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Modeling and Design of Multiwinding Magnetics for High Frequency Power Electronics

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High Frequency Magnetics Workshop, 2020

PRINCETON POWERLAB

We Need Better Magnetics

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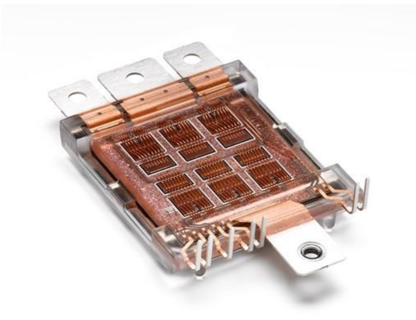
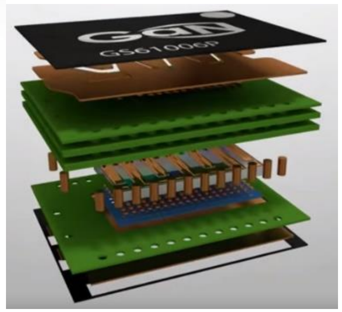
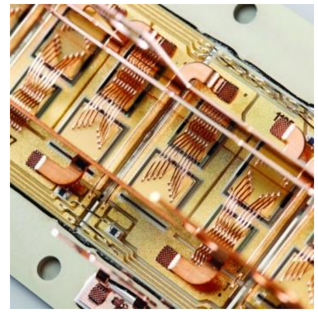
- Breakthroughs in semiconductor devices (SiC and GaN)



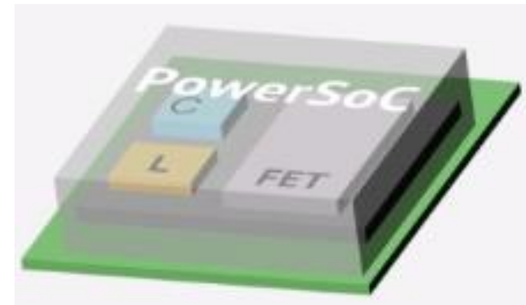
SiC modules



GaN Switches

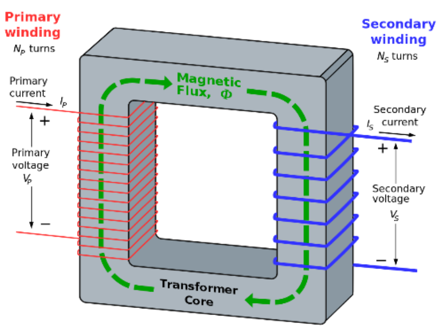


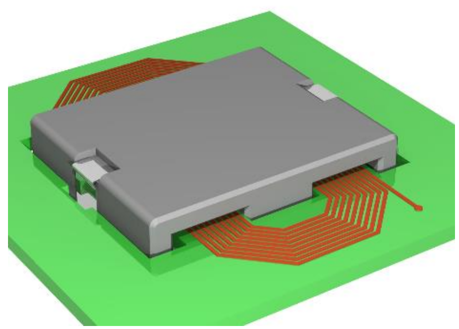
IGBT Modules

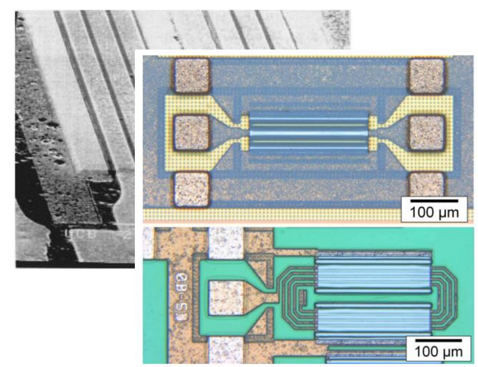


Power SoC

- Magnetics are lagging behind

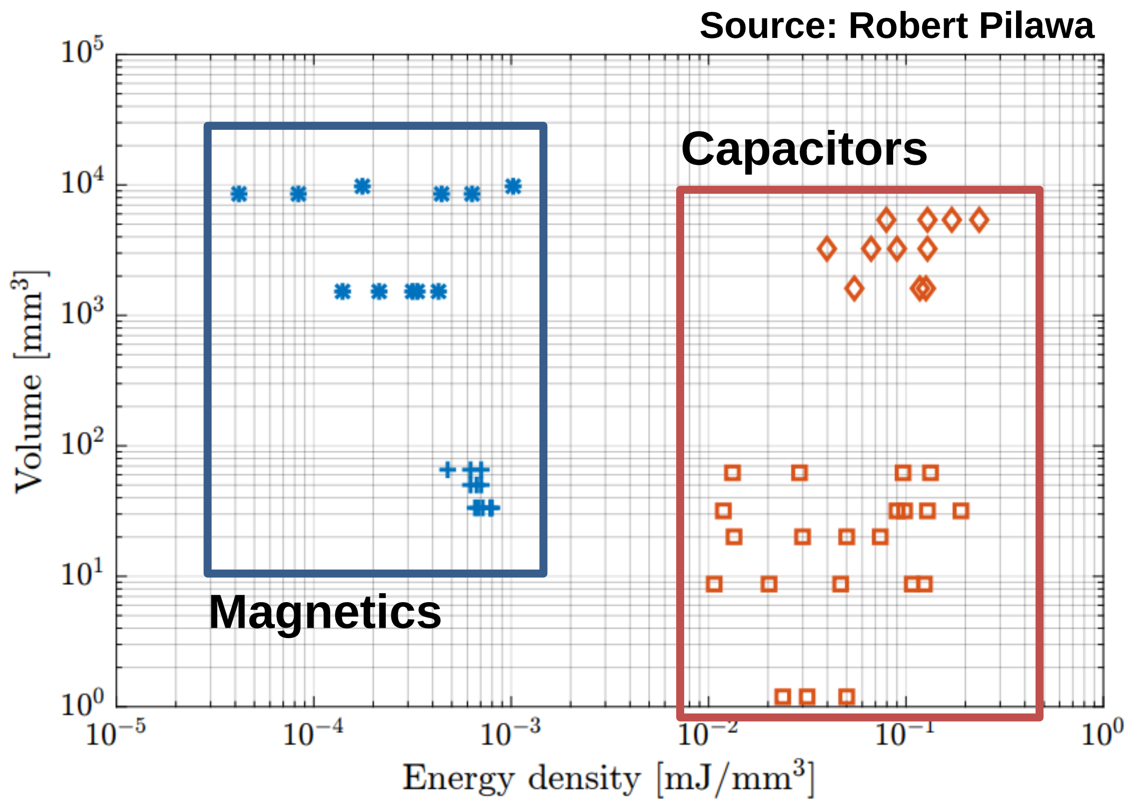


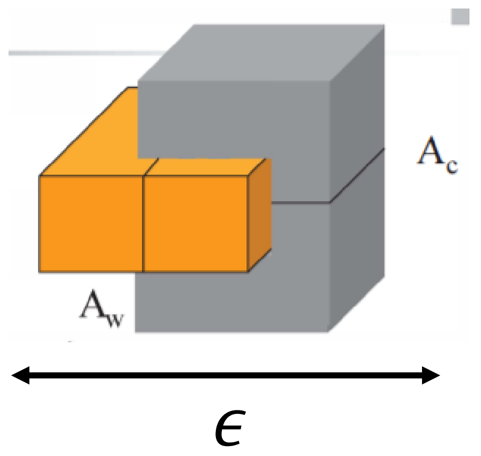




- L. Daniel, "Design of microfabricated inductors", *IEEE Trans. Power Electron., 1999*
- D.S. Gardner, "Review of on-chip inductor structures with magnetic films", *IEEE Trans. Magn., 2009*

Energy Density vs. Functionality





$$VA \propto \epsilon^4$$

Linear scaling factor

- Capacitors win in energy density
- Larger magnetics has better figure-of-merits
- Magnetics win in functionality
- **Multi-winding, multi-leg, multi-functional magnetics @ high frequency**

Multi-Functional Magnetics

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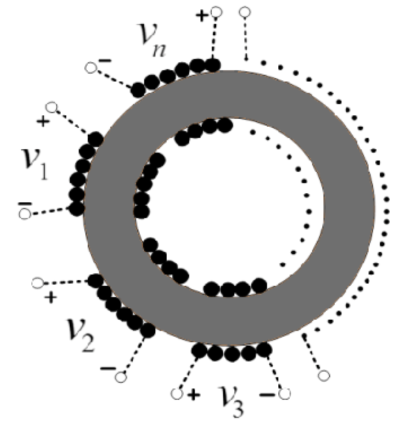
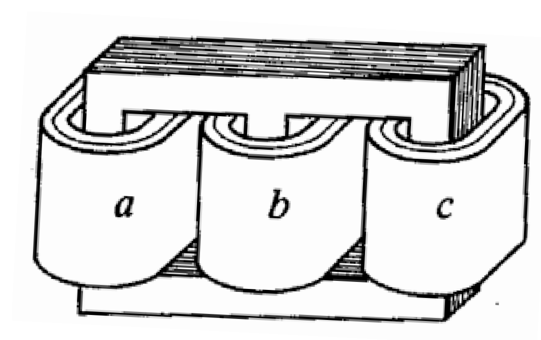
Single Purpose Magnetics

Multiwinding Magnetics

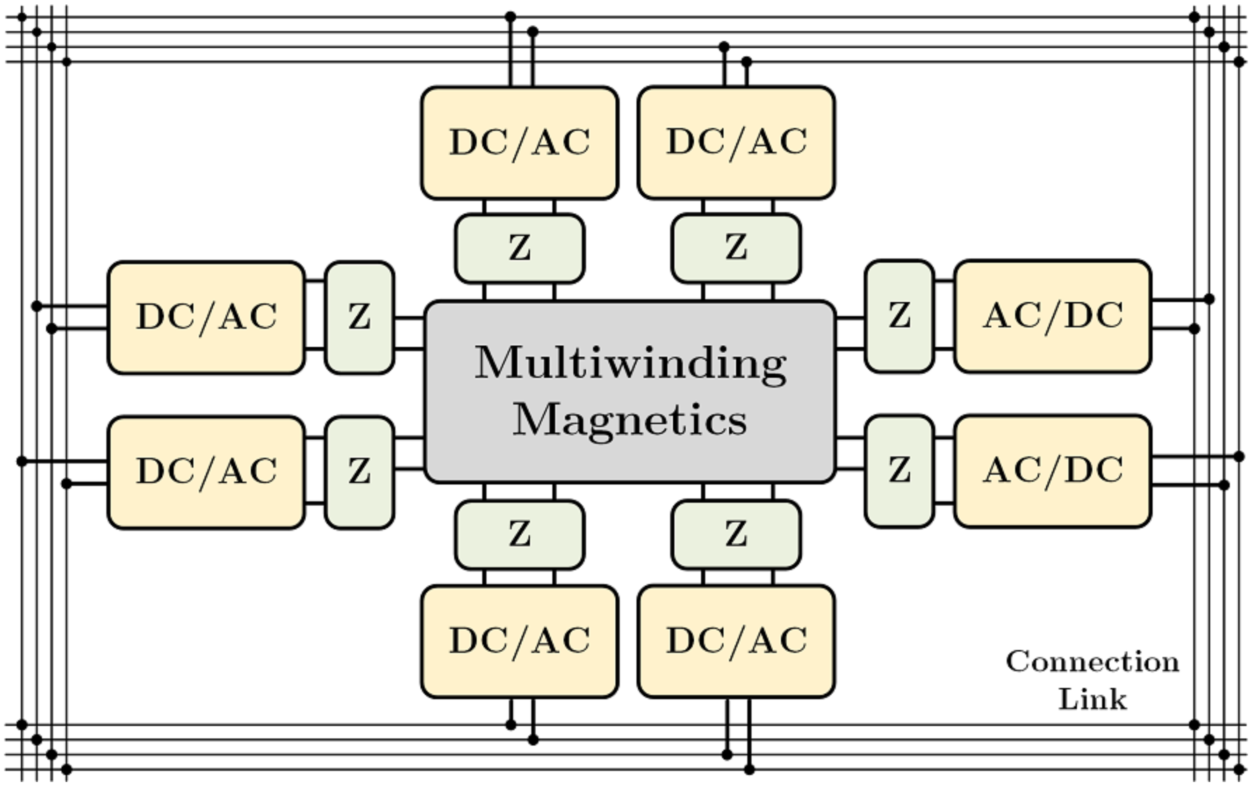


Multileg Magnetics



The “Integrated Magnetics” Concept

The “integrated magnetics” concept started from 1980s’



1980s

Zero-ripple Cuk

1990s

Multiphase Buck

2000s

Integ. EMI Filter

2010s

Resonant

Need tools and methods to design for high frequencies

Multi-Winding Magnetics: Two Categories

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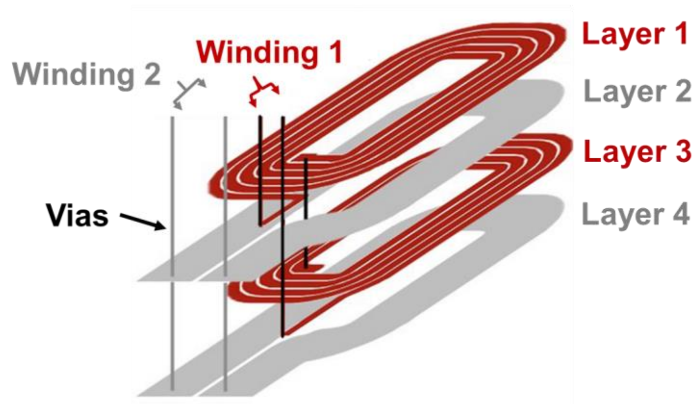
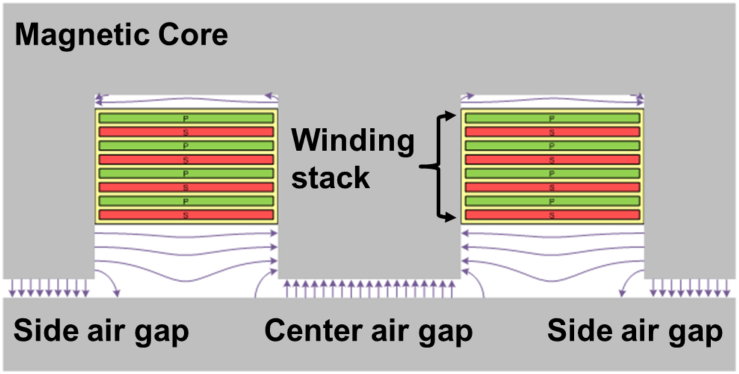
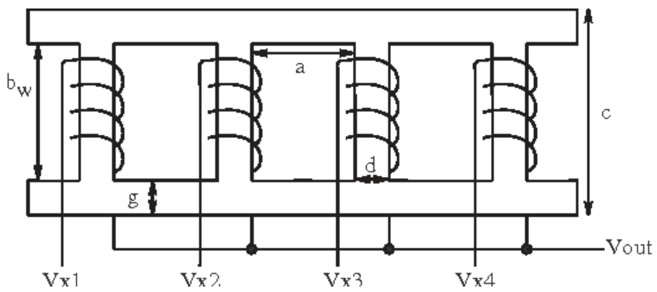
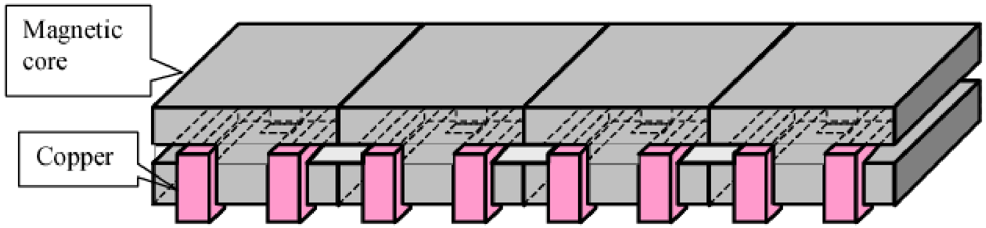
- Multiple windings couple to a single magnetic linkage





- Multiple windings couple to multiple magnetic linkages





- M. Chen, "A Systematic Approach to Modeling Impedances and Current Distribution in Planar Magnetics," TPEL 2016
- J. Li et al., "Using coupled inductors to enhance transient performance of multi-phase buck converters," APEC 2004

Design Options for Planar Magnetics

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

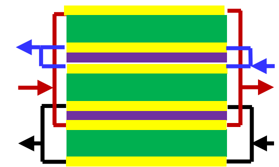
Alternating interleaved

1 & 3 as primary
2 & 4 as secondary

Symmetric interleaved

1 & 4 as primary
2 & 3 as secondary

More complicated?



