Systematically Managing Complexity in Power Electronics Modeling and Design

Minjie Chen

Princeton University

PRINCETON POWER ELECTRONICS

IEEE WORKSHOP CONTROL AND MODELING OF POWER ELECTRONICS

JUNE 22–26, 2025 | KNOXVILLE, TENNESSEE, USA

Princeton Power Electronics Research Team

Freedom!

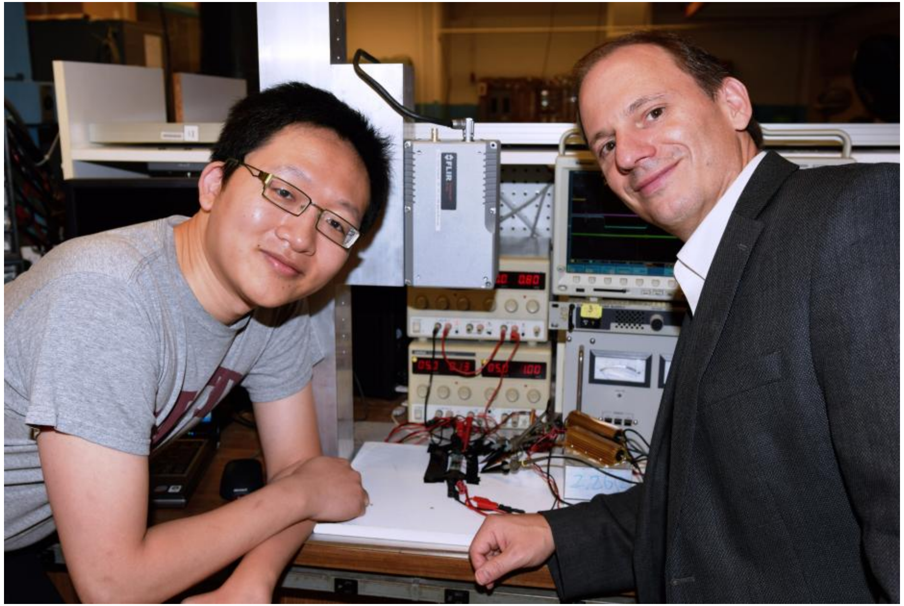
Useful Projects !!!

- MIMO
- LEGO
- MagNet
- Power + Grid
- Power + Robotics

Useless Concepts ???

Power Architecture Research, from MIT to Princeton

PRINCETON UNIVERSITY



2010 @ MIT, need a summer project

Minjie: What does power architecture really mean ???

Dave: first increase the complexity, then talk about architecture …

… **15 years later** … ???

Power architecture:

- **Theories and methods to manage the complexity in power electronics …**

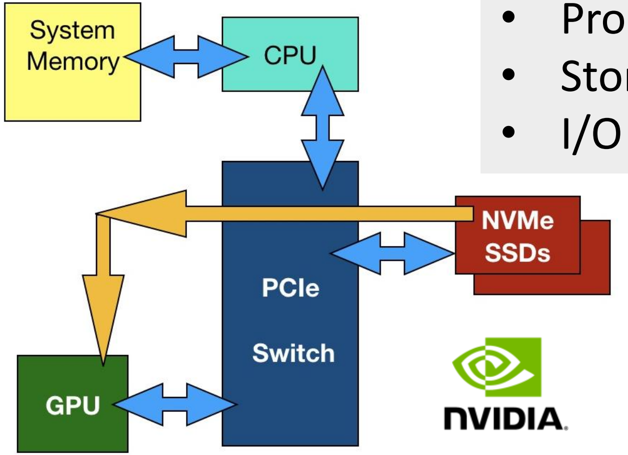
Computer Architecture and Power Architecture

PRINCETON UNIVERSITY

Computer Architecture

Information

- Processing
- Storage
- I/O

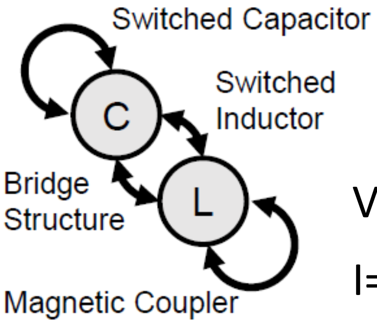


Von Neumann** vs. **In Memory Computing

Power Architecture ???

Energy

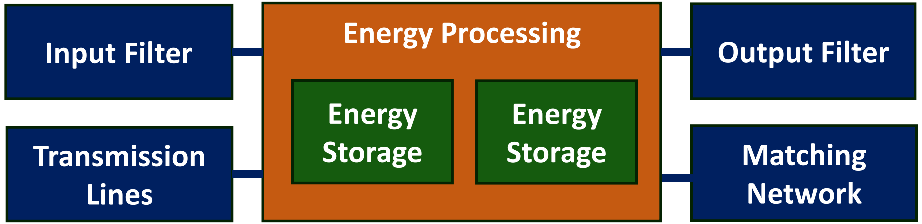
- Processing
- Storage
- I/O



P=VI

V=L di/dt

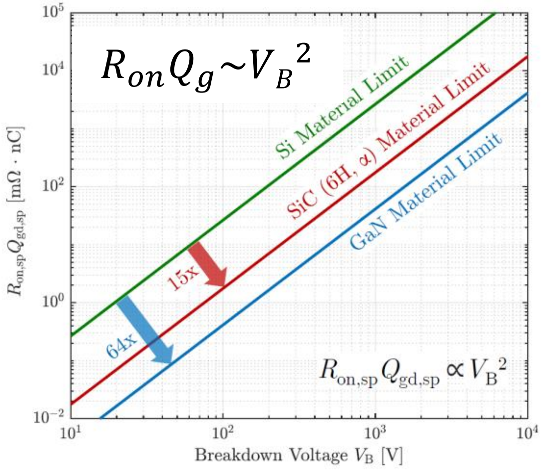
I=C dv/dt



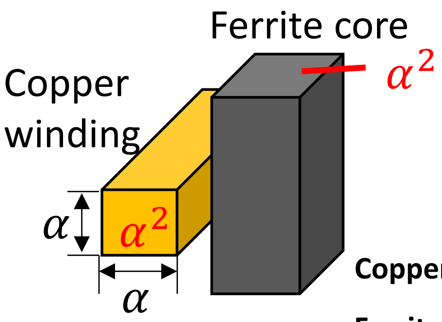
Power Architecture: Managing Complexity for Energy Processing, Storage, and I/O

Architecture is about "Scaling Laws" …

- **Power Semiconductors (R)**



- **Magnetics (L)**

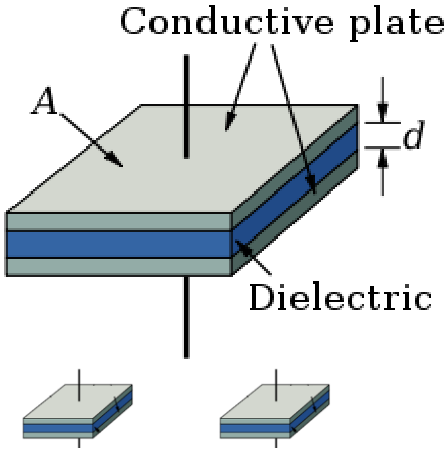


Copper ~ I ~ α^2

Ferrite ~ V ~ α^2

Power/Volume ~ $\alpha^{4/3}$

- **Capacitors (C)**



Smaller switches better

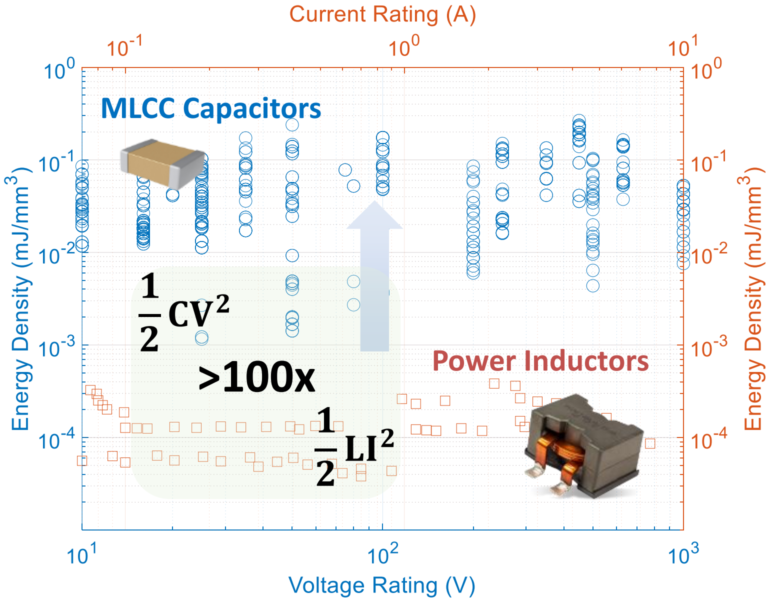
Larger / integrated magnetics better

Capacitors - indifferent

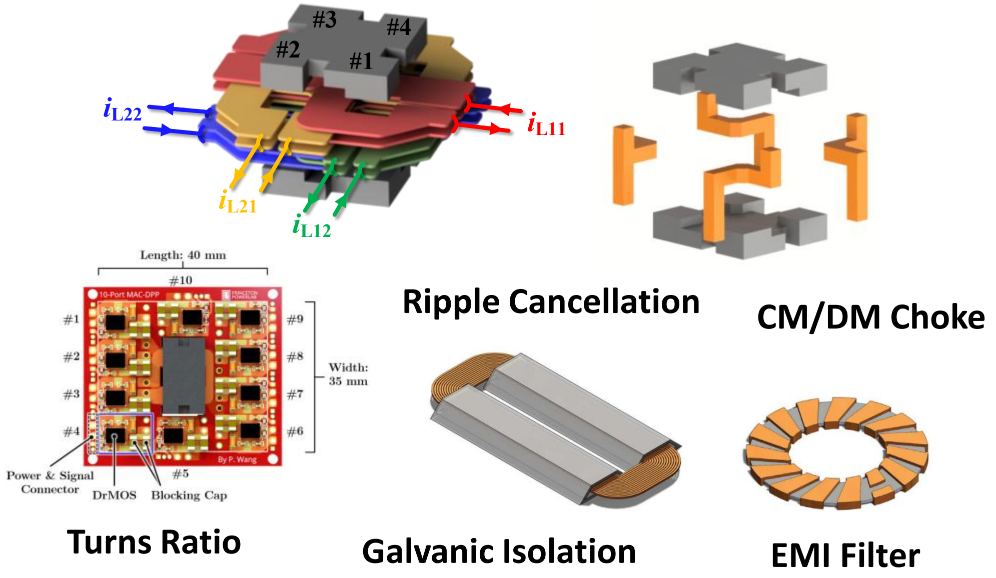
- *B. J. Baliga, Fundamentals of Power Semiconductor Devices, ISBN-13: 978-0387473130, 1996.*
- *C. R. Sullivan et al., "On Size and Magnetics: Why Small Efficient Power Inductors are Rare," 3D-PEIM'16.*
- *M. Chen et al., "Coupled Inductors for Fast-Response High-Density Power Delivery: Discrete and Integrated," CICC'21.*

Architecture is about "Memory Technologies" …

Capacitors : high density, high Q



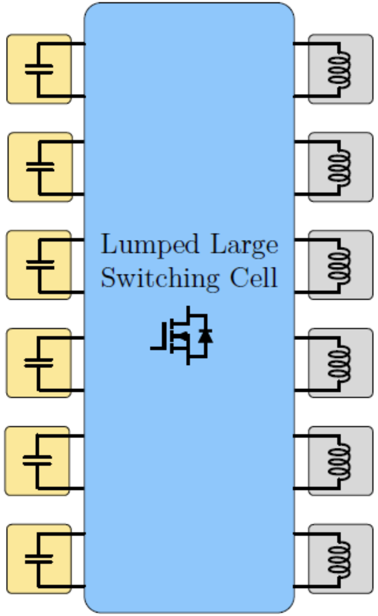
Magnetics : deep cycling & design flexibility



