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Hybrid Switched Capacitor Circuits and Magnetics for Miniaturized Power Delivery

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Department of Electrical and Computer Engineering

Andlinger Center for Energy and the Environment

Princeton University

Princeton Power Electronics Research Lab

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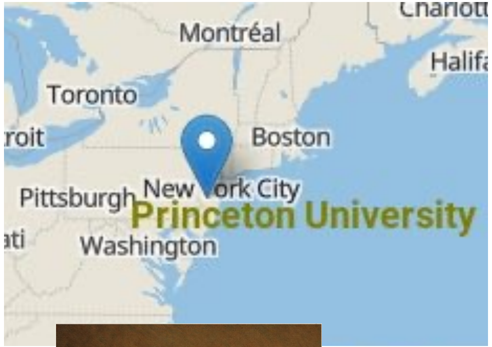

Joseph Henry
1832-1846
Chair of Natural History
Princeton University

NSF
Google
intel
AMERICAN TOWE
CENTER FOR STATISTICS AND MACHINE LEARNING
SRC Semiconductor Research Corporation
andlinger center for energy+the environment
SIEBEL ENERGY INSTITUTE
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Overview of Princeton Power Electronics Research

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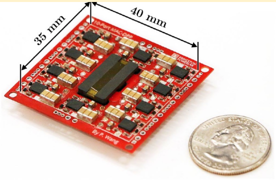
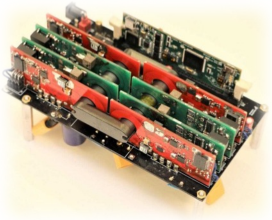
MIMO energy router (MAB Converter)



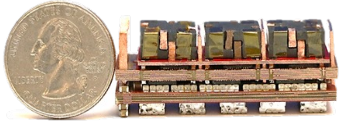
DPP-MAB, *TPEL'21*



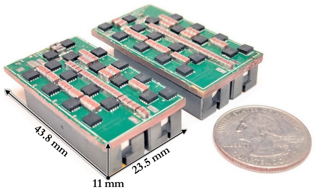
MIMO Energy Router, *TPEL'20 Prize Paper*

Very high current CPU-VRM

VIB-PoL Converter, *TPEL'22*
COMPEL'20 Prize Paper



LEGO-PoL Converter, *TPEL'22*
OCP'21 Prize Paper



Google

intel

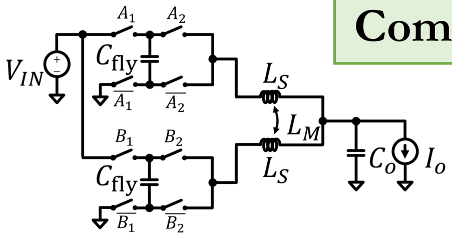
Architecture

Complex Architecture and Magnetics

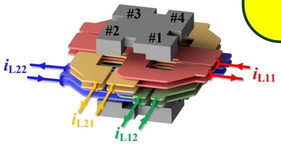
Complexity

Miniaturization

Magnetics

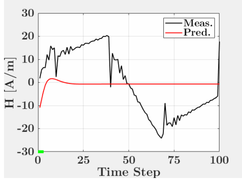


FCML+CoupL, *COMPEL'22*



All-in-One-Mag, *APEC'22*

Machine learning B-H loop



Princeton MagNet

Princeton Power Electronics Research Lab

MagNet Database, *APEC'22*

Dartmouth

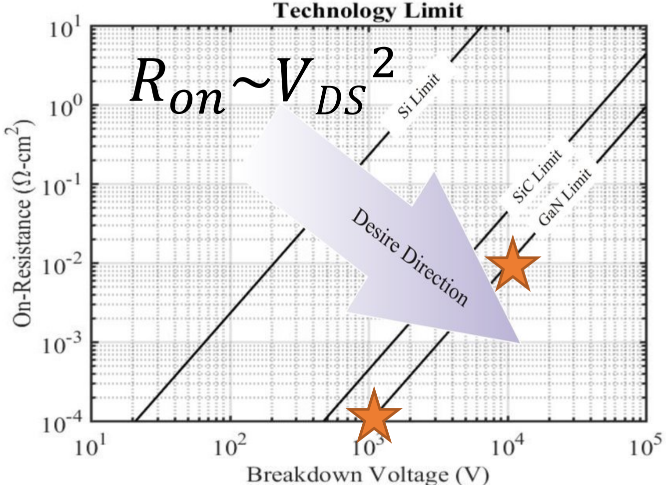
FCML converter and coupled magnetics

Machine learning for modeling power magnetics

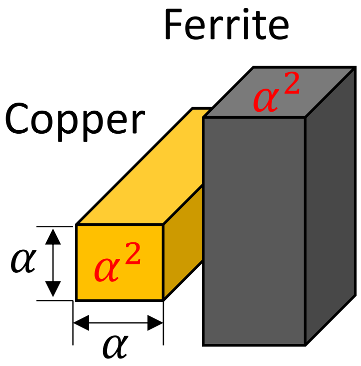
plexim electrical engineering software

Scaling Laws of Power Components

- **Switches (R)**
- **Magnetics (L)**
- **Capacitors (C)**



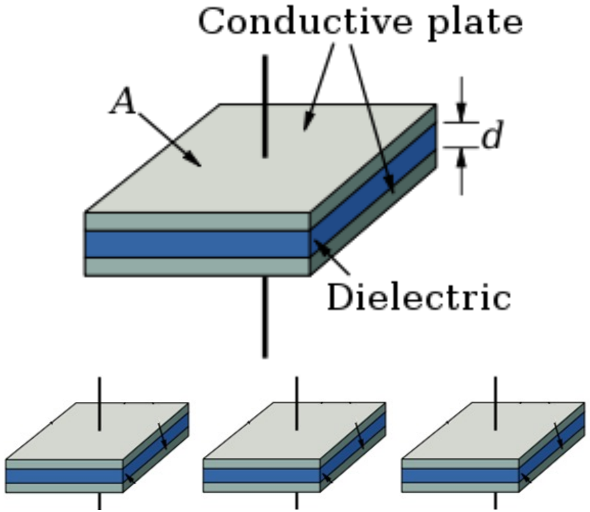
"Baliga Figure-of-Merit"



Copper Area ~ I ~ α^2

Ferrite Area ~ V ~ α^2

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



Smaller switches better

Larger magnetics better

Capacitors - indifferent

- *B. J. Baliga, Fundamentals of Power Semiconductor Devices, ISBN-13: 978-0387473130.*
- *S. Ćuk, "A New Zero-Ripple Switching DC-to-DC Converter and Integrated Magnetics," IEEE Transactions on Magnetics, March 1983.*
- *C. R. Sullivan et al., "On size and magnetics: Why small efficient power inductors are rare," 3D-PEIM'16.*

Capacitors for Density & Magnetics for Functionality

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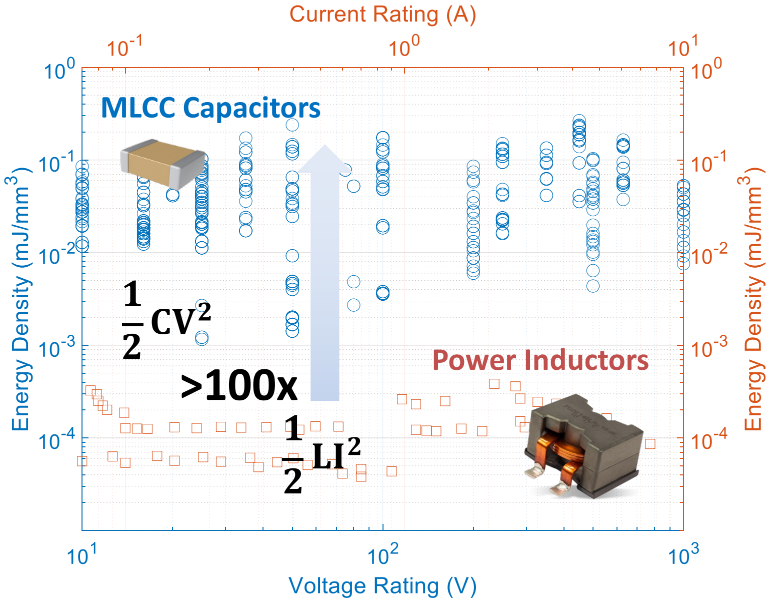
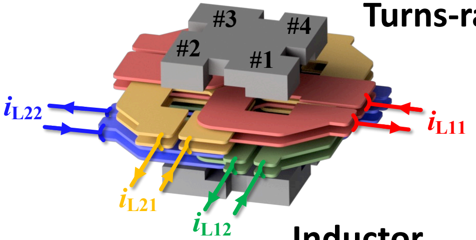
Capacitors offer >100x higher density

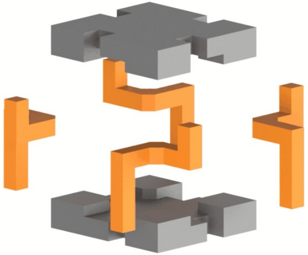


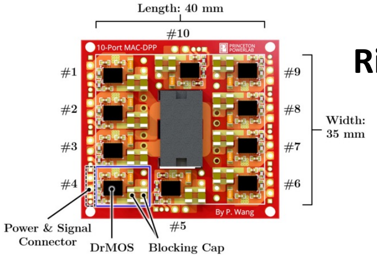
Magnetics create innovation opportunities



Turns-ratio

Inductor

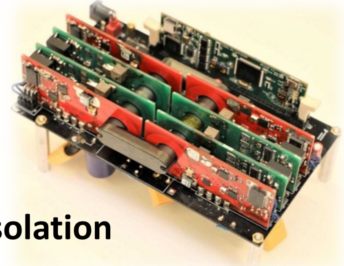




Ripple Cancellation

EMI Filter

Transformer



ZVS

ZCS

Galvanic Isolation

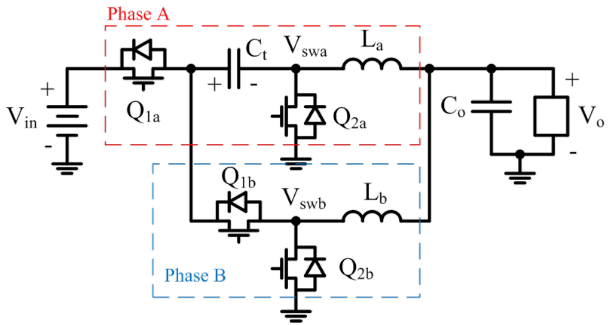
CM/DM Choke

- *Sullivan et al., "On Size and Magnetics: Why Small Efficient Power Inductors are Rare," 3D-PEIM'16.*
- *Kyaw et al., "Fundamental Examination of Multiple Potential Passive Component Technologies …," TPEL'18.*

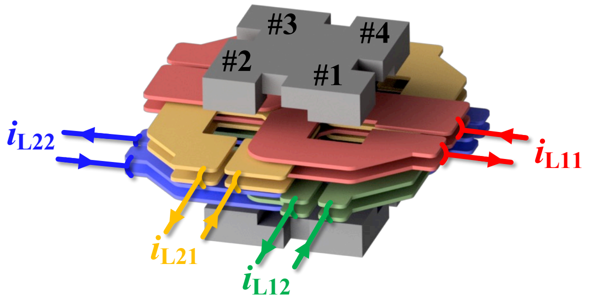
Contents

1. Architecture – Hybrid SC Circuits and Magnetics for CPU-VRMs
2. Magnetics – Open-Source Database and Design Methods
3. Control – Synergy between FCML and Coupled Magnetics