……?

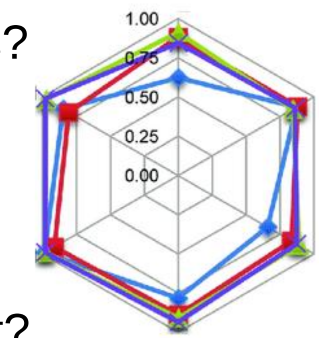
2. What are the optimal winding stack and winding spacing?

Thin Middle Spacing

Thick Middle Spacing

3. Multi-object optimization problem

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



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 ~100MHz).

Magneto-Quasi-Static Maxwell's equations

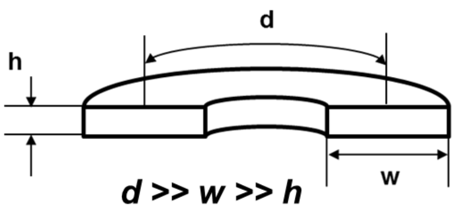
$$\begin{cases} \nabla E = \frac{\rho}{\varepsilon_0} \\ \nabla B = 0 \\ \nabla \times E = -\frac{\partial B}{\partial t} \\ \nabla \times B = \mu_0 (J + \varepsilon_0 \frac{\partial E}{\partial t}) \end{cases}$$

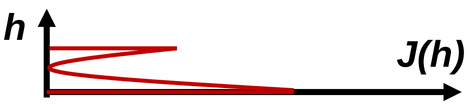
Ignore the time evolution of the electric field

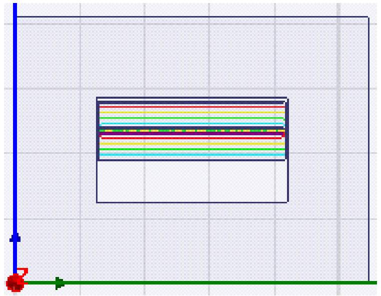
(2) 1-D assumption

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

Magnetic core guides the flux



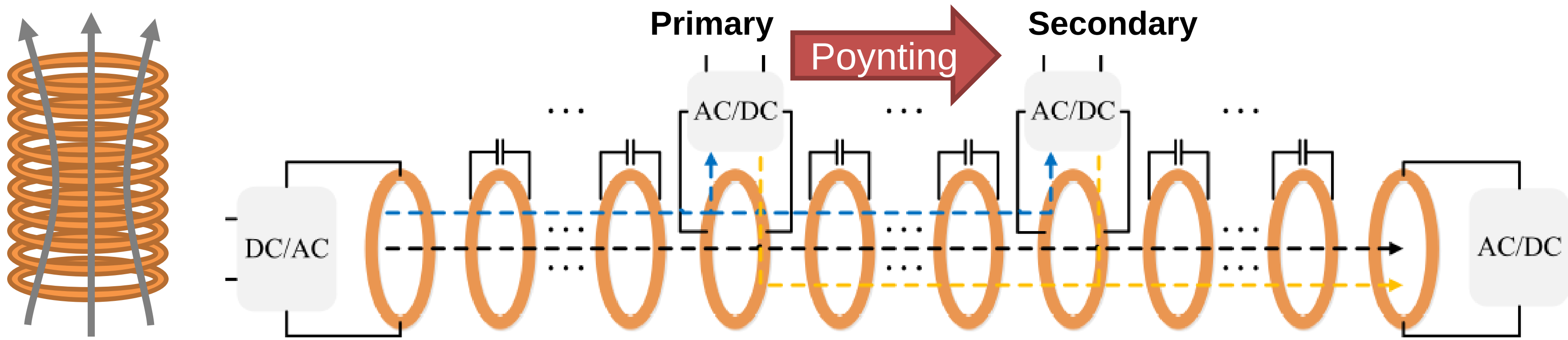




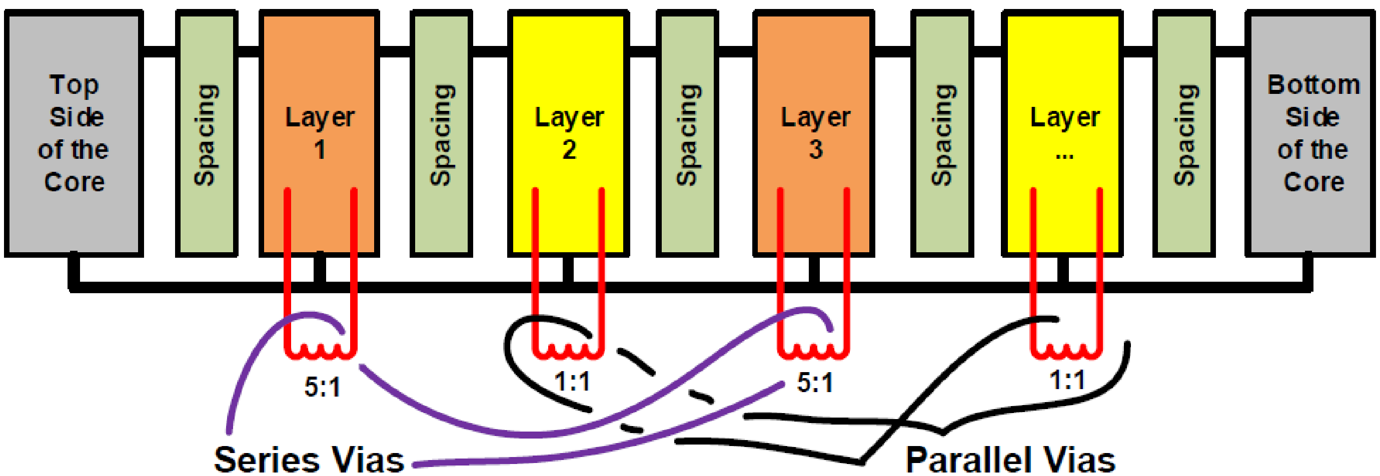
Skin and proximity effects change current distribution

Wave Propagation in Planar Windings

- 1-D energy wave (Poynting vector) propagation principles



- Modular lumped circuit models for repeating building blocks



Modeling a Single Conductor Layer

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Field diffusion equations:

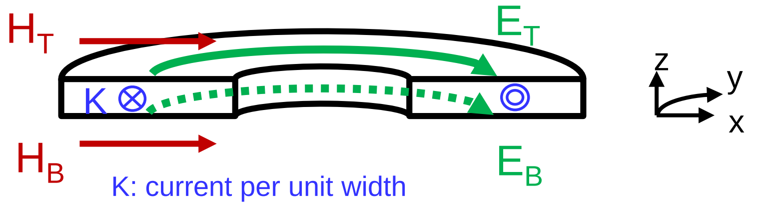
$$H_X(z) = \frac{H_T\, sinh(\Psi z) + H_B\, sinh(\Psi(h-z))}{sinh(\Psi h)}$$

Ampere's law:

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

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

Electromagnetic Fields



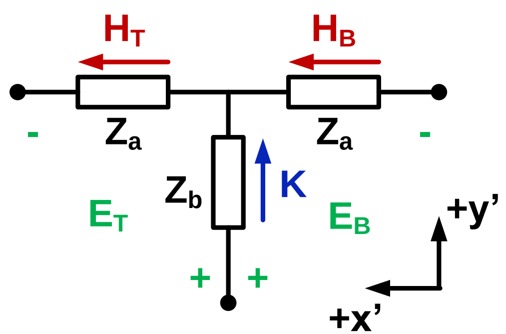
E field as a function of H and K:

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

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

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

Modular Layer Model



KVL/KCL relationships:

$V/m \qquad \Omega \qquad A/m$

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

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

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

Z_a, Z_b: impedances ~ unit (**Ω**)

Modeling Two Adjacent Layers

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Intuition:

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

Faraday's Law and Field Continuity

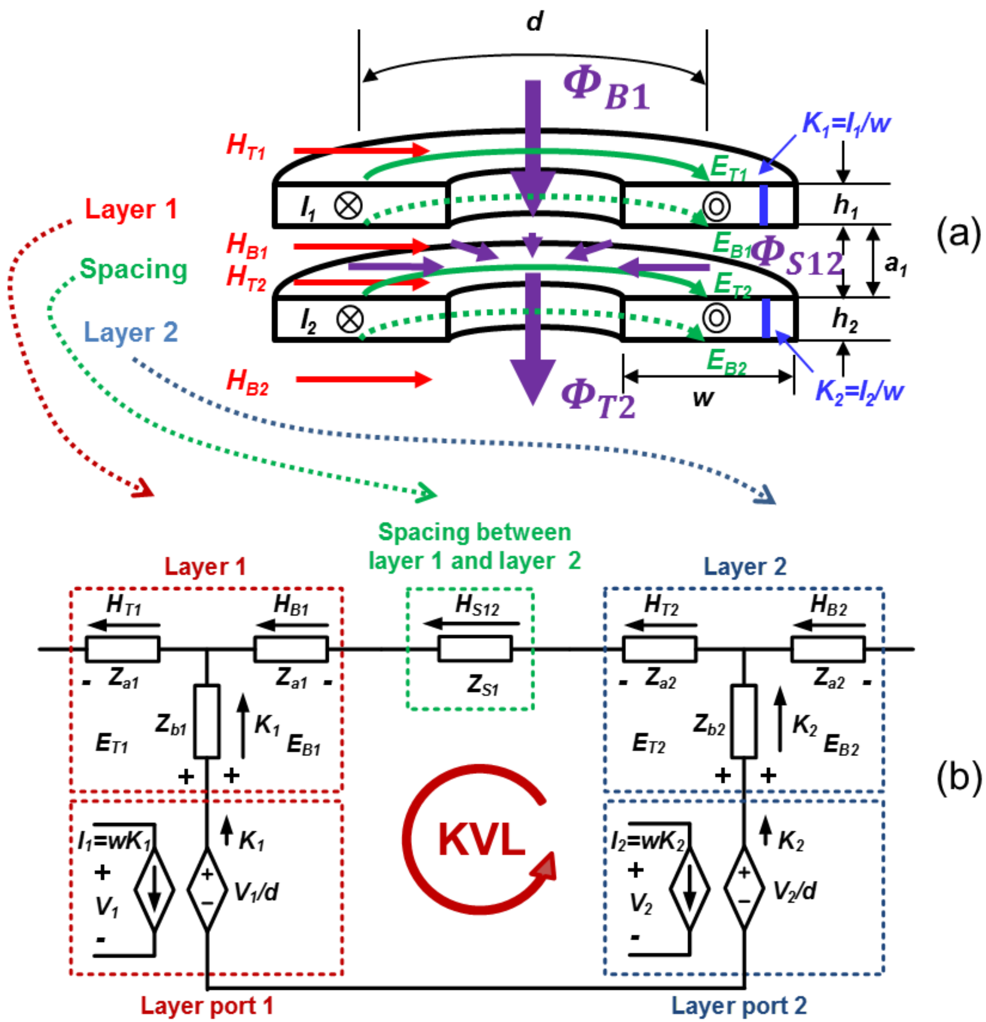
$$E_{B1}d - V_1 = -\frac{d\Phi_{B1}}{dt} \qquad E_{T2}d - V_2 = -\frac{d\Phi_{T2}}{dt}$$

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

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

Modeling Layers with Multiple Turns

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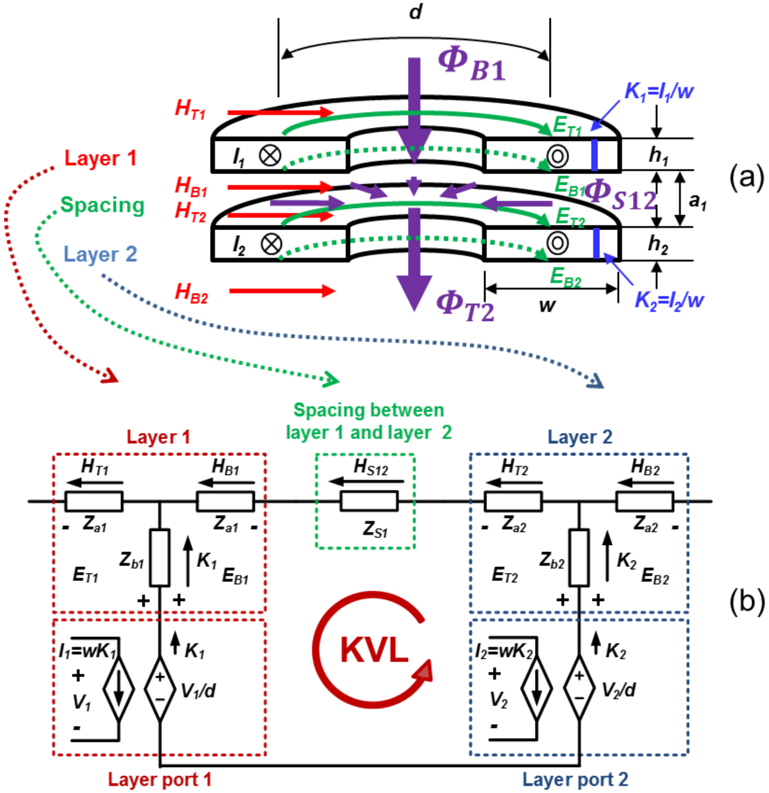
Fields distributions in multiple-turns layers are linearly related to those in single-turn layers