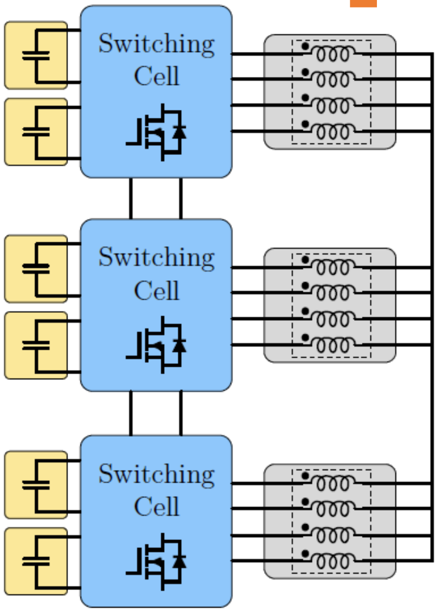
- *C. R. Sullivan et al., "On Size and Magnetics: Why Small Efficient Power Inductors are Rare," 3D-PEIM'16.*
- *M. Chen and C. R. Sullivan, "Unified Models for Coupled Inductors Applied to Multiphase PWM Converters,", TPEL'21 Prize Paper.*

Focus #1: Distributed Switching and Coupled Passives

Distributed Switching



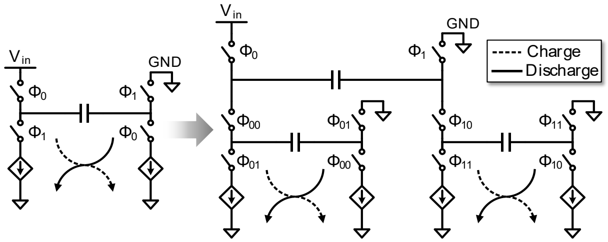
Centralized



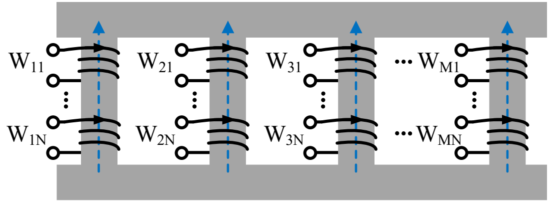
Distributed

Coupled Passives

Series-Stacked Capacitors



Parallel/Matrix-Coupled Magnetics

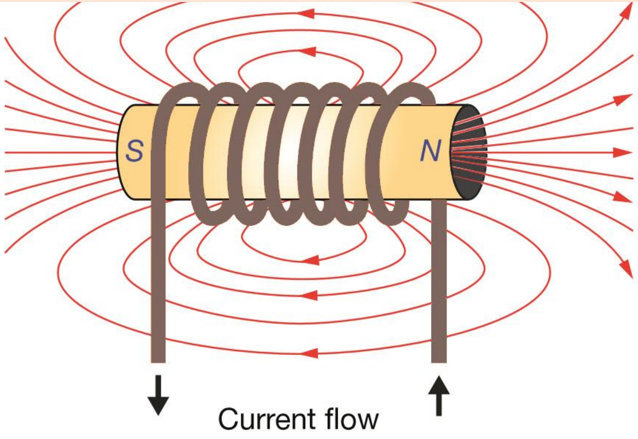


Passive Integration and Deep Cycling

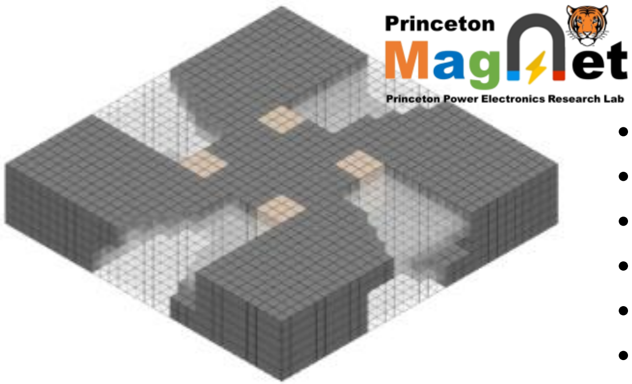
Focus #2: Precise, Non-Linear Models for Passives

- Passives are dominating the size of power electronics (**L, C, PZT, Filters** …)
- Most existing models for passives are **overly simplified** and **inaccurate** …
- Precise engineering of passives (material, geometry, design) **across wide range**

Approximated Linear Magnetics



Precise & Non-Linear Magnetics



- Memory effects
- Geometry effects
- Temperature impact
- Waveform impact
- Losses
- Saturation

Embrace and manage the complexity in passive components …

Architecture is about “Applications” …

Renewable Energy Systems

Data Center and Computing

Complex, Modular Power Electronics

Complex Sources

Complex Loads

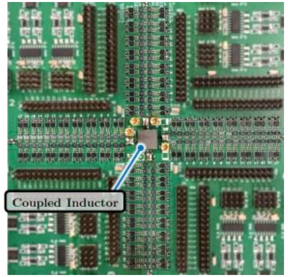
Grid-Scale Energy Storage

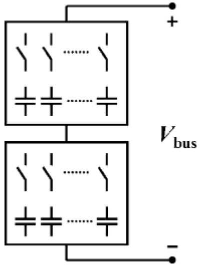
Electro-Manufacturing

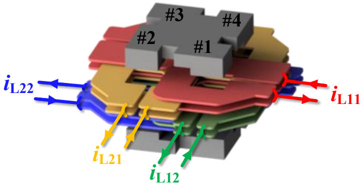
Princeton Power Architecture Research Team

Jaeil Baek	Yenan Chen	Ping Wang	Youssef Elasser	Daniel Zhou	Haoran Li	Steven Zeng	Gyeong-Gu Kang	Shukai Wang
Assist. Prof. @KAIST	Prof. @Zhejiang U.	Assist. Prof. @HKUST	Nvidia Research	Princeton PhD'25	Princeton PhD'25	Princeton Postdoc	Princeton Postdoc	Princeton PhD'27

2017 → **2025**







Princeton MagNet
Princeton Power Electronics Research Lab

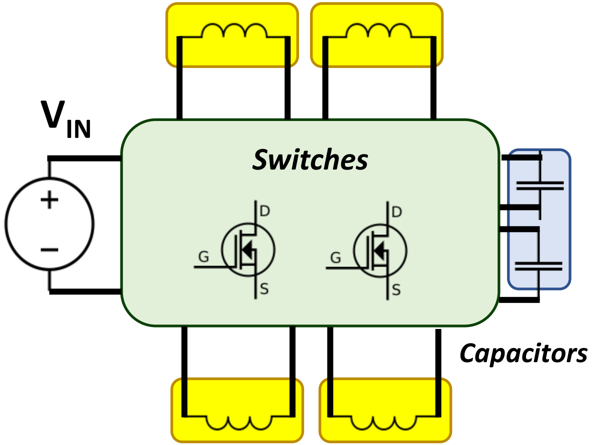
Circuits 40%

Passives 40%

Models 20%

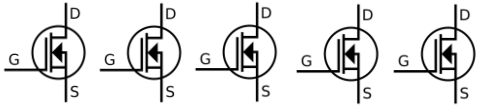
Engineering Circuits: Distributed Power Conversion

Traditional

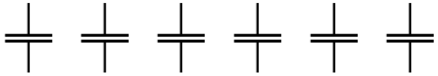


Small Building Blocks

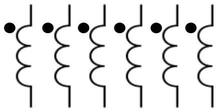
Granular Switches



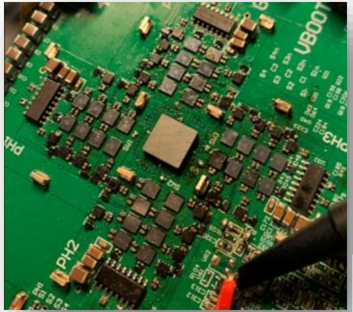
Granular Capacitors



Integrated Magnetics

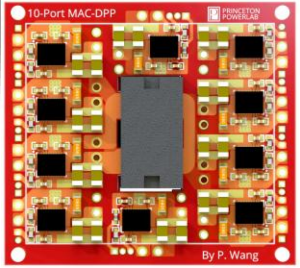


Distributed Power Conversion



4x4 Coupled FCML
- Daniel Zhou

MIMO Energy Router
- Ping Wang

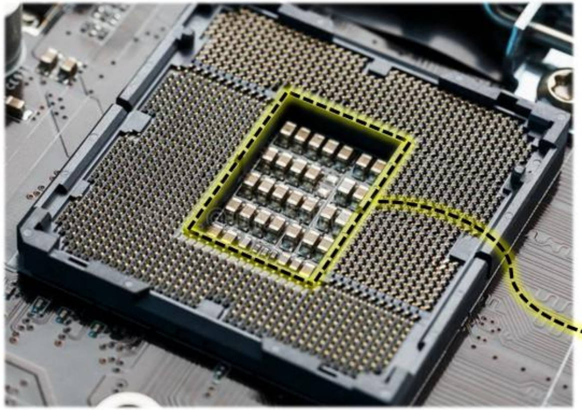


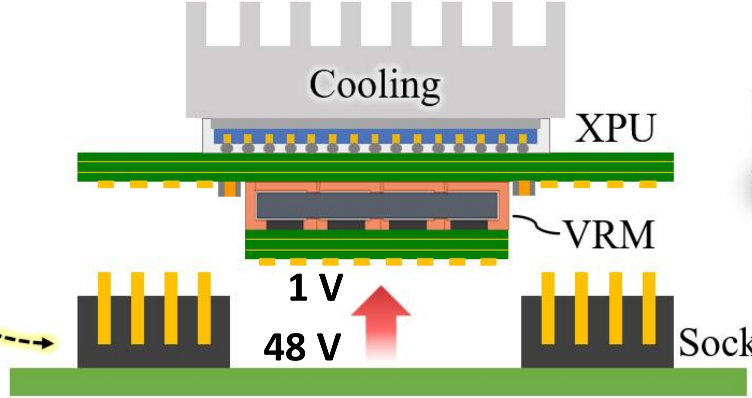
Distributed Switching and Coupled Passives

1. *Materials + circuits + systems + control + architecture + applications*
2. *Hardware + software + design method + scaling factor + performance limit*

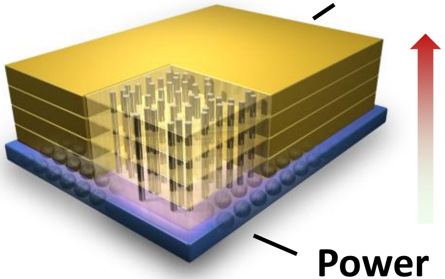
Vertical Power Delivery for "High Density Computing" …