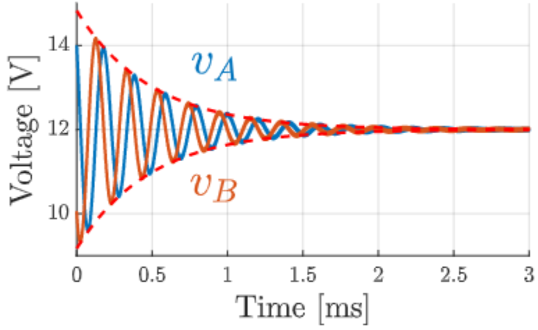
Architecture



Magnetics



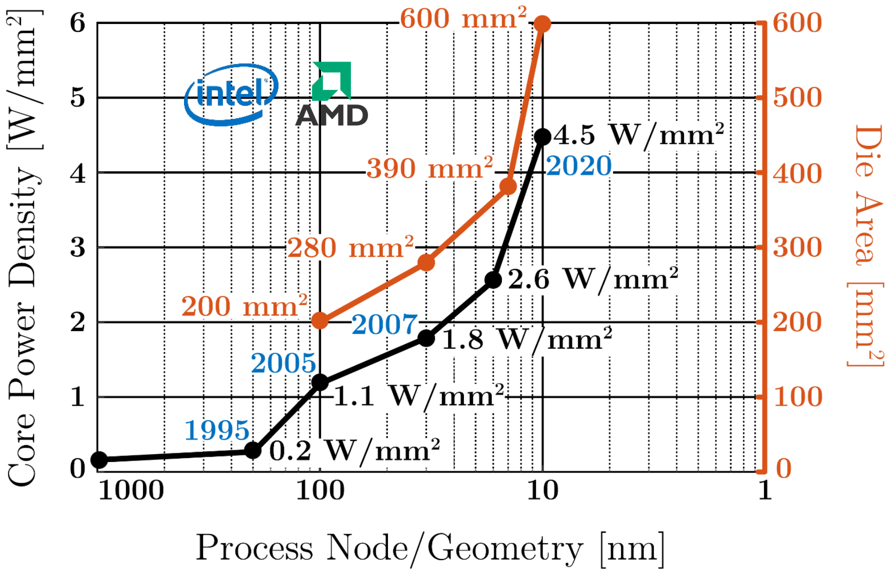
Control

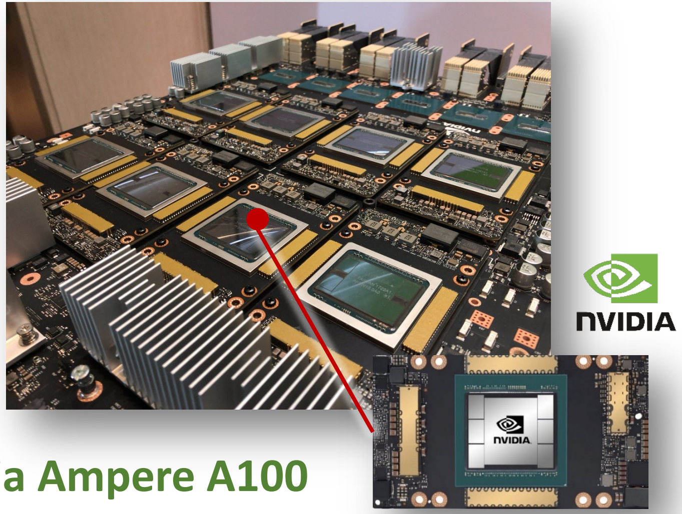


Massive Power Demand in Future Computing

- Transistor power density rapidly growing
- Processor die area continuously expanding
- More microprocessors on server motherboards

- *J. Beak, M. Chen et al., "Vertical Stacked LEGO-PoL CPU Voltage Regulator," TPEL'22.*

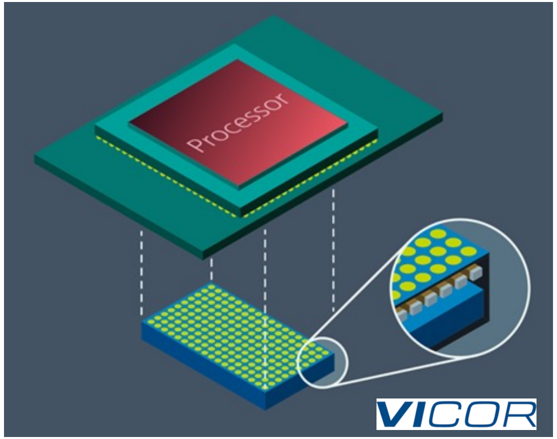




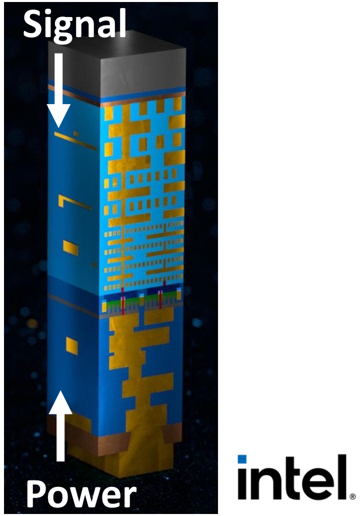
Nvidia Ampere A100
48V-1V, 1000A

Vertical Power Delivery to Microprocessors

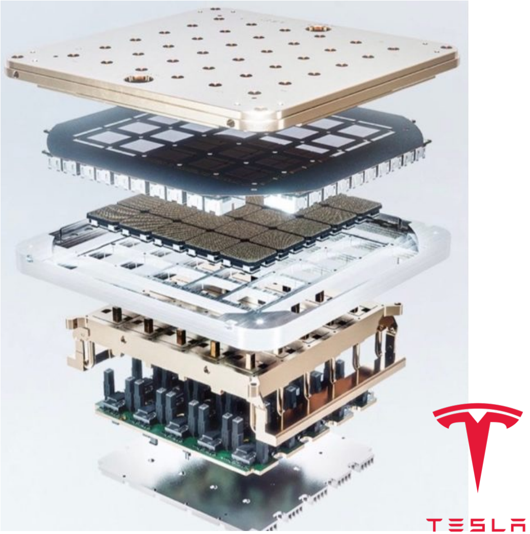
Vertical Power Delivery



Intel PowerVia



Tesla Dojo



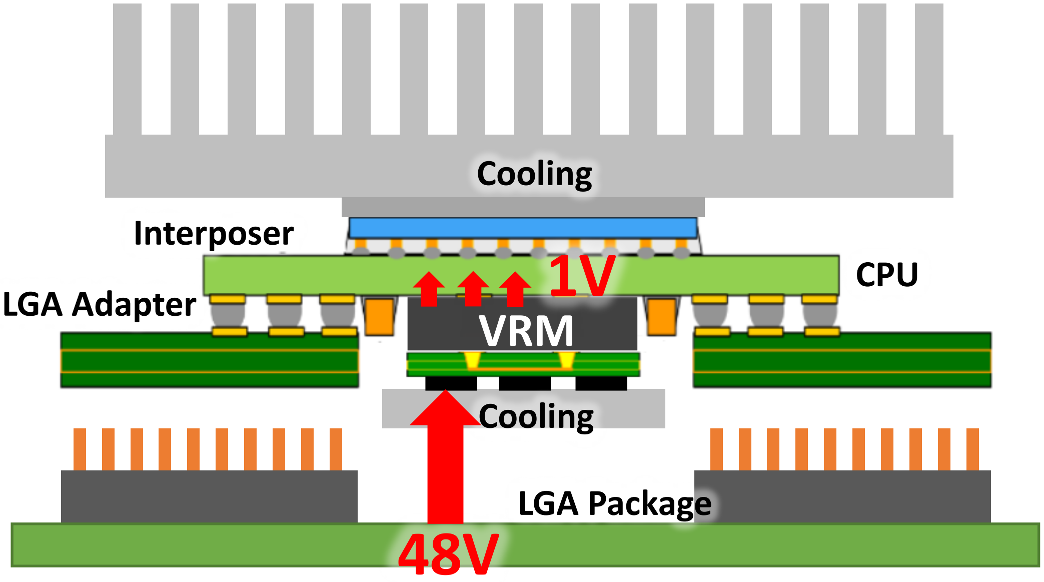
Benefits

- Reduced interconnect length
- Reduced loss
- Better signal integrity

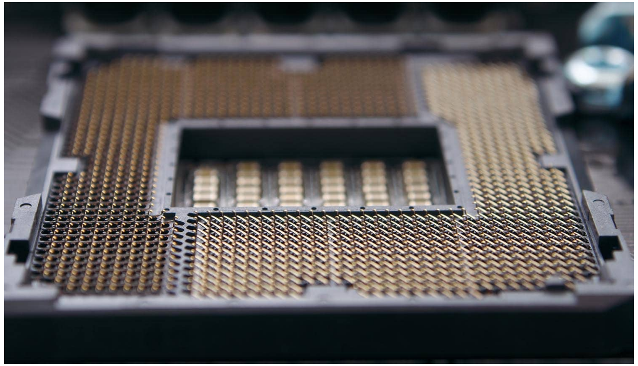
- Better power electronics enable better computing

Image Courtesy: Vicor, Intel & Tesla

Princeton Vertical-Power-in-Package for CPU Power Delivery



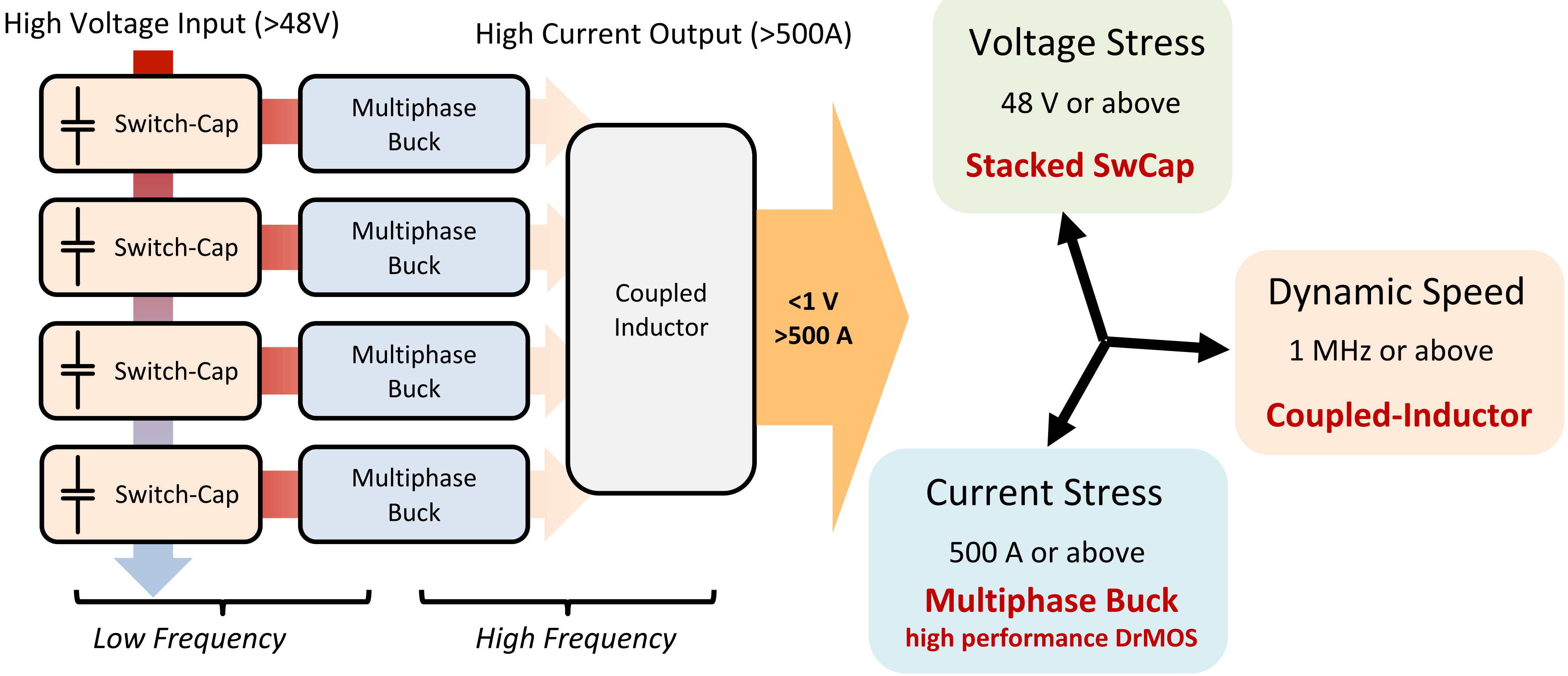
- VRM Area smaller than CPU Area
- Minimize the VRM Height



Next Generation Targets

- 48V – 1V , or 48V – 0.5V
- Output current (> 1 kA)
- Current density (> 1 A/mm^2)
- Very low profile (< 8 mm)
- Power density (> 1 kW/in^3)
- Efficiency (> 95%)

Princeton Series-Input Parallel-Output Architecture



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

Merged-Two-Stage Hybrid Switched-Capacitor Architecture

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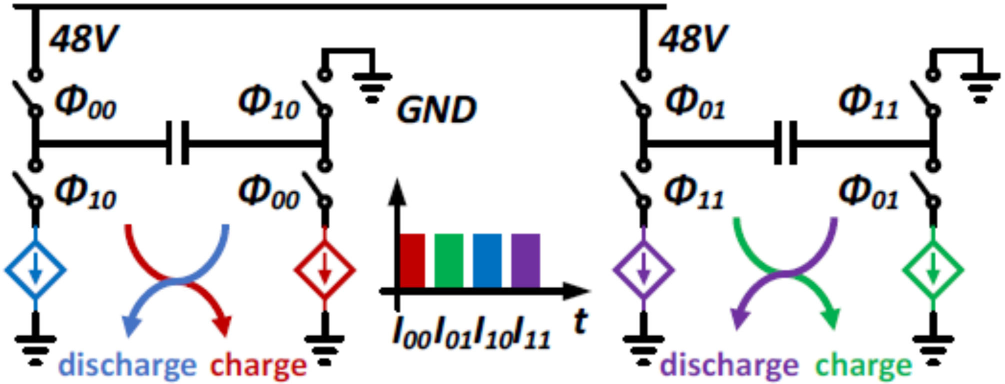
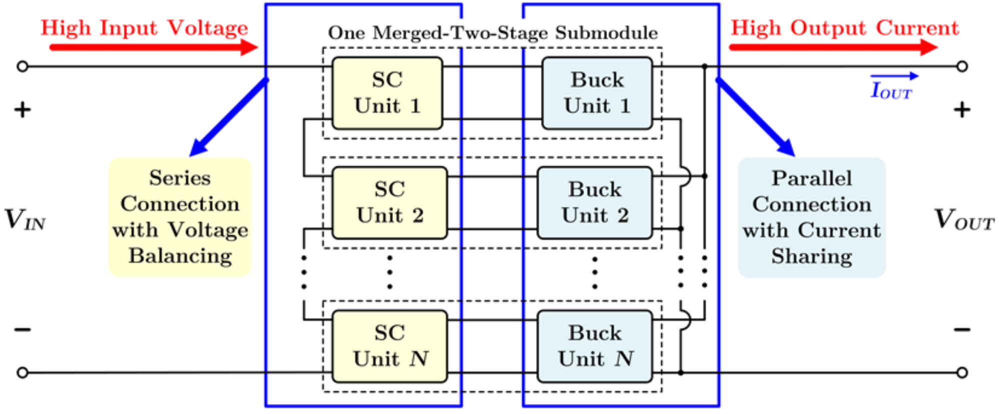
- Merge two types of building blocks and create mutual advantages
  - 1st stage: switched capacitor voltage source @ low frequency (split voltage)
  - 2nd stage: switched inductor current source @ high frequency (split current)