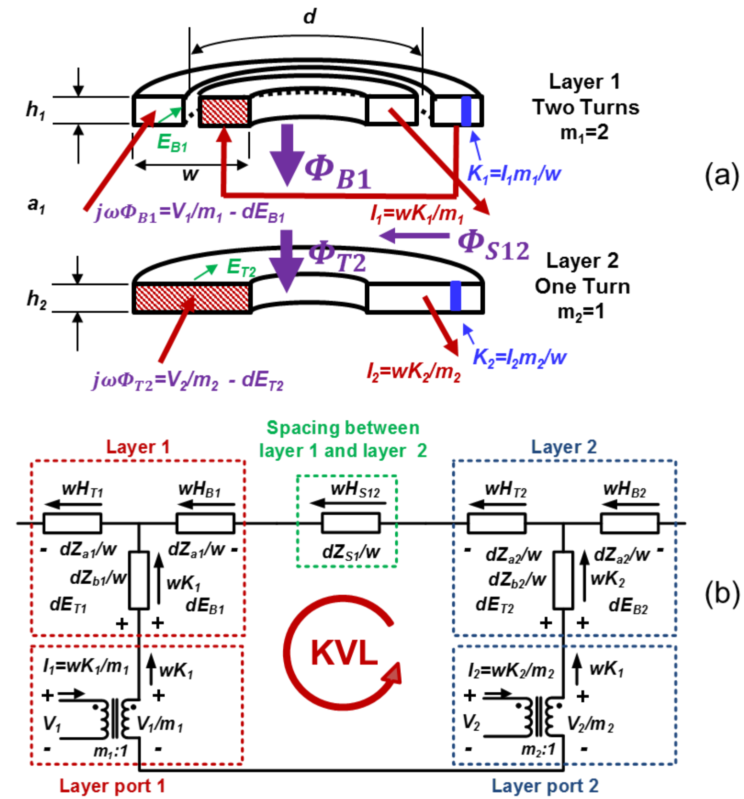
Multiple turns → Additional Linear Conversions



E&M Domain

Circuit Domain

Intuitive Ideal Transformers

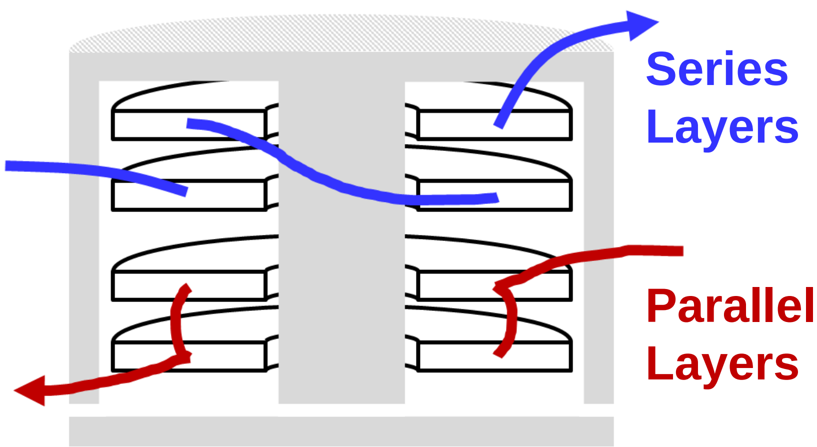


Modeling Electrical Interconnects (Vias)

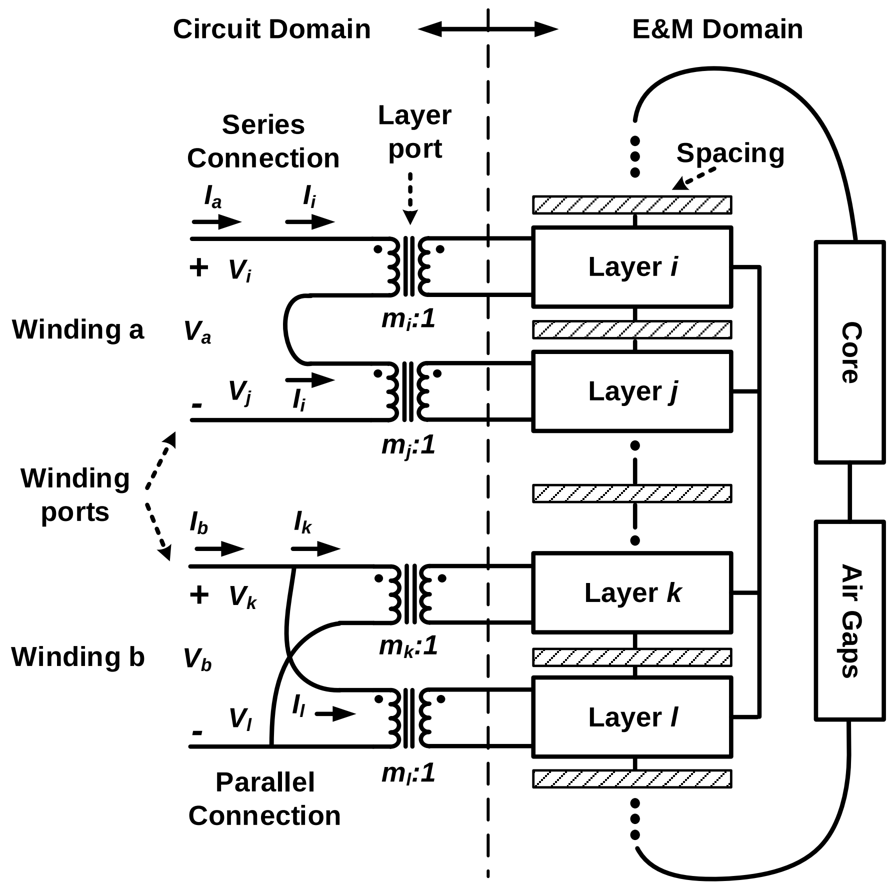
Modeling vias is equivalent to adding KVL, KCL constraints:

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



An Open-Source SPICE Modeling Tool

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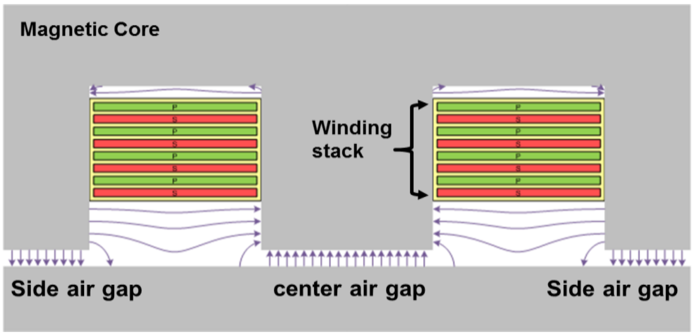
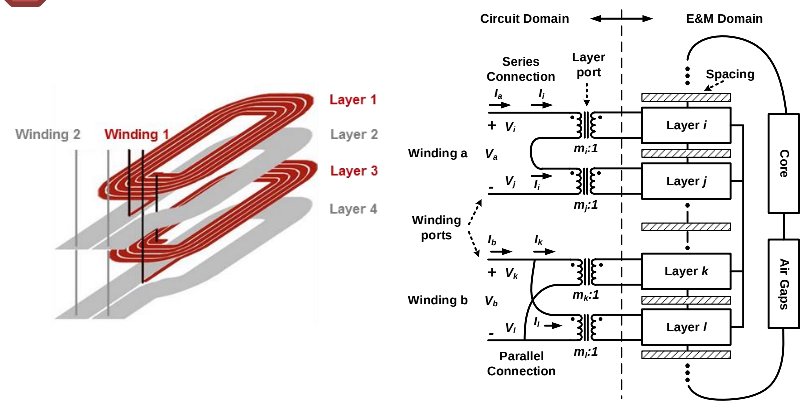
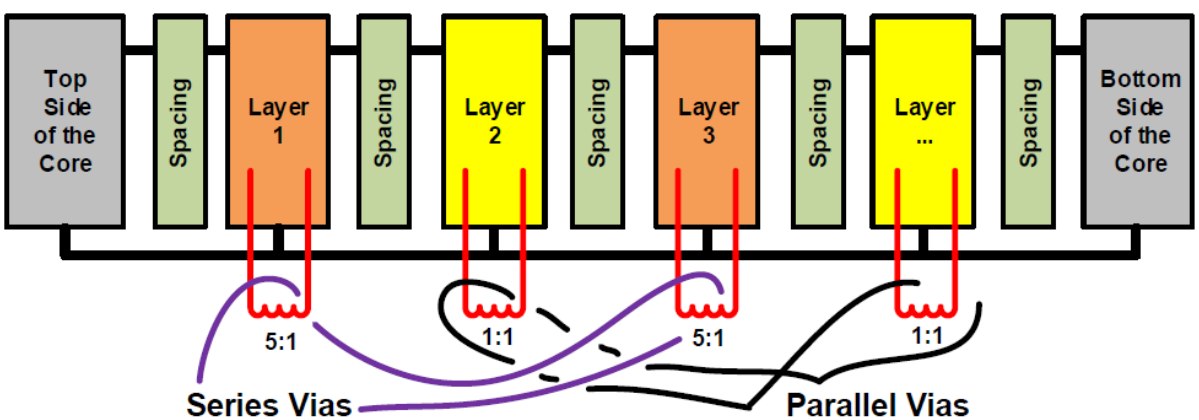
1 Geometry Information



3 SPICE Netlist



2 Modular Layer Model



Simulations!

GitHub

Search: M2SPICE

Impacts of Interleaving Patterns

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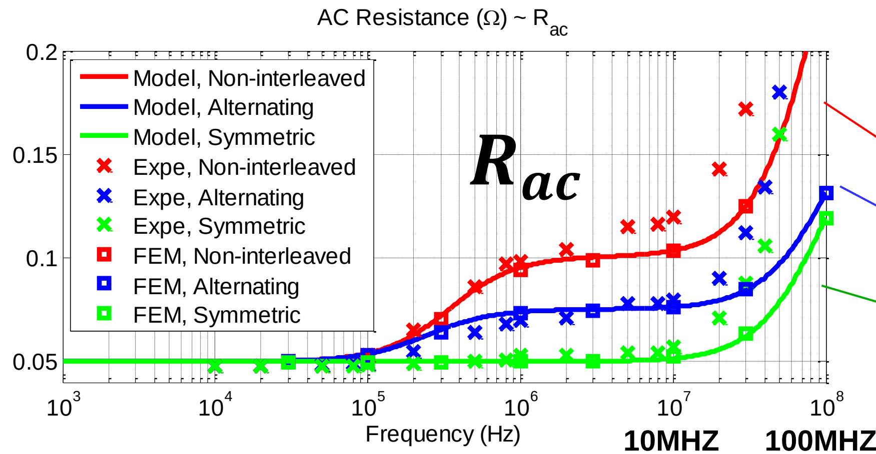
Comparing the P_{ac} and E_{ac} of three 1: 1 transformers with three different interleaving patterns

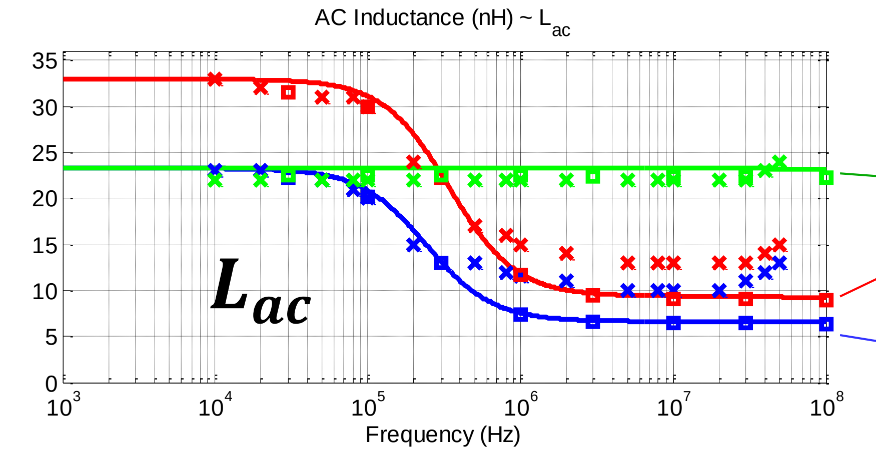
Non interleaved

Alternating

Symmetric



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



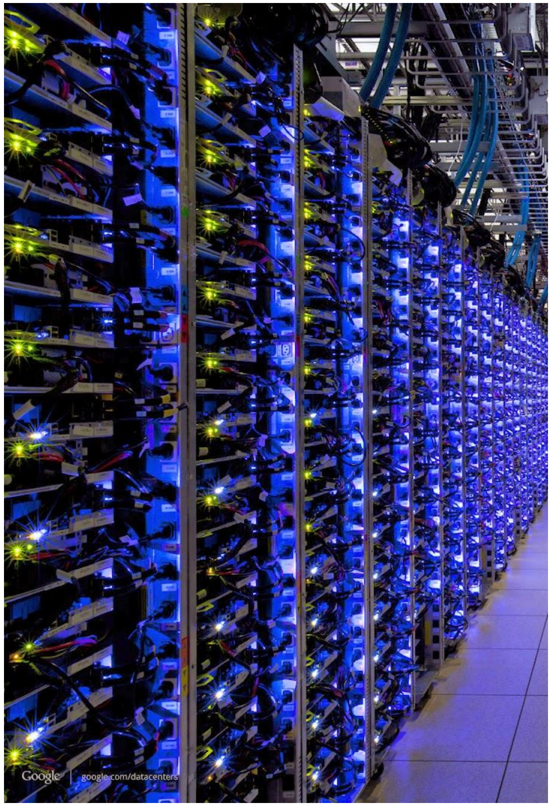
$$E_{ac} = \frac{1}{2} \sum I^2 L_{ac}$$