PRINCETON UNIVERSITY





3D Stacked ICs



Power

Rapidly increasing power-per-area

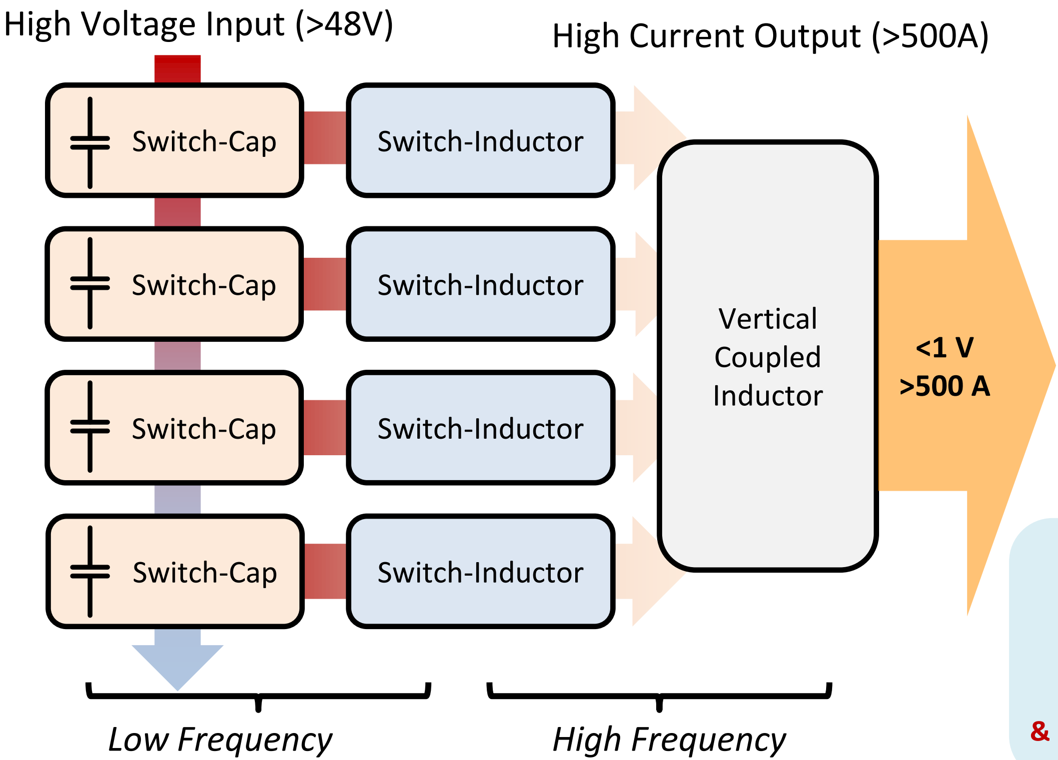
Research Partners

intel. Google tsmc SRC Semiconductor Research Corporation pSemi A Murata Company Texas Instruments NVIDIA ITG Trusted Innovation Magnetics & EMI Filters WE WÜRTH ELEKTRONIK

Requirements 400 V / 48 V-1 V >1 A/mm^2 <3 mm height 500 A~2000 A 10 A/ns >90%

Motivate very high performance with complex architecture, not cost sensitive …

LEGO Point-of-Load Composite VRM Architecture



Voltage Stress

48 V or above

Stacked SwCap
& automatic balancing

Dynamic Speed

1 MHz or above

Coupled Inductor
& in-package magnetics

Current Stress

500 A or above

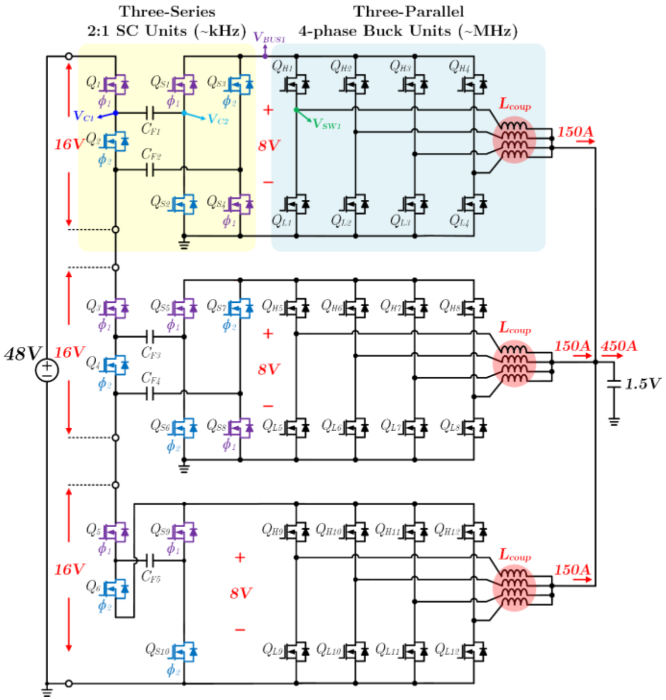
Switched-Inductor
& phase rotating & interleaving

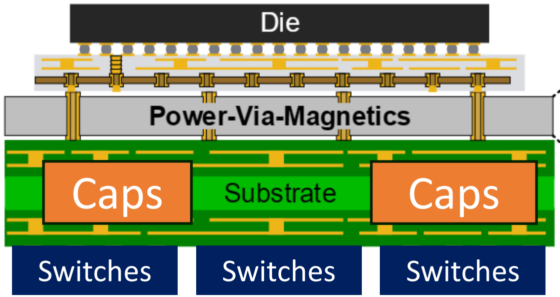
Jaeil Baek

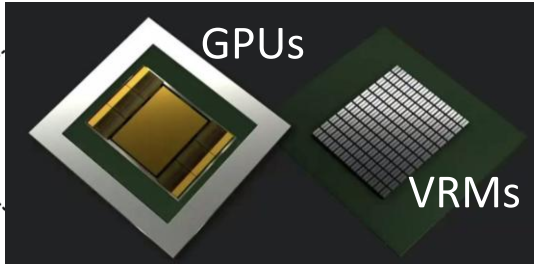
Youssef Elasser

- *J. Beak, Y. Elasser et al., "Vertical Stacked LEGO-PoL CPU Voltage Regulator," TPEL'22 Prize Paper.*

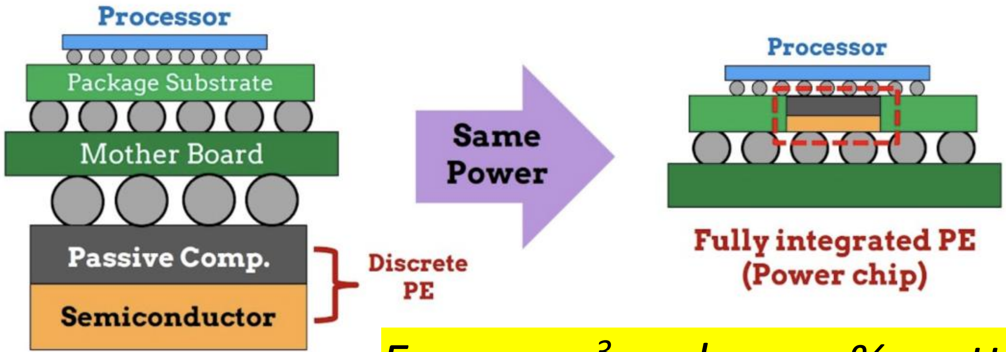
Architecture is about “Packaging” …







$1A/mm^2 = 1A/mm^2$



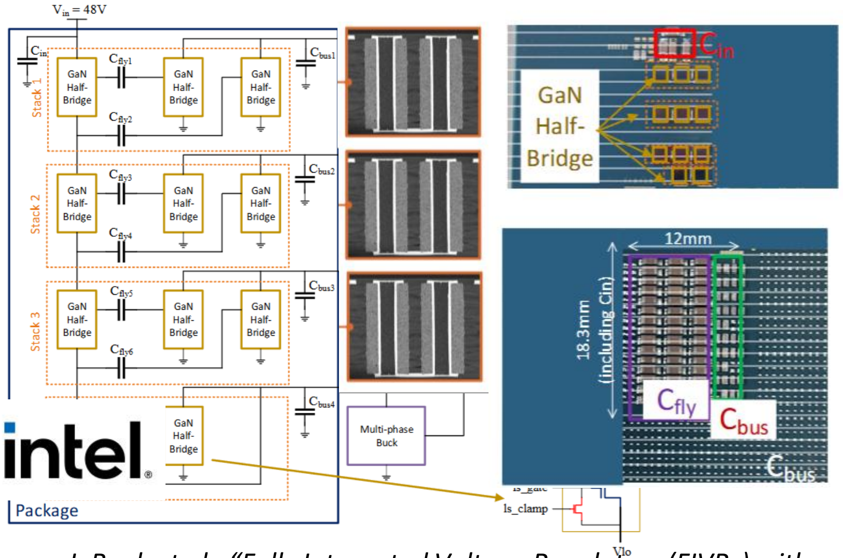
Every mm^3 and every % matters !!!

- *J. Beak, Y. Elasser et al., “Vertical Stacked LEGO-PoL CPU Voltage Regulator,” TPEL’22 Prize Paper.*
- *M. Chen and C. R. Sullivan, “Unified Models for Coupled Inductors Applied to Multiphase PWM Converters,” TPEL’21 Prize Paper.*

Further Development of the LEGO Architecture

PRINCETON UNIVERSITY

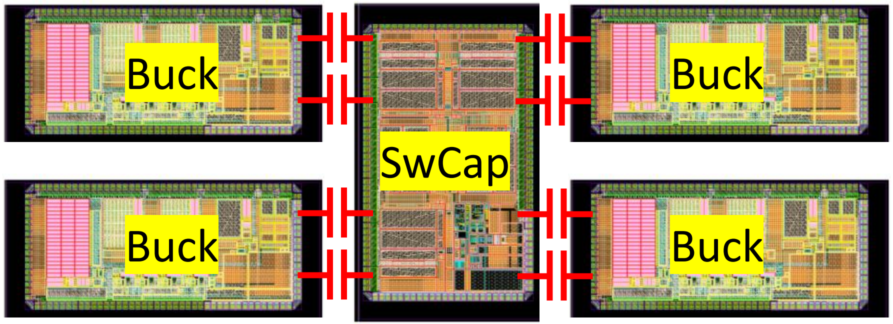
Intel's GaN-LEGO and CoaxMIL Magnetics [APEC'25]



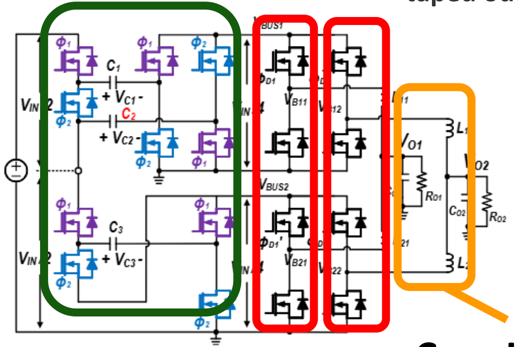
- J. Baek et al., "Fully Integrated Voltage Regulators (FIVRs) with Package In-situ Coupled CoaxMIL Inductor for High Power Density Microprocessor Applications," APEC'25.

[COMPEL'25] Chiplet-LEGO: Delivering Multiple Voltage Rails to Chiplets with Chiplet VRMs *Thursday, 11:45am*