1. **Low Frequency Switched Capacitor Voltage Source**
2. **High Frequency Switched Inductor Current Source**



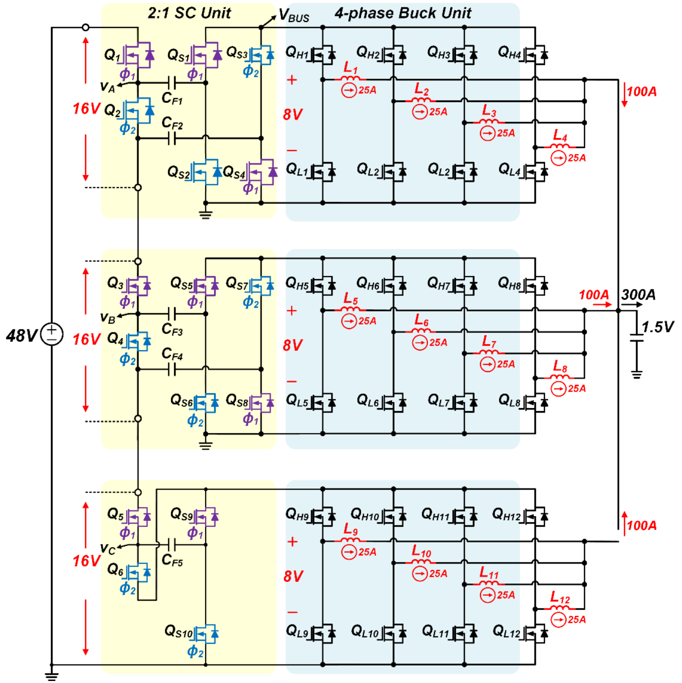
- M. Chen, *Merged Multi-Stage Power Conversion: A Hybrid Switched-Capacitor Magnetics Approach*, Ph.D. Thesis, MIT, June, 2015.
- D. M. Giuliano, M. E. D'Asaro, J. Zwart, and D. J. Perreault, "Miniaturized low-voltage power converters with fast dynamic response," *IEEE Trans. Emerg. Sel. Topics Power Electron.*, vol. 2, no. 3, pp. 395–405, Sep. 2014.
- R. C. N. Pilawa-Podgurski, D. M. Giuliano, and D. J. Perreault, "Merged-two-stage power converter architecture with soft charging switched capacitor energy transfer," in *Proc. IEEE Power Electron. Specialists Conf.*, Rhodes, Greece, 2008, pp. 4008–4015.

LEGO-PoL: Granular Building Blocks for PoL



Submodules ➔ Linear Extendable & Group Operated (LEGO)

2:1 SC Units **8:1 Buck Units**



- Automatic voltage balancing
- Automatic current sharing
- Distributed thermal stress
- Capable of doing current mode control
- Fully modular and highly extendable

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

Merged Two Stage Operation with Mutual Benefits

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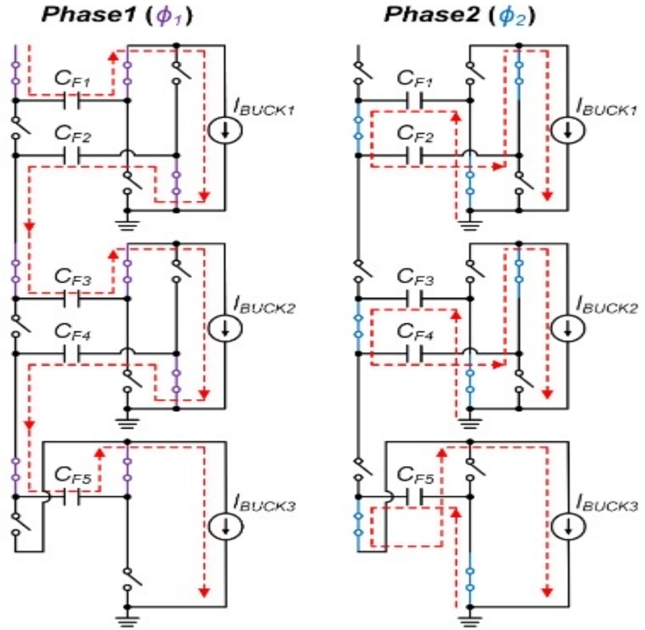
➢ Soft-Charging Operation of SC Circuit

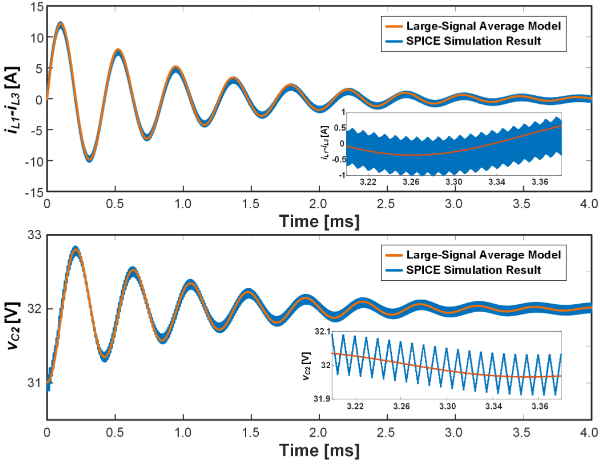


➢ Dynamics of Current Balancing

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

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

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

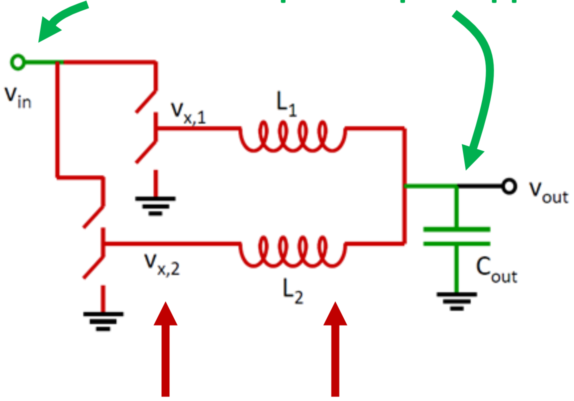


- Inductors soft-charge the switched capacitors
- Automatic current balancing of switched-capacitor circuits
- Low frequency step down & high frequency regulation

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

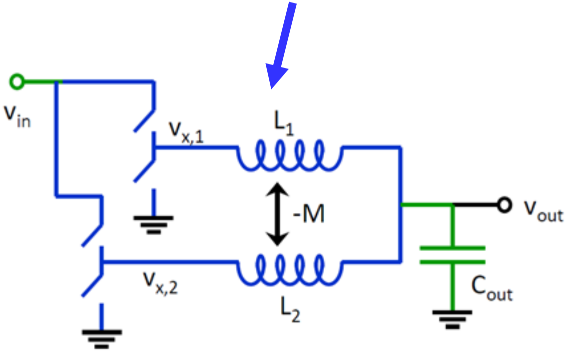
Unified Models for Multiphase Coupled Inductors

Reduced Input Output Ripple

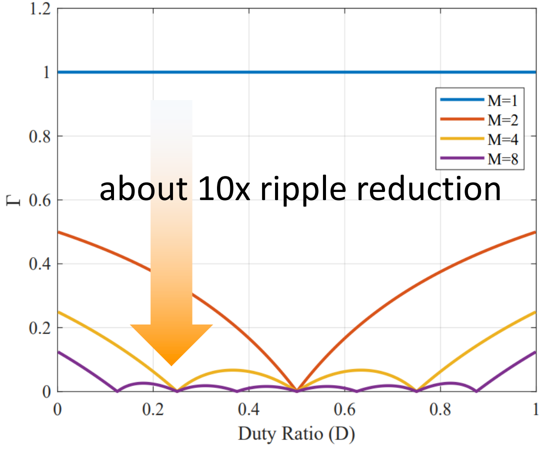


Uncoupled, Same Phase Ripple

Reduced Phase Ripple



Ripple Reduction from Coupling



- Interleaving Ripple Reduction Ratio

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

- Magnetic Coupling

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

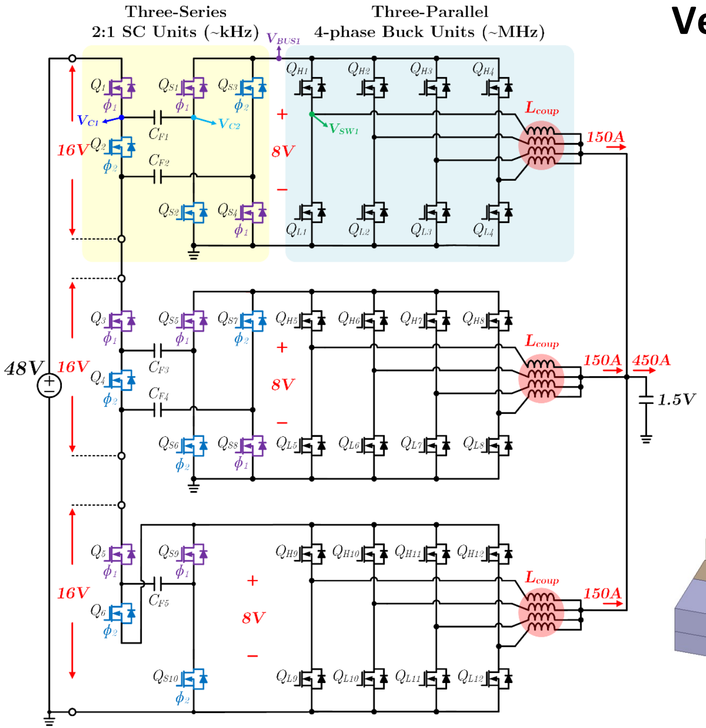
- Coupling Ripple Reduction Ratio

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

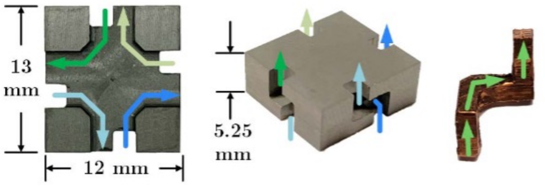
- Stronger coupling → better ripple reduction and faster dynamics

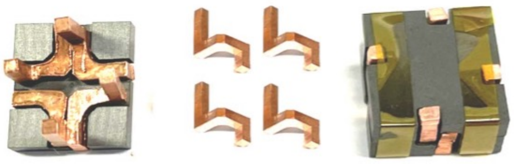
- *M. Chen and C. R. Sullivan, “Unified Models for Coupled Inductors Applied to Multiphase PWM Converters,” TPEL’21.*

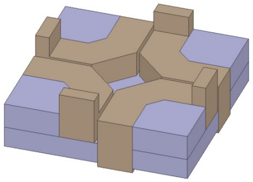
Multiphase Coupled Inductor for Voltage Regulation



Vertical Multiphase Coupled Magnetics







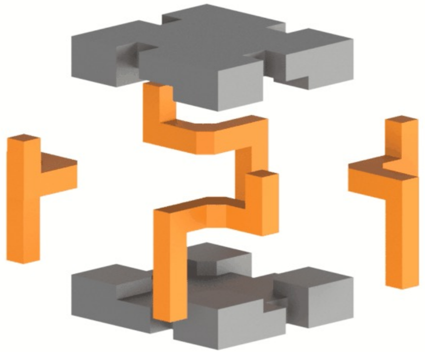
Transient (leakage)

~12 nH

Steady-State (magnetizing)

