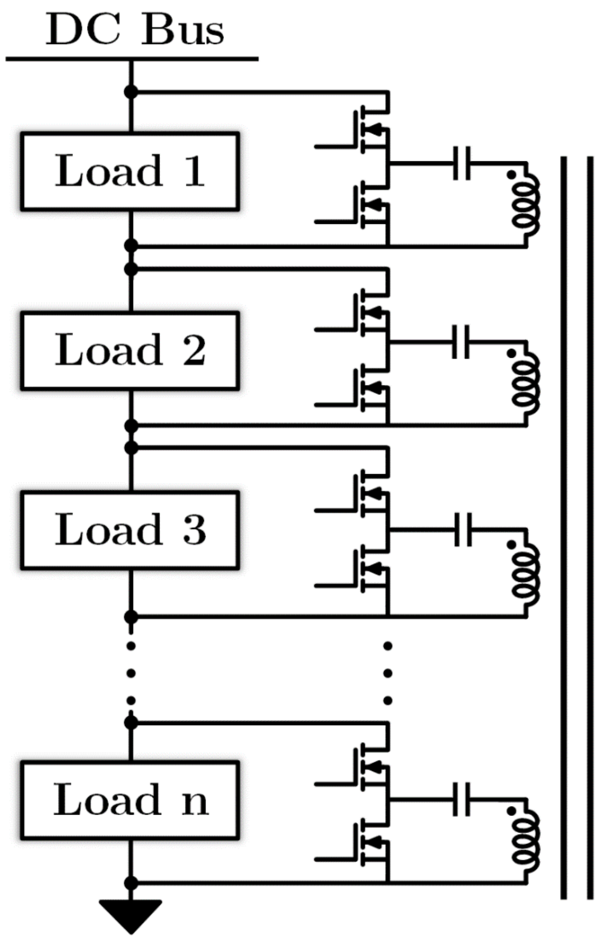
Interleaving has to be done in the right way !!!

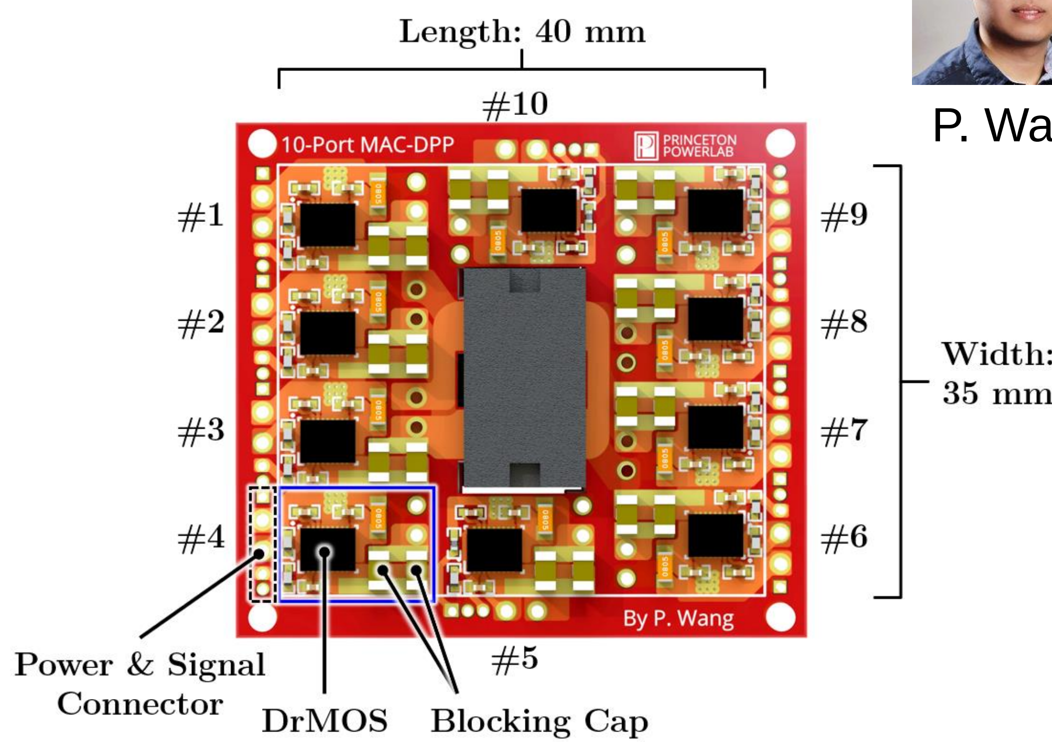
MIMO Energy Balancer for DPP



P. Wang

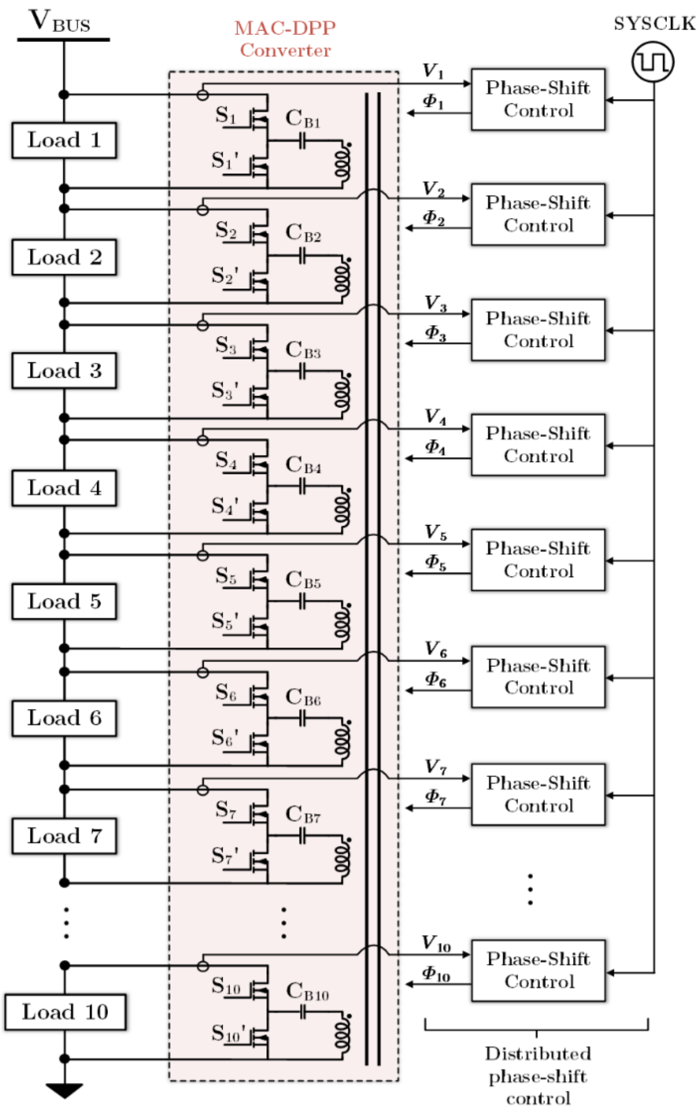
Distributed Phase-Shift Modulation for MIMO Power Flow

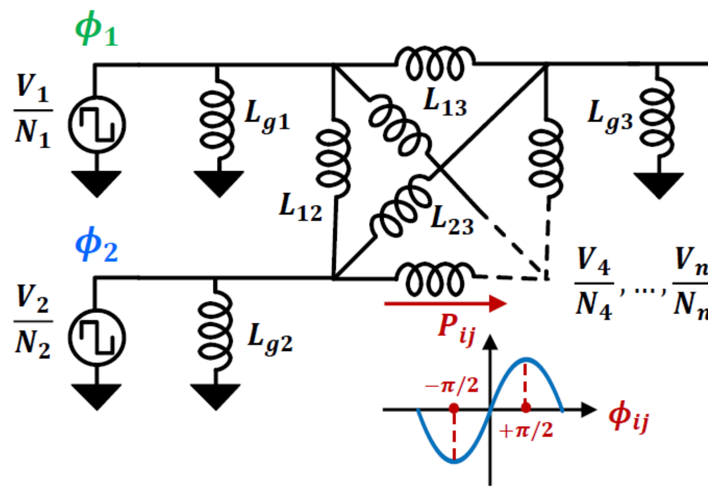


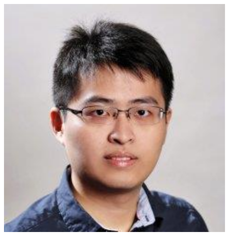


[P. Wang, M. Chen et al., TPEL’21]

Power Flow Control of Multi-Active-Bridge







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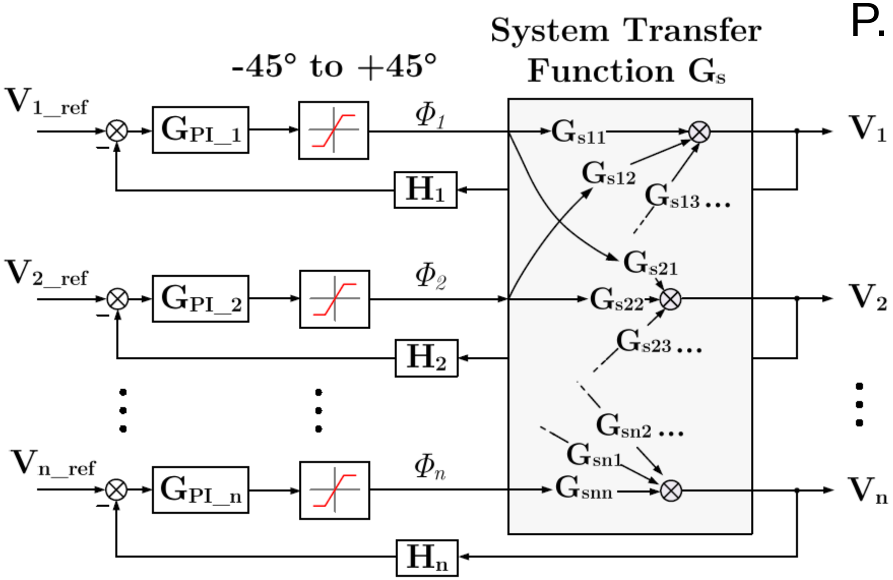
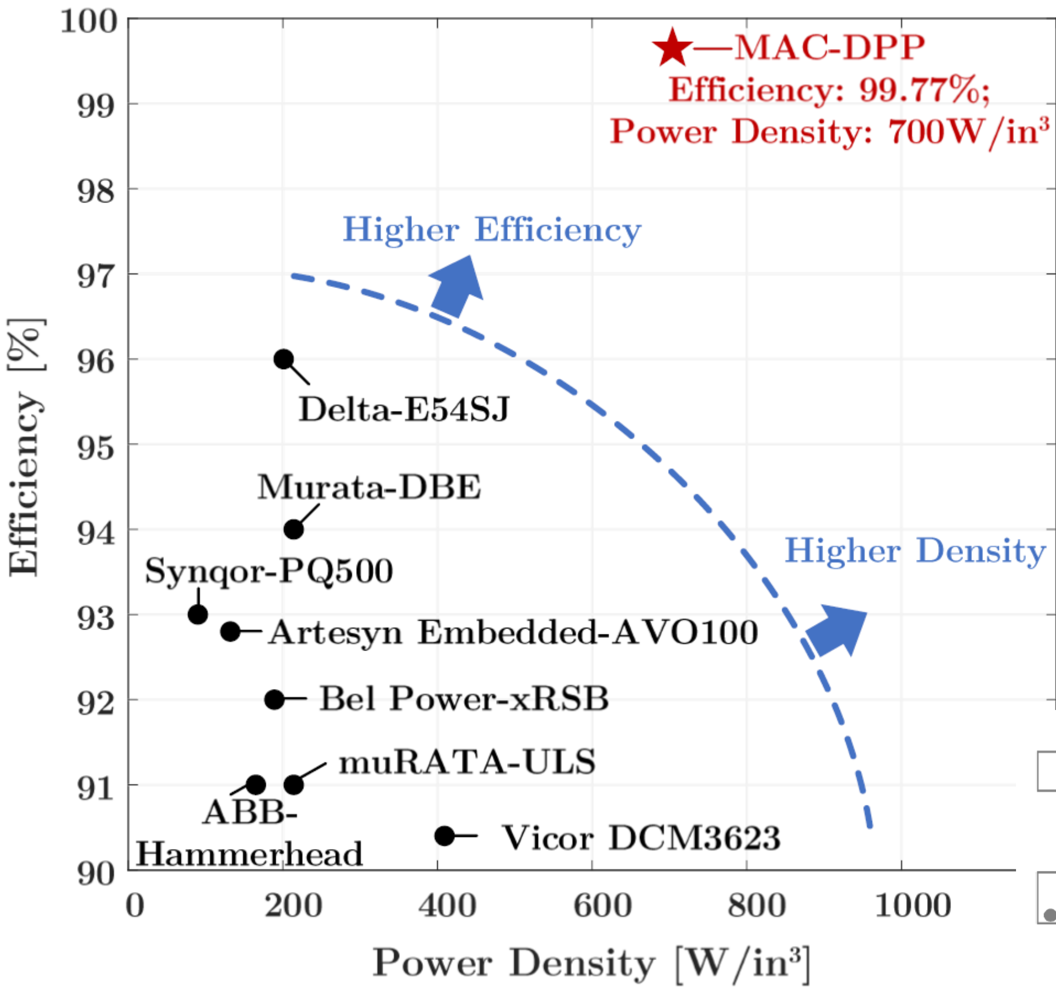
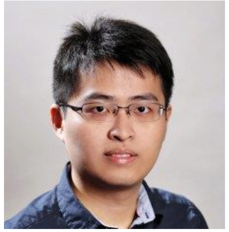


[P. Wang, M. Chen et al., TPEL'21]