Princeton Chiplet-LEGO



taped out TSMC 180nm BCD, May 2025

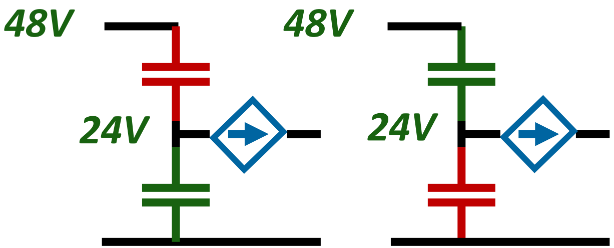


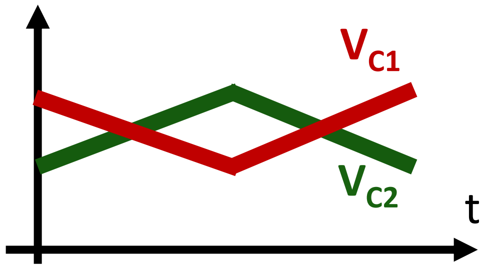
Penn
tsmc
pSemi A Murata Company

Steven Zeng

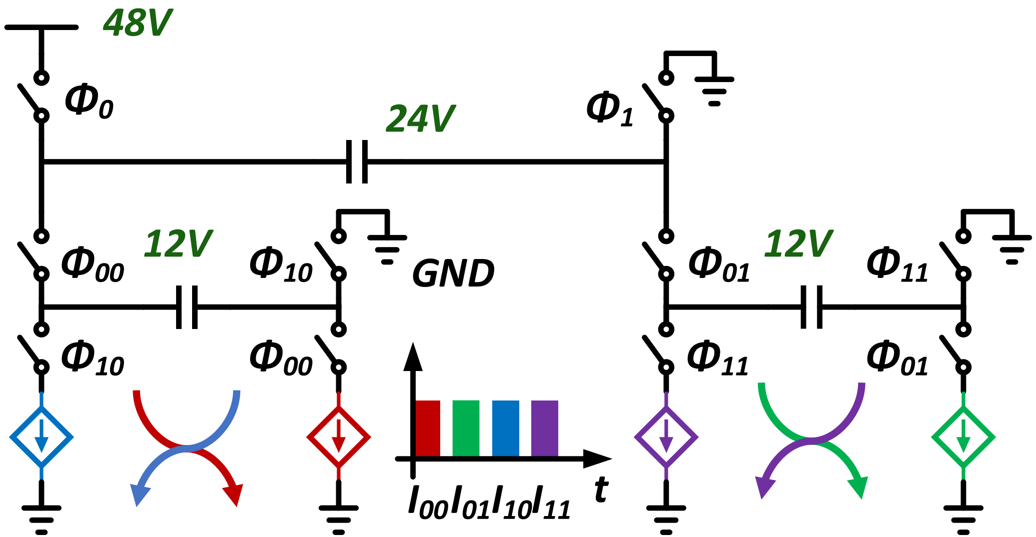
Gyeong-Gu Kang

Architecture is about “Mechanisms” …





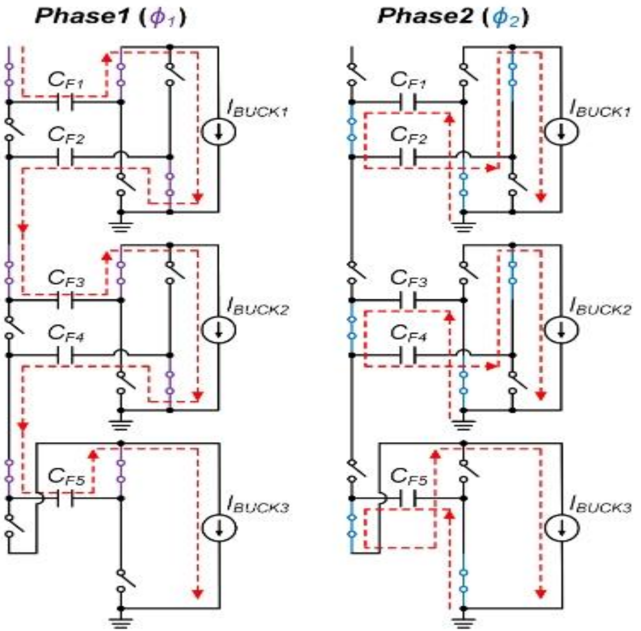
- *Balancing and Scalable Distributed Architecture*



- *M. Chen, “Merged-Multi-Stage Power Conversion: a Hybrid Switched-Capacitor Magnetics Approach,” MIT Thesis.*
- *P. Wang et al., “Interphase LC Resonance and Stability Analysis of Series-Capacitor Buck Converters,” TPEL’23.*
- *P. S. Shenoy et. al., “Comparison of a Buck Converter and a Series Capacitor Buck Converter for High-Frequency, High-Conversion-Ratio Voltage Regulators,” TPEL’15.*

Architecture is about "Modeling and Control" …

- **Automatic Current Sharing**

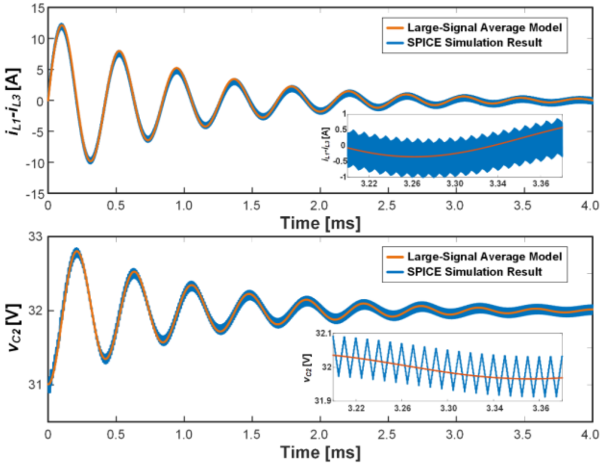


- **Dynamics of Switched Capacitor Voltages**

$$\ddot{\mathbf{X}} + \frac{R}{L}\dot{\mathbf{X}} + \frac{D^2}{4LC}M\mathbf{X} = 0,$$

$$\ddot{\mathbf{X}} = \begin{bmatrix} \frac{d^2 i_{L1}}{dt^2} \\ \frac{d^2 i_{L2}}{dt^2} \\ \vdots \\ \frac{d^2 i_{LN}}{dt^2} \end{bmatrix}, \quad \dot{\mathbf{X}} = \begin{bmatrix} \frac{di_{L1}}{dt} \\ \frac{di_{L2}}{dt} \\ \vdots \\ \frac{di_{LN}}{dt} \end{bmatrix}, \quad \mathbf{X} = \begin{bmatrix} i_{L1} \\ i_{L2} \\ \vdots \\ i_{LN} \end{bmatrix},$$

$$M = \begin{bmatrix} 1 & -1 & 0 & 0 & \cdots & 0 \\ -1 & 2 & -1 & 0 & \cdots & 0 \\ 0 & -1 & 2 & -1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \cdots & \vdots \\ 0 & 0 & \cdots & -1 & 2 & -1 \\ 0 & 0 & \cdots & 0 & -1 & 1 \end{bmatrix}.$$



- Soft charging switched capacitors
- Automatic current balancing
- Composite frequency operation

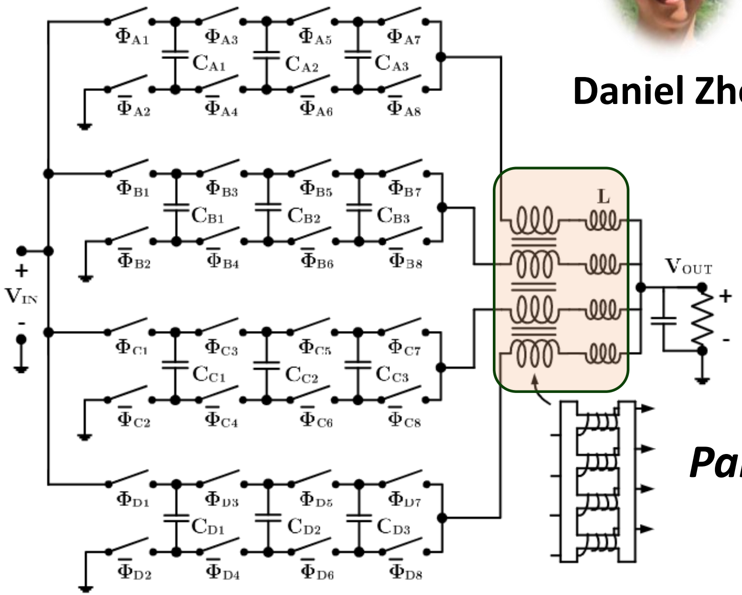
Jaeil Baek

Ping Wang

- *J. Beak et al., "Vertical Stacked LEGO-PoL CPU Voltage Regulator," TPEL'22 Prize Paper.*
- *P. Wang et al., "Interphase L-C Resonance and Stability Analysis of Series-Capacitor Buck Converters," TPEL'23.*

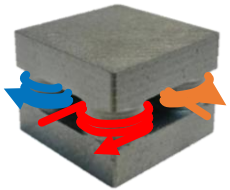
Architecture is about "Co-Design" …

Series-Stacked Capacitors



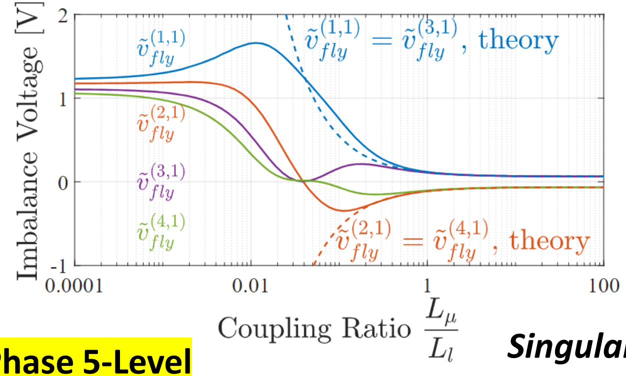
Daniel Zhou

Jenko Celikovic



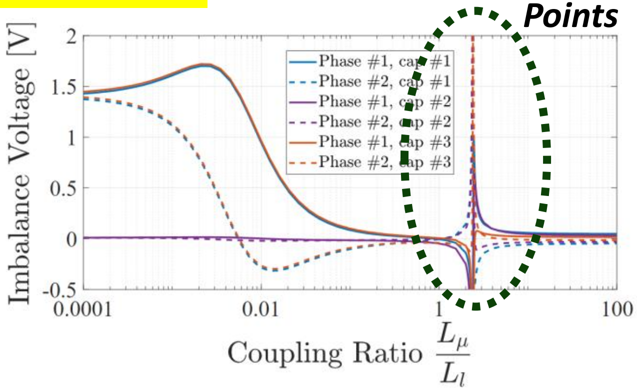
Parallel-Coupled Magnetics

4-Phase 3-Level



2-Phase 5-Level

Singular Points

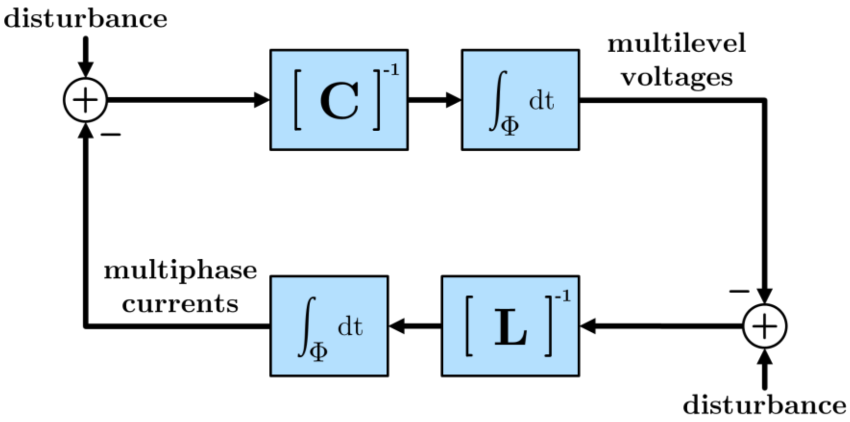


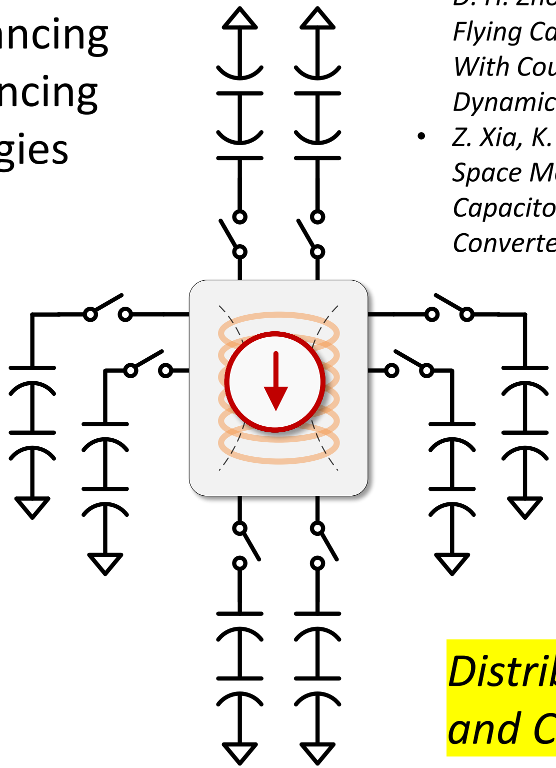
- *D. H. Zhou, J. Čeliković, D. Maksimović and M. Chen, "Balancing Multiphase FCML Converters With Coupled Inductors: Modeling, Analysis, Limitations", TPEL'24.*

“Simple Theories” for “Complex Systems” …

PRINCETON UNIVERSITY

- Scalable methods for analyzing passive balancing
- Applicability and limitations of passive balancing
- Design guidelines for L-C and control strategies
- Design guidelines for coupled inductors