~85 nH

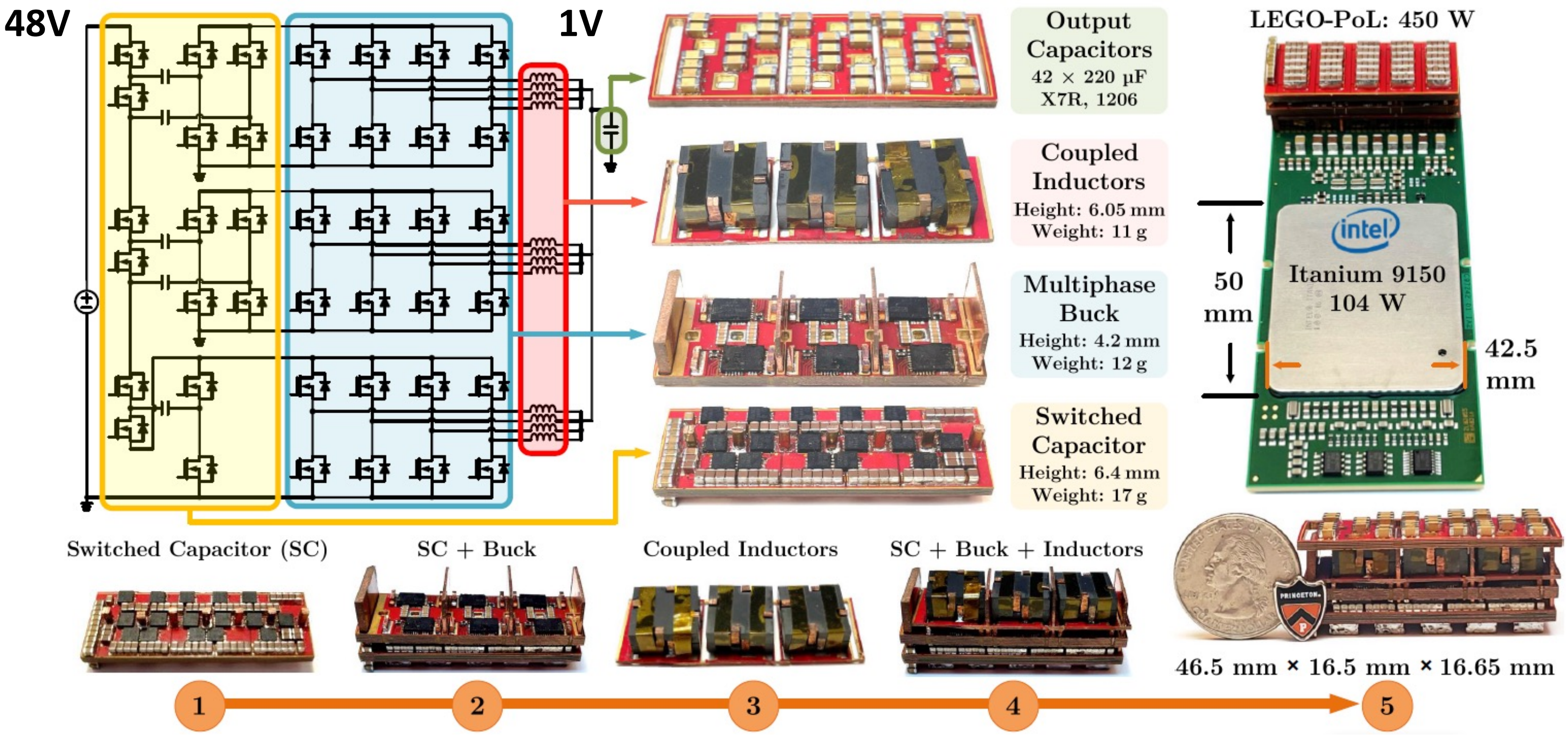
Assembly Process



12mm x 12mm x 5mm

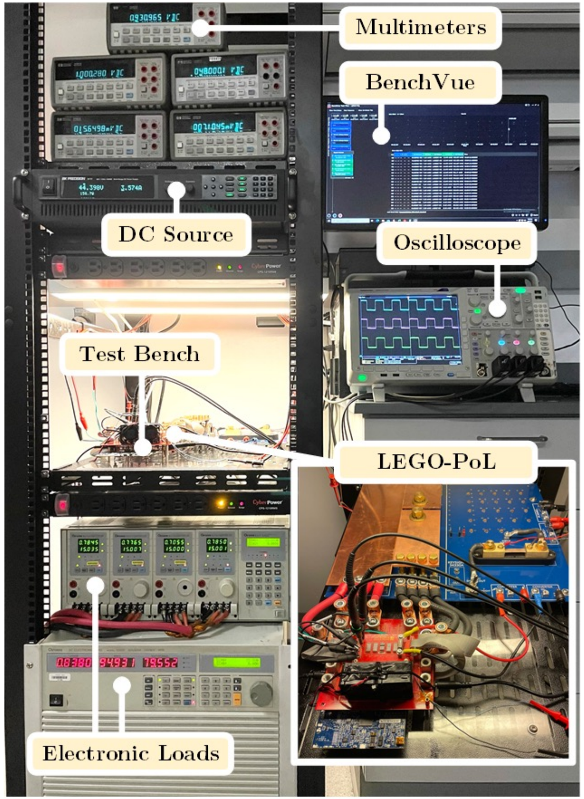
- *J. Beak et al., "Vertical Stacked LEGO-PoL CPU Voltage Regulator," TPEL'22.*

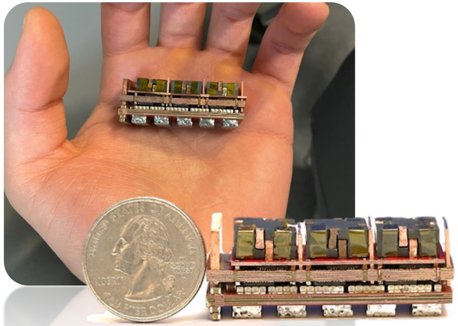
3D Stacked Packaging for Vertical Power Delivery



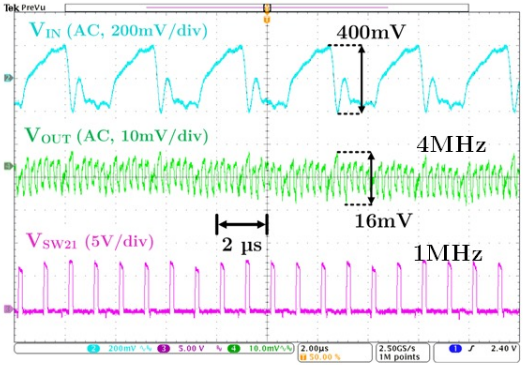
- *J. Beak et al., "Vertical Stacked LEGO-PoL CPU Voltage Regulator," TPEL'22.*

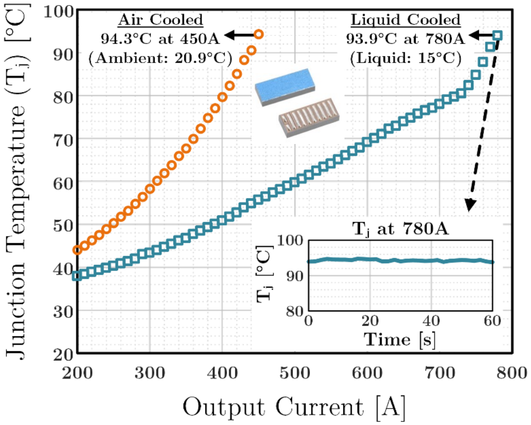
Performance Summary

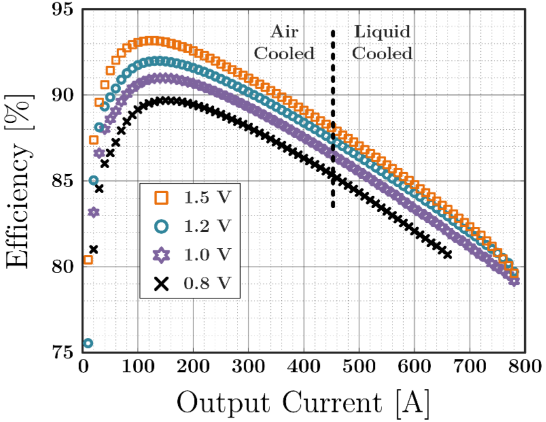




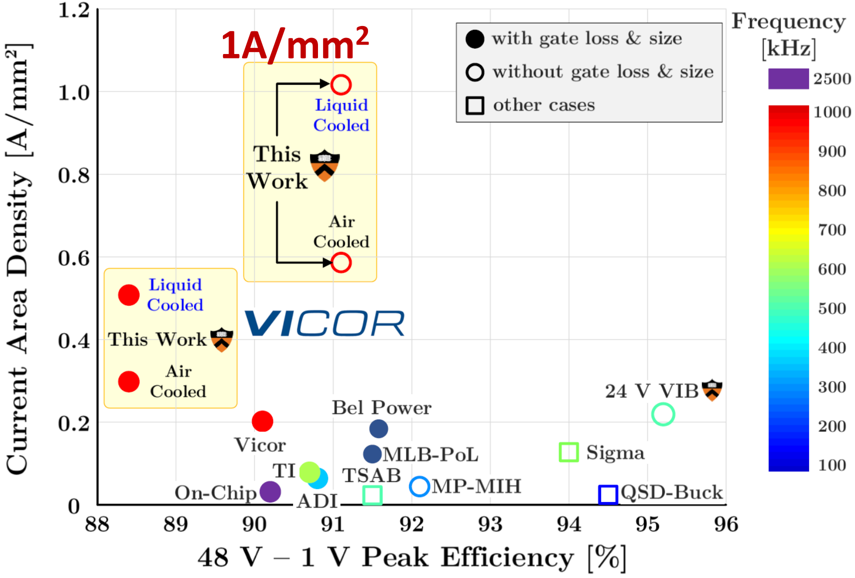
780 A, 1 V, 1 A/mm^2, 1,000 W/in^3

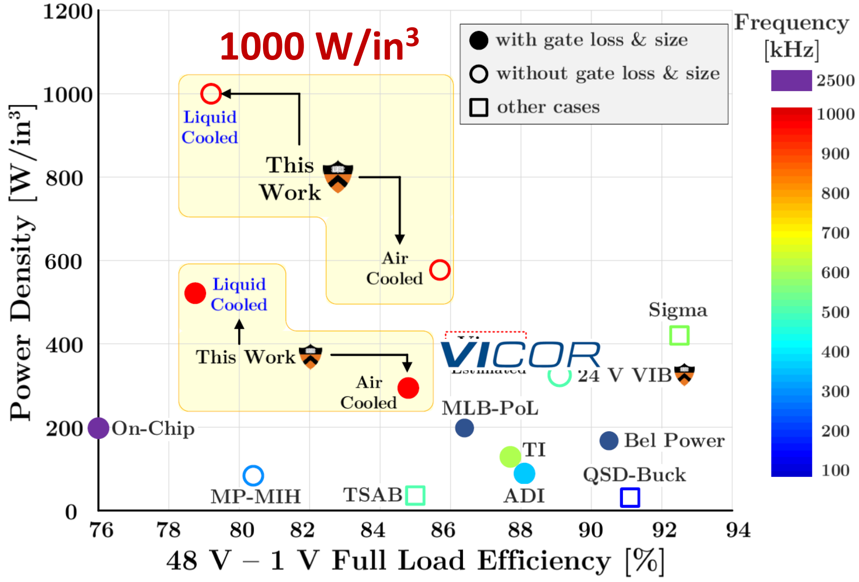






Performance Comparison



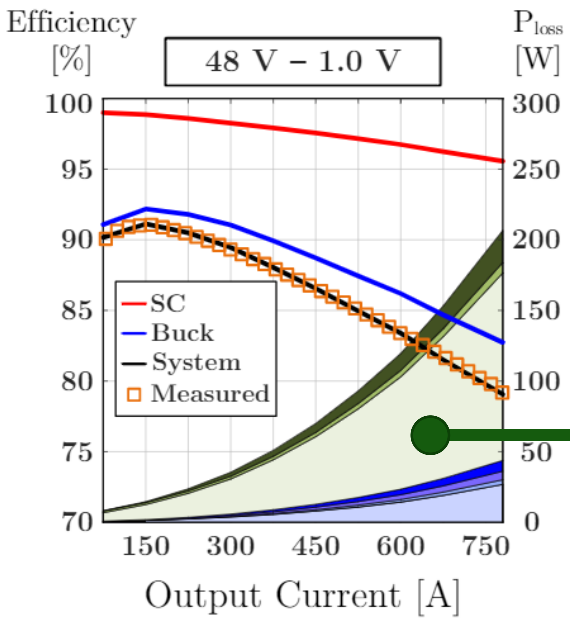


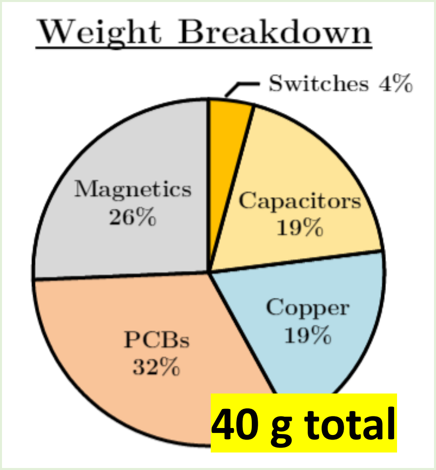
* Note: these designs usually have very different voltage regulation capability

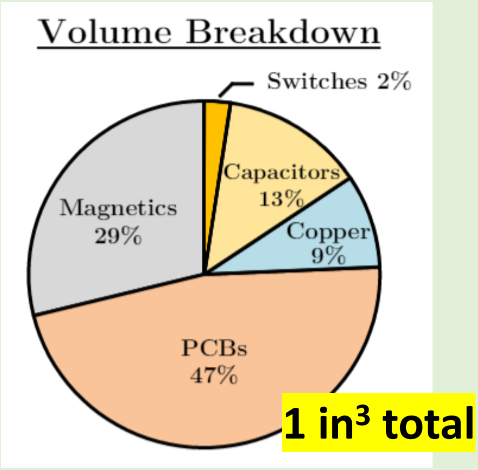
Sponsors & Collaborators: Google intel Dartmouth