Ultra Efficient DPP System

Efficiency comparison of 50 V-5 V dc-dc systems





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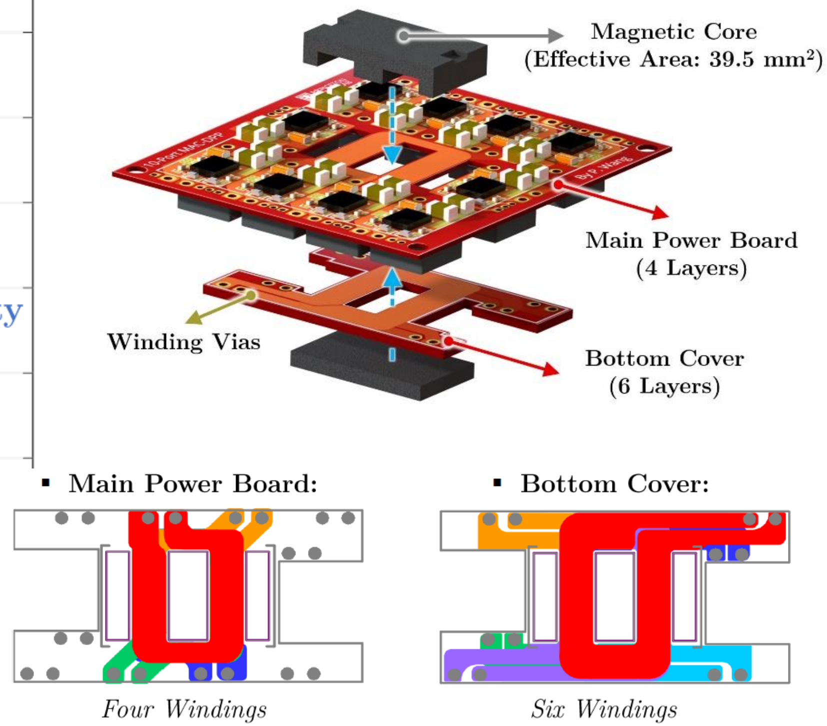
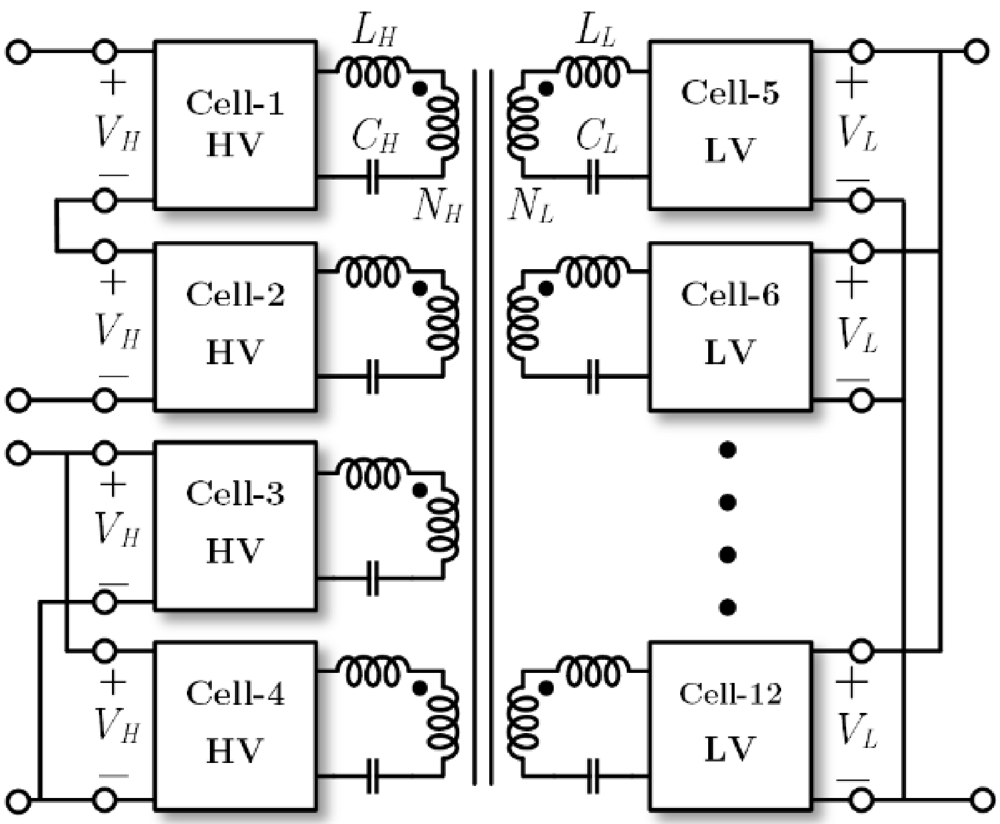
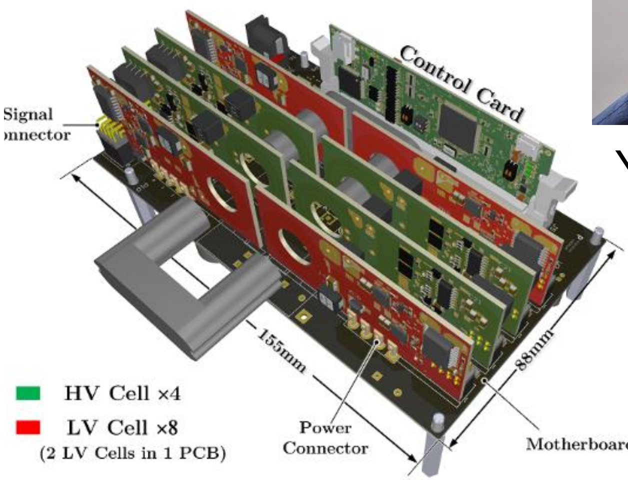


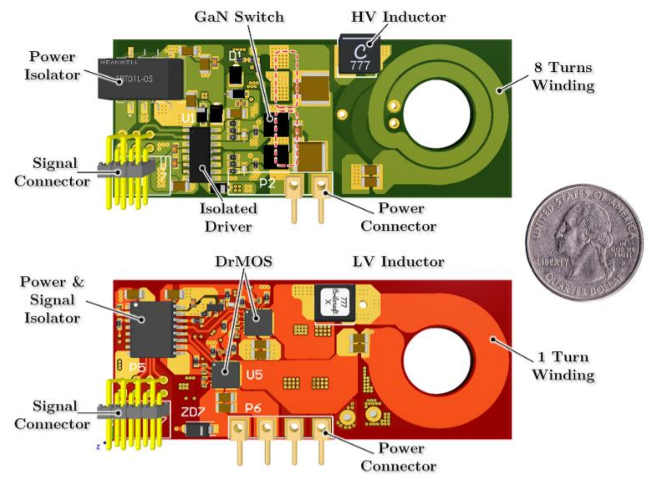
[P. Wang, M. Chen et al., TPEL'21]

MIMO Reconfigurable Energy Router

Reconfigurable MIMO Energy Router







Y. Chen

[Y. Chen, M. Chen et al., TPEL'20]

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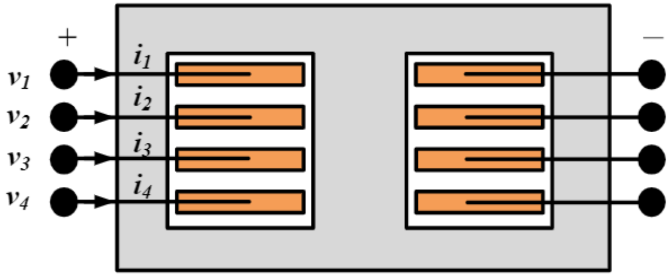
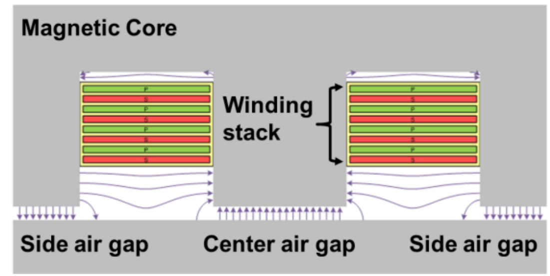
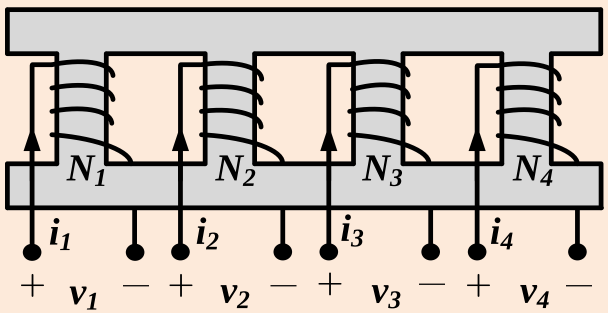
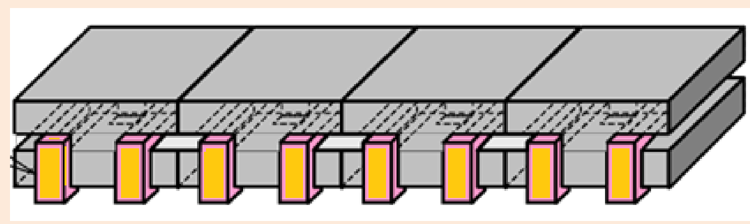


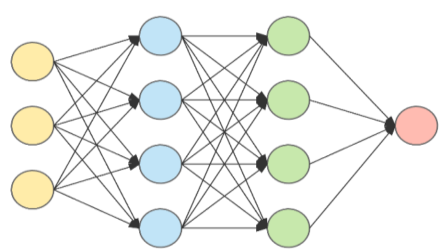


- ❑ Design methodologies for parallel coupled structure (ladder core)





- ❑ Machine learning based magnetic core loss modeling methods



Princeton MagNet

Circuit Models for Mathematical Modeling

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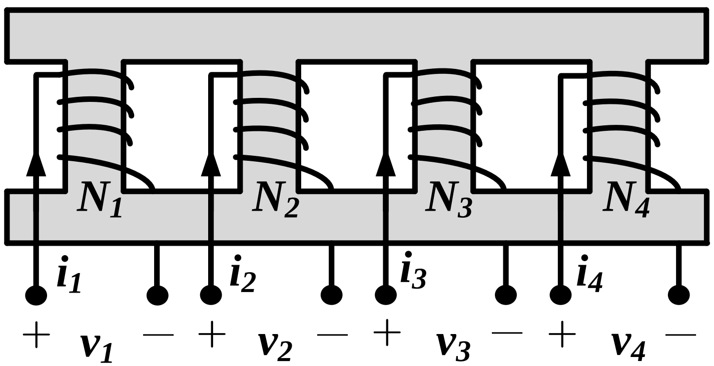
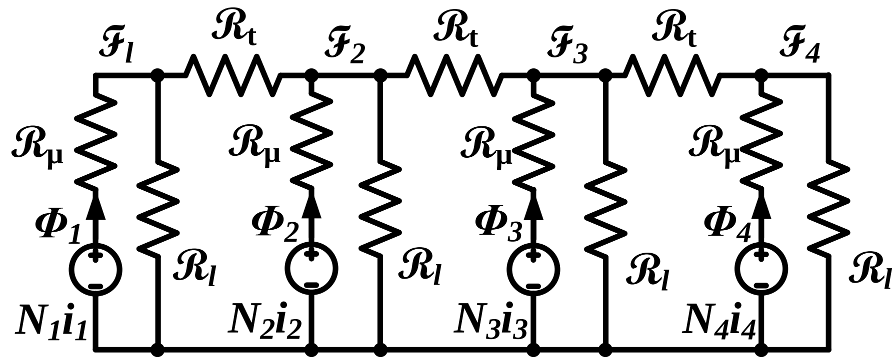
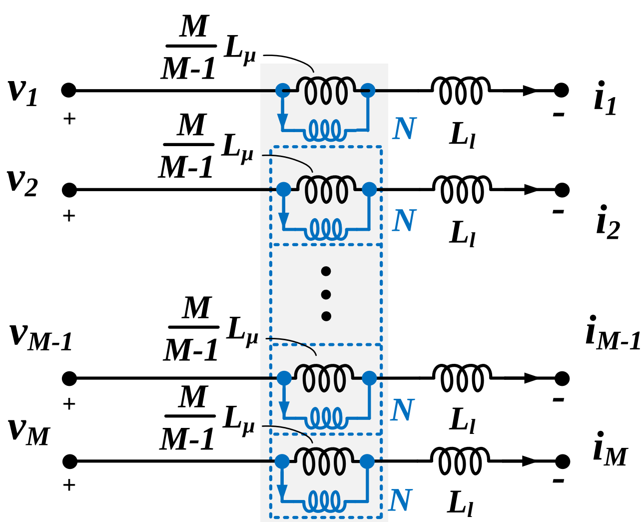
Physical Structure



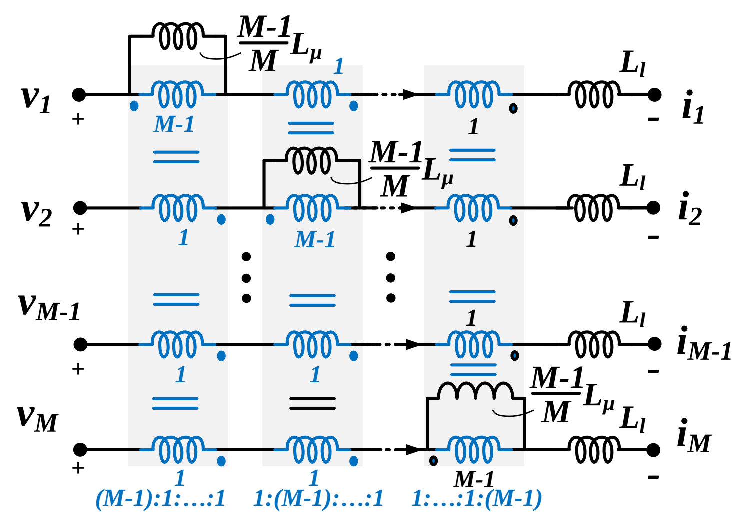
Reluctance Model



Current Equalizing Transformer Model



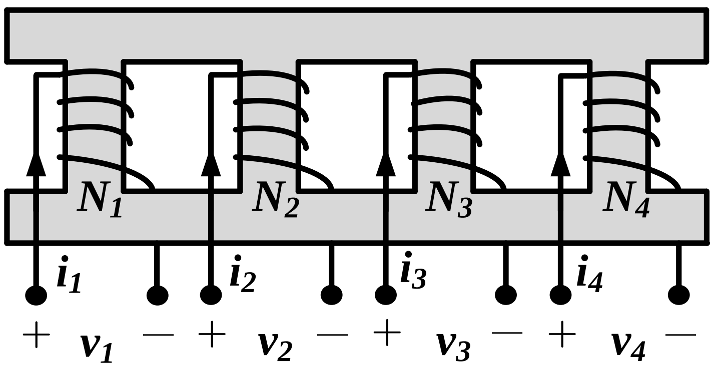
Voltage Equalizing Transformer Model



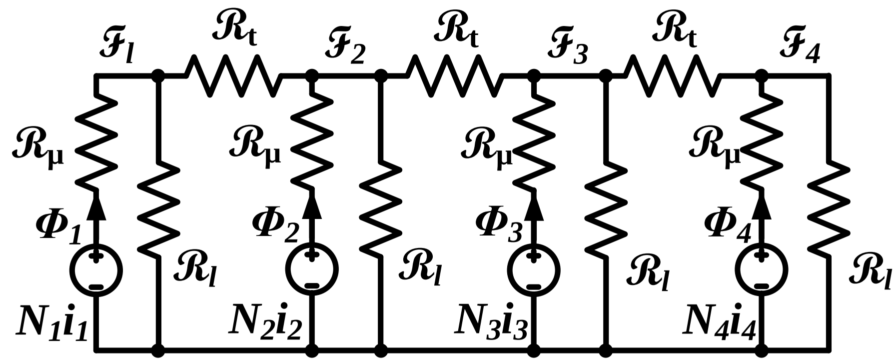
[M. Chen and C. R. Sullivan, TechRxiv'20]