- *D. H. Zhou and M. Chen, “Balancing Flying Capacitor Multilevel Converters With Coupled Inductors: Multiresonant Dynamics,” TPEL’25.*
- *Z. Xia, K. Datta and J. T. Stauth, “State-Space Modeling and Control of Flying-Capacitor Multilevel DC–DC Converters,” TPEL’23.*

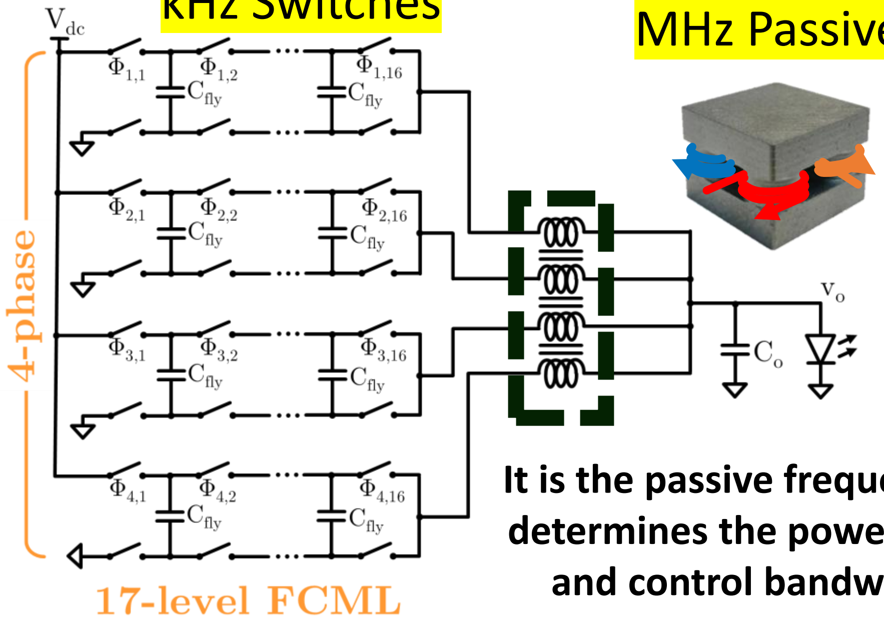
Daniel Zhou

Distributed Switching and Coupled Passives

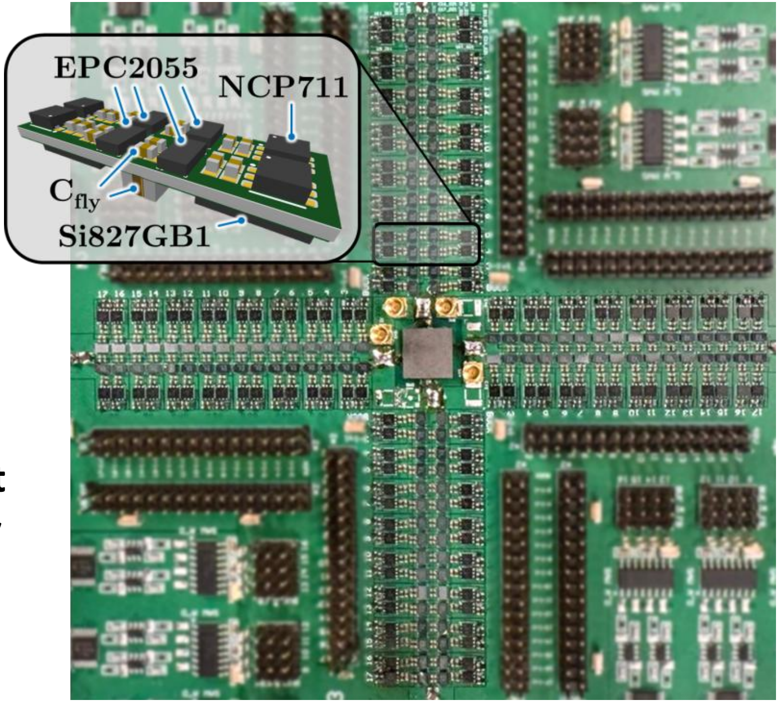
Switching Frequency ≠ Passive Frequency

kHz Switches

MHz Passives



It is the passive frequency that determines the power density and control bandwidth …



[COMPEL'25] "Distributed Switching and Coupled Passives for High Performance Power Electronics"
Wednesday, 1:10 PM

64× frequency multiplication

Very Beginning of Power Architecture Research

Gen 1: Canonical Cells

- Buck
- Boost
- Flyback
- DAB
- LLC
- Cuk

Gen 2: Modular Cells

- FCML
- MMC
- NPC

Gen 3: Composite Cells

- LEGO
- VIB
- STC
- MSC
- SBC
- …

Lots of other power architecture research going on:

MIT

UNIVERSITY OF TORONTO

Berkeley UNIVERSITY OF CALIFORNIA

Dartmouth

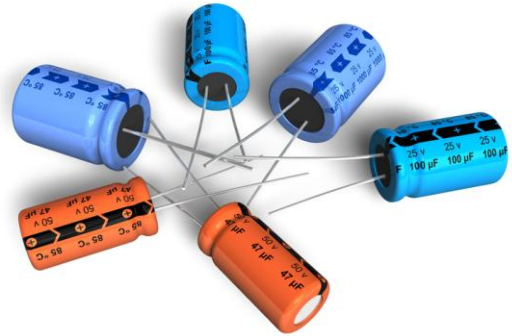
CU

UC San Diego

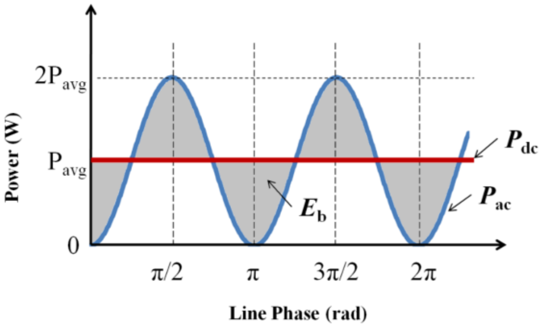
CURENT

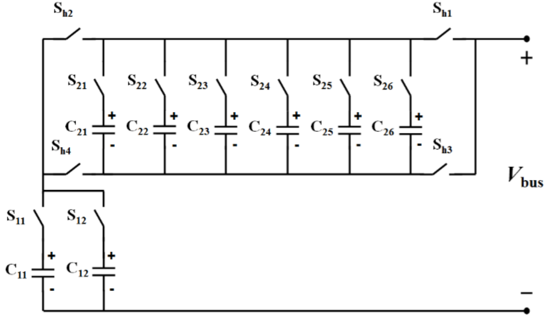
CPES Center for Power Electronics Systems

"In-Passive Power-Processing" vs. "In-Memory Computing"

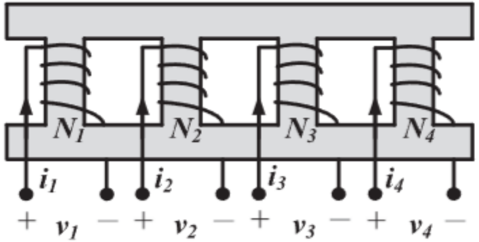


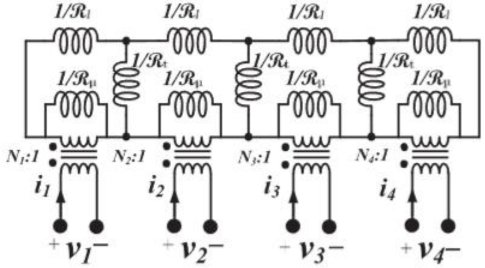
"Capacitors" – Active Buffer and Deep Cycling of Capacitors





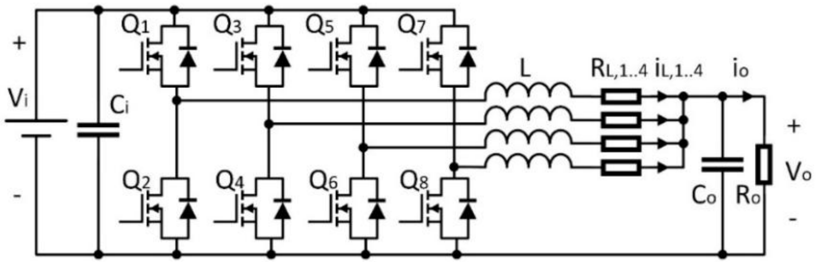
"Magnetics" – Coupling and Deep Cycling of Magnetics