Youssef Elasser **Jaeil Baek**

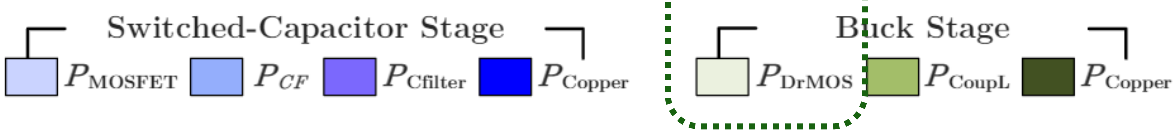
Loss Analysis and Performance Evaluation







R_{dson} is still the bottleneck



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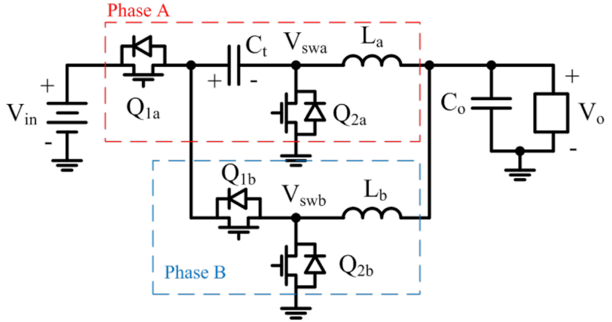
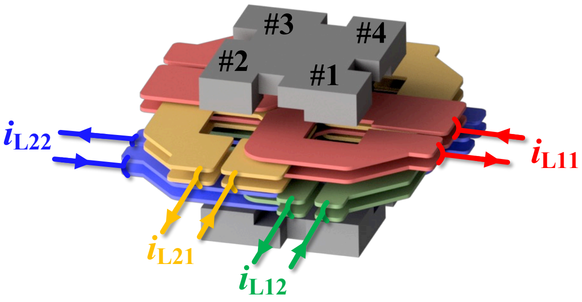
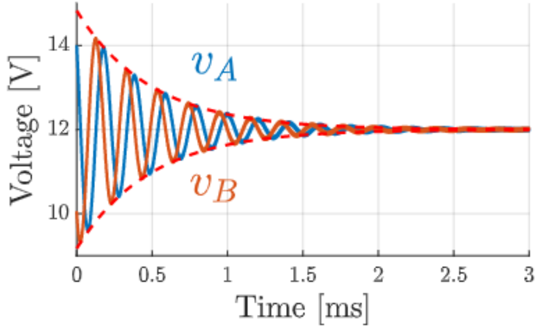
Architecture



Magnetics



Control



Magnetics Enable New Design Opportunities

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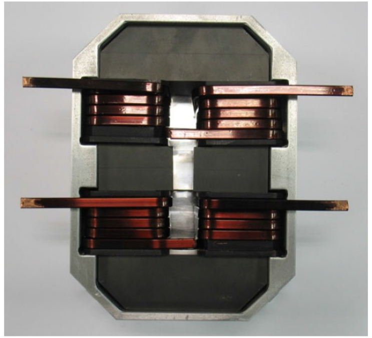
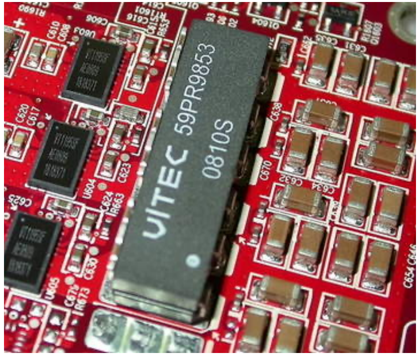
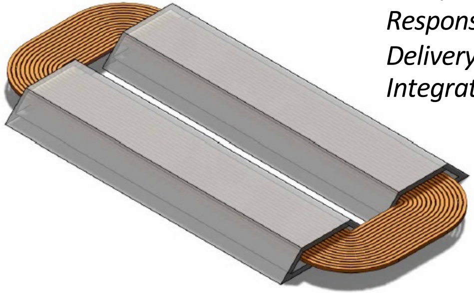


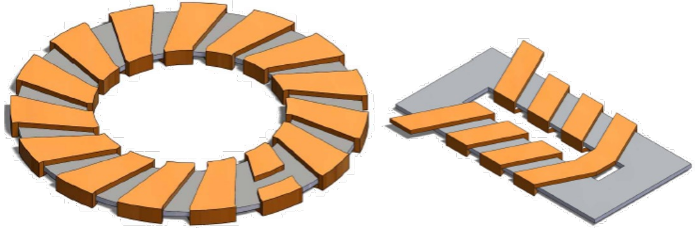
[Hayes, UC Cork, Ireland, 2004]



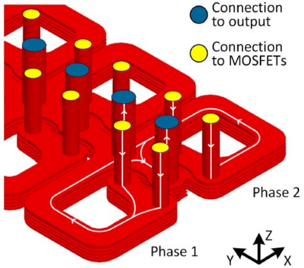
[Motherboard VRs ~2005]



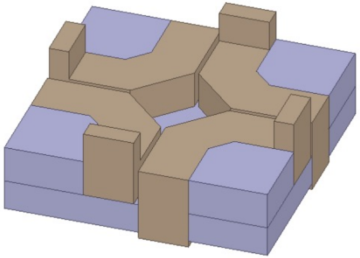
- *C. R. Sullivan and M. Chen, "Coupled Inductors for Fast-Response High-Density Power Delivery: Discrete and Integrated," CICC'21.*



[Sullivan, Integrated Coupled Magnetics]



[Intel, FIVR]



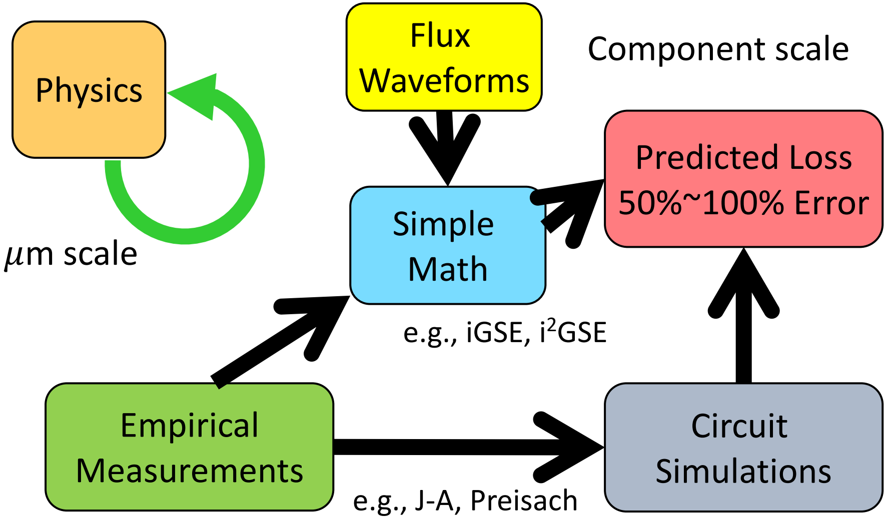
[Princeton, LEGO-PoL]

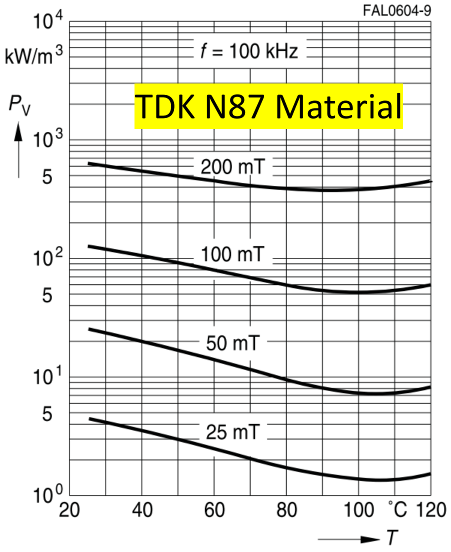
Good Magnetic Design Needs Precise Models

No Good Models for Magnetic Materials

Steinmetz equation (1890s) $P_v = k \cdot f^a \cdot B^b$

No temperature, dc-bias, waveform shape information





Core loss design margin

Temperature ~ 50%-200%

Dc Bias ~ 80%-200%

Batch2Batch ~ +/-20%

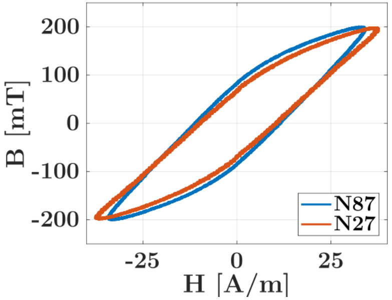
Geometry ~ +/-20%

Relaxation ~ +/-20%

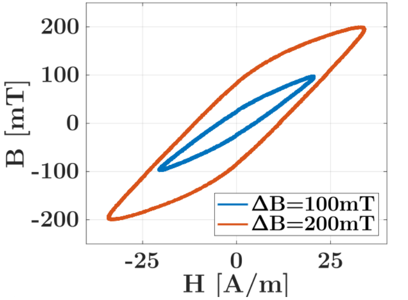
Waveform ~ +/-50%

DO NOT WORK …

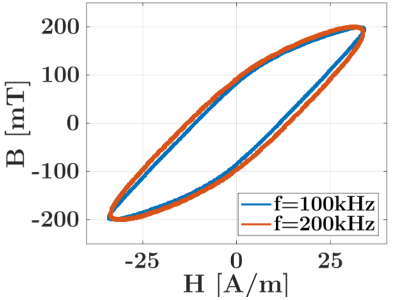
Modeling B-H loops is Even More Challenging …



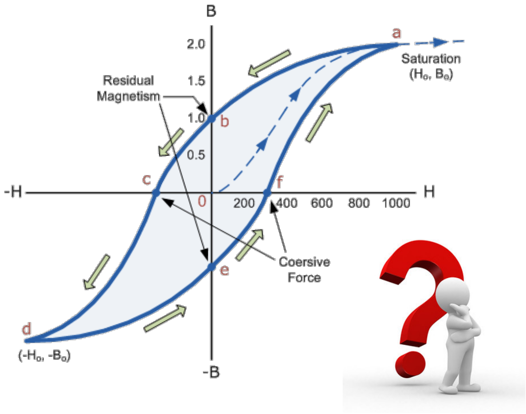
Material property

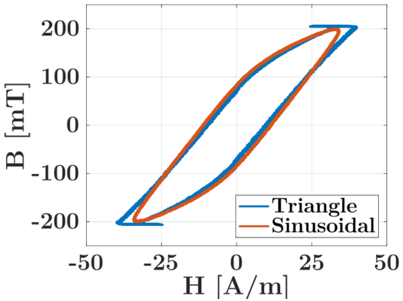


Flux density range

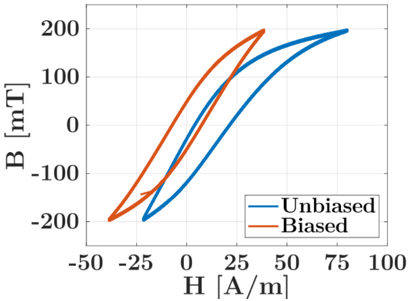


Frequency

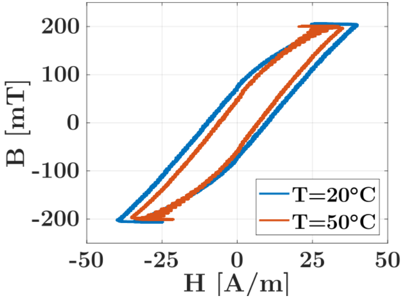




Waveform shape



DC bias



Temperature

How to capture all these factors under a unified modeling framework?