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

Example Applications

Multi-Input Multi-Output Power Electronics Systems

Battery Banks

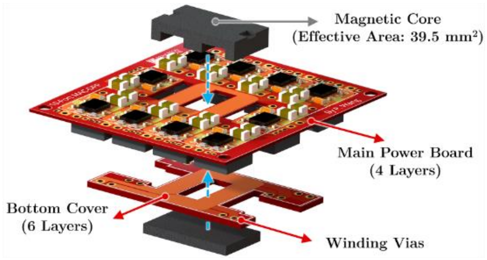


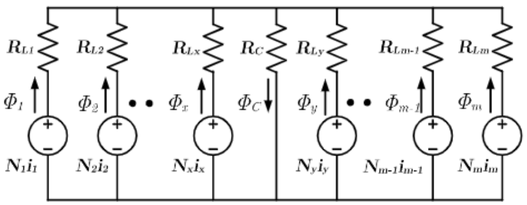
Server Racks

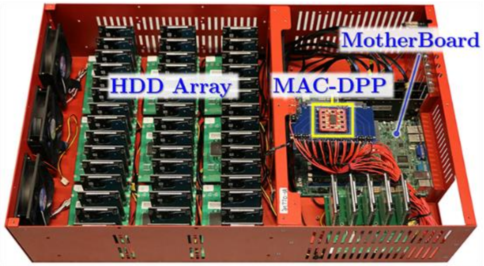
Solar Farms

Power Management for Storage Servers

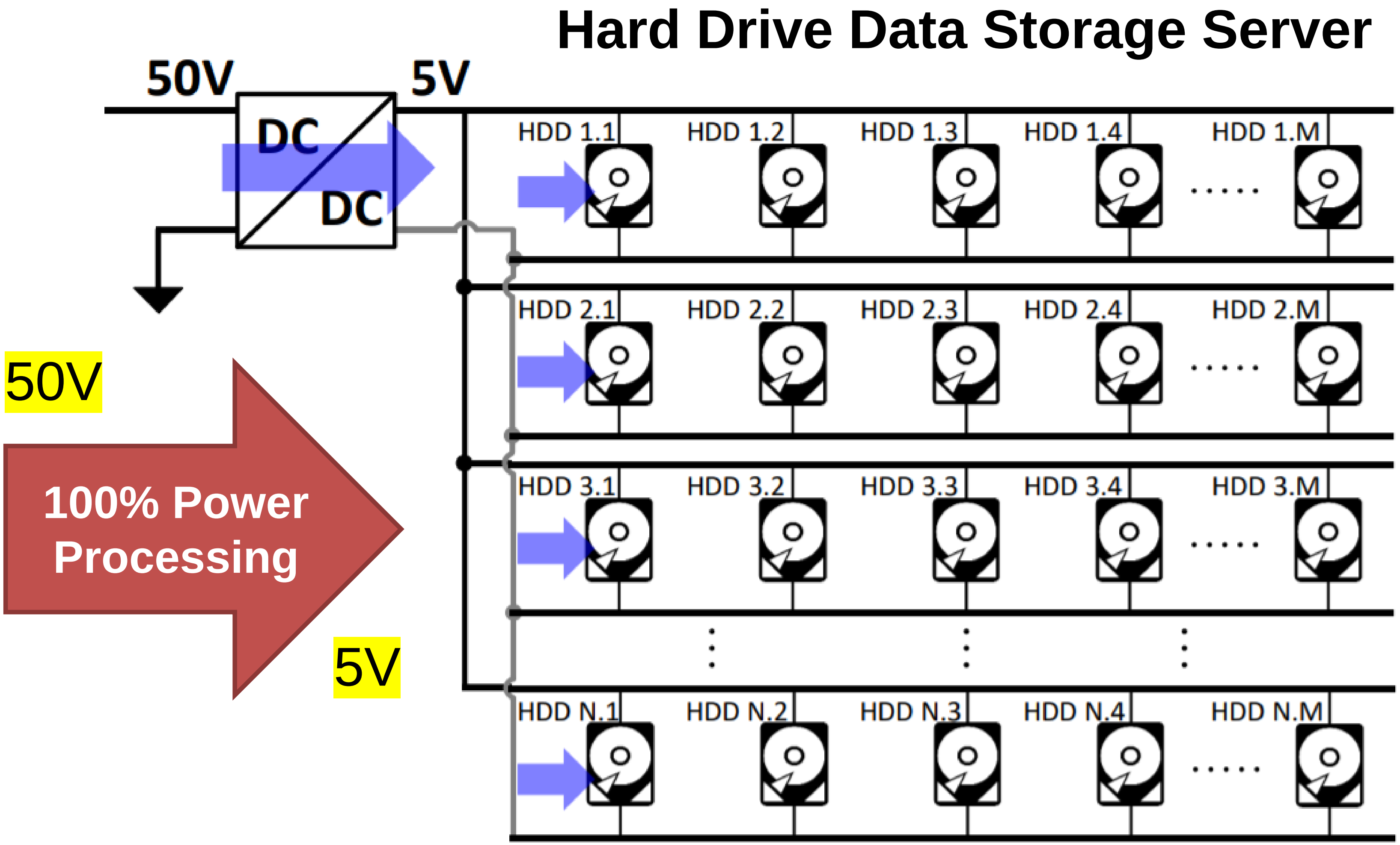
Magnetics Design → **Circuit Topology** → **System Integration**



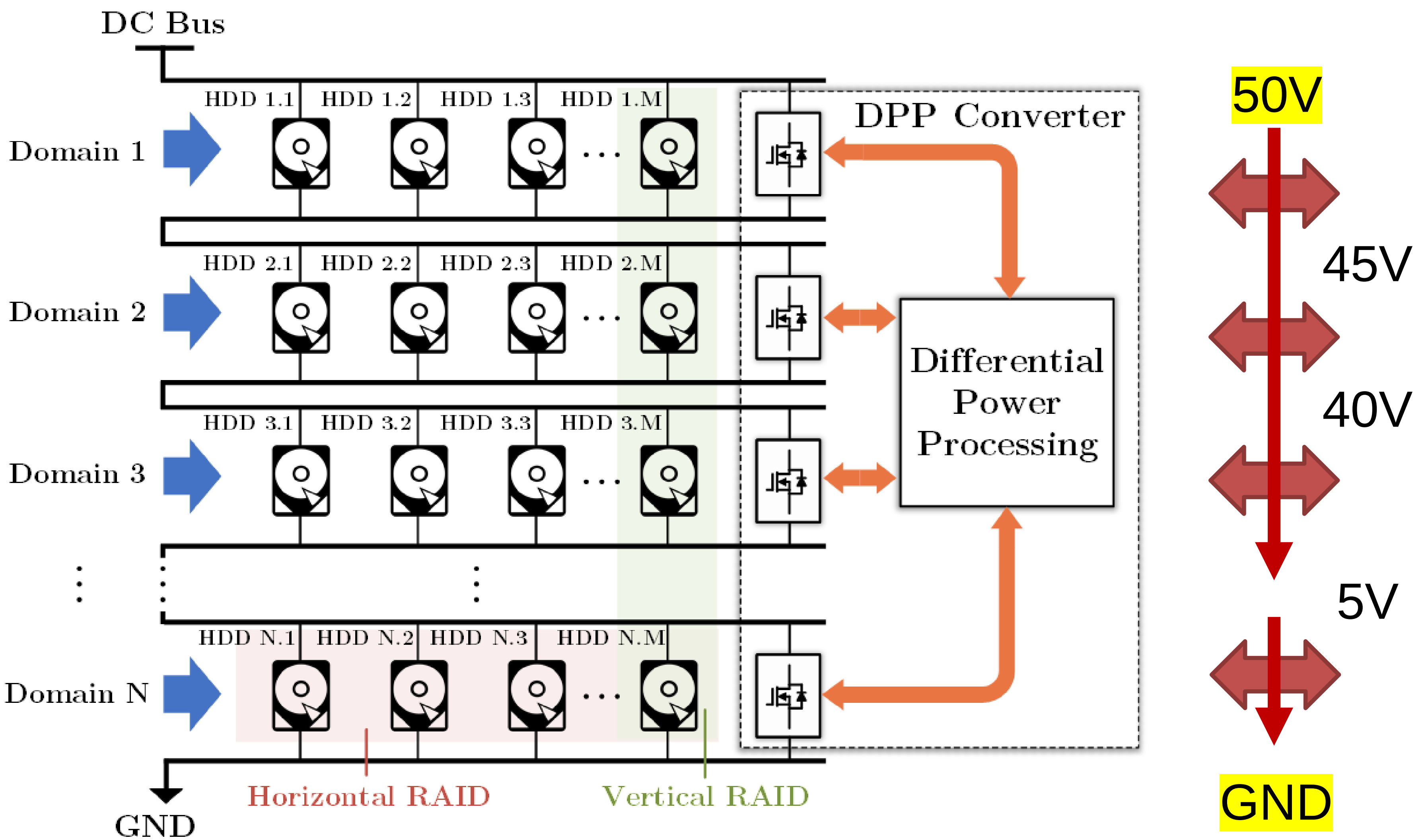




A Conventional Dc-Dc Approach



Differential Power Processing



<10% Differential Power

Existing DPP Solutions

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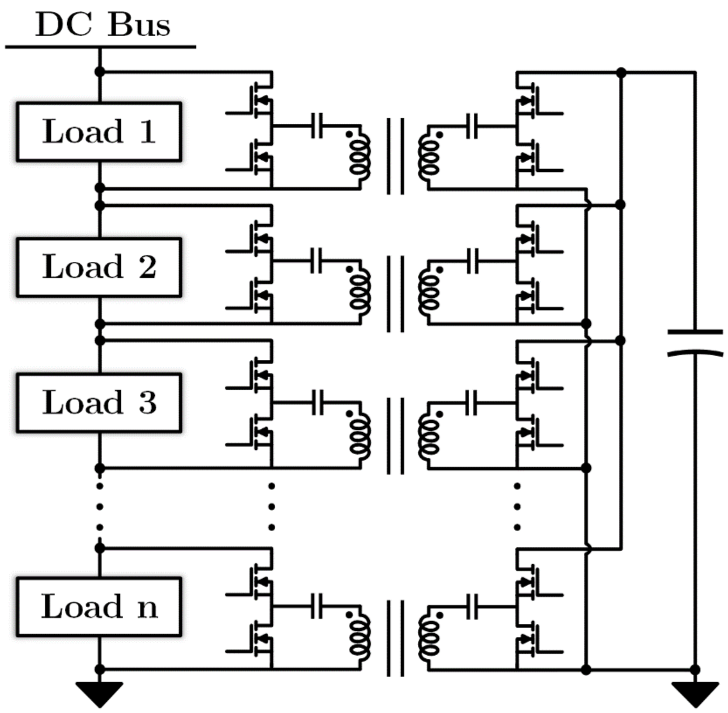
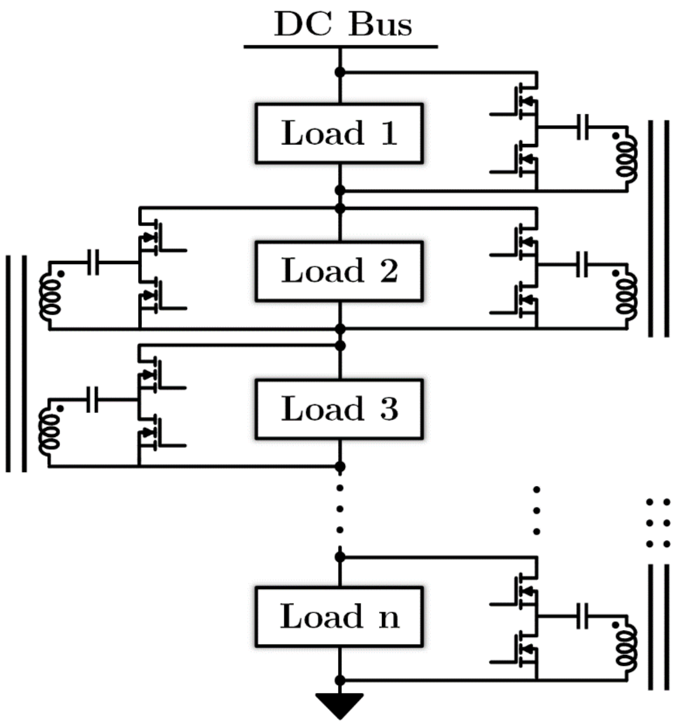
DPP with a buffer port

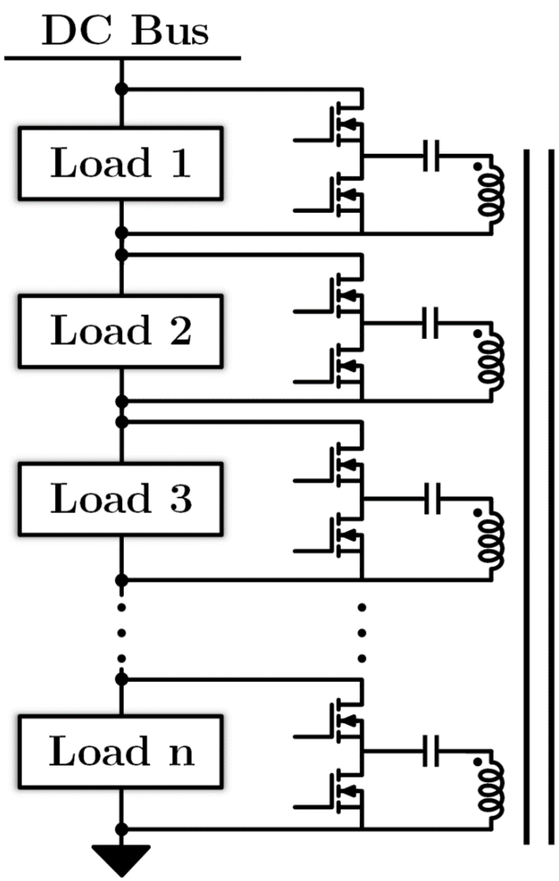


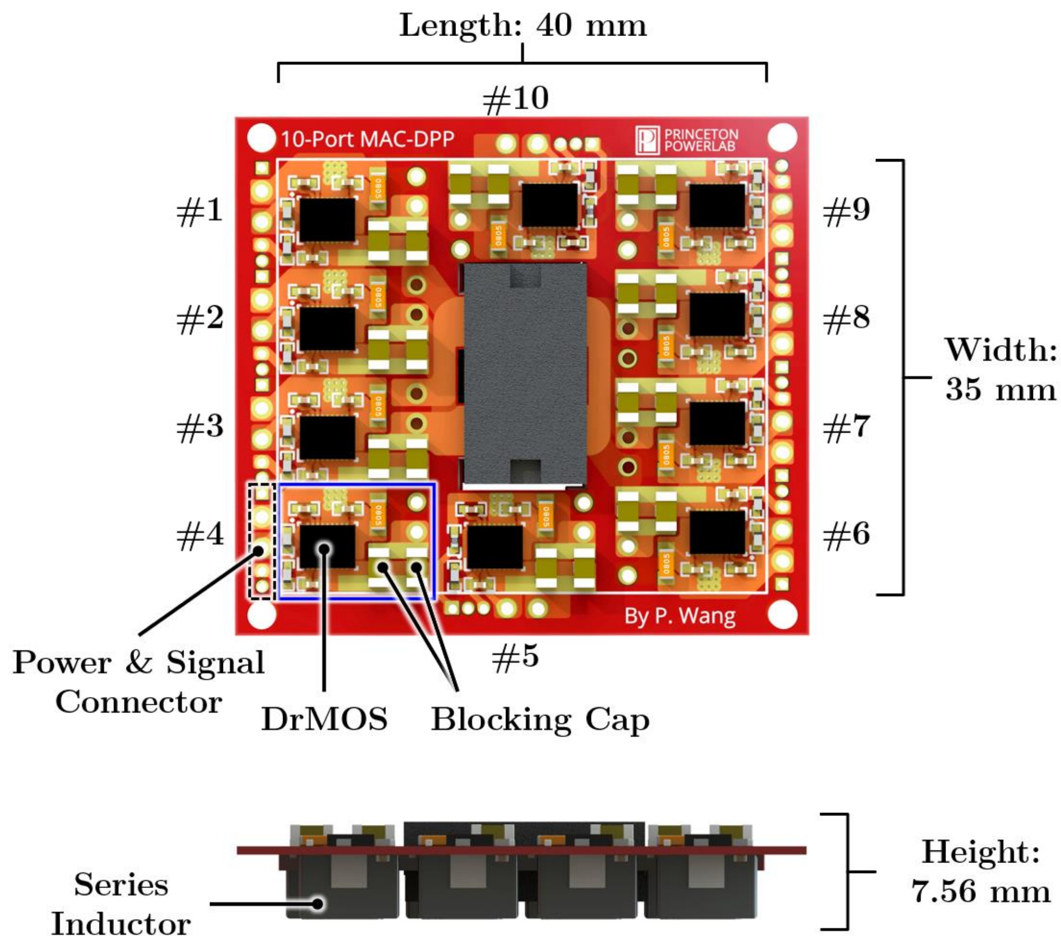
Ladder DPP



- E. Candan, P. S. Shenoy and R. C. N. Pilawa-Podgurski, “A Series-Stacked Power Delivery Architecture with Isolated DifferentialPower Conversion for Data Centers,” TPEL 2016.
- H. Schmidt and C. Siedle, “The charge equalizer-a new system to extend battery lifetime in photovoltaic systems, UPS and electricvehicles,” INTELEC 1993.