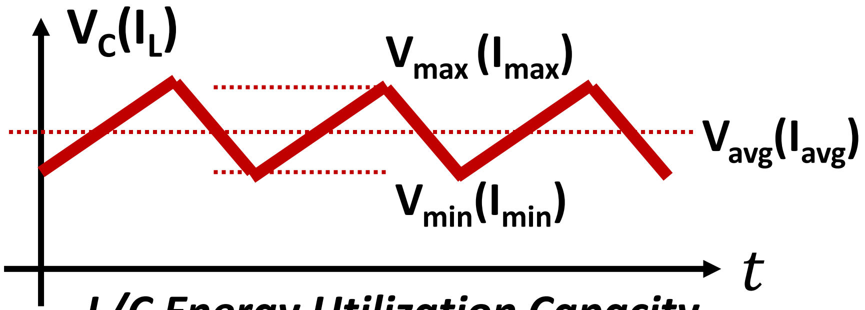


Utilization of Passive Components in Power Electronics

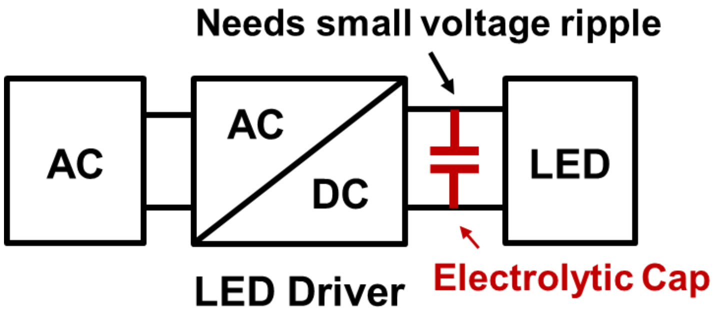
PWM operated Capacitors & Magnetics

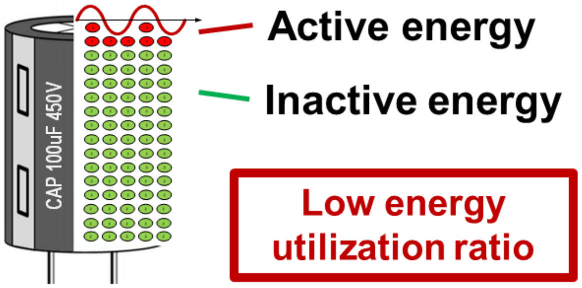


Passive Utilization << 50%

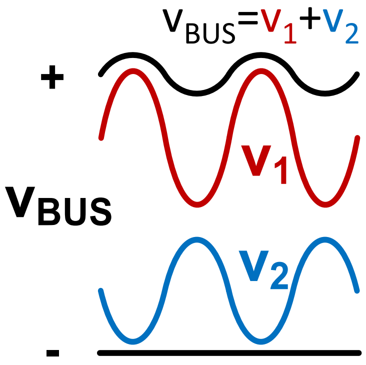


L/C Energy Utilization Capacity



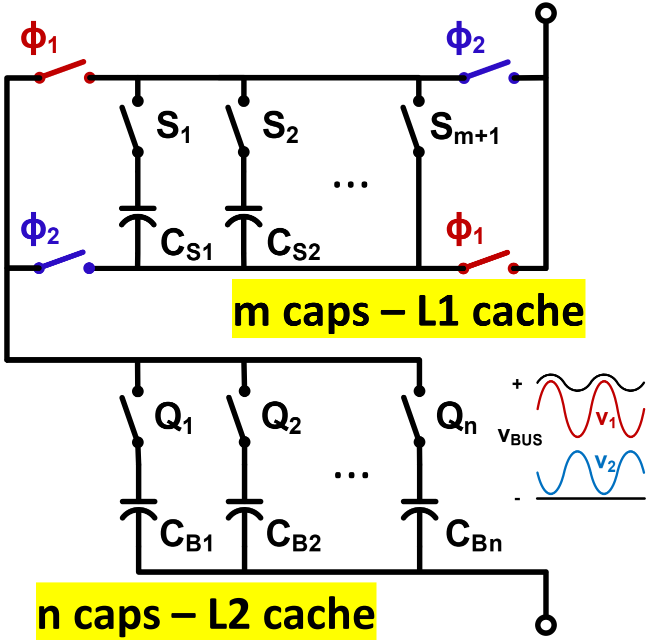


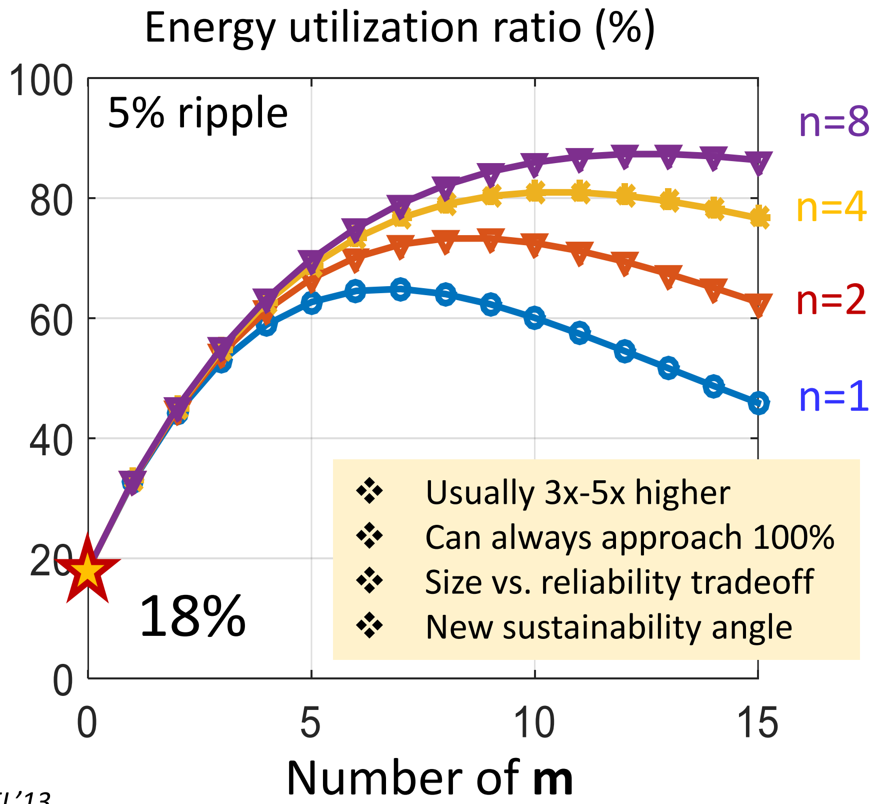
twice line-frequency buffer



Stacked Switched Capacitor Energy Buffer

n-m Bipolar SSC





- Usually 3x-5x higher
- Can always approach 100%
- Size vs. reliability tradeoff
- New sustainability angle

K. K. Afridi

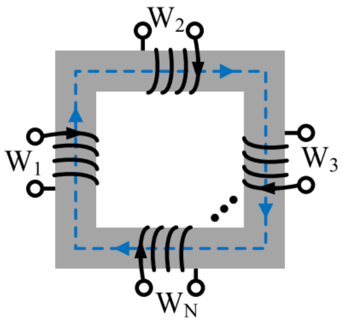
D. J. Perreault

- *M. Chen, K. K. Afridi and D. J. Perreault, "Stacked Switched Capacitor Energy Buffer Architecture," TPEL'13.*

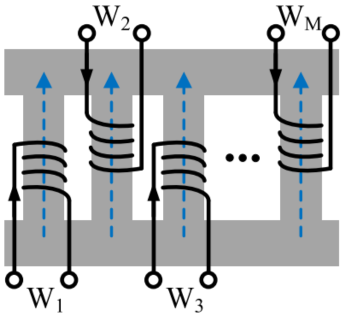
Invented @

Series Coupling, Parallel Coupling, Matrix Coupling …

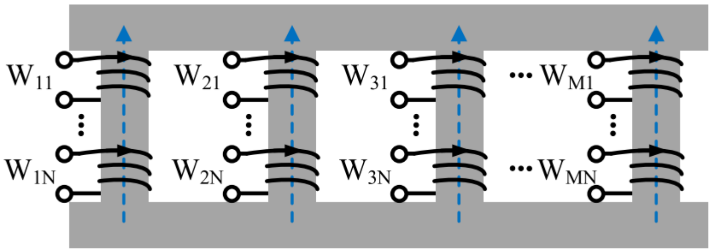
Series Coupled



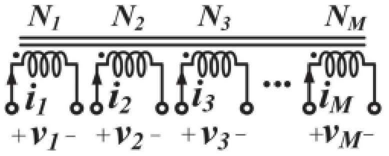
Parallel Coupled



Matrix Coupled



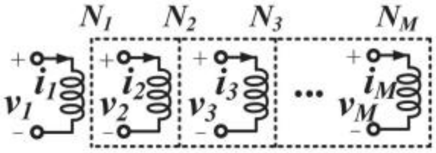
Series Coupled
Voltage Equalizing



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



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

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

Quantified benefits for scalable coupled inductor

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

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

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

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

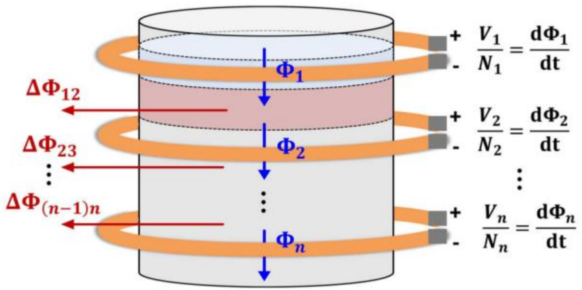
$$\Gamma = \frac{(k + 1 - DM)(DM - k)}{(1 - D)DM^2}$$

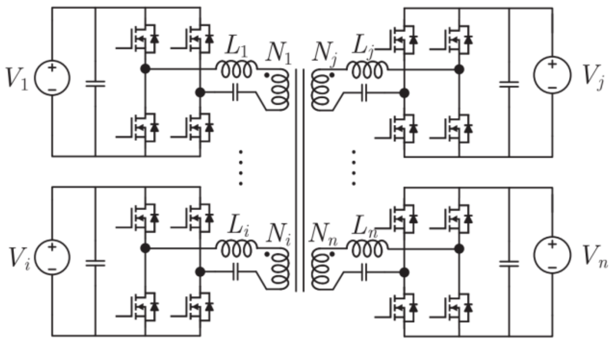
Charles Sullivan

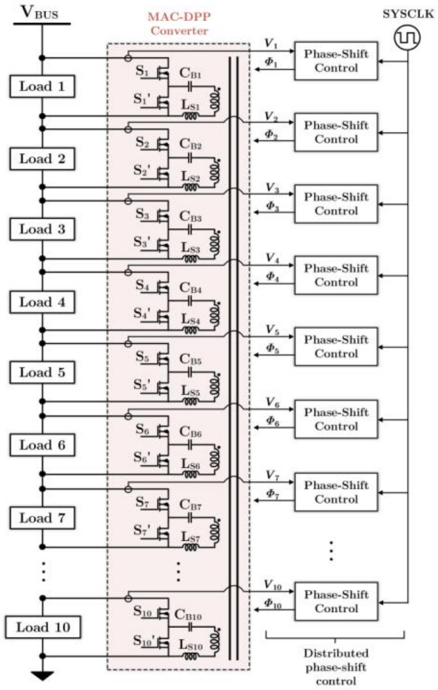
- *M. Chen and C. R. Sullivan, "Unified Models for Coupled Inductors Applied to Multiphase PWM Converters," TPEL'21 Prize Paper.*

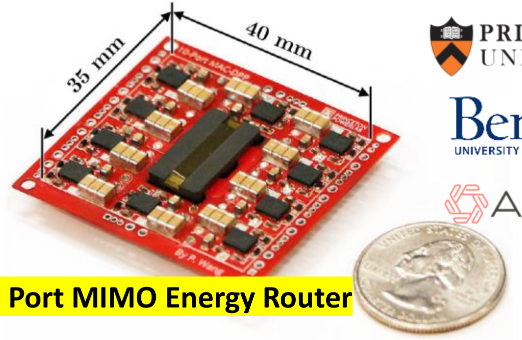
Multi-Winding Magnetics as Multiport Energy Router

PRINCETON UNIVERSITY







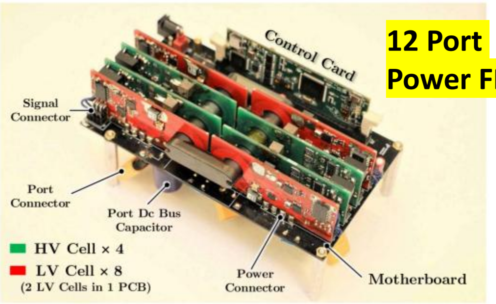


8 Port MIMO Energy Router

PRINCETON UNIVERSITY

Berkeley UNIVERSITY OF CALIFORNIA

ARPAE

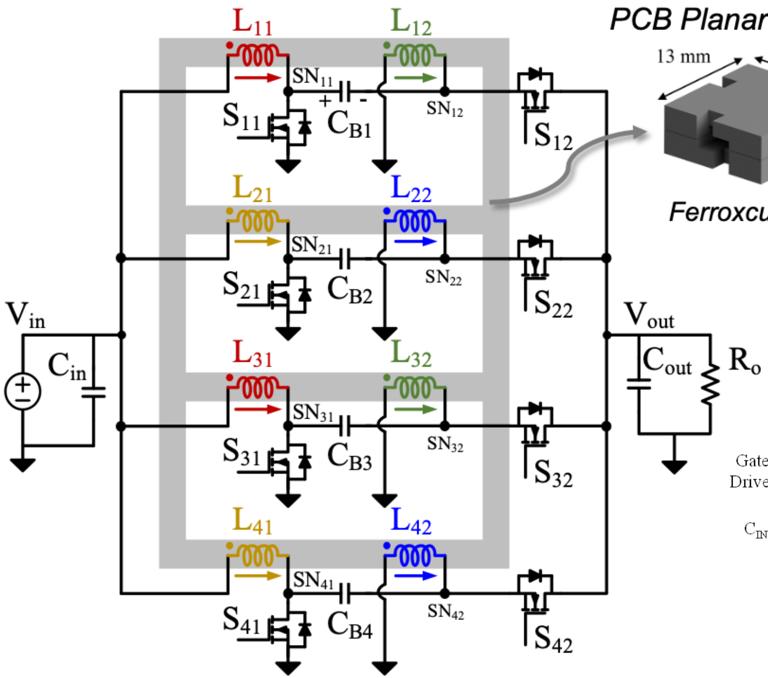


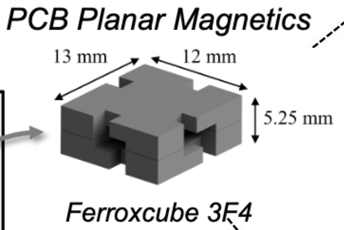
12 Port Power FPGA

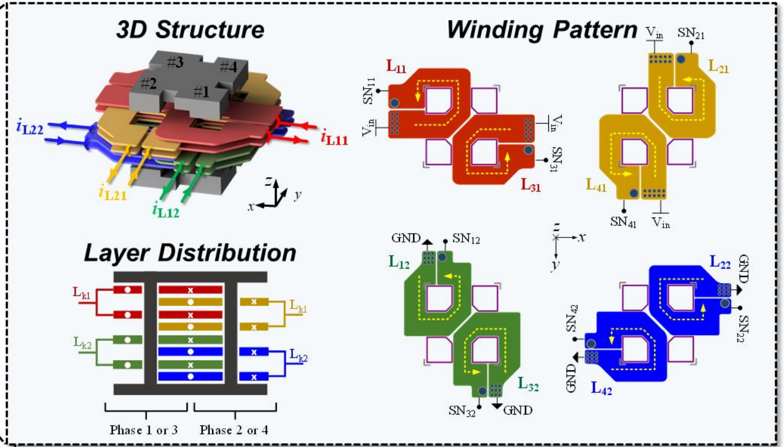
- *Y. Chen, P. Wang, Y. Elasser and M. Chen, "Multicell Reconfigurable Multi-Input Multi-Output Energy Router Architecture," TPEL'20 Prize Paper.*
- *P. Wang, Y. Chen, J. Yuan, R. C. N. Pilawa-Podgurski and M. Chen, "Differential Power Processing for Ultra-Efficient Data Storage," TPEL'21 Prize Paper.*
- *M. Liao et al., "Machine Learning Methods for Feedforward Power Flow Control of Multi-Active-Bridge Converters," TPEL'23.*