Modeling Magnetics with Machine Learning …

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- **Steinmetz Equation (SE), 1890s**

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

3 parameters

- **Improved Generalized Steinmetz Equation (iGSE), 2000s**

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

3 parameters

- **Improved-improved GSE (i^2GSE), 2010s**

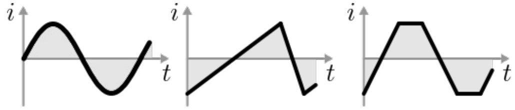
$$P_V = \frac{1}{T}\int_0^T k_i \cdot \left|\frac{\mathrm{d}B}{\mathrm{d}t}\right|^{\alpha} \cdot (\Delta B)^{\beta}\,\mathrm{d}t + \sum_{l=1}^{n} Q_{rl} \cdot P_{rl}$$

8 parameters

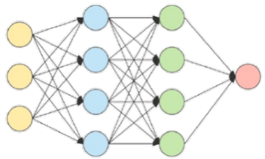
- **Neural Network Models**

> 100 parameters

Excitation waveforms

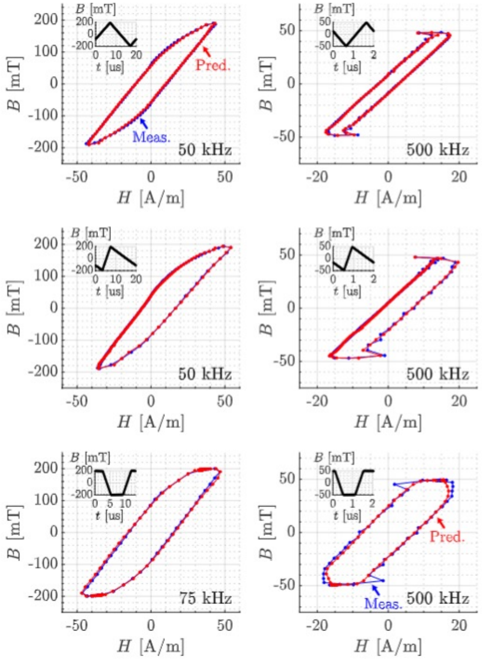


frequency, temperature, dc-bias



>100 parameters

Input: f, B, D, H_{DC}; Output: B-H Loops



A typical ML problem with mature software tools

Princeton-Dartmouth-Plexim MagNet Project (2019-2022)

Princeton MagNet

Princeton Power Electronics Research Lab

http://mag-net.princeton.edu

IMAGENET

Joseph Henry's Magnet in 1832

Website Development

Magnetics Simulation

plexim electrical engineering software

Automatic Data Acquisition

MagNet Database

Machine Learning Methods

Data Quality Control

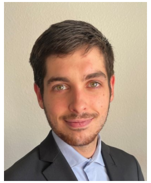
Physics Models

arpa·e CHANGING WHAT'S POSSIBLE

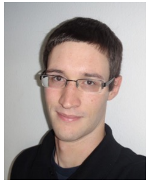
H. Li, M. Chen et al., "MagNet: an Open-Source Database for Data-Driven Magnetic Core Loss Modeling," APEC'22.

MagNet Team:

Haoran Li

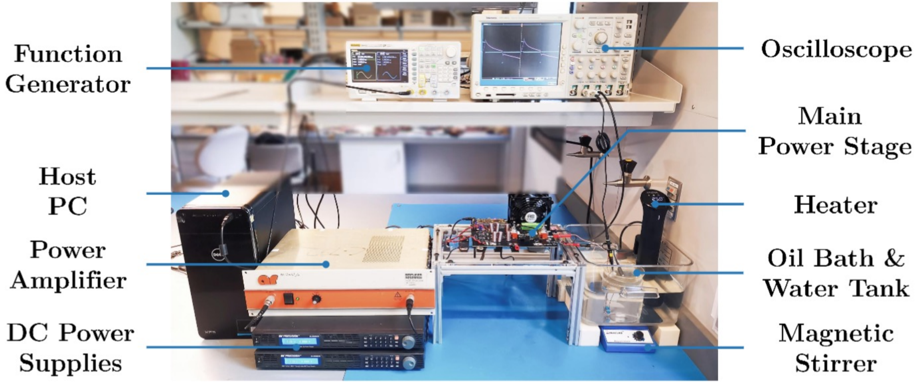


D. Serrano



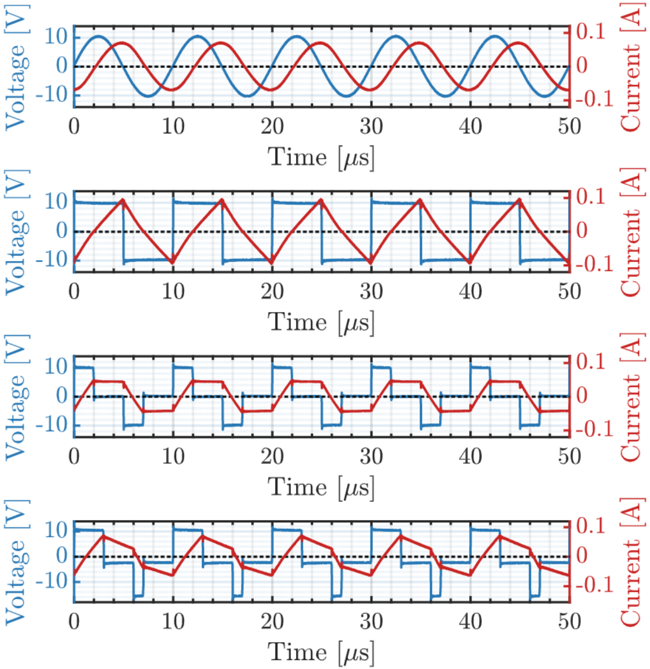
T. Guillod

Automatic Data Acquisition and Database Construction



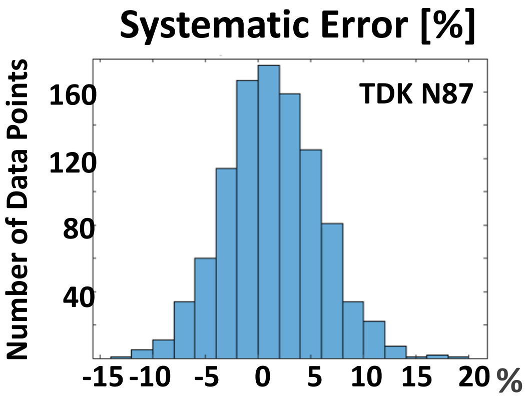
- Frequency range: 50~500 kHz
- Flux density range: 20~300 mT
- Temperature range: 25~90 ^{o}C
- Dc-bias range: 0~300 mT
- Sinusoidal (f, B, THD)
- Triangular (f, B, D)
- Trapezoidal (f, B, D_1, D_2)

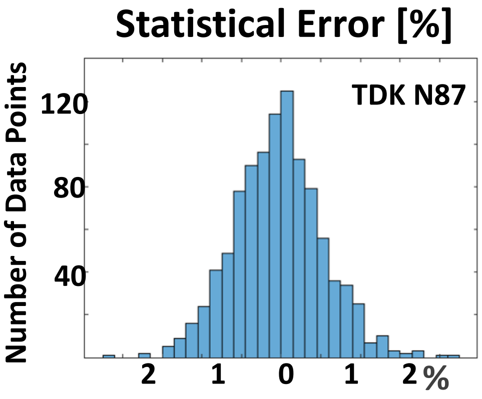
50 datapoints/min, 3000 datapoints/hour



More than 300,000 B-H loop pairs available for 10 materials under different operating conditions

Data Quality Control of the MagNet Database

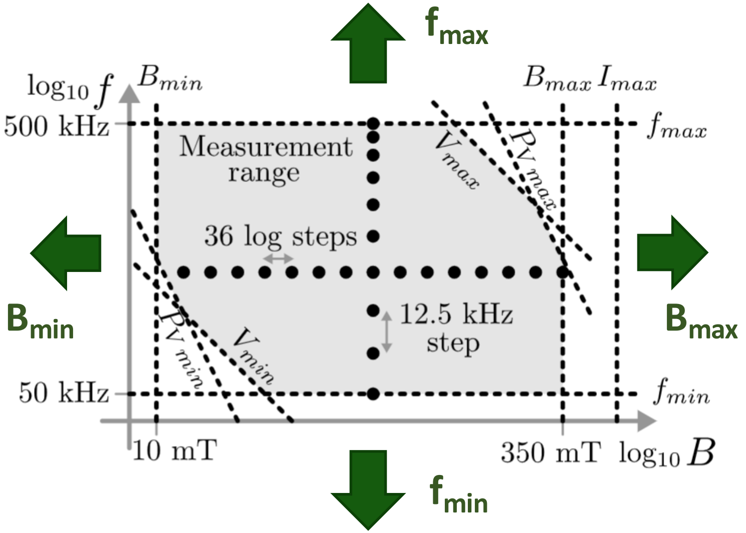




- **Amplitude error**
  - Voltage bias/gain
  - Current bias/gain
- **Phase error**
  - Voltage delay
  - Current delay
- **Parasitic capacitance**
- **Temperature drift**
- **…**

- **Amplitude noise**
  - Voltage noise
  - Current noise
- **Phase noise**
  - Voltage noise
  - Current noise
- **Quantization error**
- **Core geometry error**
- **…**

Limited by phase error at high frequency



Limited by amplitude error at low loss

MagNet Data Quality (self-evaluated)

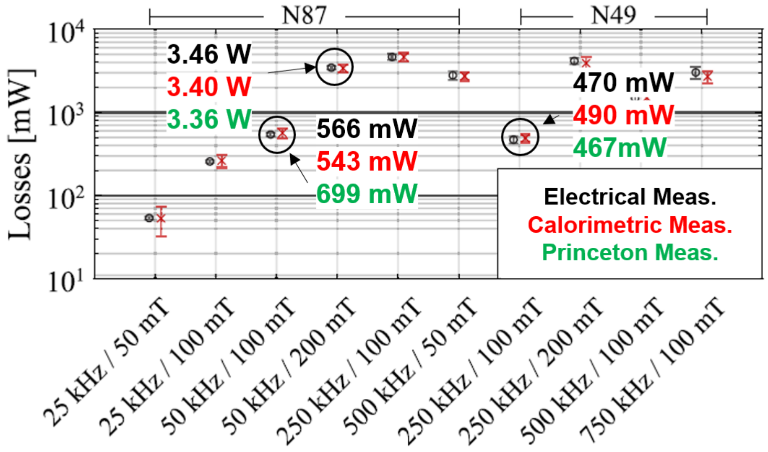
- ~10% core loss error
- 5% ~ 20% batch-to-batch variation

Compare to the "Ground Truth?"

Transient Calorimetric Measurement of Ferrite Core Losses up to 50 MHz

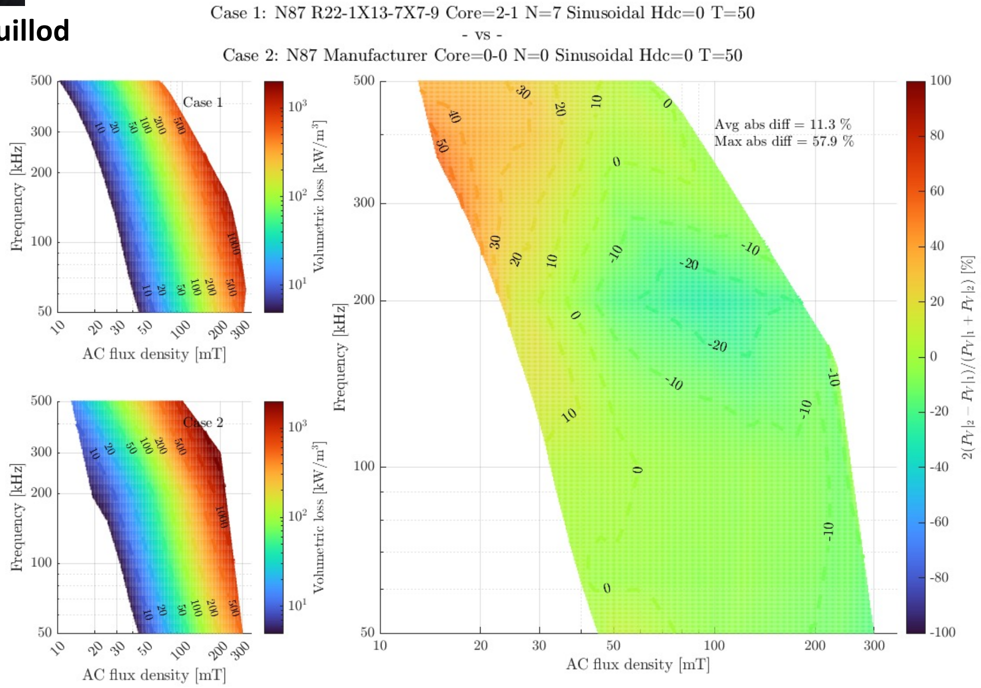
Panteleimon Papamanolis, *Student Member, IEEE*, Thomas Guillod, *Member, IEEE*, Florian Krismer, *Member, IEEE*, and Johann W. Kolar, *Fellow, IEEE*

Thomas Guillod



- *P. Papamanolis, T. Guillod, F. Krismer and J. W. Kolar, "Transient Calorimetric Measurement of Ferrite Core Losses up to 50 MHz," TPEL'21.*

Compare to private data from TDK



MagNet: Open-Source Power Magnetics Database

PRINCETON UNIVERSITY

Raw data available for download in
"**.json**", "**.mat**", "**.hdf5**", "**.csv**" on MagNet
python matlab html5 excel

	Field	Value
DUT Information	Material	'N87'
	Core_Shape	'R22.1X13.7X7.9'
	Effective_Area	3.2600e-05
	Effective_Volume	1.7630e-06
	Effective_Length	0.0542
	Primary_Turns	10
	Secondary_Turns	10
Excitation Information	Excitation_Type	'Trapezoidal'
	Sampling_Time	1.0000e-08
Raw Time Series Data	Voltage	*24773x10000 single*
	Current	*24773x10000 single*
	Time	*24773x10000 single*
Post-processed Data	Power_Loss	*24773x1 double*
	Frequency	*24773x1 double*
	Flux_Density	*24773x1 double*
	Duty_Ratio	*24773x4 double*
	Outlierness	*24773x1 double*
	B_Cycle	*24773x100 single*
	H_Cycle	*24773x100 single*