Circuit Models for Physical Design

Physical Structure

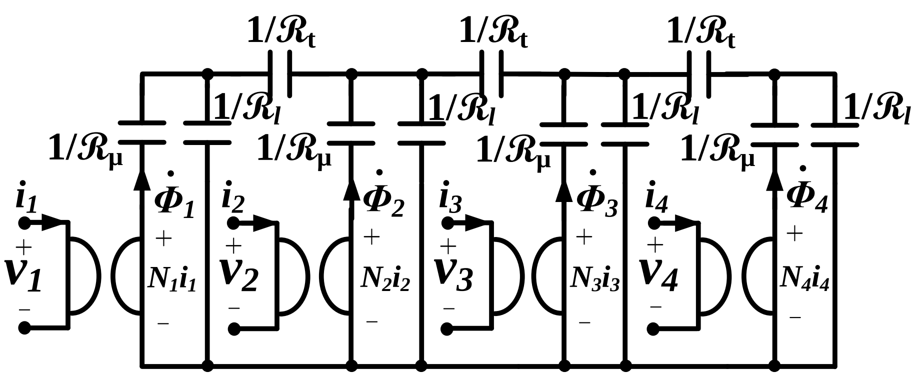


Reluctance Model

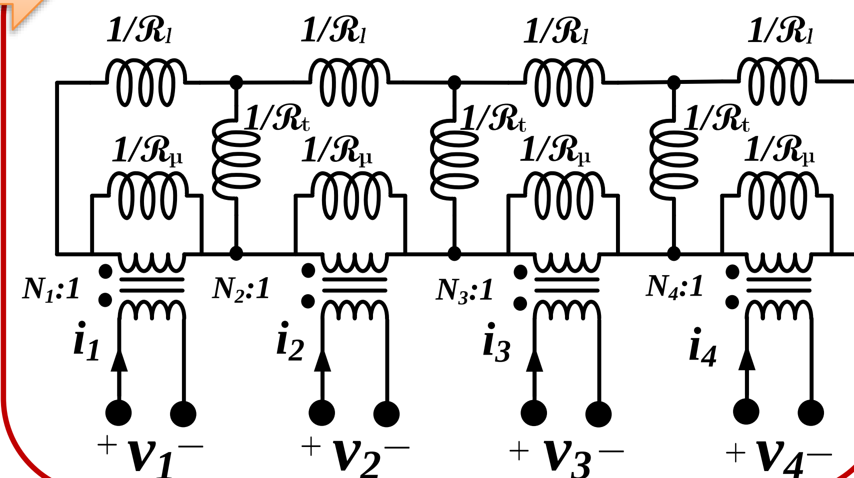


Gyrator-Capacitor Model

dual



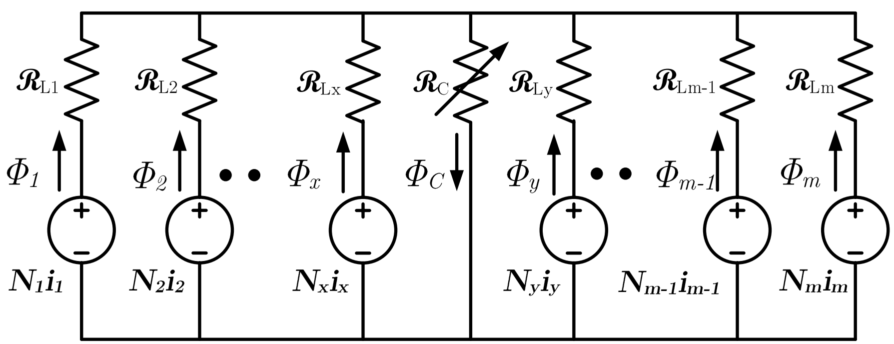
Inductance Dual Model

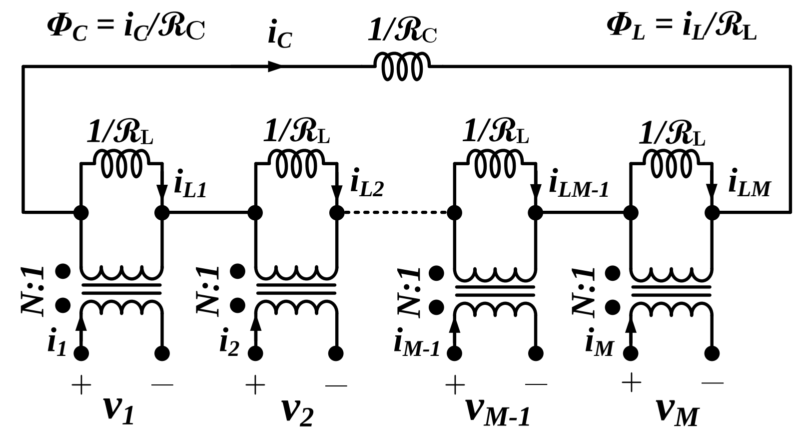


[M. Chen and C. R. Sullivan, TechRxiv'20]

Principles of Inductance Dual Model

Reluctance Model ⟺ dual ⟺ Inductance Dual Model





- Through variable: Flux (Φ)
- Cross variable: MMF (Ni)
- Element value: Reluctance (R)
- Energy storage: $E = \frac{1}{2}R\Phi^2$
- Power: $MMF\frac{d\Phi}{dt}$ or $R\Phi\frac{d\Phi}{dt}$

- Through variable: Current (I)
- Cross variable: Voltage (V)
- Element value: Inductance (L)
- Energy storage: $E = \frac{1}{2}LI^2$
- Power: VI

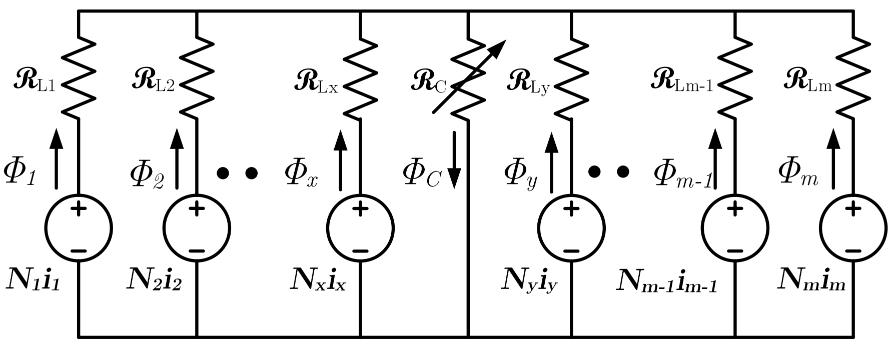
[M. Chen and C. R. Sullivan, TechRxiv'20]

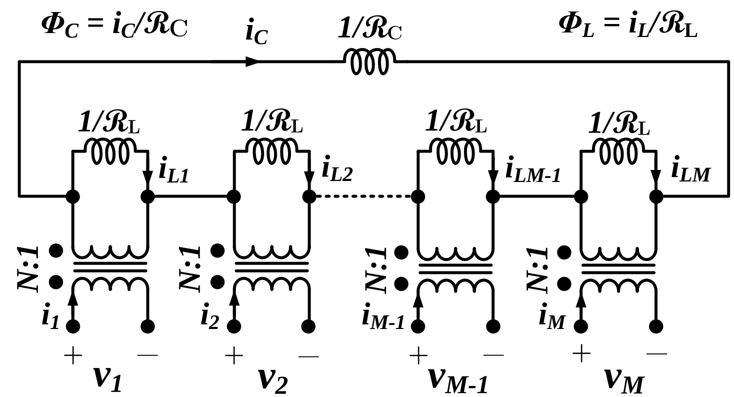
Simulate for Core Loss and Flux Density

Reluctance Model

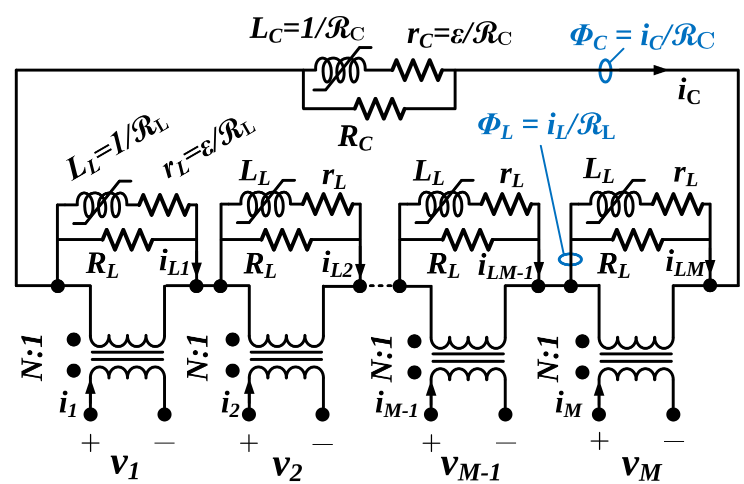
dual

Inductance Dual Model





Inductance Dual Model with Core Loss



Advantage:

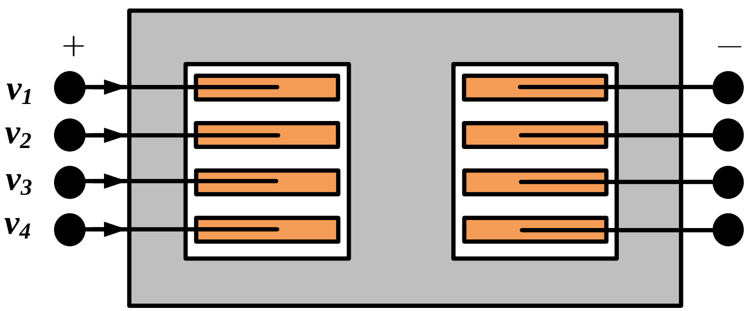
- Simple
- Intuitive
- No coupling relationships
- Explicit design equations
- Capability of capturing core loss
- Visualizing flux distribution

[M. Chen and C. R. Sullivan, TechRxiv'20]

Geometrical Dual

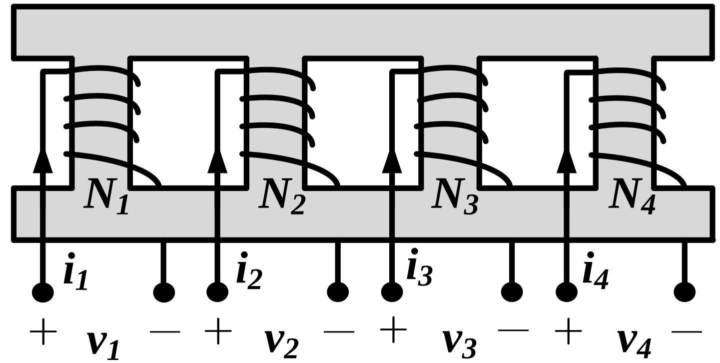
Equal Φ

Series Coupled

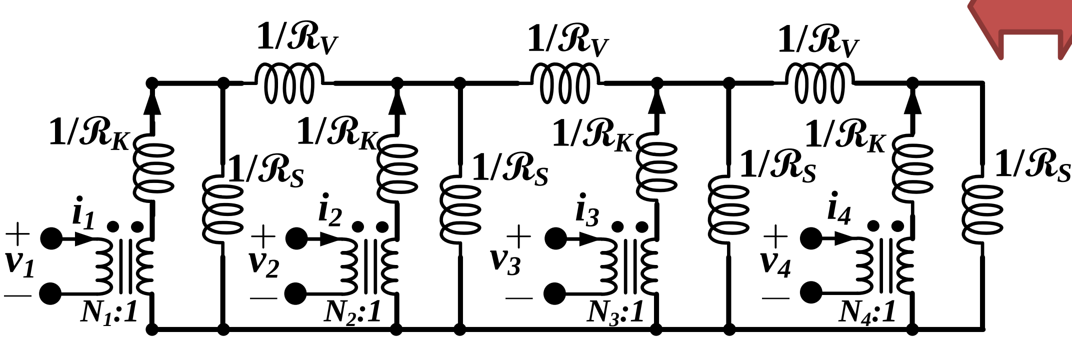


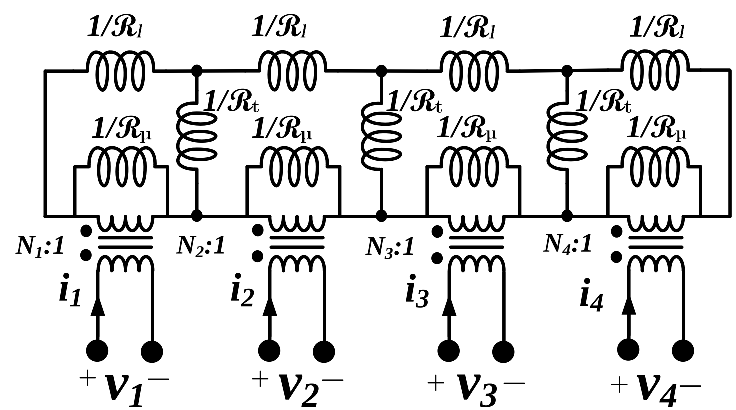
Equal MMF

Parallel Coupled



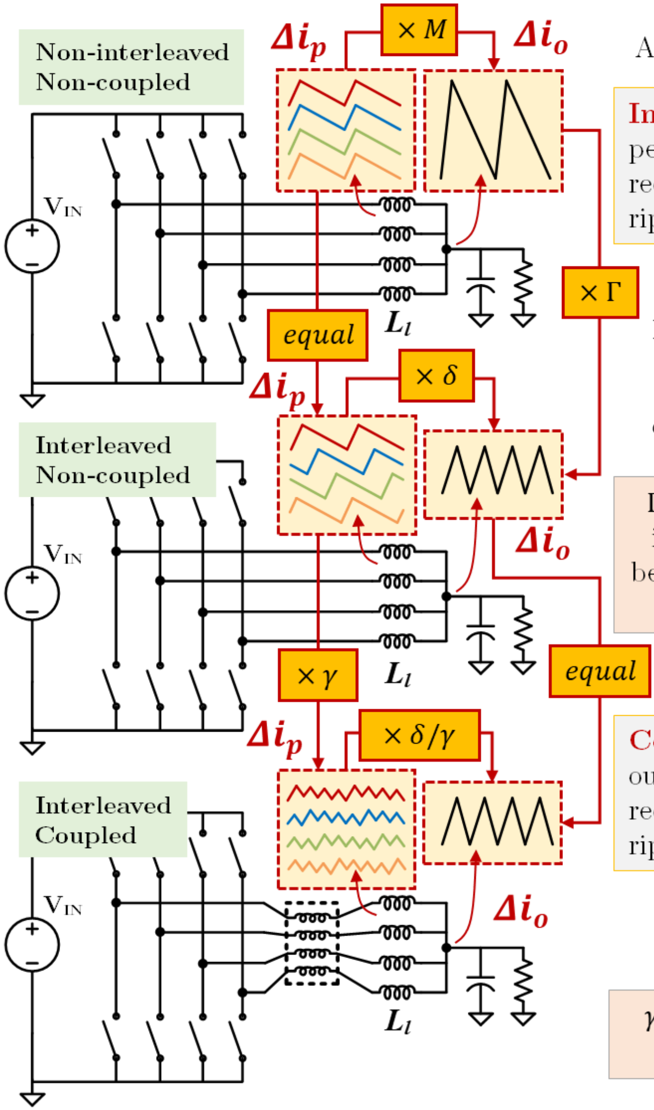
Topological Dual





[M. Chen and C. R. Sullivan, TechRxiv’20]

Unified Design Methods for CoupL



All designs have identical L_l

Interleaving maintains the per-phase current ripple and reduces the output current ripple by a factor of Γ.