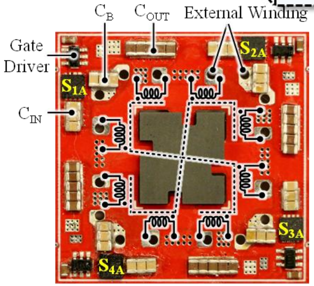
All-in-One Magnetics for High-Order PWM Converters

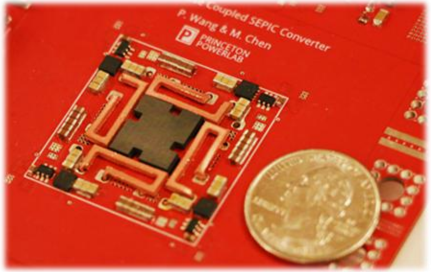
PRINCETON UNIVERSITY











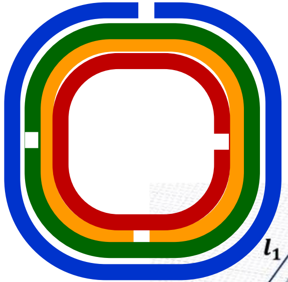
Ping Wang

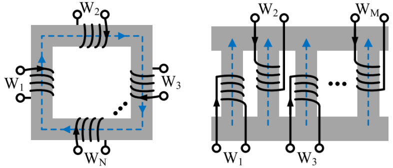
- P. Wang, D. H. Zhou, Y. Elasser, J. Baek and M. Chen, "Matrix Coupled All-in-One Magnetics for PWM Power Conversion," in IEEE Transactions on Power Electronics, vol. 37, no. 12, pp. 15035-15050, Dec. 2022.
- S. Cuk, "A New Zero-Ripple Switching DC-to-DC Converter and Integrated Magnetics," IEEE Trans. Magn., 1983.

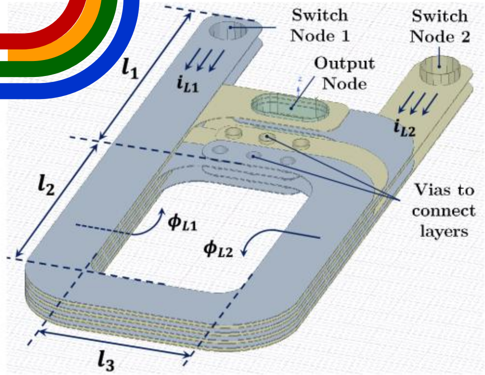
Multiphase Air-Coupled Magnetics …

PRINCETON UNIVERSITY

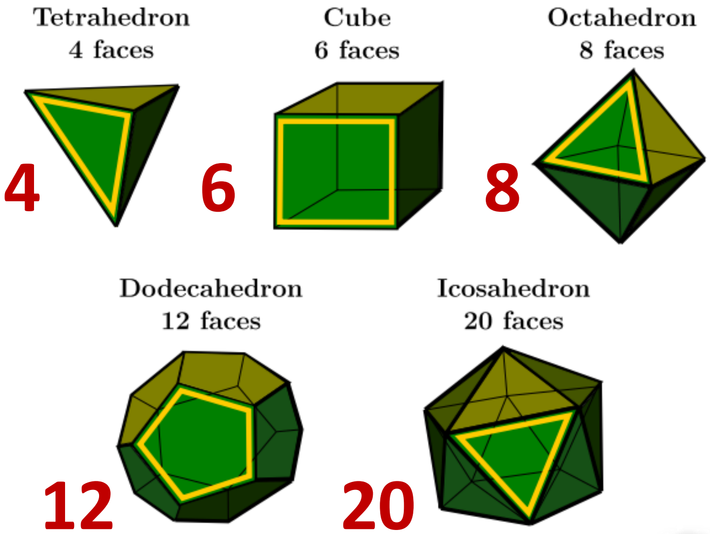
Series Coupled Air-Core

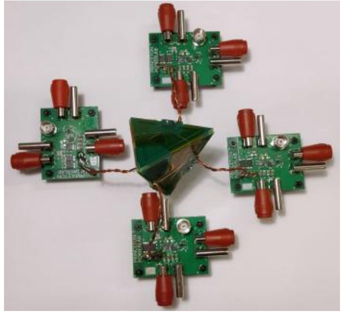


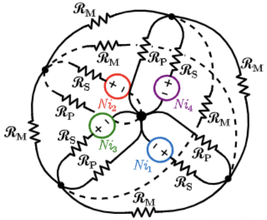




Parallel Coupled Air-Core (Platonic Geometry)







- *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.*
- *H. Li, W. Zeng, Y. Elasser and M. Chen, "Air-LEGO: A Magnetic-Free Ultra-Thin 24V-to-1V 120A VRM with Air-Coupled Inductors," APEC'25.*

Haoran Li

Tanuj Sen

MagNet Project and Data Driven Methods

Princeton MagNet

Princeton Power Electronics Research Lab

http://mag-net.princeton.edu

- Inductors
- Capacitors
- Transformers
- EMI Filters
- Piezoelectric

Website Development

Magnetics Simulation

plexim electrical engineering software

Automatic Data Acquisition

MagNet Database

Machine Learning Methods

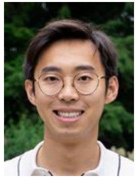
Data Quality Control

Equation-based Models

- *M. Chen et al., "MagNet Challenge for Data-Driven Power Magnetics Modeling," OJPE'24.*

MagNet Core Team Members:

Haoran Li

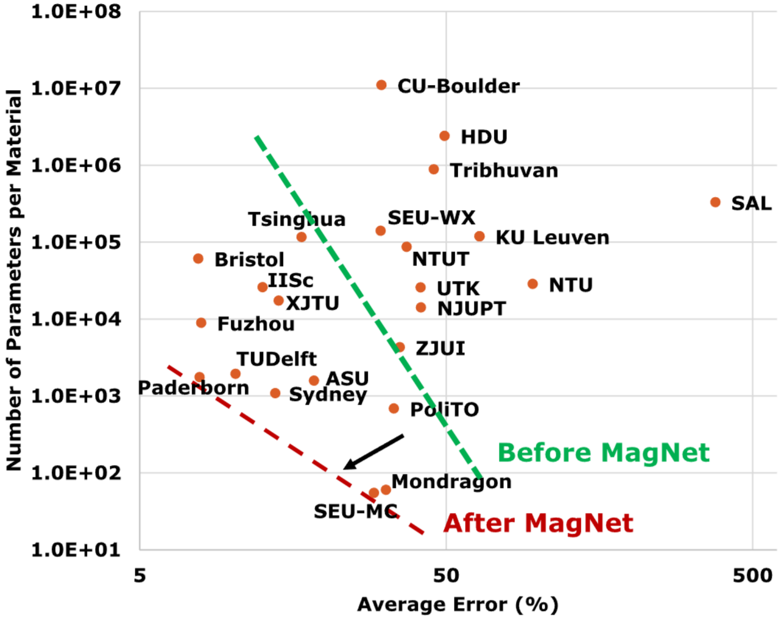


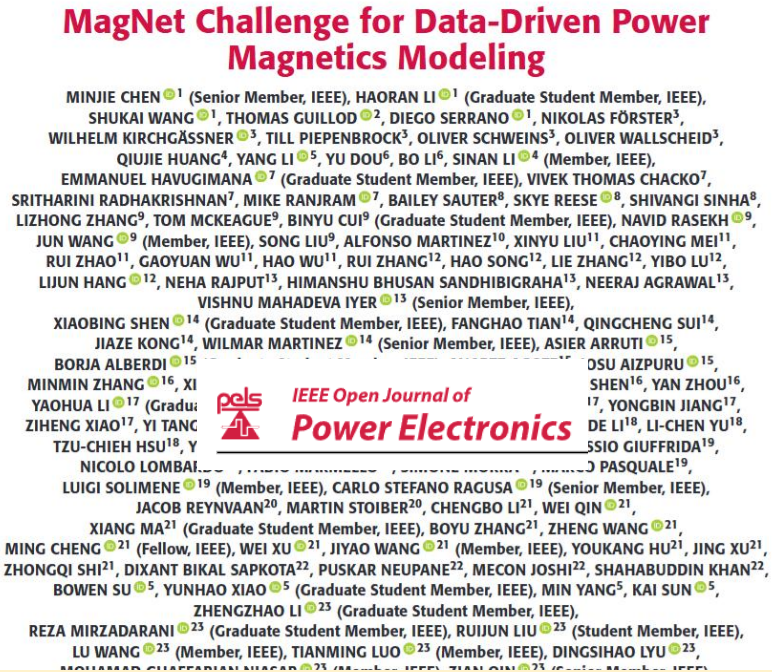
Shukai Wang

T. Guillod

Hyukjae Kwon

MagNet Challenge 1: Steady State Behavior of Magnetics …





MagNet Challenge for Data-Driven Power Magnetics Modeling

MINJIE CHEN [1] (Senior Member, IEEE), HAORAN LI [1] (Graduate Student Member, IEEE),
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 [5], YU DOU [6], BO LI [6], SINAN LI [4] (Member, IEEE),
EMMANUEL HAVUGIMANA [7] (Graduate Student Member, IEEE), VIVEK THOMAS CHACKO [7],
SRITHARINI RADHAKRISHNAN [7], MIKE RANJRAM [7], BAILEY SAUTER [8], SKYE REESE [8], SHIVANGI SINHA [8],
LIZHONG ZHANG [9], TOM MCKEAGUE [9], BINYU CUI [9] (Graduate Student Member, IEEE), NAVID RASEKH [9],
JUN WANG [9] (Member, IEEE), SONG LIU [9], ALFONSO MARTINEZ [10], XINYU LIU [11], CHAOYING MEI [11],
RUI ZHAO [11], GAOYUAN WU [11], HAO WU [11], RUI ZHANG [12], HAO SONG [12], LIE ZHANG [12], YIBO LU [12],
LIJUN HANG [12], NEHA RAJPUT [13], HIMANSHU BHUSAN SANDHIBIGRAHA [13], NEERAJ AGRAWAL [13],
VISHNU MAHADEVA IYER [13] (Senior Member, IEEE),
XIAOBING SHEN [14] (Graduate Student Member, IEEE), FANGHAO TIAN [14], QINGCHENG SUI [14],
JIAZE KONG [14], WILMAR MARTINEZ [14] (Senior Member, IEEE), ASIER ARRUTI [15],
BORJA ALBERDI [15] … OSU AIZPURU [15],
MINMIN ZHANG [16], XI … SHEN [16], YAN ZHOU [16],
YAOHUA LI [17] (Gradu… [17], YONGBIN JIANG [17],
ZIHENG XIAO [17], YI TANG … DE LI [18], LI-CHEN YU [18],
TZU-CHIEH HSU [18], Y … SSIO GIUFFRIDA [19],
NICOLO LOMBAR… PASQUALE [19],
LUIGI SOLIMENE [19] (Member, IEEE), CARLO STEFANO RAGUSA [19] (Senior Member, IEEE),
JACOB REYNVAAN [20], MARTIN STOIBER [20], CHENGBO LI [21], WEI QIN [21],
XIANG MA [21] (Graduate Student Member, IEEE), BOYU ZHANG [21], ZHENG WANG [21],
MING CHENG [21] (Fellow, IEEE), WEI XU [21], JIYAO WANG [21] (Member, IEEE), YOUKANG HU [21], JING XU [21],
ZHONGQI SHI [21], DIXANT BIKAL SAPKOTA [22], PUSKAR NEUPANE [22], MECON JOSHI [22], SHAHABUDDIN KHAN [22],
BOWEN SU [5], YUNHAO XIAO [5] (Graduate Student Member, IEEE), MIN YANG [5], KAI SUN [5],
ZHENGZHAO LI [23] (Graduate Student Member, IEEE),
REZA MIRZADARANI [23] (Graduate Student Member, IEEE), RUIJUN LIU [23] (Student Member, IEEE),
LU WANG [23] (Member, IEEE), TIANMING LUO [23] (Member, IEEE), DINGSIHAO LYU [23],