Fully-Coupled DPP Architecture





- P. Wang, M. Chen et al., “A 99.7% Efficient 300 W Hard Disk Drive Storage Server with Multiport Ac-Coupled Differential Power Processing (MAC-DPP) Architecture,” ECCE 2019

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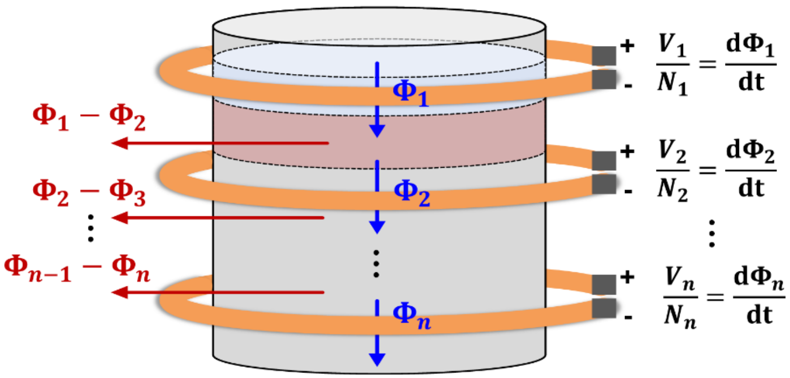
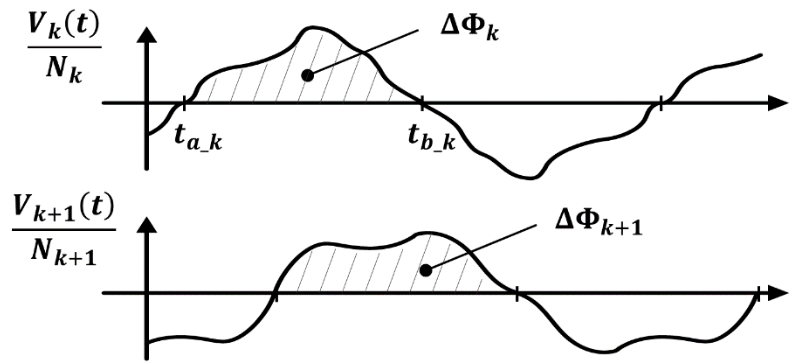
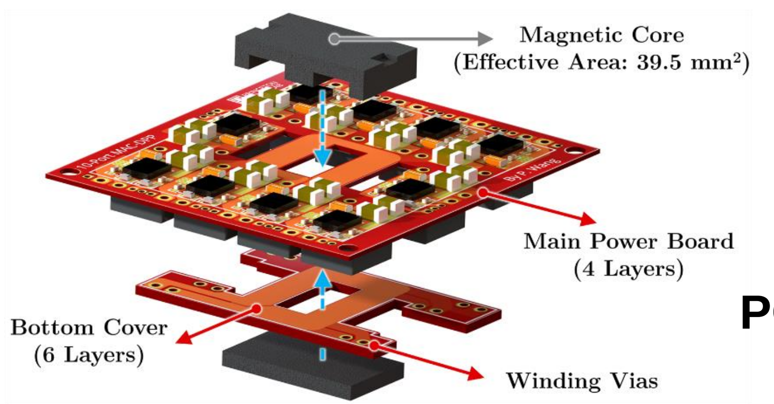
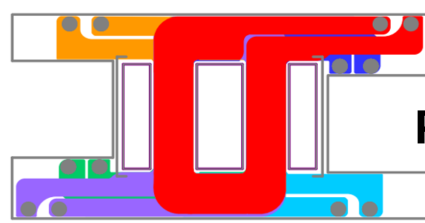
Transformer saturation requirements: maximum volt-seconds per turn





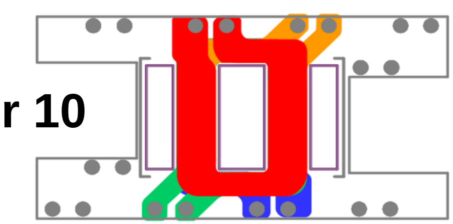
3D stacked multiwinding transformer with modular planar modeling



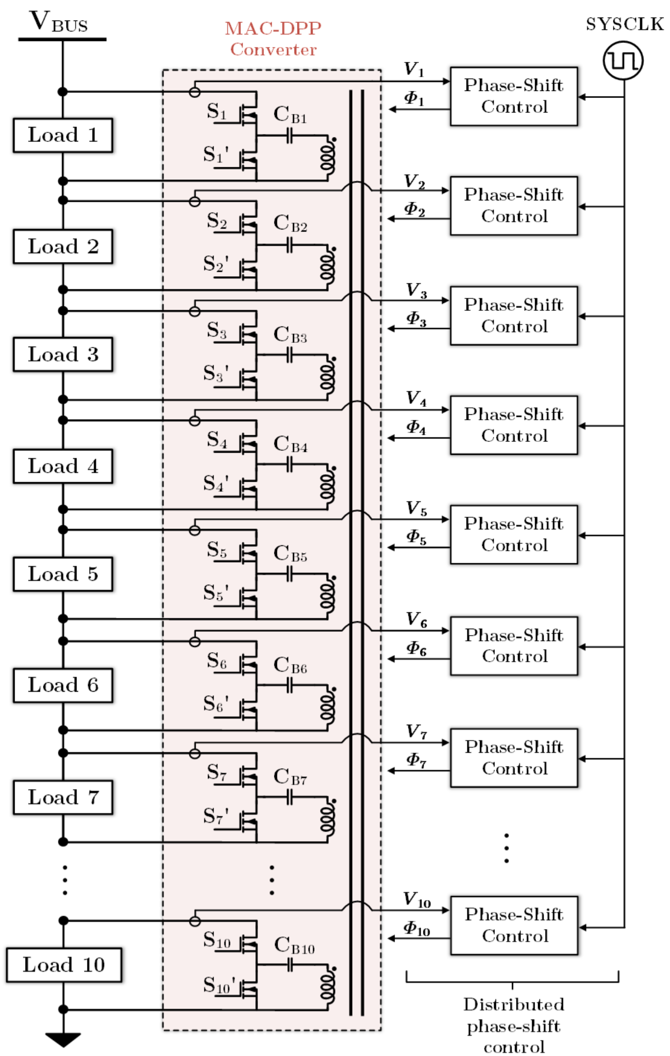


PCB1: Layer 1 – Layer 6

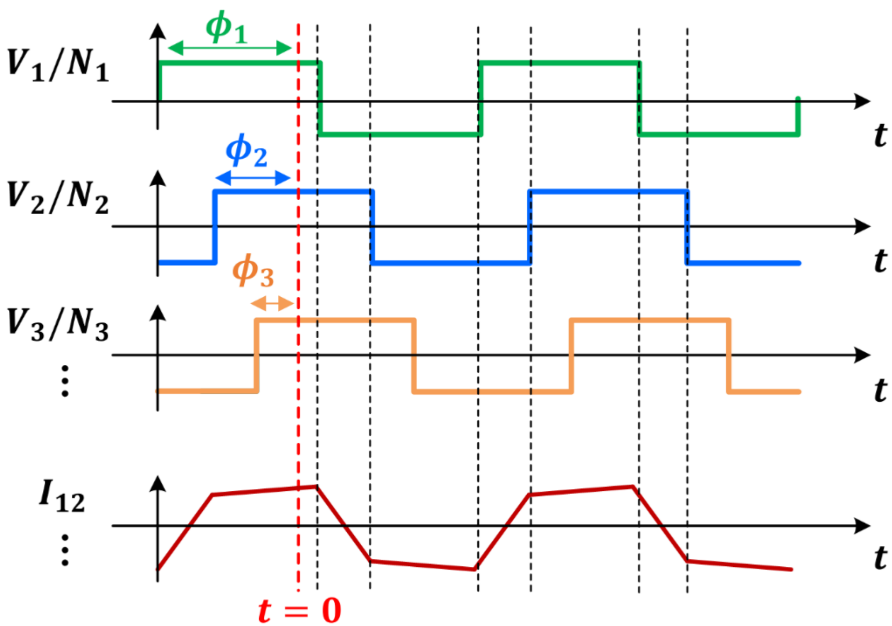
PCB2: Layer 7 – Layer 10



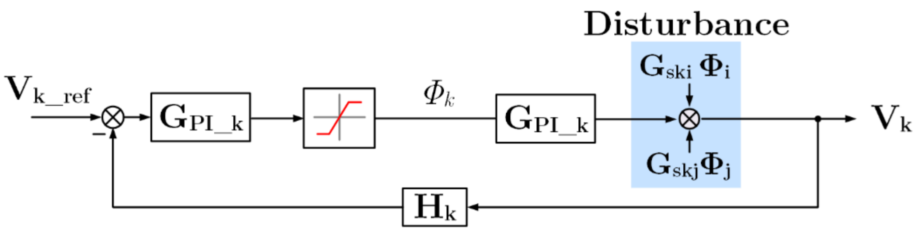
Distributed Phase Shift Control



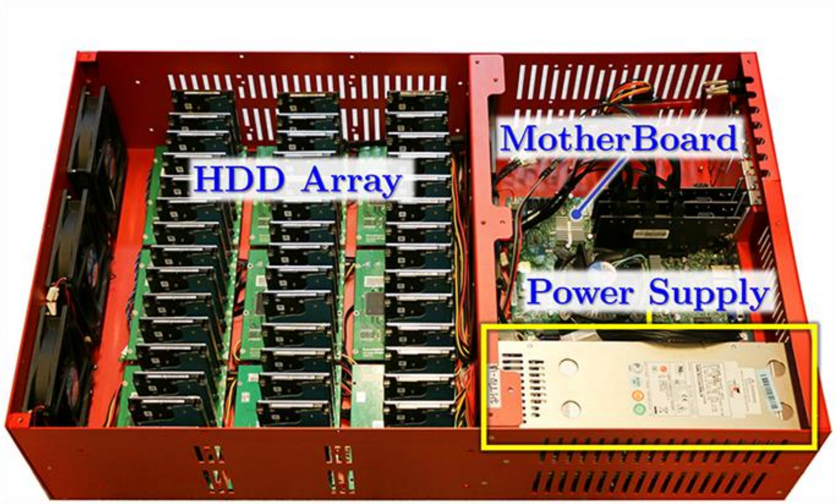
Phase shift determines the power flow

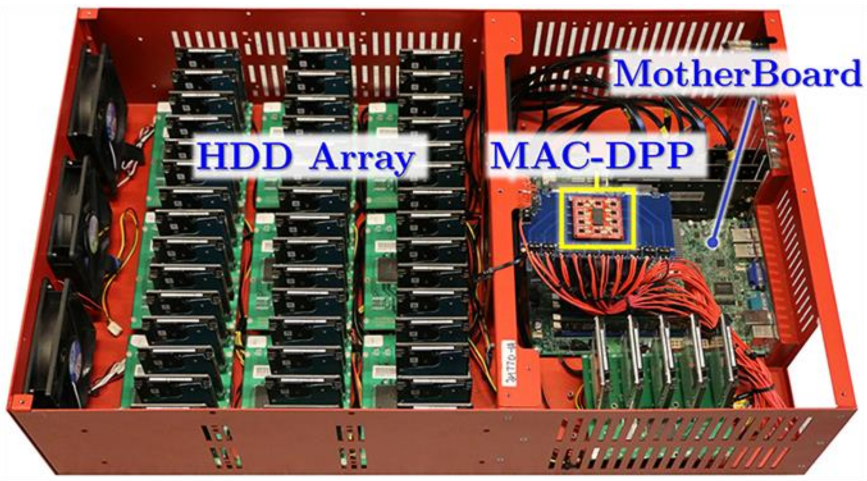


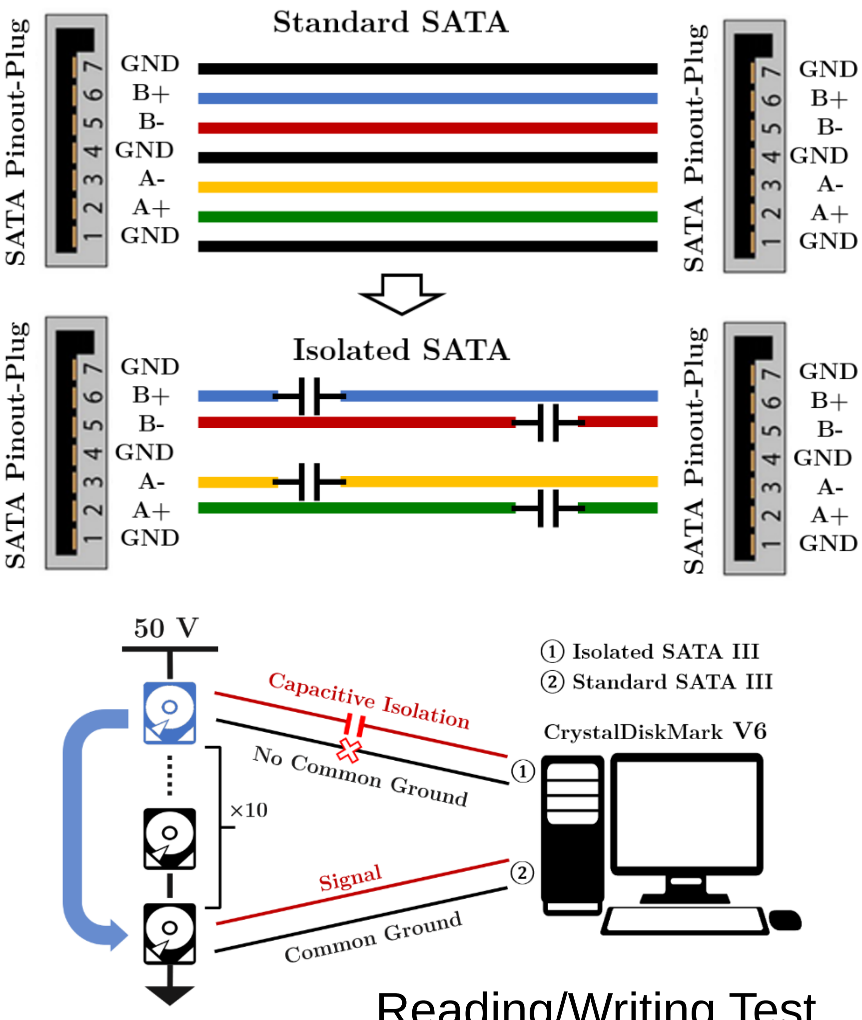
Block diagram of the distributed control