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

$$\delta = \frac{(k+1-DM)(DM-k)}{(1-D)DM}$$

Γ quantifies the benefits of interleaving; δ is the ratio between the phase ripple and output ripple.

Coupling maintains the output current ripple and reduces the per-phase current ripple by a factor of γ.

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

γ quantifies the benefits of multiphase coupling.

Benefits of interleaving

- reduced output current ripple

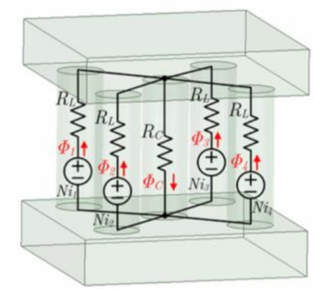
$$\Gamma = \frac{(k+1-DM)(DM-k)}{(1-D)DM^2}$$

Benefits of coupling

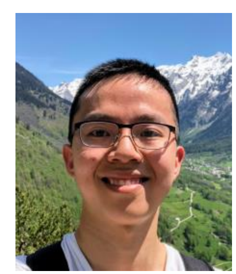
- reduced per-phase current ripple

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

$$\beta = \frac{MR_C}{R_L}$$



Clarified the relationship between multiphase coupling and multiphase interleaving!



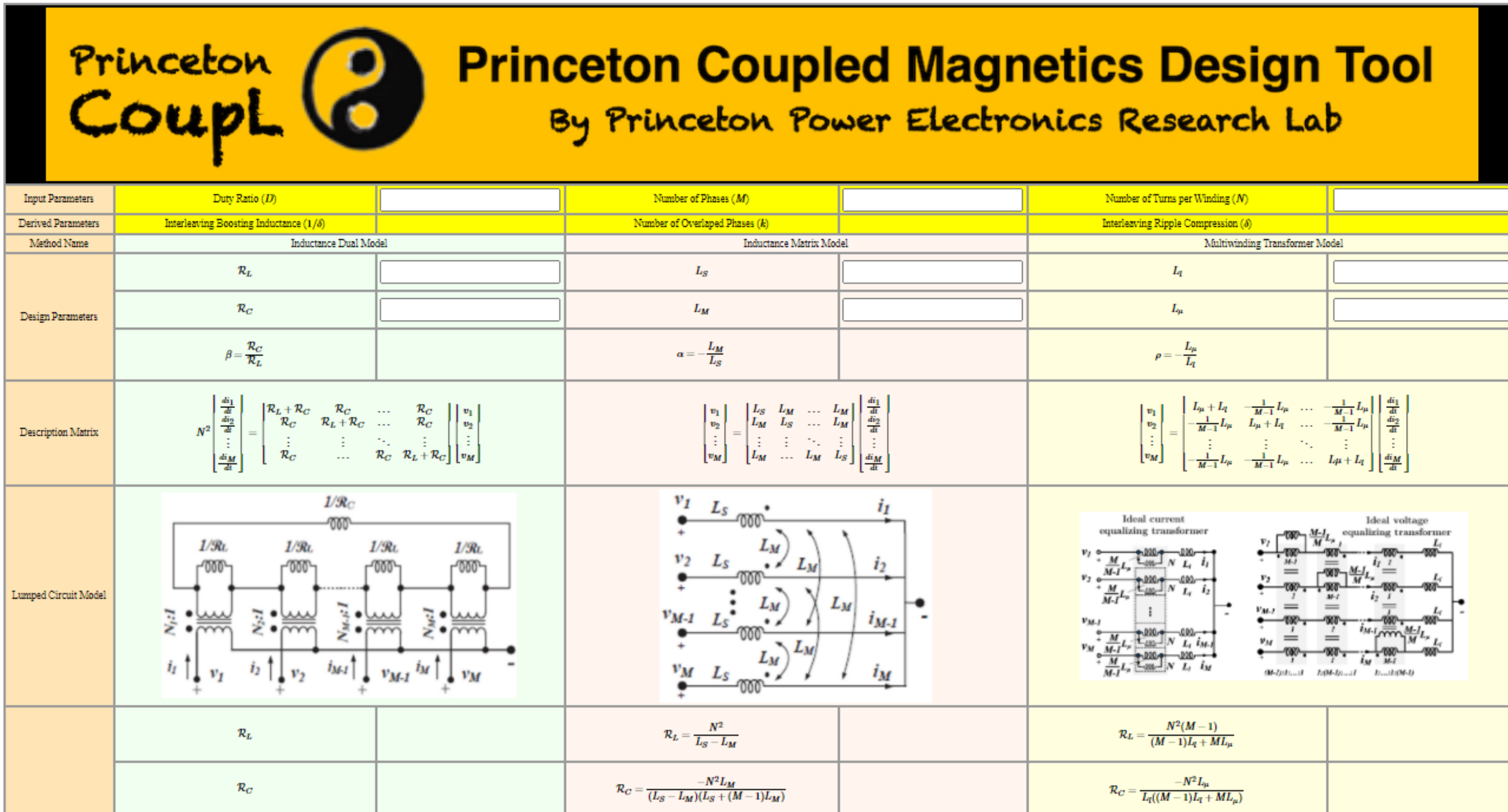

D. Zhou C. R. Sullivan

[M. Chen and C. R. Sullivan, TechRxiv'20]

Princeton Coupled Magnetics Design Tool

Unifies the design equations for multiphase coupled inductors for different models

http://www.princeton.edu/~minjie/coupL/coupL.html



CPU Power Delivery Challenge

High Voltage Conversion Ratio
- 48 V: 1 V is the future standard

High Output Current
- Approaching 1000 A

Fast Transient Response
- Over 5 A/ns

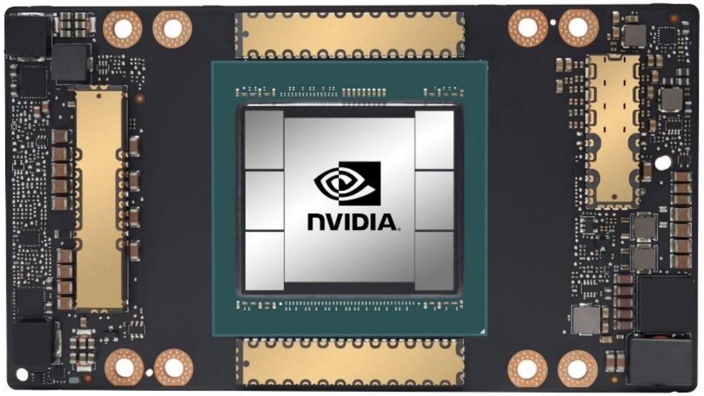
Extreme Power Density
- >100 A/cm2

Extreme Efficiency Target
- >95% peak; >80% full load

Collaborators

intel Google pSemi A Murata Company

- J. Baek, M. Chen et al., "LEGO-PoL: A 48V-1.5V 300A Merged-Two-Stage Hybrid Converter for Ultra-High-Current Microprocessors," *APEC 2020.*



Nvidia Tesla A100

Nvidia A100 AI Server

Hybrid Converter with Coupled Magnetics

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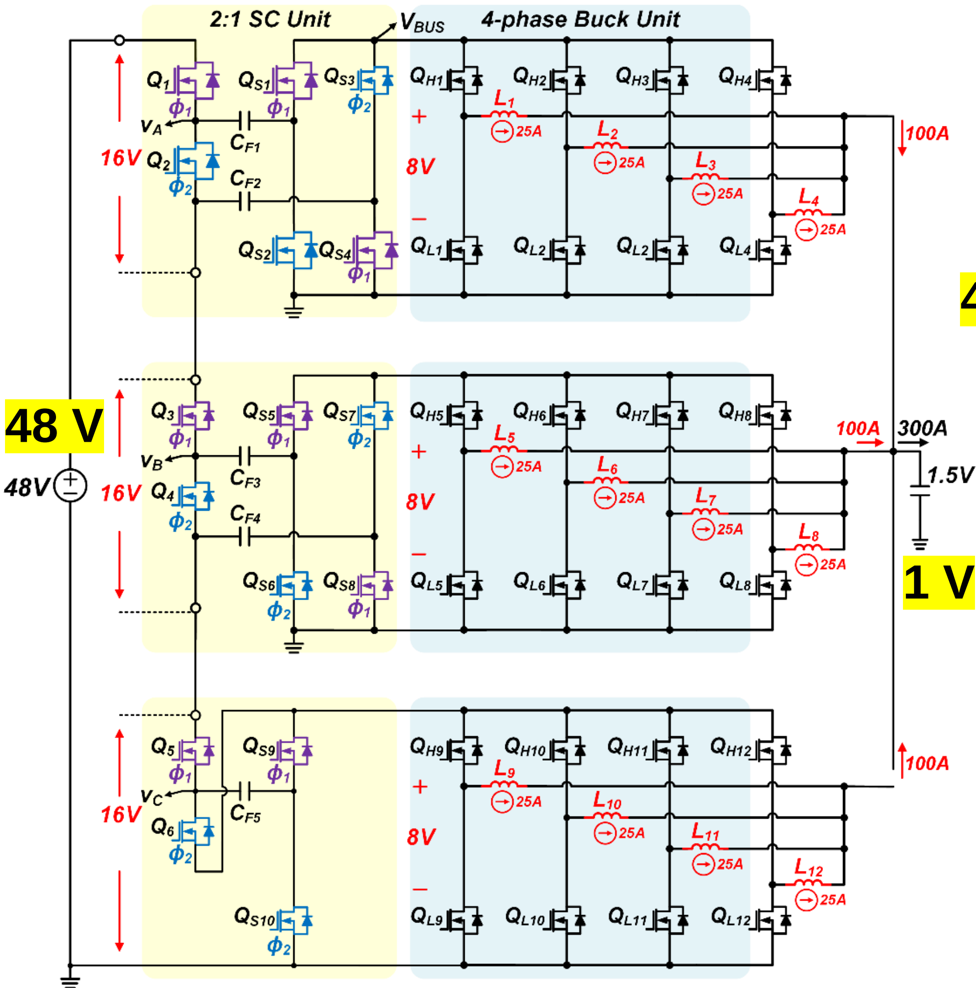
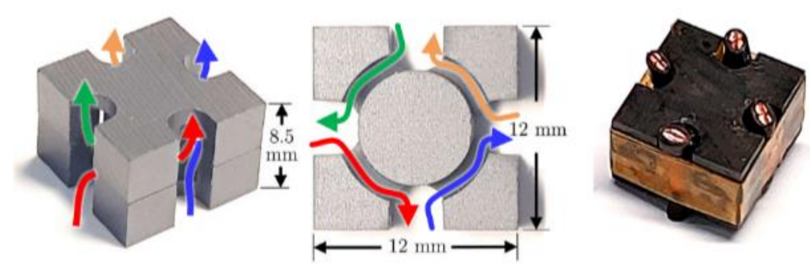
LEGO-PoL Architecture

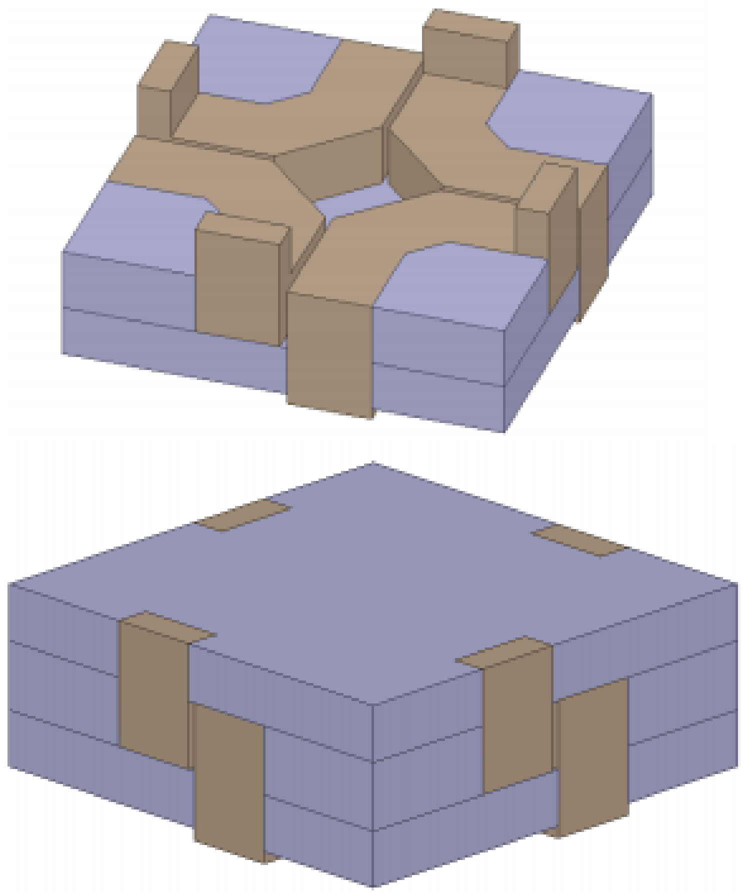




Four-Phase Coupled Magnetics (250 A)

[J. Baek, M. Chen et al., APEC'20]

Vertical Multiphase Coupled Inductor

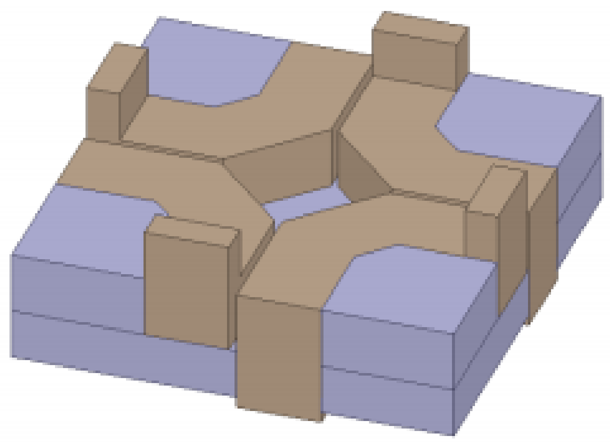


Sophisticated design space
- Side leg area
- Center leg area
- Winding area
- Plate thickness
- 2D layout
- 3D structure