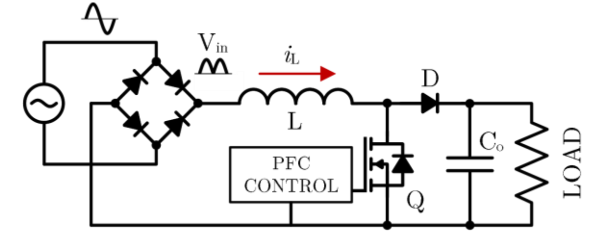
pels IEEE Open Journal of Power Electronics

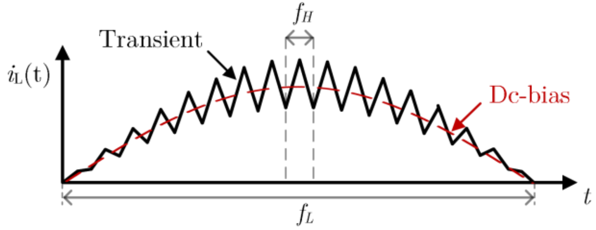
- < 600 parameters to model a material within 20% error across temperature, dc-bias, freq, waveform
- An open-source community with > 200 members developing various software tools for design

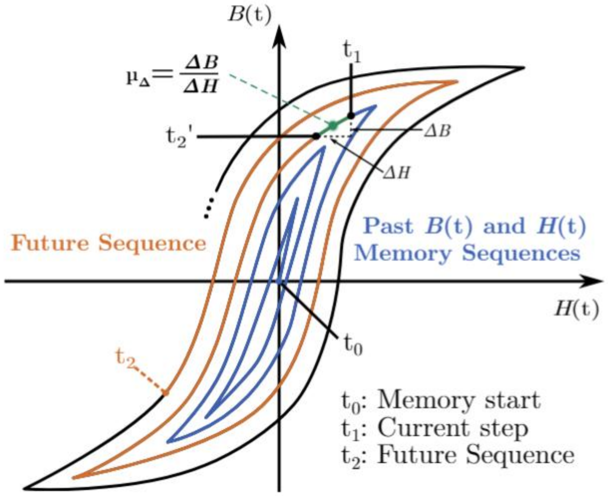
AND CHARLES R. SULLIVAN (Fellow, IEEE)

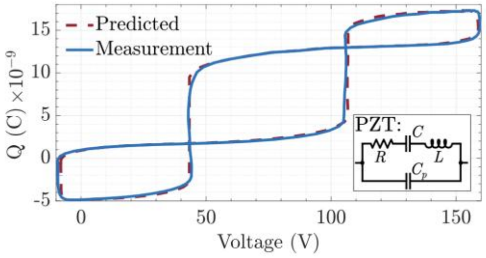
MagNet Challenge 2: Non-linear Transient Models for SPICE

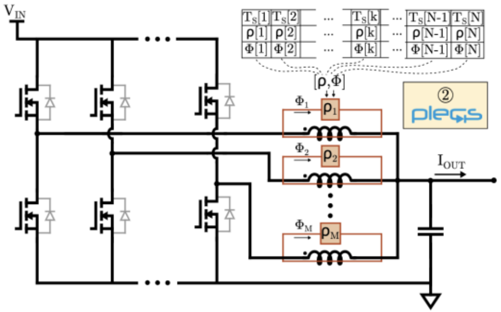
PRINCETON UNIVERSITY











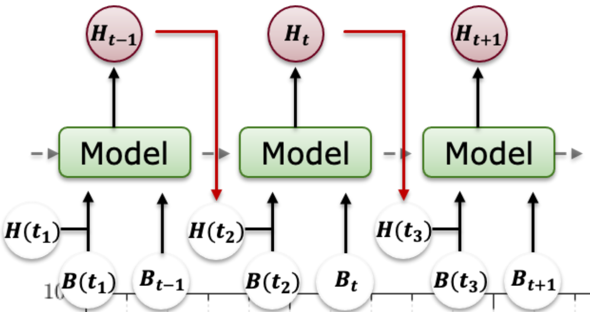
IEEE pels MagNetX Challenge 2

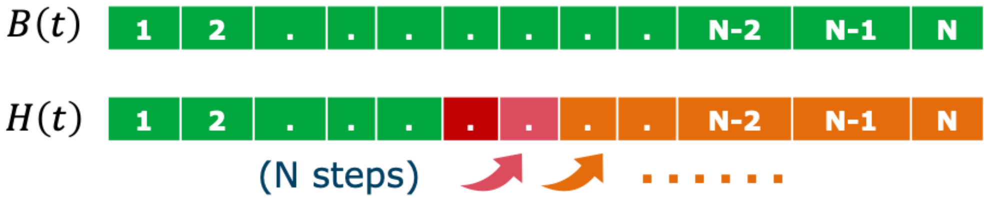
Shukai Wang

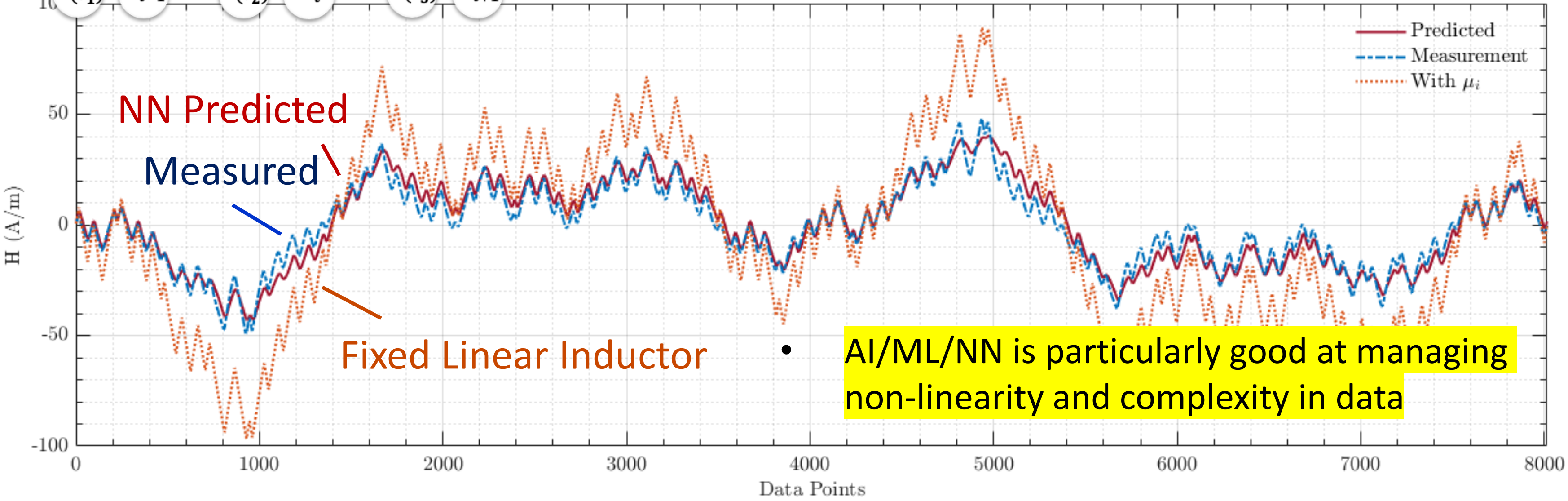
[COMPEL'25] "Unified Time Domain Foundation Models for Hysteretic Passive Components"
Wednesday, 11:00 AM

MagNet Challenge 2: Participating Teams and Impact

Data-Driven Models for Transient Modeling of Magnetics







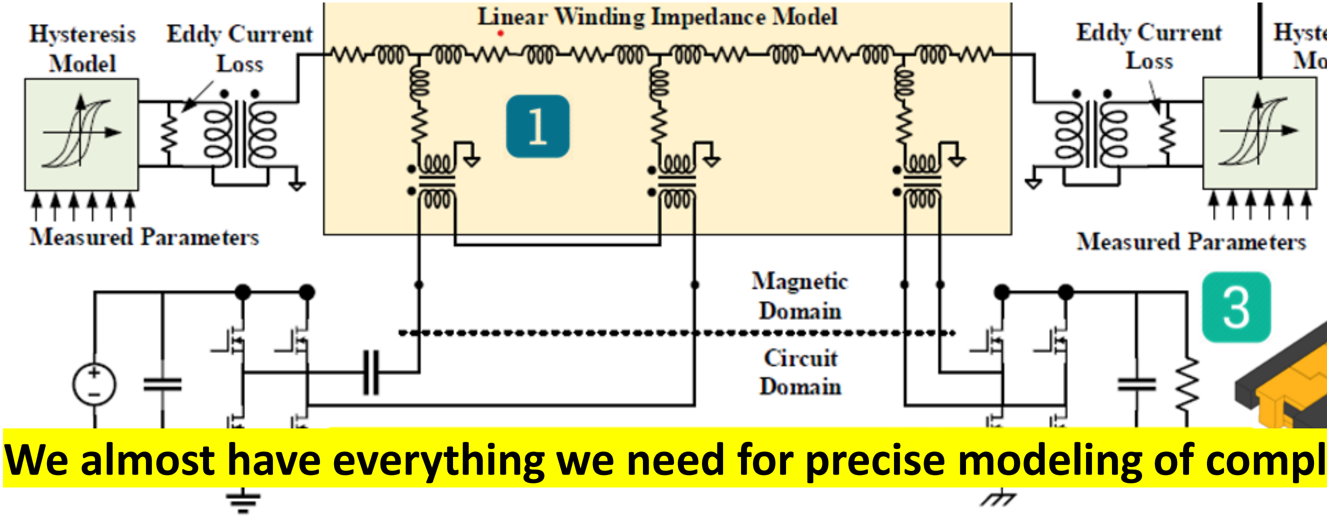
- AI/ML/NN is particularly good at managing non-linearity and complexity in data

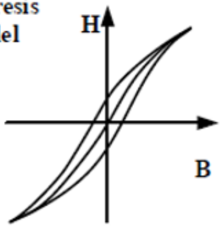
Hybrid Data-Driven Models for Complex Magnetics Design

PRINCETON UNIVERSITY

Linear Model for Windings

Non-Linear Model for Cores (LLG/NN)





Thomas Guillod

Helen Cui

We almost have everything we need for precise modeling of complex magnetics !!!

Davit Grigoryan

- *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," TPEL'16 Prize Paper.*
- *S. Dulal, S. B. Sohid, H. Cui, G. Gu, D. J. Costinett and L. M. Tolbert, "A Physics-Based Circuit Model for Nonlinear Magnetic Material Characteristics," APEC'24.*

Summary

Power Architecture Research = Embrace Complexity + Manage Complexity

- There is plenty of room at the top, **above topologies**.
- There is plenty of room at the bottom, **into materials**.
- There is plenty of room around the edge, **across applications**.
- There is plenty of room at the heart, **software tools & AI**.