Complete HDD Storage System







Reading/Writing Test

Performance of the DPP Architecture

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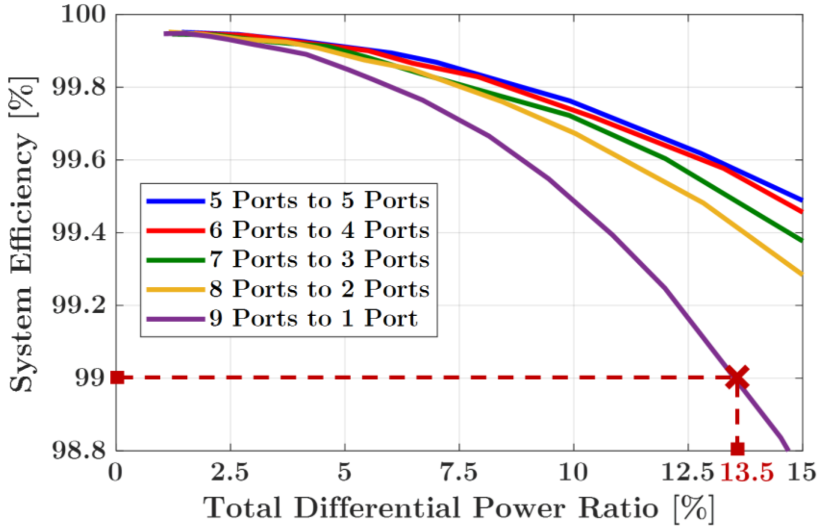

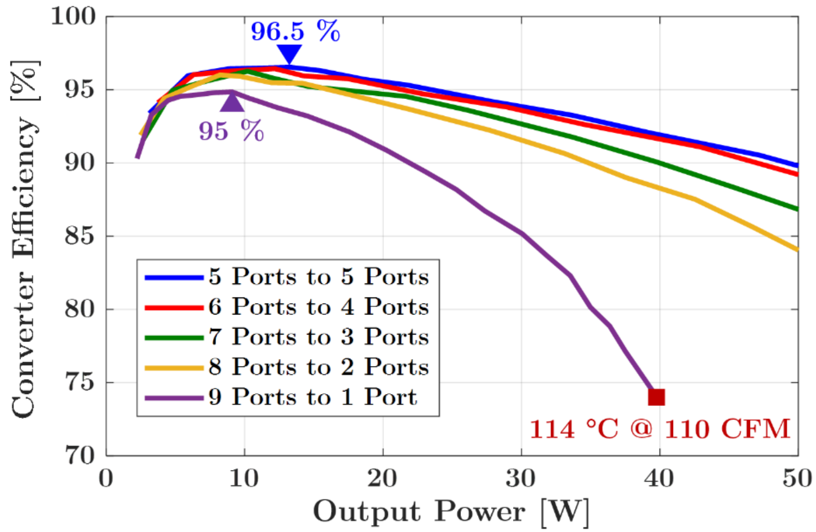

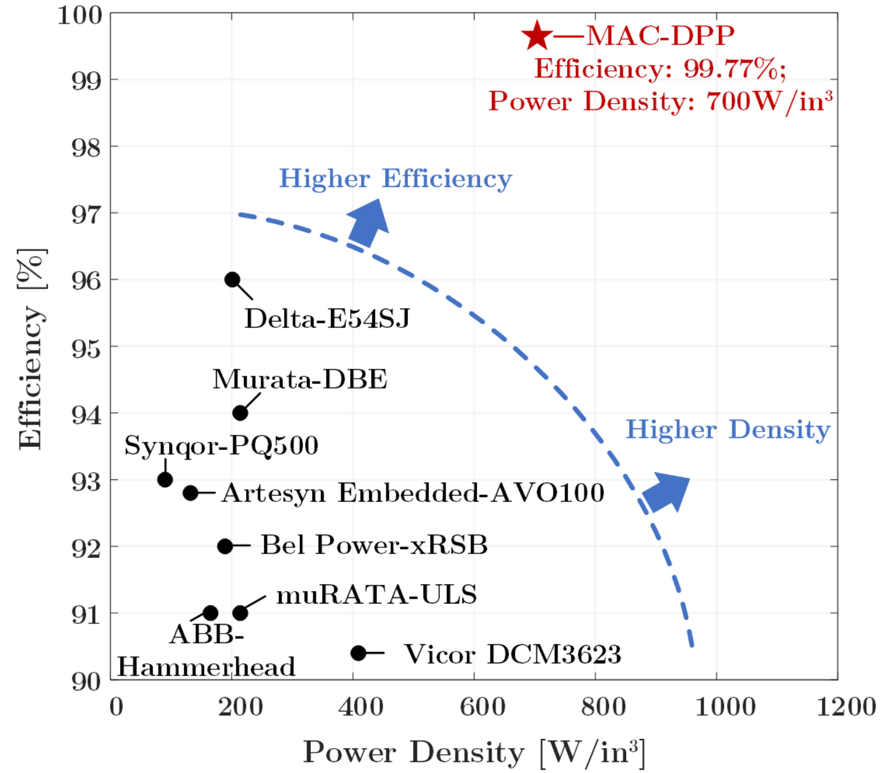

Summary:

- Multiwinding transformer enables ultra high performance DPP
- DPP architecture fits well to large scale modular systems

MIMO Reconfigurable Energy Router

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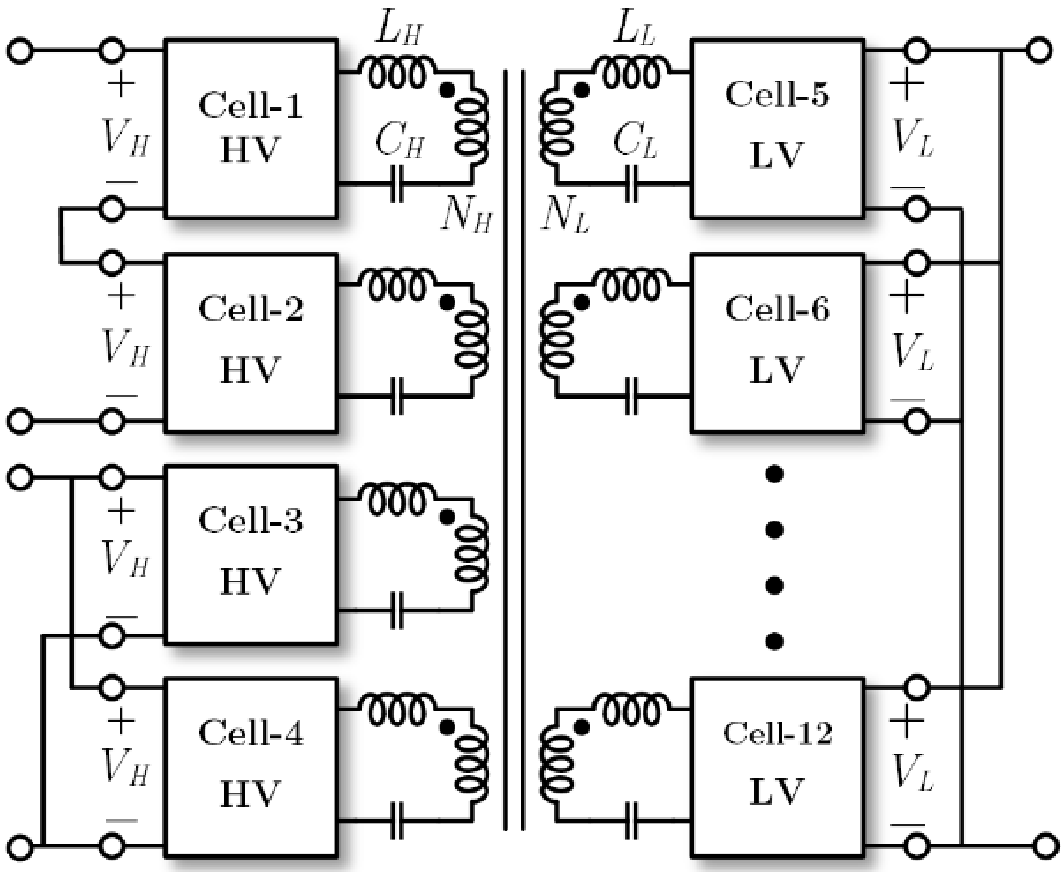
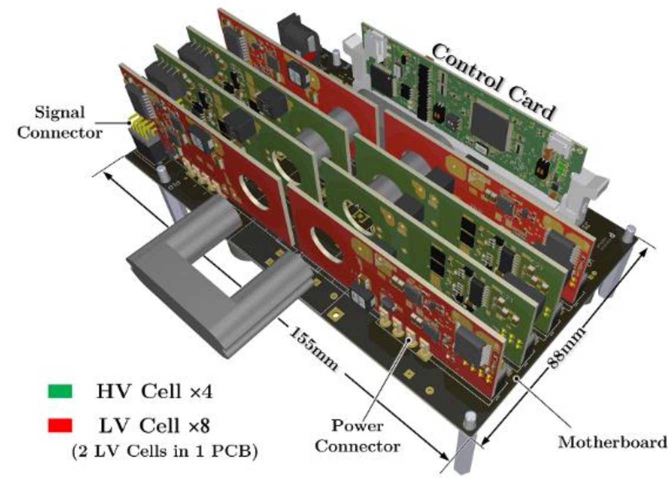
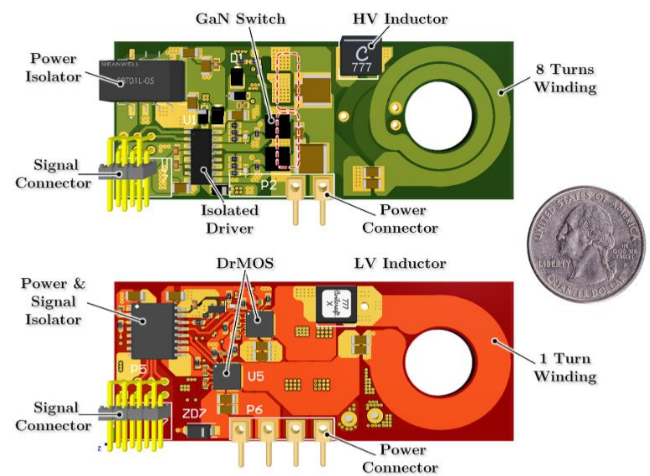


Series-Parallel Reconfigurable

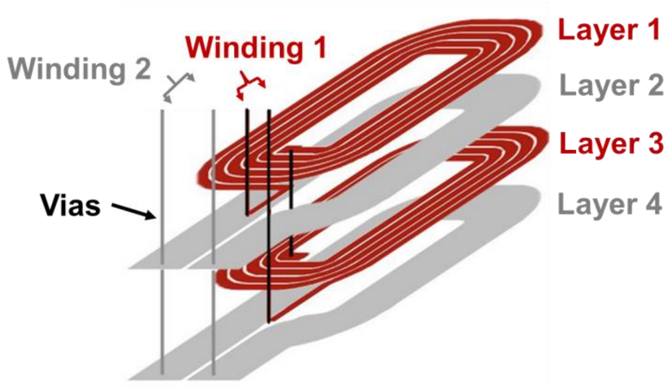




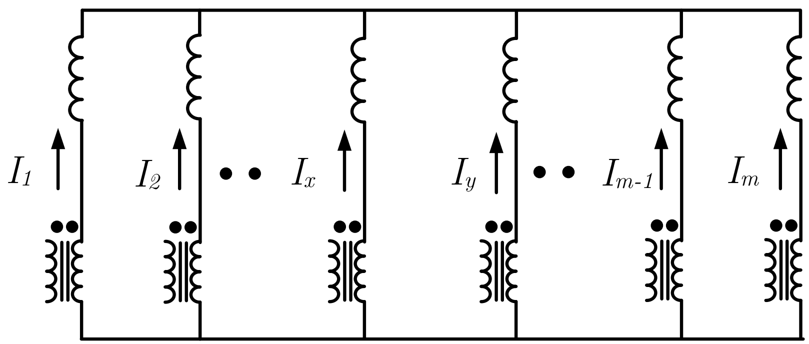
- Y. Chen, M. Chen et al., "LEGO-MIMO Architecture: A Universal Multi-Input Multi-Output (MIMO) Power Converter with Linear Extendable Group Operated (LEGO) Power Bricks," ECCE19.