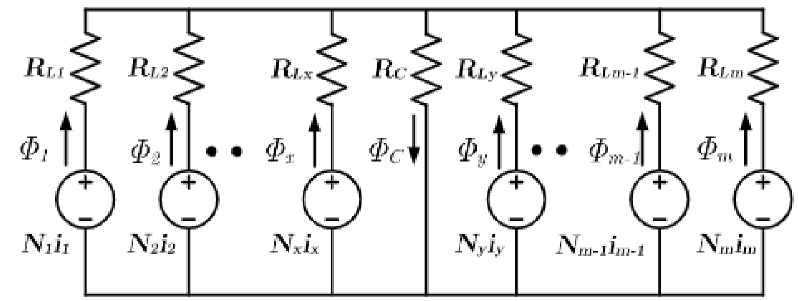
Optimization targets
- Smallest leakage inductance
- Largest magnetizing inductance
- Lowest loss
- Smallest size
- Sufficient saturation margin

[J. Baek, M. Chen et al., APEC'20]

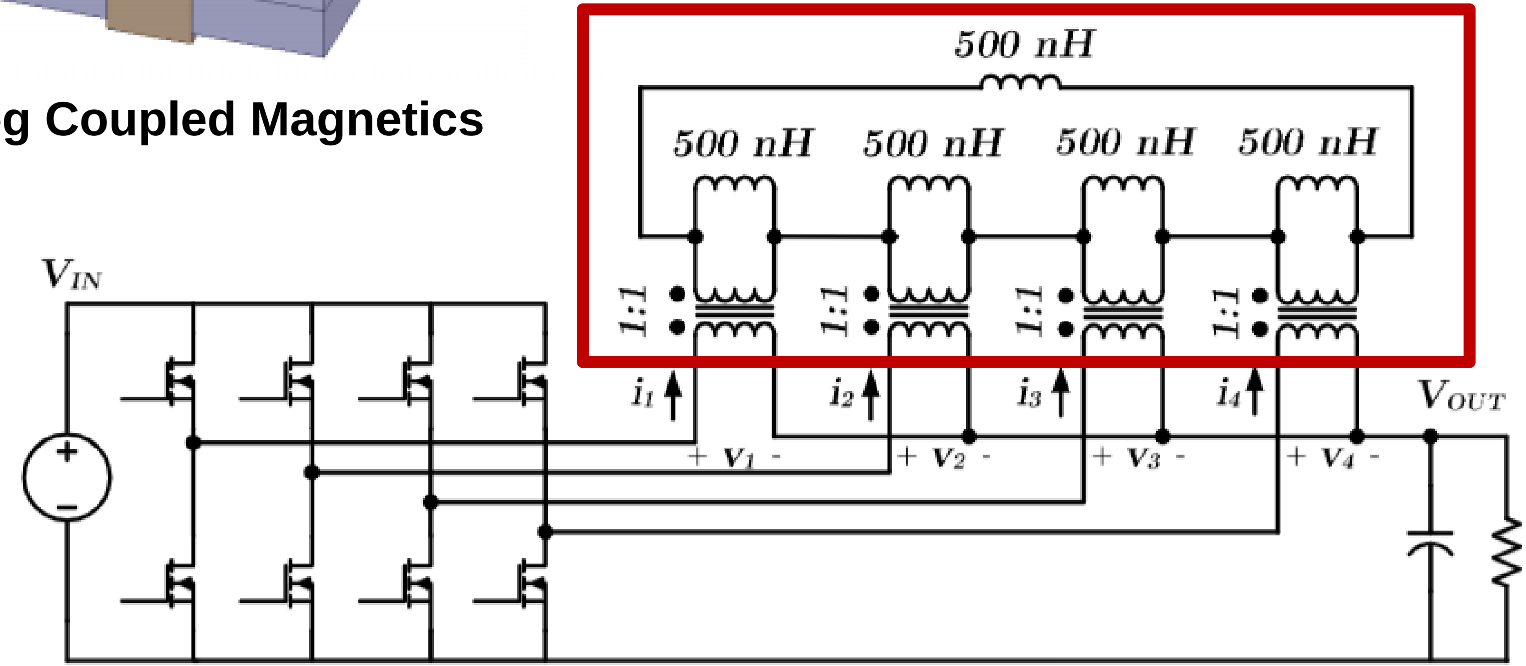
Magnetic in Circuit Analysis



Multileg Coupled Magnetics



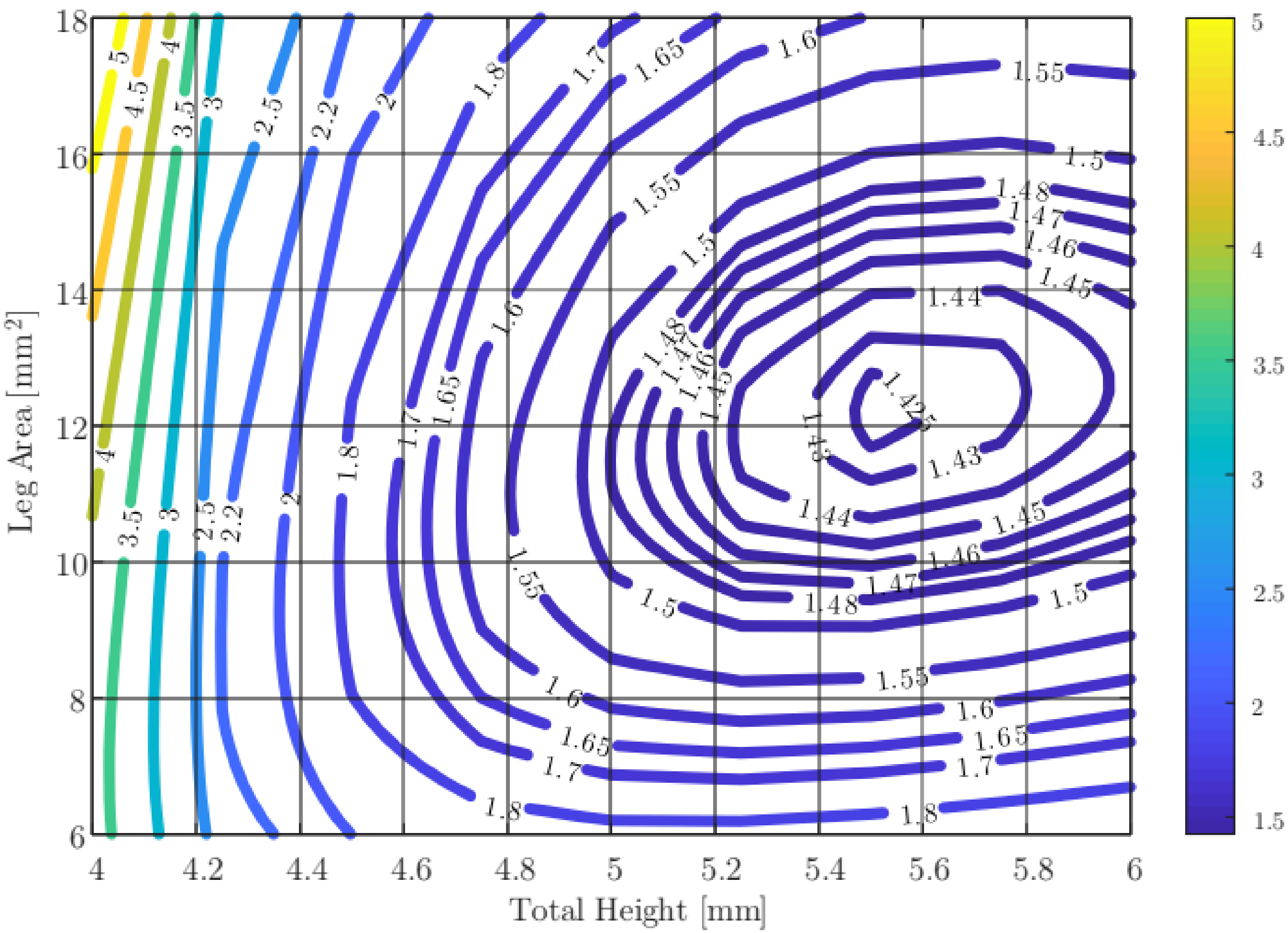
Topological duality



[J. Baek, M. Chen et al., APEC'20]

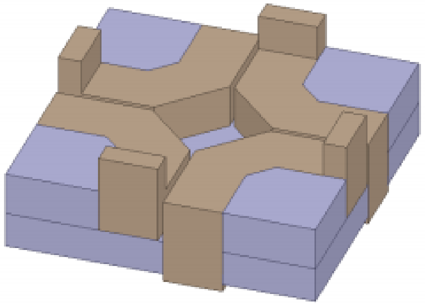
Vertical Magnetics Optimization

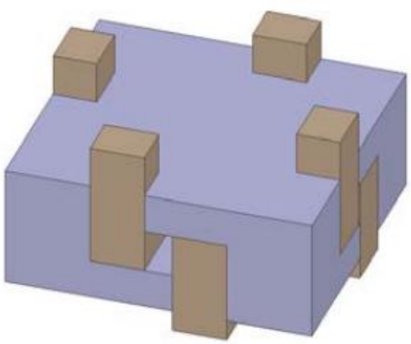
Min Loss: 1.4231W at h=5.5mm, A_{leg}=12.25mm²



J. Baek

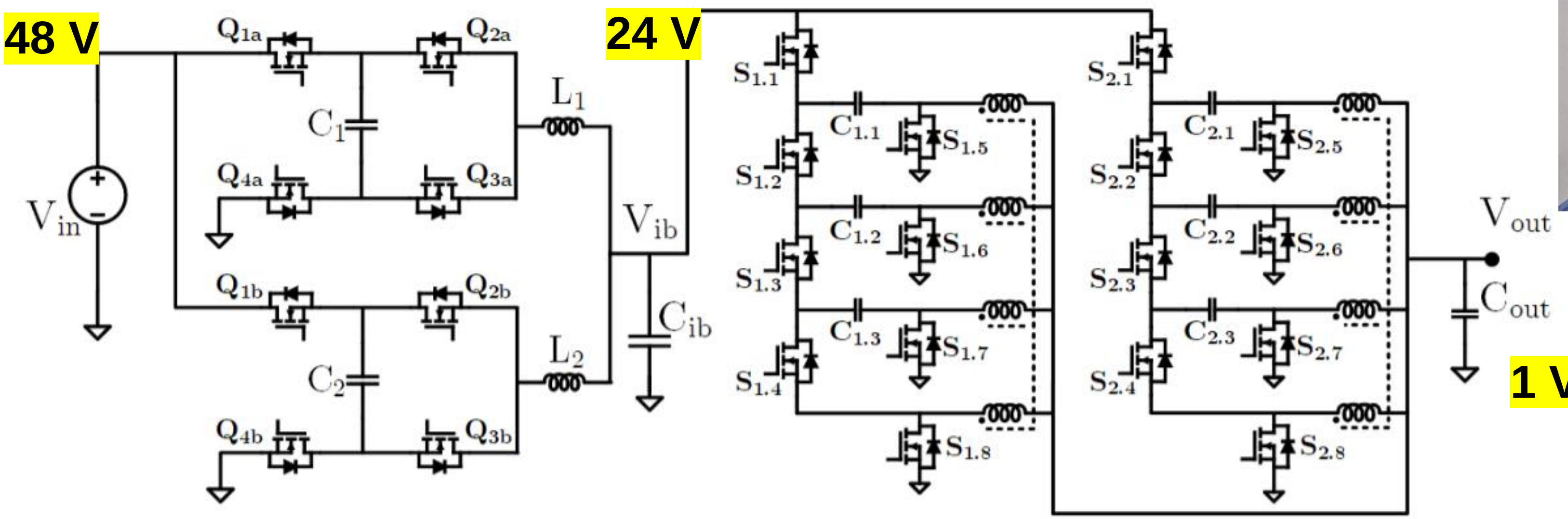
Y. Elasser



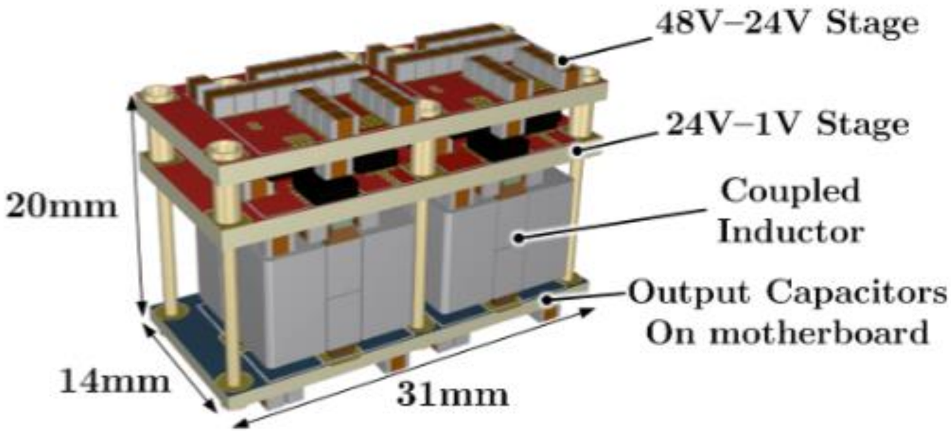


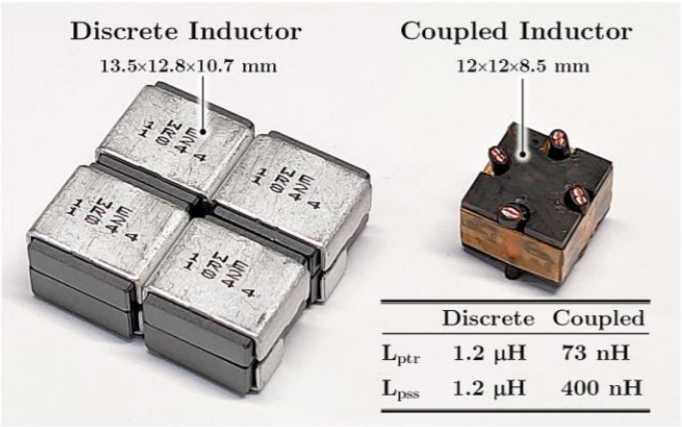
[J. Baek, M. Chen et al., APEC'20]