All details documented for cross-checking and verification

TABLE II
NUMBER OF DATA POINTS CURRENTLY IN THE MAGNET DATASET

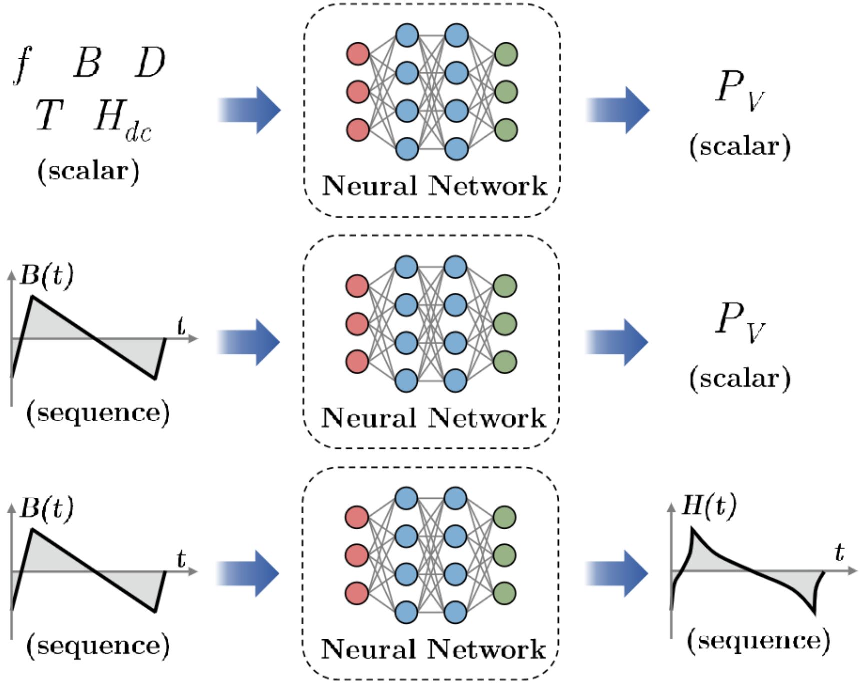
Material	Sine	Tri.	Trap.	Total
TDK N27	1,037	9,106	16,147	26,290
TDK N30	1,194	8,703	16,021	25,918
TDK N49	1,144	8,991	16,318	26,453
TDK N87	3,860	36,092	63,000	102,952
Ferroxcube 3C90	946	8,758	15,330	25,034
Ferroxcube 3C94	1,079	9,072	16,315	26,466
Ferroxcube 3F4	697	7,477	12,906	21,080
Ferroxcube 3E6	1,251	6,406	12,459	20,116
Fair-Rite 77	1,018	9,109	16,080	26,207
Fair-Rite 78	980	9,051	15,850	25,881
Total	13,206	112,765	200,426	326,397

http://mag-net.princeton.edu

- Many other tools available on the website
- Monthly update with new data and new tools

Diego Serrano

Machine Learning Methods for Power Magnetics Modeling



Scalar to Scalar Model

- Predicting volumetric loss based on operating conditions

Sequence to Scalar Model

- Predicting volumetric loss based on excitation waveforms

Sequence to Sequence Model

- Predicting time-domain magnetics response with excitation waveforms

- *H. Li, M. Chen et al., "MagNet: an Open-Source Database for Data-Driven Magnetic Core Loss Modeling," APEC'22.*

Sequence-to-Sequence Neural Network

Language-to-language Q & A (Alexa)

- Voice input
- Voice output

Stock price forecasting

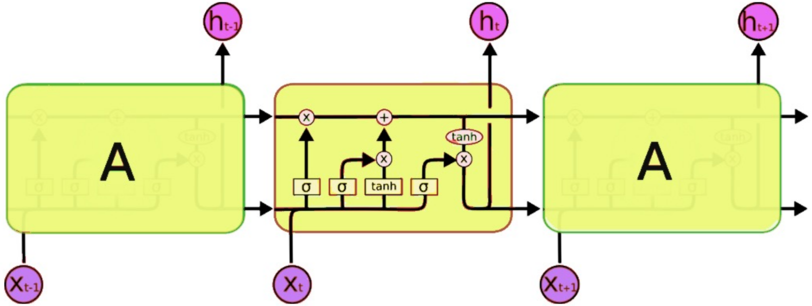
- Interest rate input
- Stock price output

Input

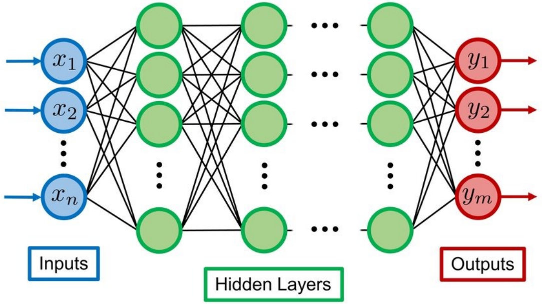
$B(t)$

Output

$H(t)$



Long-Short-Term-Memory (LSTM) Network

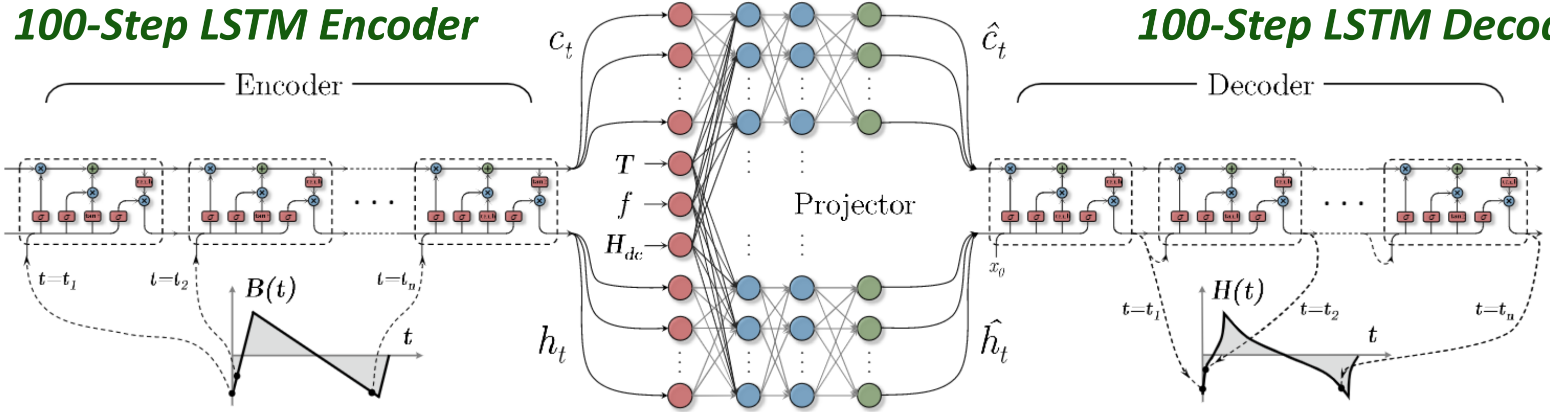


Feed-Forward Neural Network (FNN)

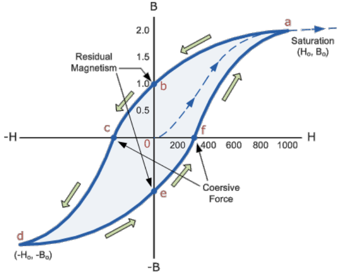
Seq2Seq LSTM Encoder-Decoder for B-H Loop Modeling

100-Step LSTM Encoder

100-Step LSTM Decoder



32-Neuron FNN Projector

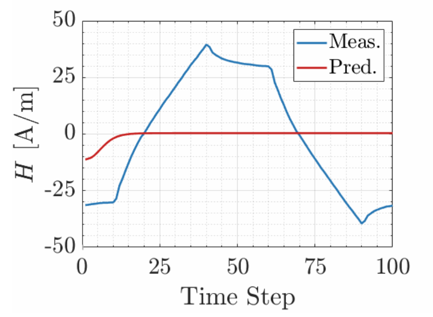


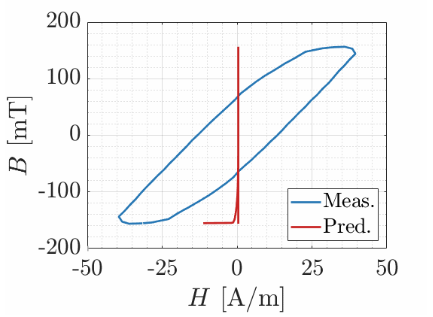
- Encoder – 100-step LSTM to capture the waveform shape in $B(t)$
- Projector – 32-neuron FNN to merge f, T, and dc-bias (H_{dc}) information
- Decoder – 100-step LSTM to unfold the information and predict the $H(t)$

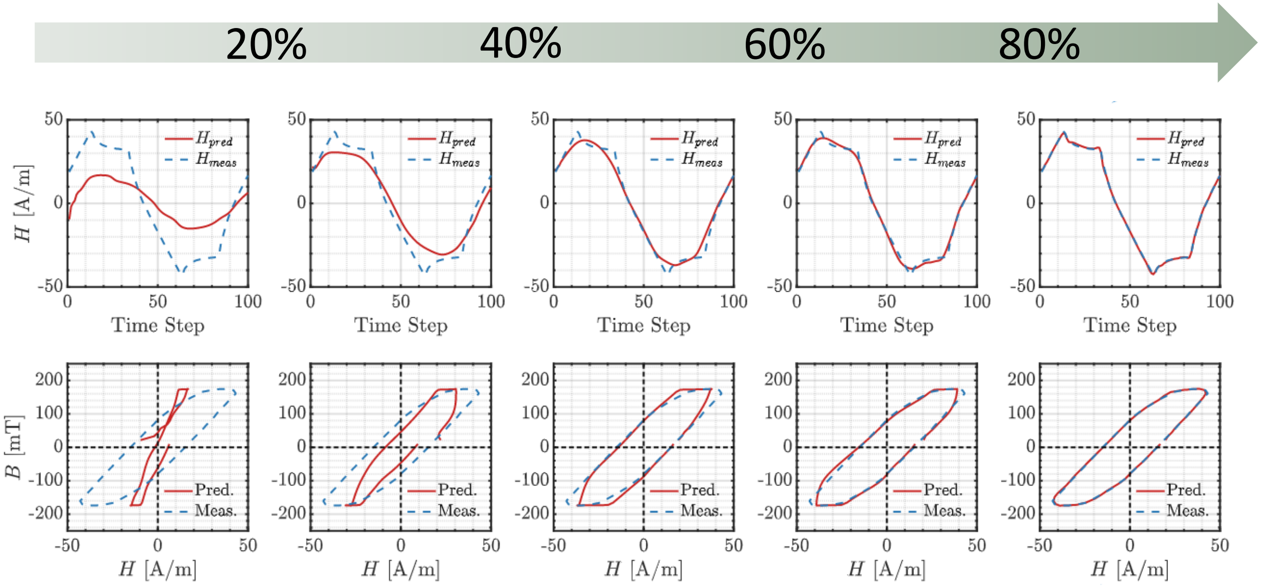
- *D. Serrano, H. Li, M. Chen, et al., “Neural Network as Datasheet: Modeling B-H Loops of Power Magnetics with Sequence-to-Sequence LSTM Encoder-Decoder Architecture,” COMPEL’22.*

Neural Network Training Process

Training Process (N87)



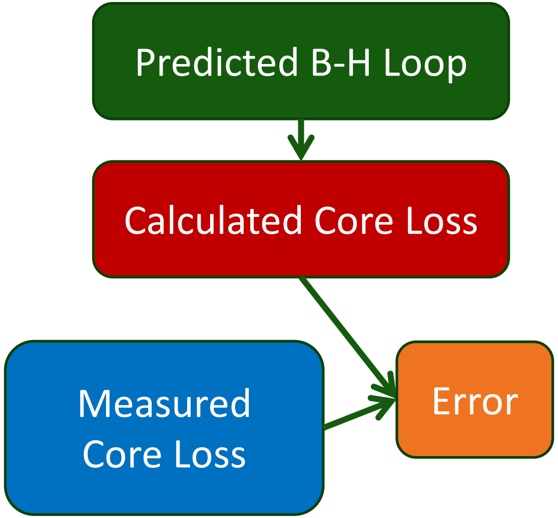




- Database: 15,327 pairs of B-H loops, sine + triangular + trapezoidal
- 70% training + 20% validation + 10% testing
- Number of parameters in the NN: 27,969
- NN training time: about 4 hours on Google Colab standard access
- Prediction error: ~ 5% average MSE, and ~15% maximum MSE