Lumped Circuit Model for Magnetics

- Multiple winding coupled to a single flux linkage

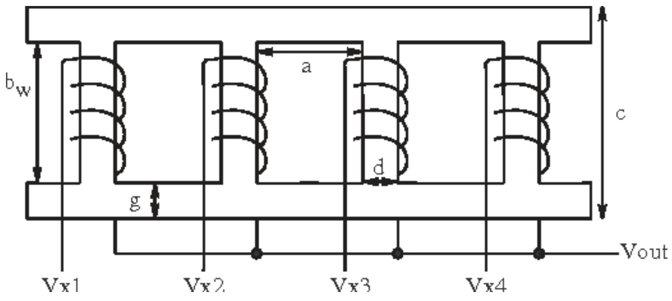


electrical circuit model

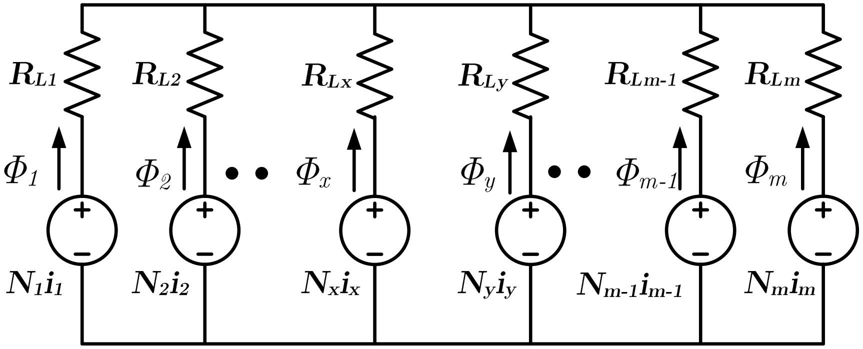


Inverse

- Multiple windings coupled to multiple flux linkages

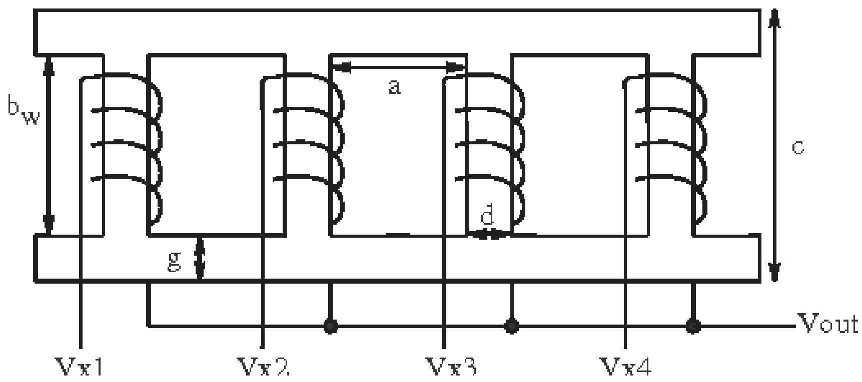


reluctance circuit model

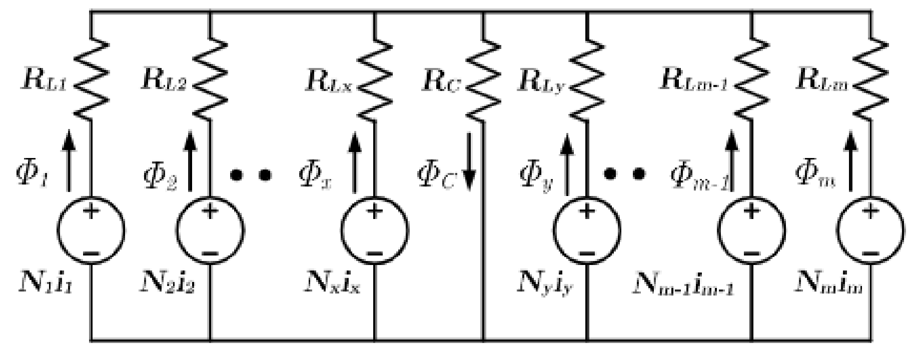


Circuit Models for Coupled Magnetics

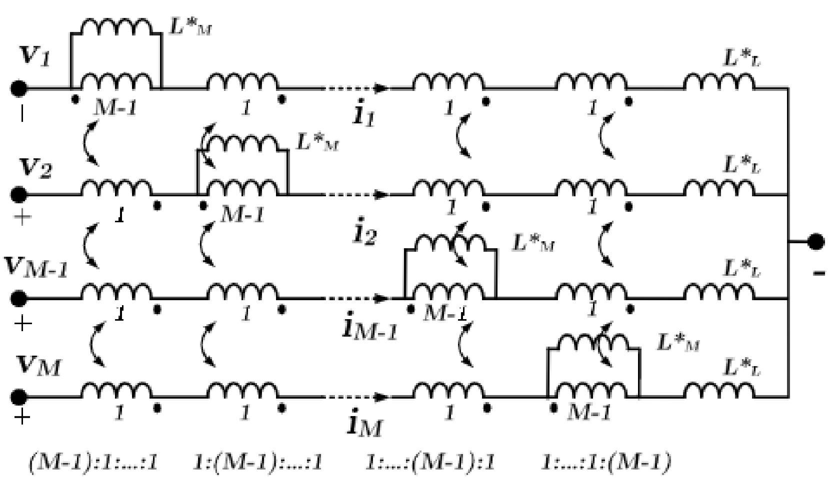
Physical Structure



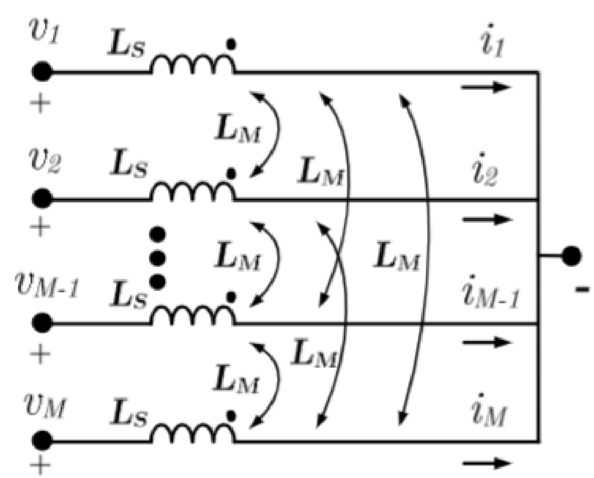
Reluctance Model



Multiwinding Transformer Model



Inductance Matrix Model

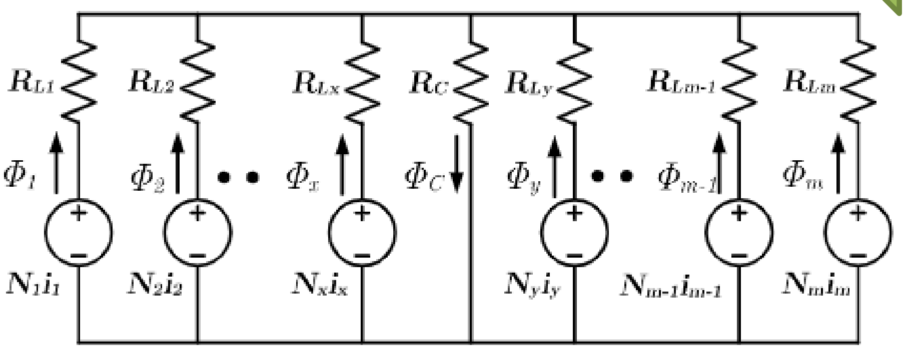


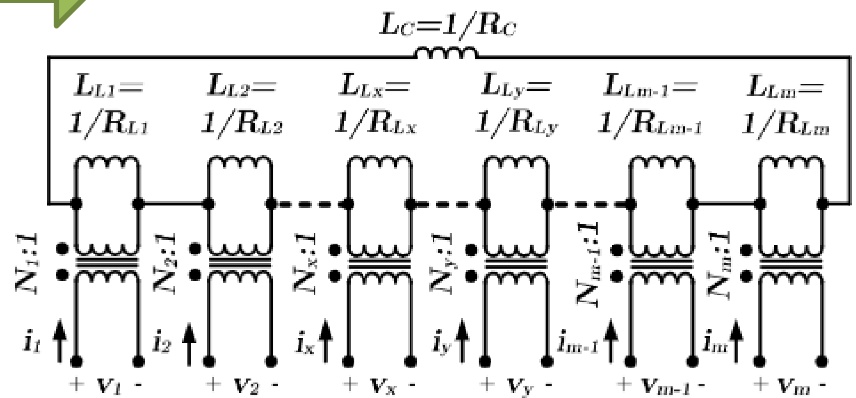
Permeance Model & Reluctance Model

Reluctance Model

dual

Permeance Model

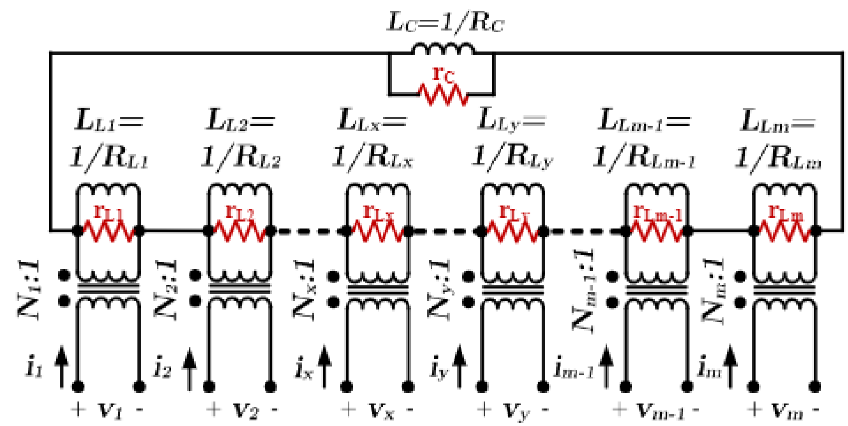




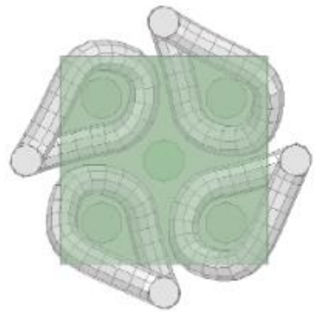
Advantage of the Permeance Model

- Simple
- Intuitive
- No coupled inductors
- Explicit design equations
- Capability of capturing core loss

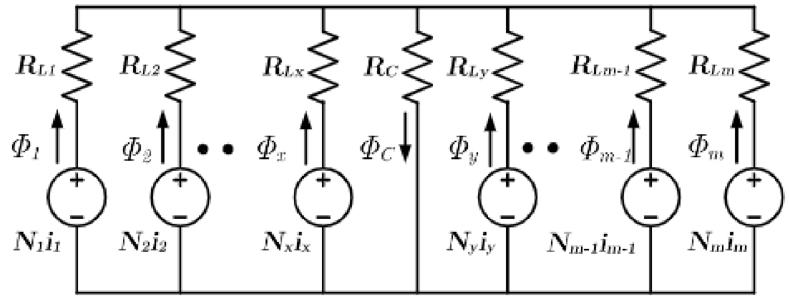
Permeance Model with Core Loss



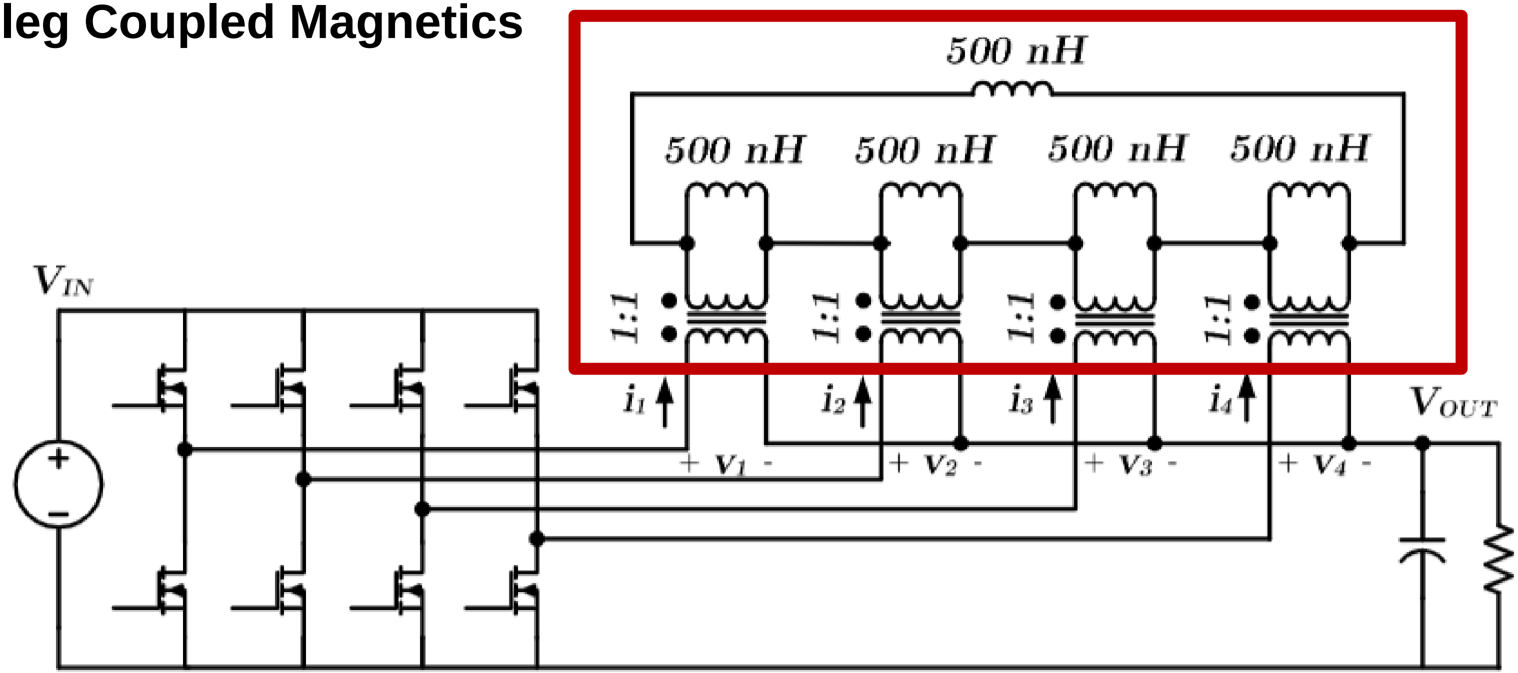
- D. Zhou and M. Chen, "Permeance Model for Multiphase Coupled Inductor, COMPEL 2020, submitted.