Other High Performance PoL Designs



Y. Chen

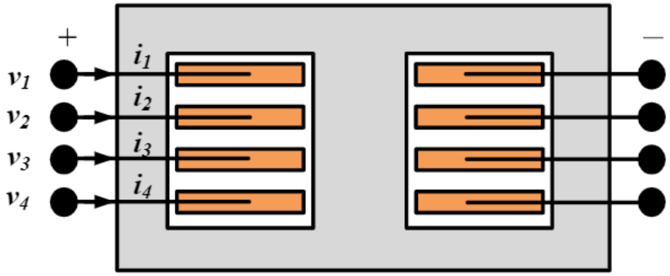


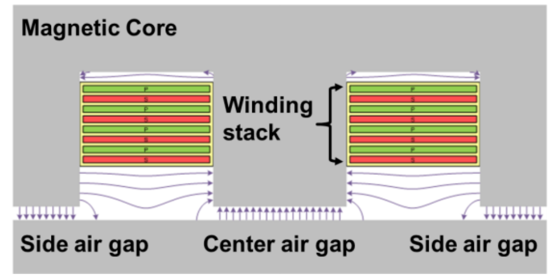


- Y. Chen, M. Chen et al., "Two-Stage 48V-1V Hybrid Switched-Capacitor Point-of-Load Converter with 24V Intermediate Bus," *COMPEL 2020.* ***[Best Paper Award]***

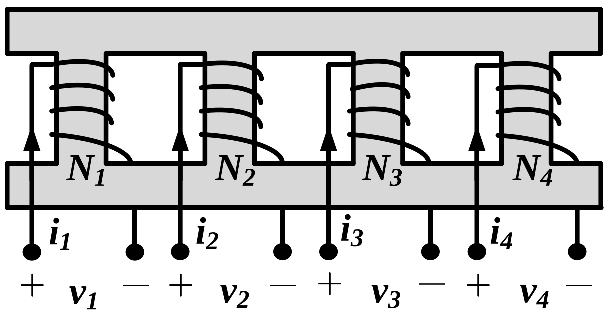
Outline

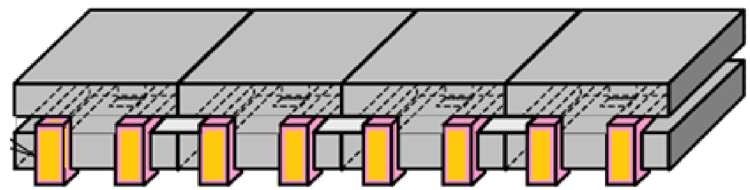
- Design methodologies for series coupled structure (planar core)



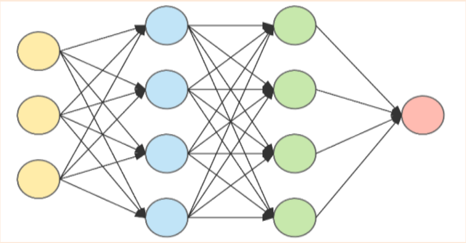


- Design methodologies for parallel coupled structure (ladder core)





- Machine learning based magnetic core loss modeling methods



Machine Learning for Core Loss Modeling

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- **Generalized Steinmetz Equation (GSE)**

$$P_v = k f^{\alpha} \hat{B}^{\beta}$$

three parameters, sine wave $k,\ \alpha,\ \beta$

- **Improved GSE (iGSE)**

three parameters, non-sine wave

$$P_v = \frac{1}{T}\int_0^T k_i \left|\frac{\mathrm{d}B}{\mathrm{d}t}\right|^{\alpha} (\Delta B)^{\beta-\alpha}\,\mathrm{d}t$$

$k_i,\ \alpha,\ \beta$

- **Improved – improved GSE (i^2GSE)**

eight parameters, non-sine wave

$$P_v = \frac{1}{T}\int_0^T k_i \left|\frac{\mathrm{d}B}{\mathrm{d}t}\right|^{\alpha} (\Delta B)^{\beta-\alpha}\,\mathrm{d}t + \sum_{l=1}^{n} Q_{rl} P_{rl}$$

$k_i,\ \alpha,\ \beta,\ \alpha_r,\ \beta_r,\ \mathrm{k}_r,\ \tau,\ q_r$

- **Machine Learning based Methods**

lots of parameters automatically trained

dc bias, temperature, memory effect, minor loops

neural network

MagNet: ML for Core Loss Modeling

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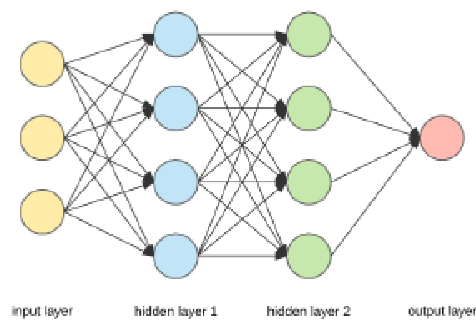
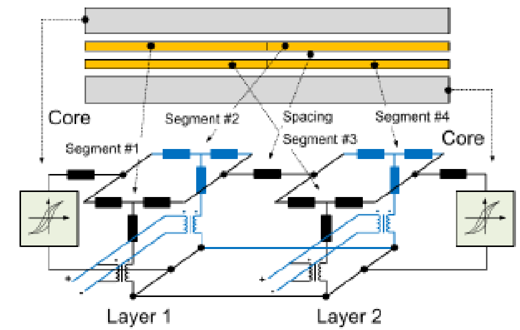
Automatic Data Acquisition | **Neural Network Training** | **SPICE Lumped Circuit**

Task 1: MIDAS A ML-Integrated Data Acquisition System

Task 2: MICLM ML-Integrated Magnetic Core Loss Model



Task 3: MLSPICE A ML-integrated Planar Magnetics SPICE Tool



MagNet - Large Scale Open Source Database, Online Collaboration and Competition Platform

H. Li

Princeton MagNet

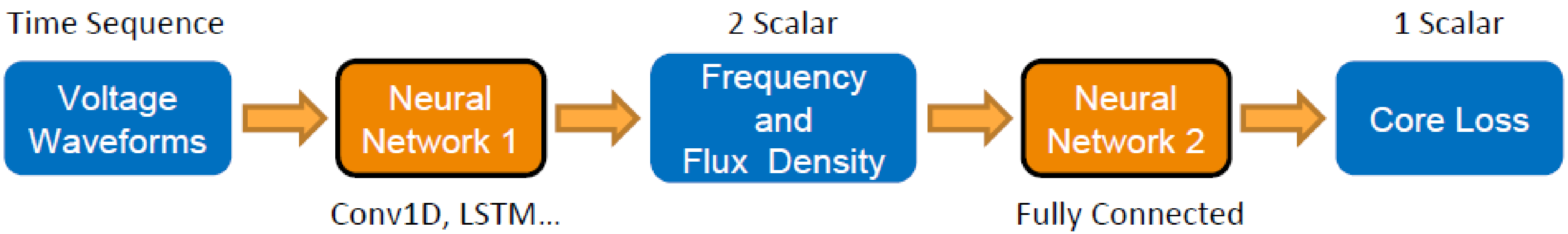
Open source at: GitHub

plexim Dartmouth arpa·e CHANGING WHAT'S POSSIBLE

- H. Li, M. Chen et al. "MagNet: A Machine Learning Framework for Magnetic Core Loss Modeling," *COMPEL'20.*

Machine Learning Methods

- **Supervised learning: use ML to replace existing design steps**



Limitation: constrained by existing knowledge on magnetic core loss

- **Unsupervised learning: end-to-end fully autonomous ML**

Limitation: all information hidden, hard to interpret the results

[H. Li, M. Chen et al., COMPEL'20]

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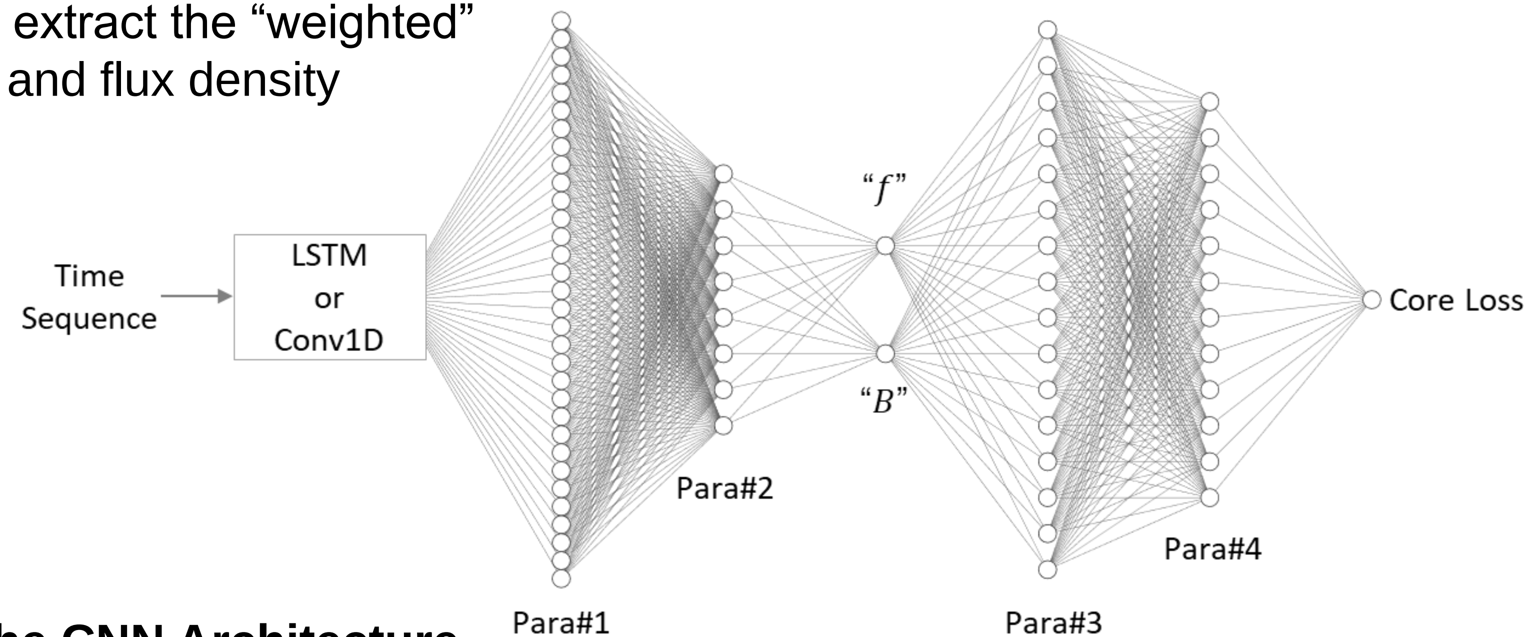
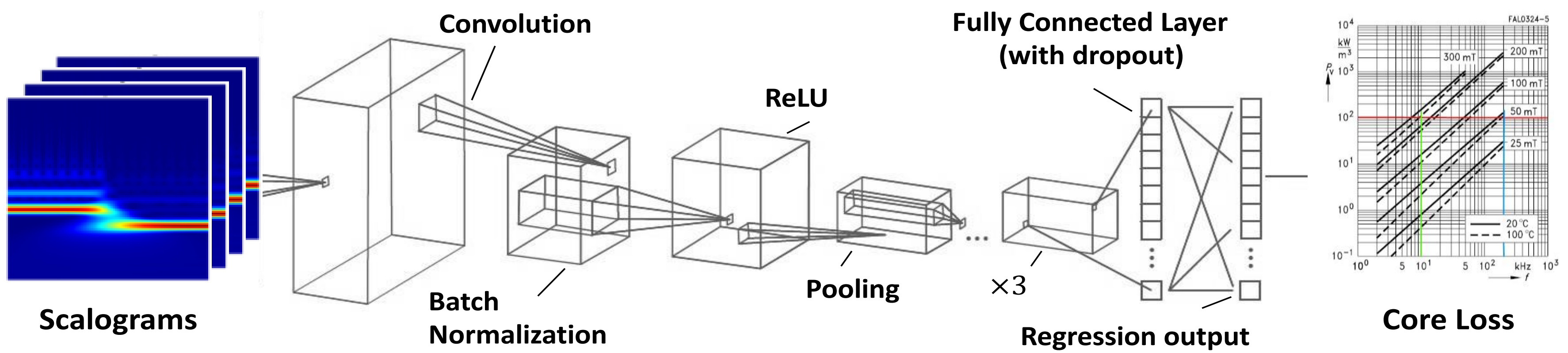
- Use ML to extract the "weighted" frequency and flux density