Multileg Coupled Magnetics

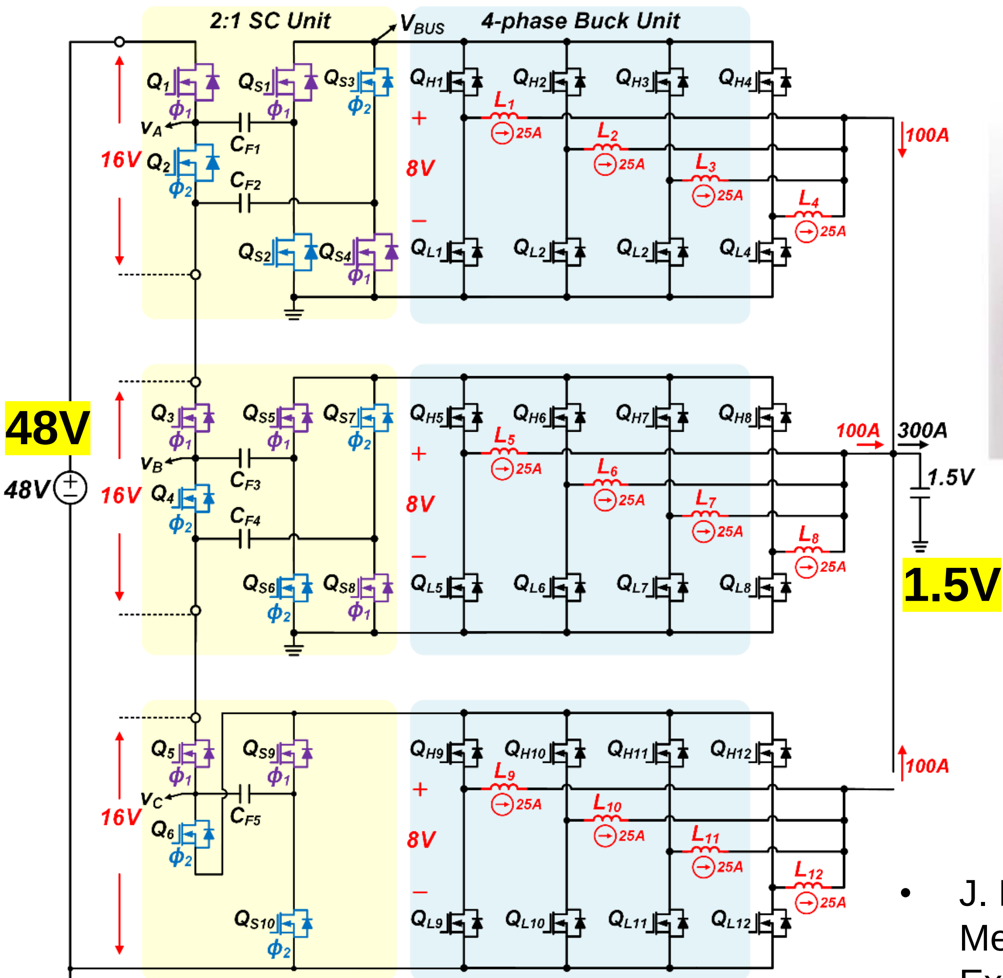


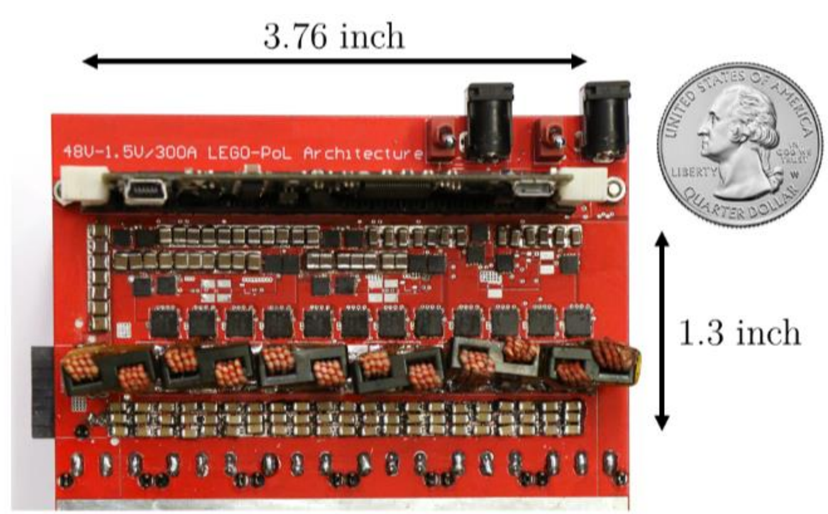
Topological duality

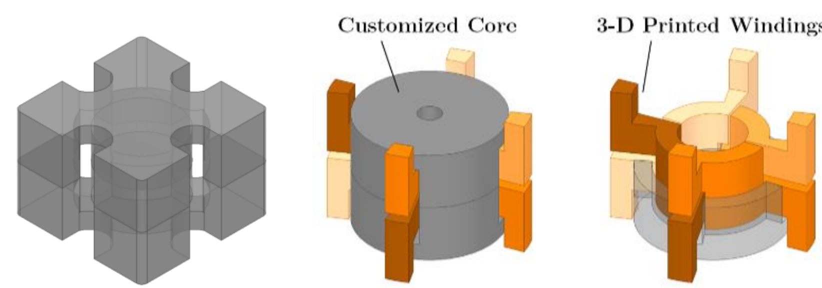


D. Zhou et al., “Permeance Model for Programmable Multiphase Coupled Magnetics”, COMPEL20, submitted

Hybrid Converter with Coupled Magnetics







- J. Baek, et al., "LEGO-PoL: A 93.1% 54V-1.5V 300A MergedTwo-Stage Hybrid Converter with a Linear Extendable Group Operated Point-of-Load (LEGO-PoL) Architecture," COMPEL 2019.

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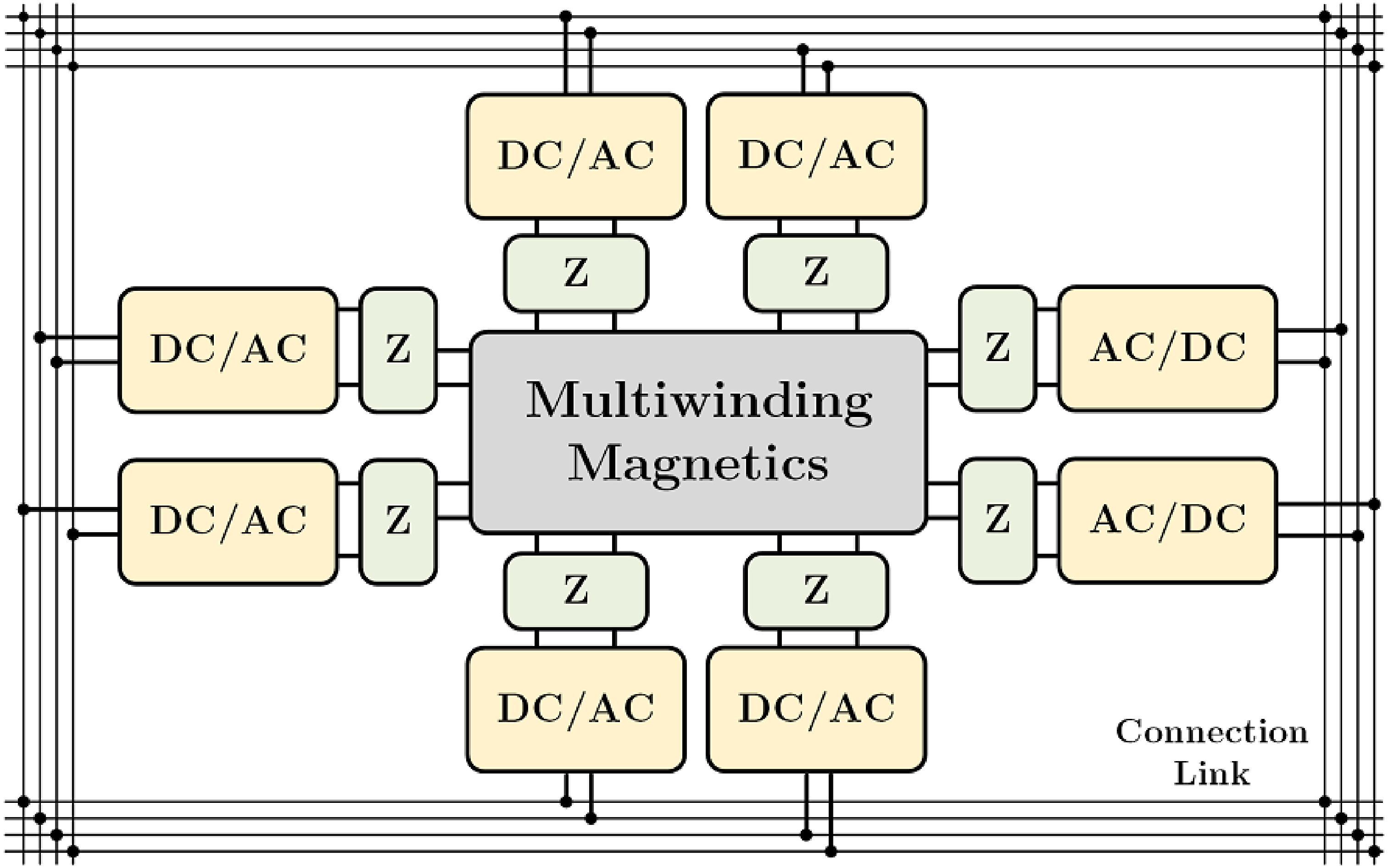
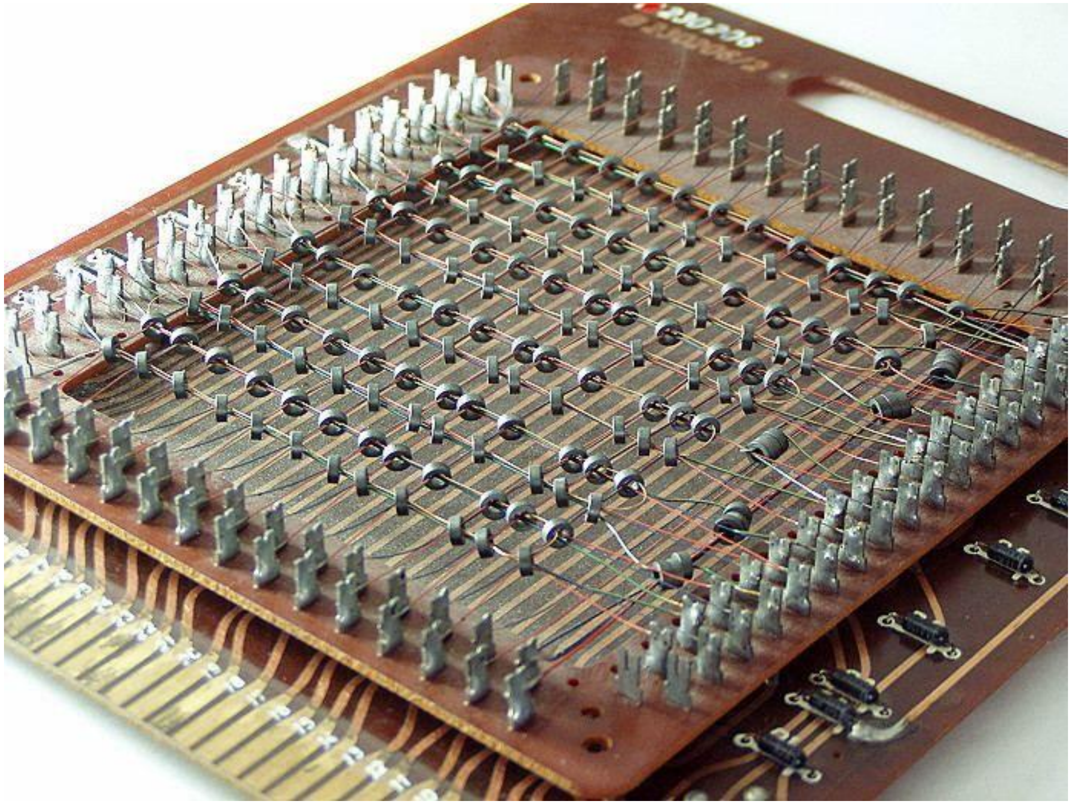
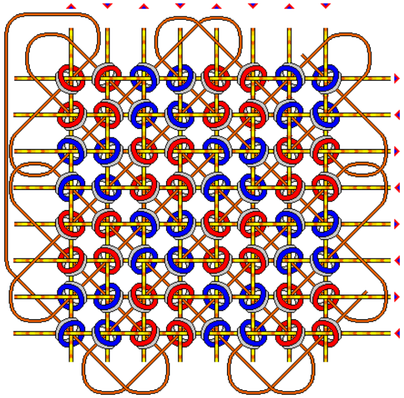
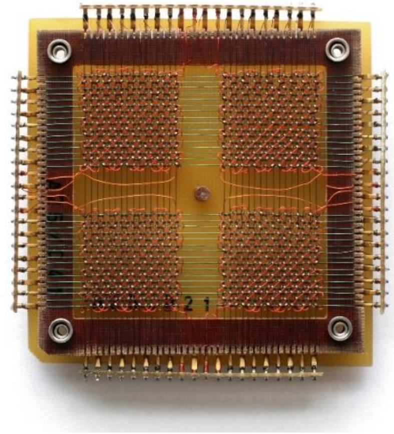
Towards a MIMO Magnetic Energy Processor



A Magnetic Memory in 1960s





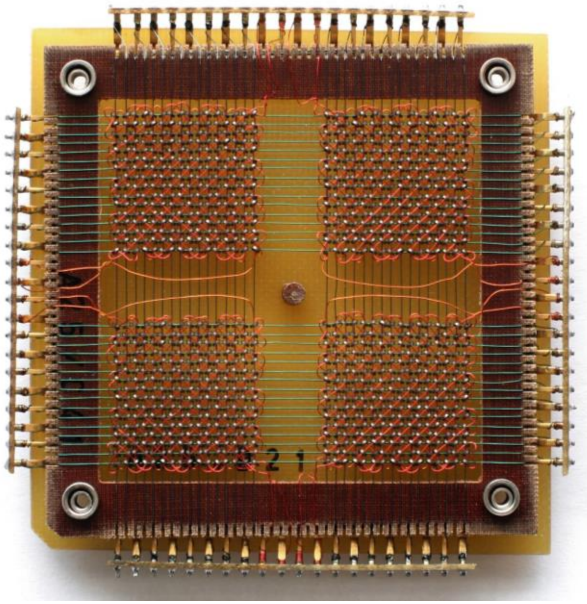


- A 32 x 32 core memory storing 1024 bits of data
- Instead of processing information, we process energy

Summary

- Exciting Opportunities for Power Electronics & Magnetics

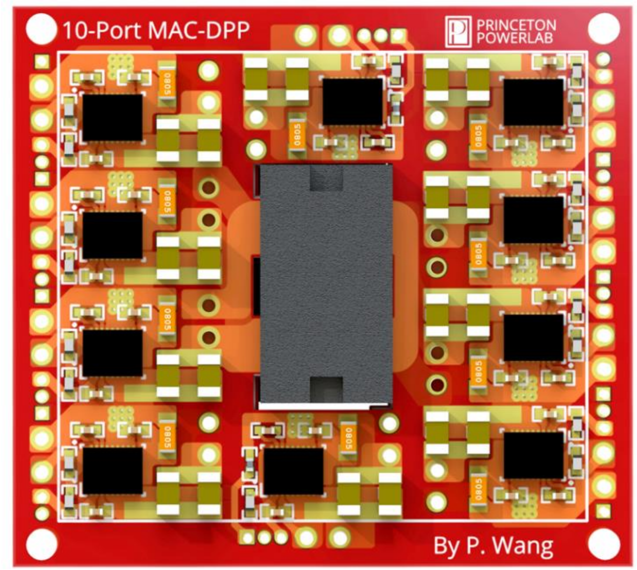
Information Processing



10101
01010
10101

32 x 32 Magnetic Memory

Energy Processing

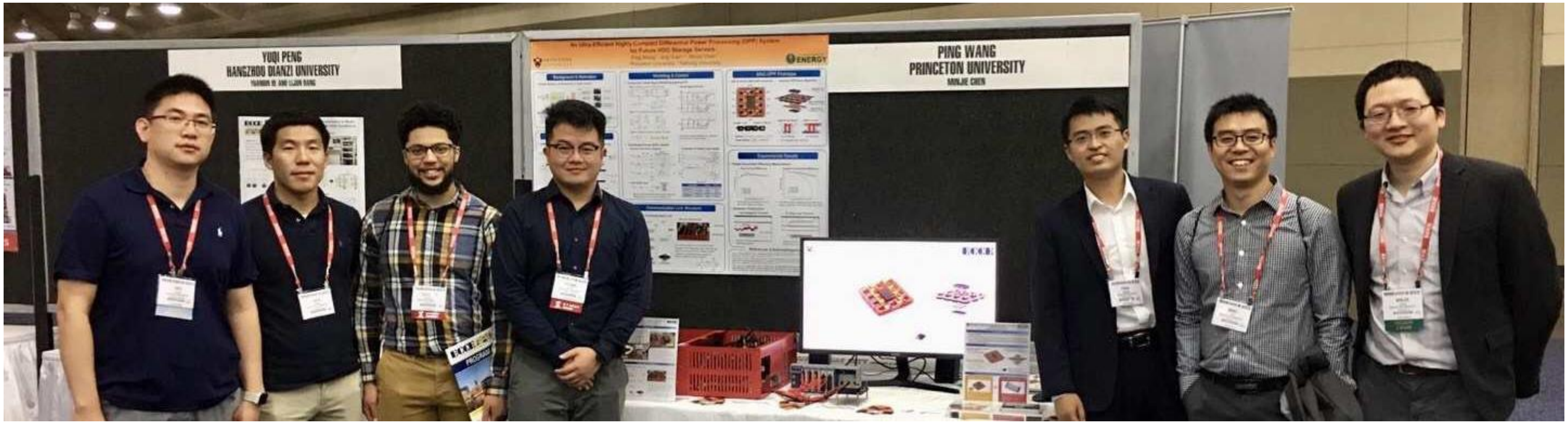


10-Port MIMO Power Converter

More topologies and designs to be investigated!

Acknowledgements

Princeton Power Electronics Research Group



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