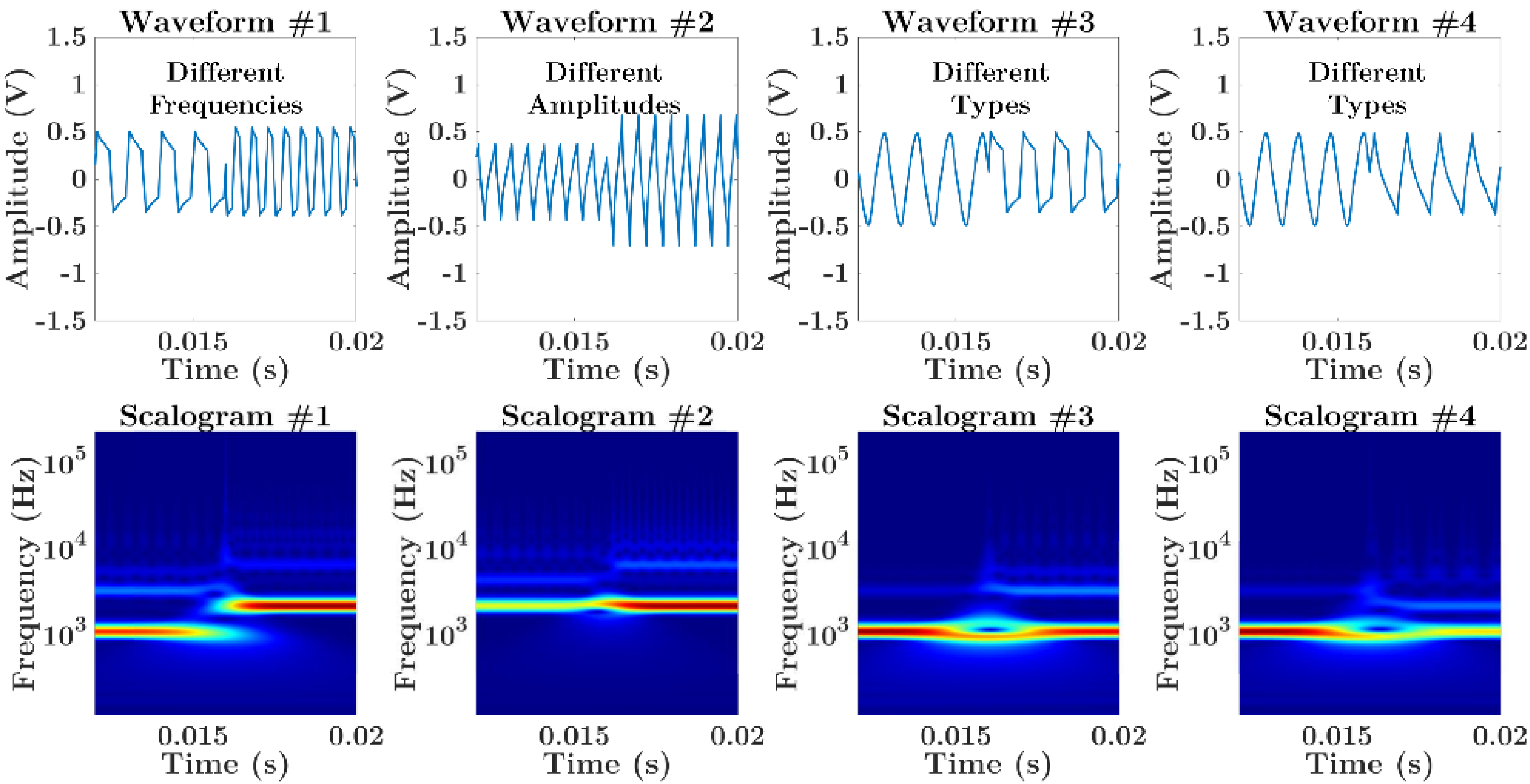


Optimizing the CNN Architecture



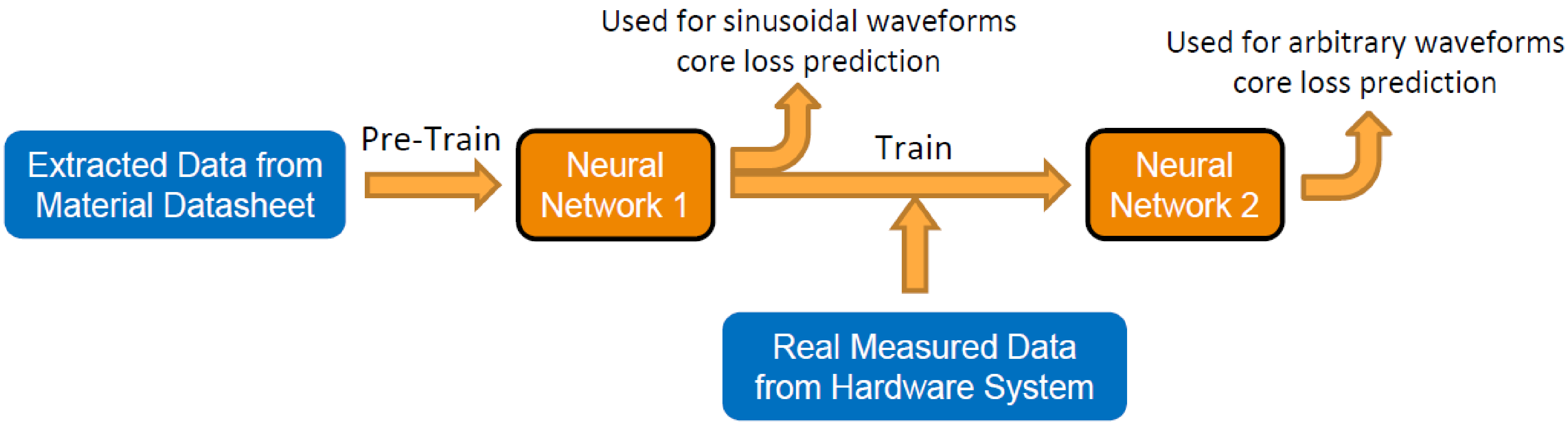
[H. Li, M. Chen et al., COMPEL'20]

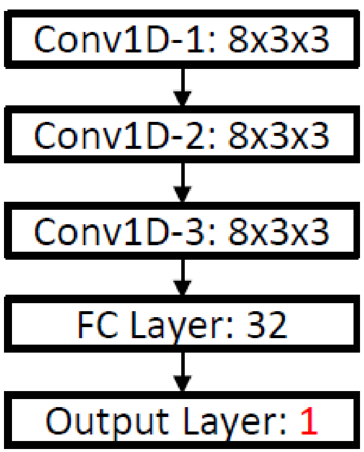
Example 2D Scalograms and CNN



[H. Li, M. Chen et al., COMPEL'20]

Overall Machine Learning Architecture

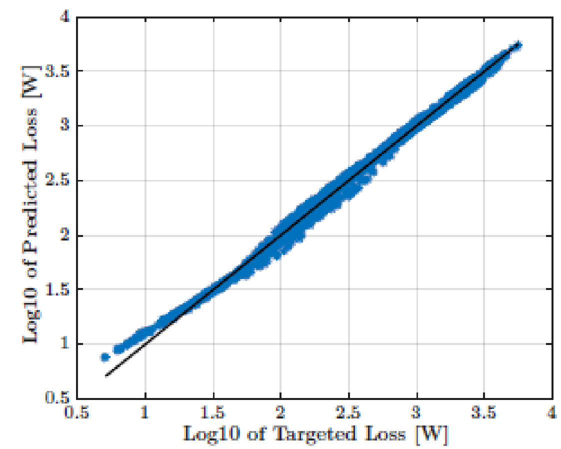




OPTUNA

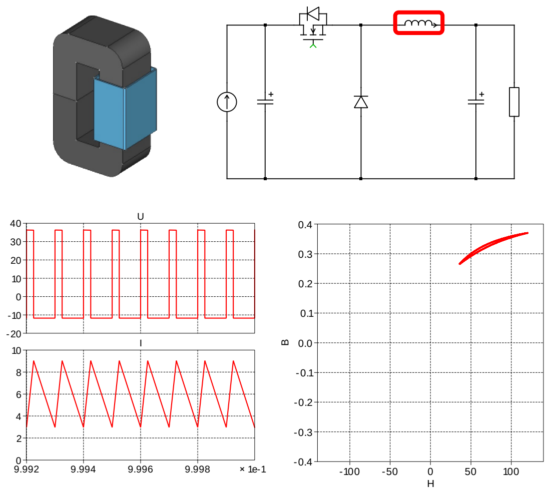
PYTORCH

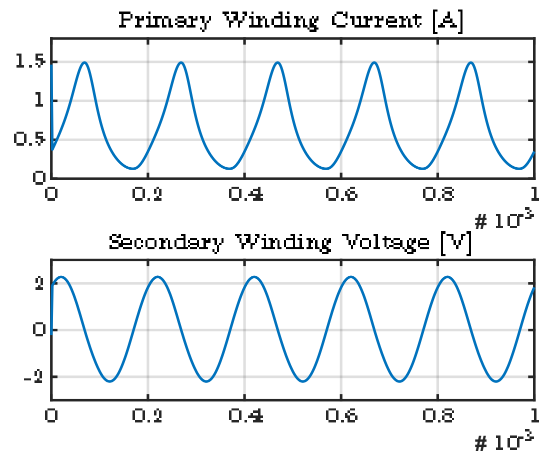
Deep Learning with PyTorch

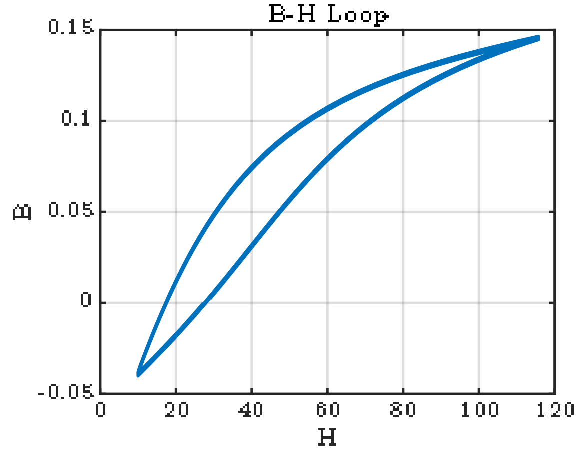


~2% average error for sine wave
~7% average error for arbitrary wave

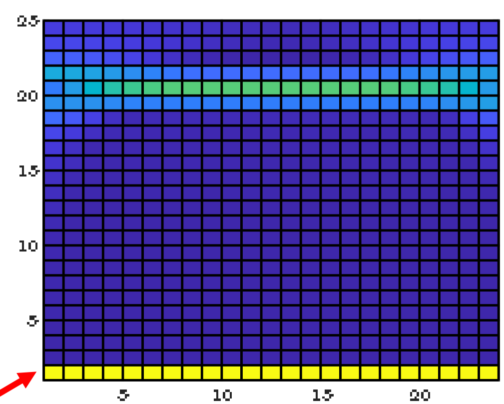
Impacts of DC Bias on Core Loss



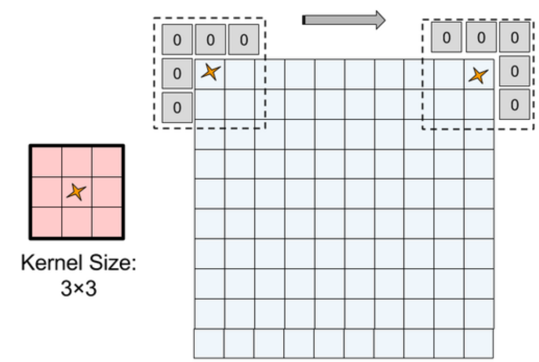




$$\text{scalogram} = \begin{bmatrix} \text{scalogram} \\ K \cdot \text{DC bias} \end{bmatrix}$$

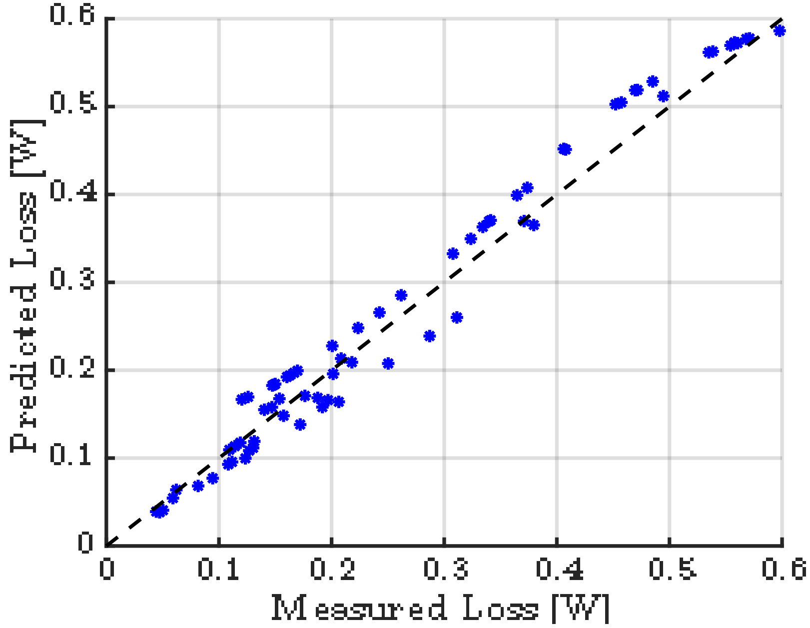


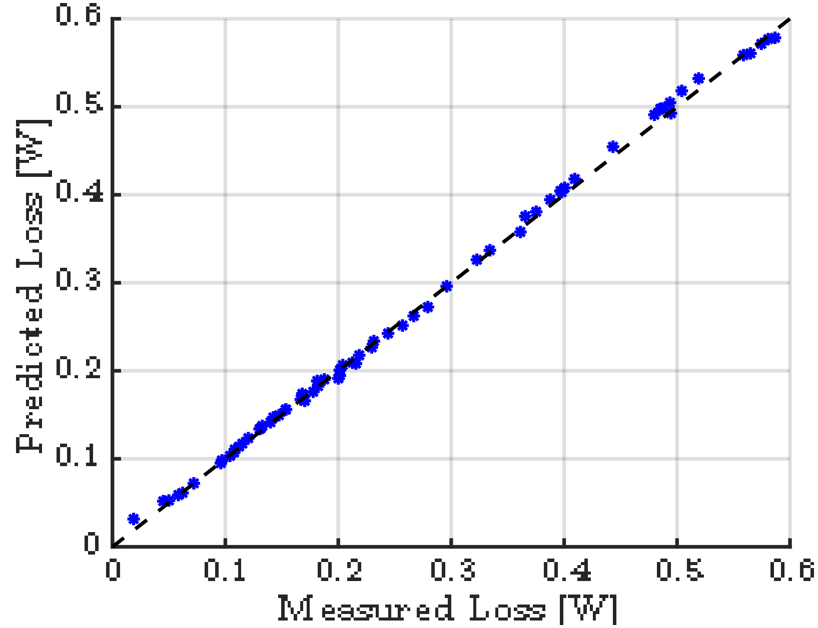
Modeling the dc bias



$$\text{scalogram} = \begin{bmatrix} \text{scalogram} \\ 0 \ldots 0 \ldots 0 \\ \text{DC bias} \end{bmatrix}$$

Core Loss Prediction with DC Bias





Before including the DC bias information: 11.12%

After including the DC bias information by modifying the scalogram: 5.23%

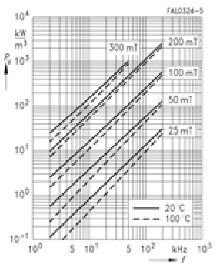
This is just scratching the surface of ML-based core loss modeling methods: dc-bias, temperature, air gap, harmonics, degradation, etc…

[H. Li, M. Chen et al., COMPEL'20]

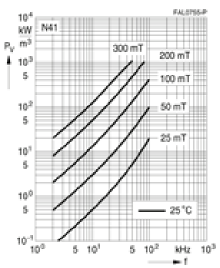
Transfer Learning for Different Materials

Transfer learning method:

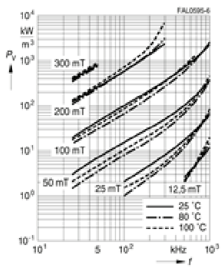
- Train a neural network architecture with data of material A
- Update the neural network parameters with training data of material B
- Test the model accuracy with testing data of material B



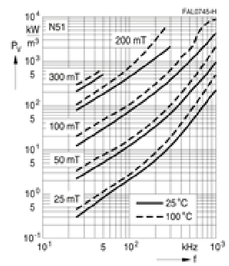
N27: 3.47%



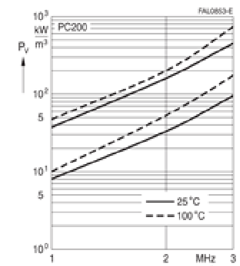
N41: 3.12%



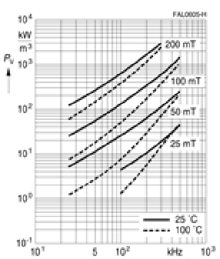
N49: 7.24%



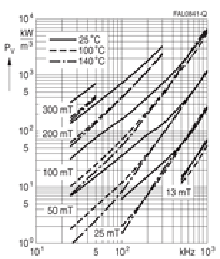
N51: 8.66%



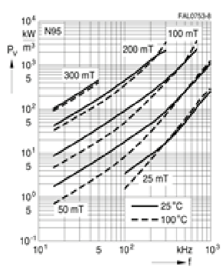
N59: 4.88%



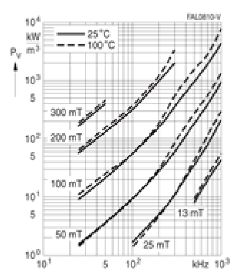
N87: 3.65%



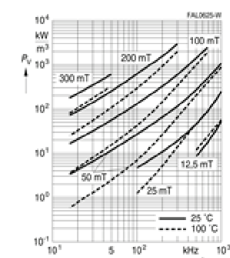
N88: 9.75%



N95: 9.02%



N96: 7.62%



N97: 7.35%

[H. Li, M. Chen et al., COMPEL'20]

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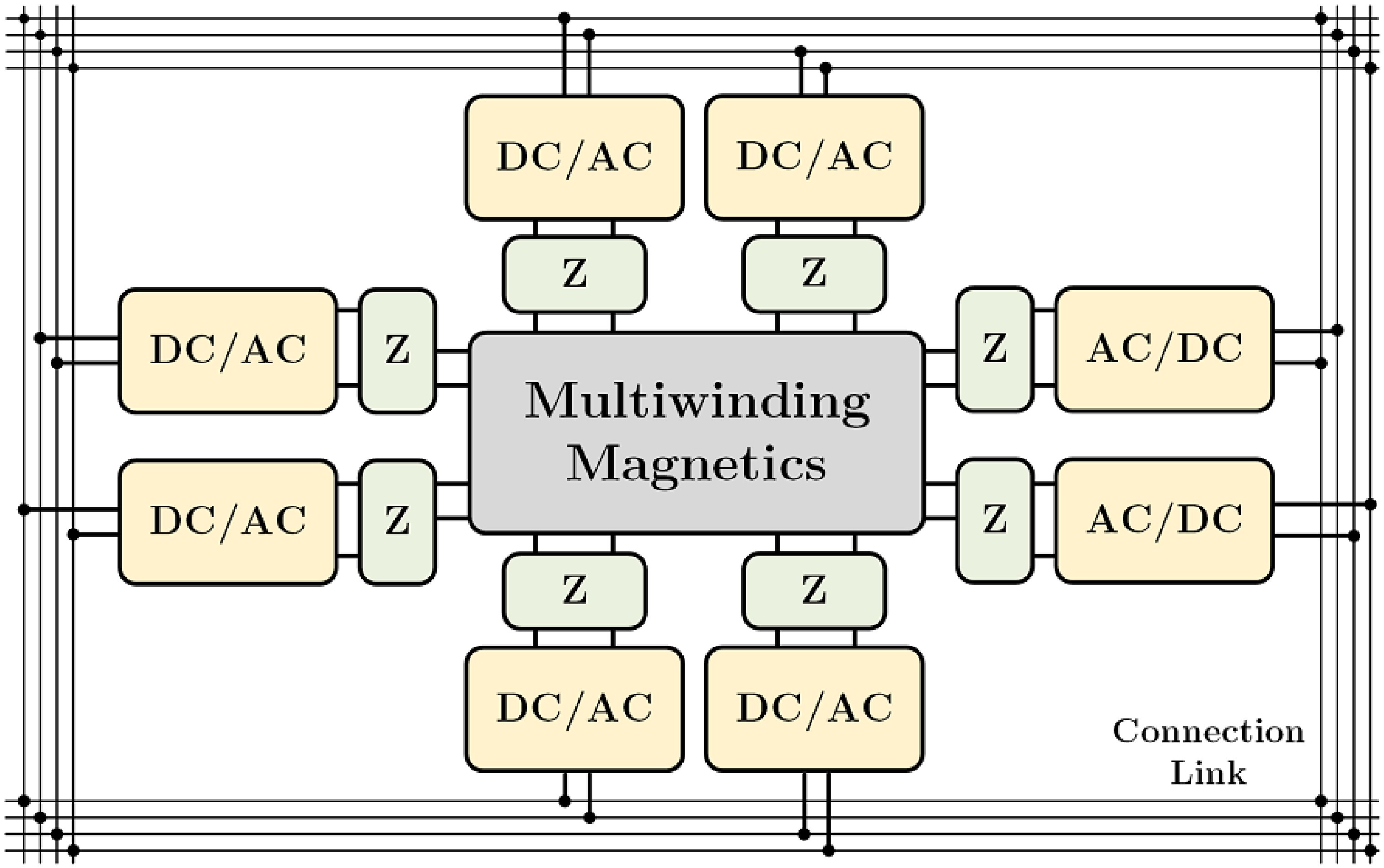
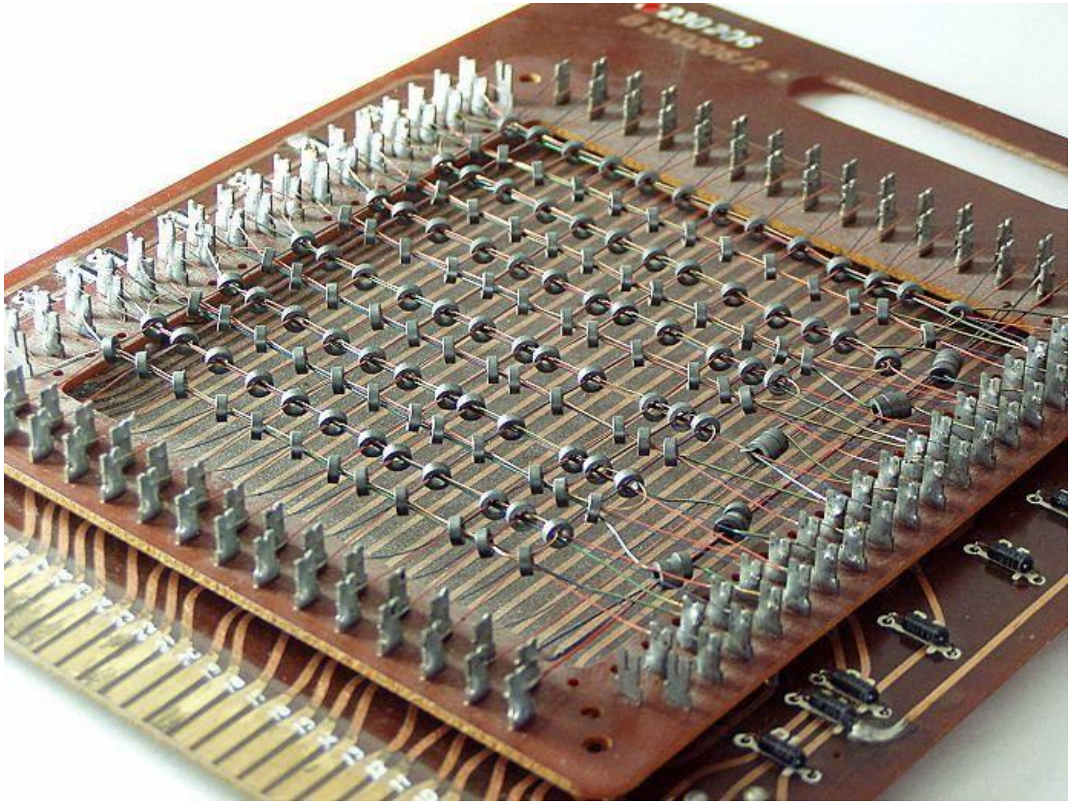
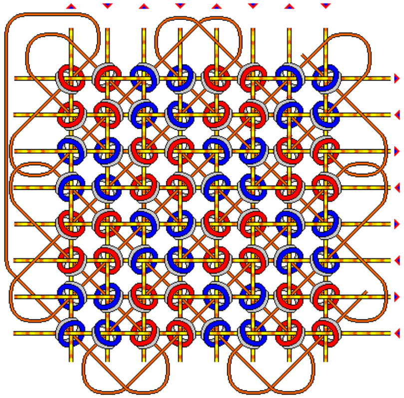
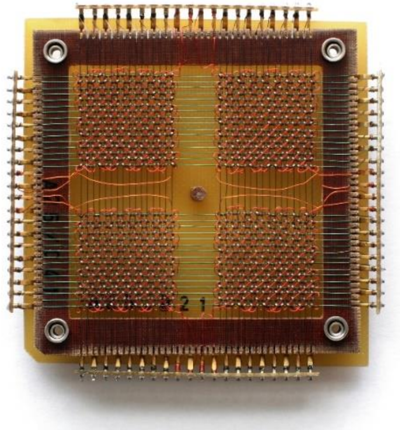
Towards a MIMO Magnetic Energy Processor



A Magnetic Register in 1960s (Memory)





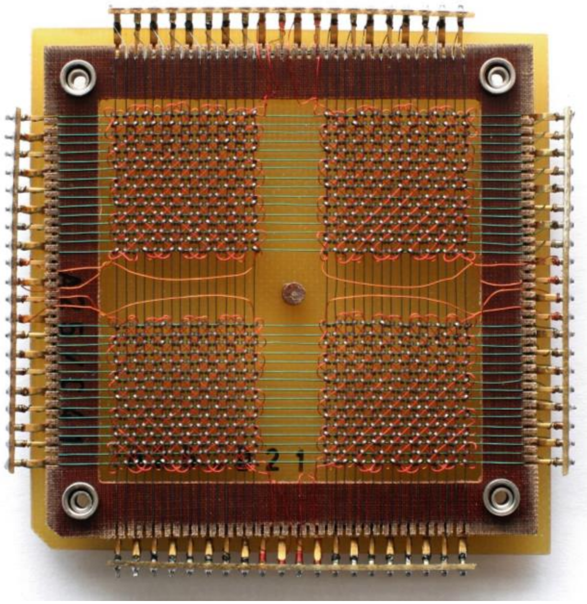


- A 32 x 32 core memory storing 1024 bits of data
- Instead of processing information, we process energy

Summary

❑ **Emerging Opportunities for More Sophisticated Magnetics**

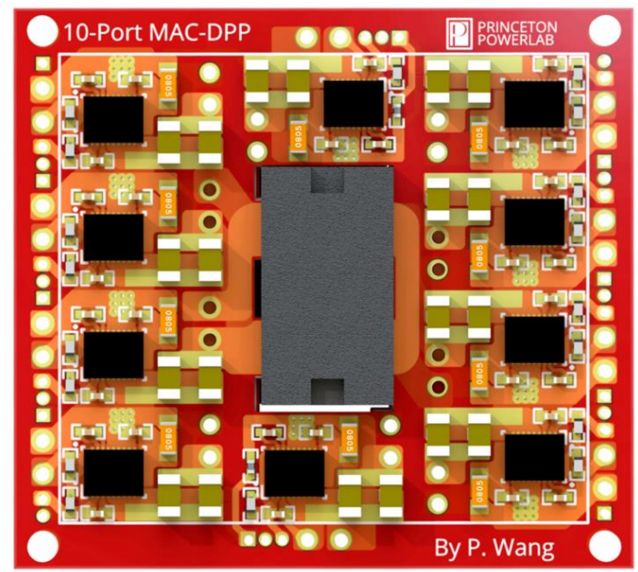
Information Processor



10101
01010
10101

32 x 32 Magnetic Memory

Energy Processor



10-Port MIMO Power Converter

Related Publications

PRINCETON UNIVERSITY

• *Series Coupled Multiwinding Magnetics: Design Methodologies*

- M. Chen, M. Araghchini, K. K. Afridi, J. H. Lang, C. R. Sullivan and D. J. Perreault, "A Systematic Approach to Modeling Impedances and Current Distribution in Planar Magnetics," in *IEEE Transactions on Power Electronics*, vol. 31, no. 1, pp. 560-580, Jan. 2016.

• *Series Coupled Multiwinding Magnetics: Applications*

- M. Chen, S. Chakraborty and D. J. Perreault, "Multitrack Power Factor Correction Architecture," in *IEEE Transactions on Power Electronics*, vol. 34, no. 3, pp. 2454-2466, March 2019.
- Y. Chen, P. Wang, Y. Elasser and M. Chen, "Multicell Reconfigurable Multi-Input Multi-Output Energy Router Architecture," in *IEEE Transactions on Power Electronics*, vol. 35, no. 12, pp. 13210-13224, Dec. 2020.
- P. Wang, Y. Chen, J. Yuan, R. C. N. Pilawa-Podgurski and M. Chen, "Differential Power Processing for Ultra-Efficient Data Storage," in *IEEE Transactions on Power Electronics*, vol. 36, no. 4, pp. 4269-4286, April 2021.
- M. Liu, Y. Chen, Y. Elasser and M. Chen, "Dual Frequency Hierarchical Modular Multilayer Battery Balancer Architecture," in *IEEE Transactions on Power Electronics*, vol. 36, no. 3, pp. 3099-3110, March 2021.

• *Parallel Coupled Multiwinding Magnetics : Design Methodologies*

- Chen, Minjie; Sullivan, Charles (2020): Unified Models for Multiphase Coupled Inductors. TechRxiv. Preprint. https://doi.org/10.36227/techrxiv.12477269.v4
- D. Zhou, Y. Elasser, J. Baek, C. R. Sullivan and M. Chen, "Inductance Dual Model and Control of Multiphase Coupled Inductor Buck Converter," *IEEE 21st Workshop on Control and Modeling for Power Electronics (COMPEL)*, Aalborg, Denmark, 2020.

• *Parallel Coupled Multiwinding Magnetics: Applications*

- Y. Chen, D. M. Giuliano and M. Chen, "Two-Stage 48V-1V Hybrid Switched-Capacitor Point-of-Load Converter with 24V Intermediate Bus," *IEEE 21st Workshop on Control and Modeling for Power Electronics (COMPEL)*, Aalborg, Denmark, 2020.
- J. Baek, P. Wang, Y. Elasser, Y. Chen, S. Jiang and M. Chen, "LEGO-PoL: A 48V-1.5V 300A Merged-Two-Stage Hybrid Converter for Ultra-High-Current Microprocessors," *IEEE Applied Power Electronics Conference and Exposition (APEC)*, New Orleans, LA, USA, 2020, pp. 490-497.

• *Machine Learning Methods for Core Loss Modeling*

- H. Li, S. R. Lee, M. Luo, C. R. Sullivan, Y. Chen and M. Chen, "MagNet: A Machine Learning Framework for Magnetic Core Loss Modeling," *2020 IEEE 21st Workshop on Control and Modeling for Power Electronics (COMPEL)*, Aalborg, Denmark, 2020.