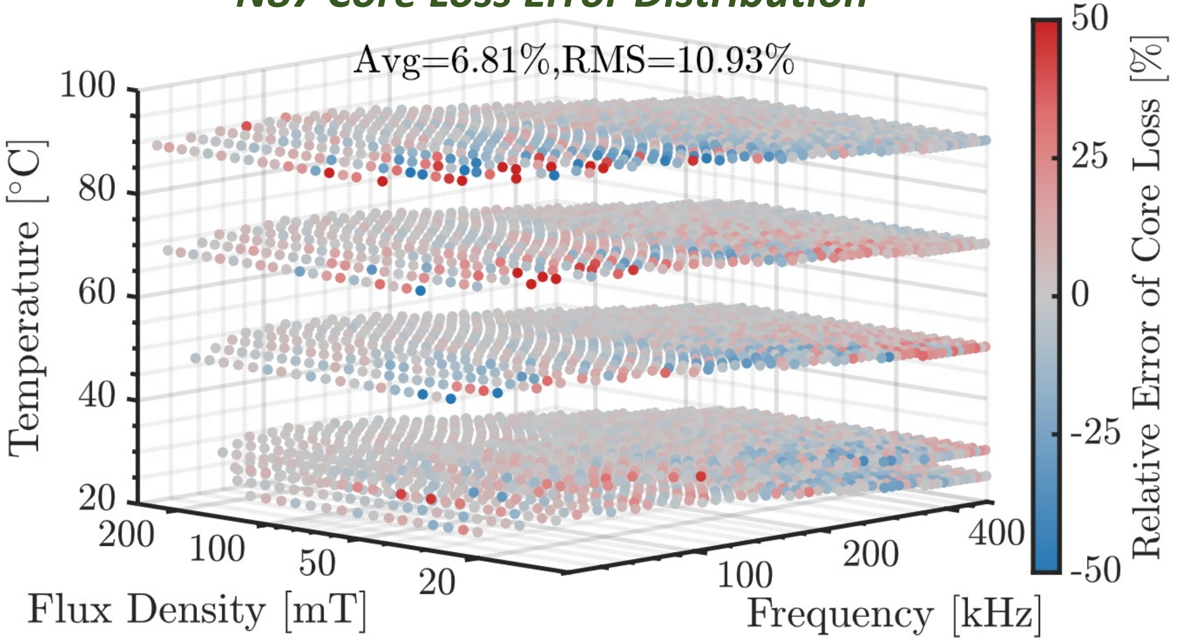
Predicting Core Loss based on B-H Loop

Neural Network predicted B-H Loop - > Calculate B-H Loop Area - > Predicted Core Loss

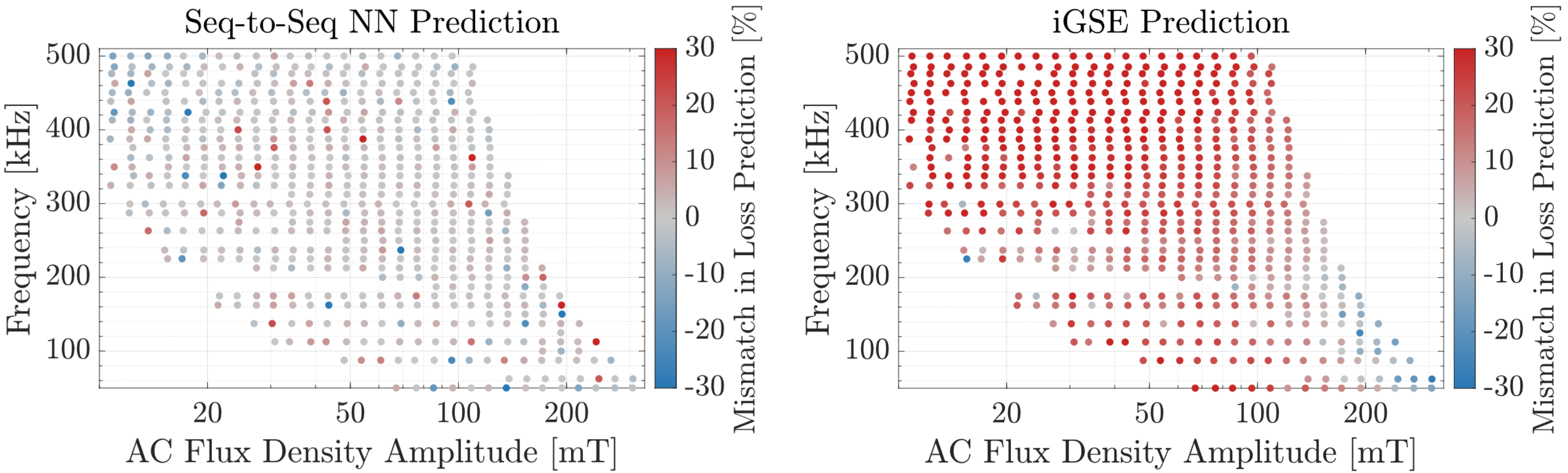


- *H. Li, M. Chen et al., "MagNet: an Open-Source Database for Data-Driven Magnetic Core Loss Modeling," APEC'22.*

N87 Core Loss Error Distribution



Seq2Seq Neural Network v.s. iGSE



- iGSE accuracy depends on how the iGSE parameters are obtained
- Local iGSE may lead to better results, but require more parameters and computation
- Machine learning can well capture the intricate patterns of the magnetic core loss

- *D. Serrano, H. Li, M. Chen, et al., "Neural Network as Datasheet: Modeling B-H Loops of Power Magnetics with Sequence-to-Sequence LSTM Encoder-Decoder Architecture," COMPEL'22.*

Transfer Learning for Data Size Reduction

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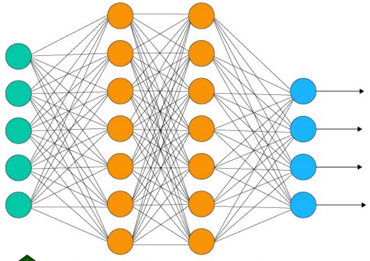
Large-scale database

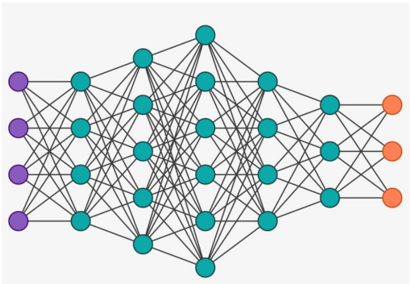
N27, 3C90, 3F3, 3F4, …
25ºC, 50ºC, 75ºC, …
Sine, Triangle, Trapezoidal, …
Bias 0 mT, 100 mT, 200 mT, …

Pre-training (4 hrs)

Generic Neural Network



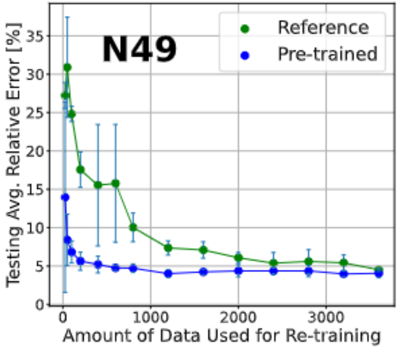
Specific Neural Network

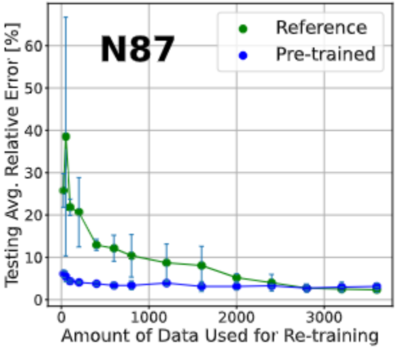


Small-scale database

A new material
N87, Sine wave, at 25ºC
No dc-bias data

Fine-tuning (10 mins)

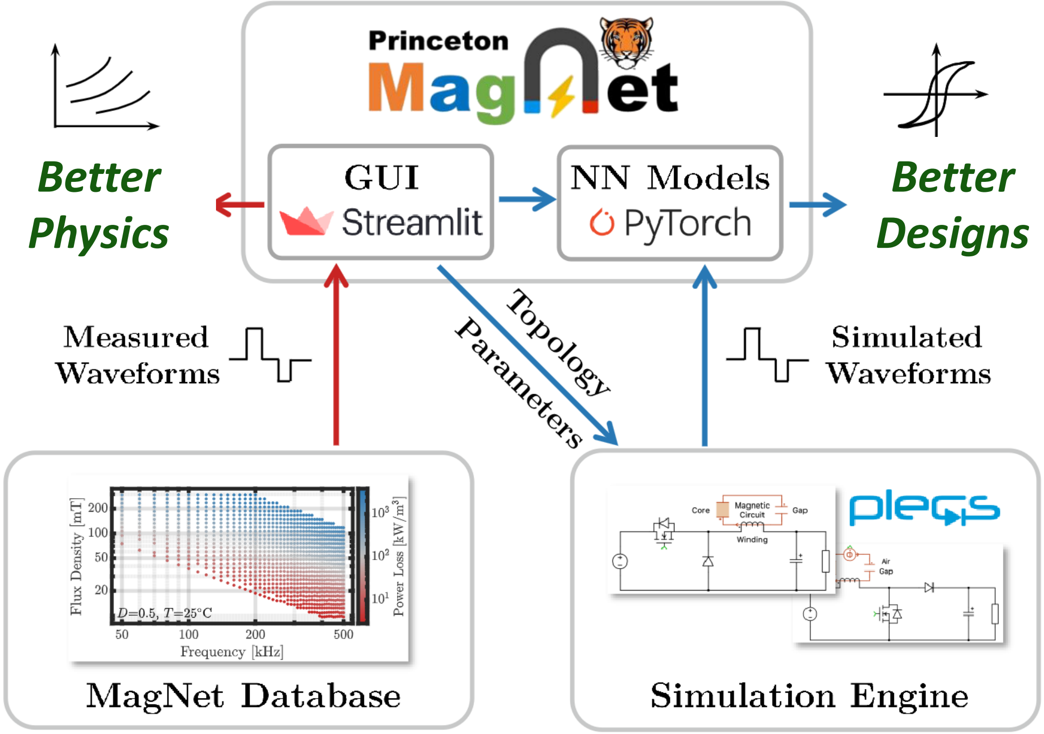




- *E. Dogariu, M. Chen, et al., "Transfer Learning Methods for Magnetic Core Loss Modeling," COMPEL'21.*
- *D. Serrano, M. Chen, et al., "Neural Network as Datasheet: Modeling B-H Loops of Power Magnetics with Sequence-to-Sequence Long-Short-Term-Memory Network," COMPEL'22.*

10x reduction in required data size

MagNet Ecosystem for Advanced Magnetics Design



https://github.com/PrincetonUniversity/Magnet

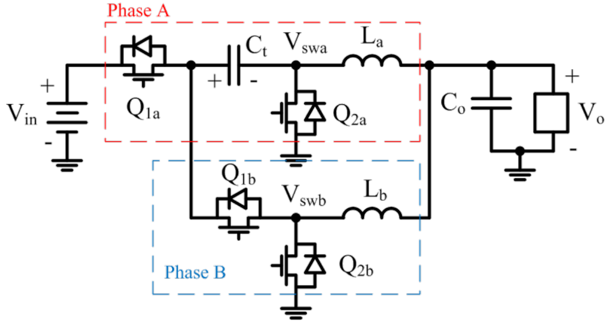
Open-Source Community Development

Data Development | Standard Development | Tool Development

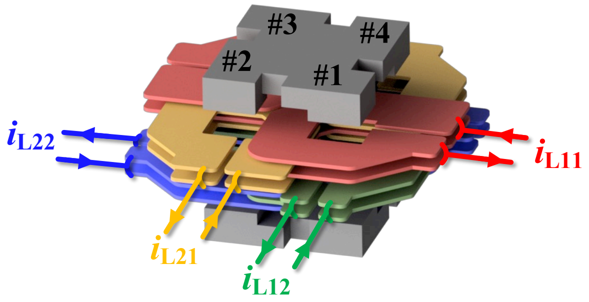
Contents

1. Architecture – Hybrid SC Circuits and Magnetics for CPU-VRMs
2. Magnetics – Open-Source Database and Design Methods
3. Control – Synergy between FCML and Coupled Magnetics

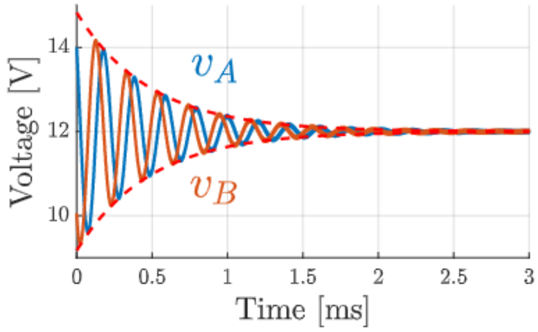
Architecture



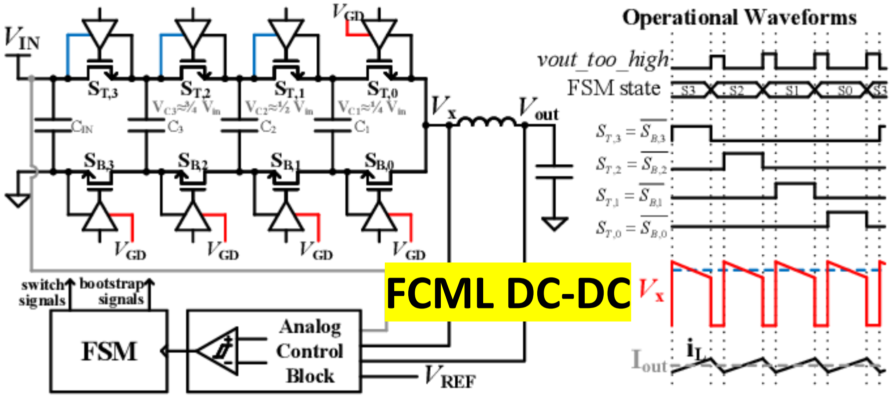
Magnetics

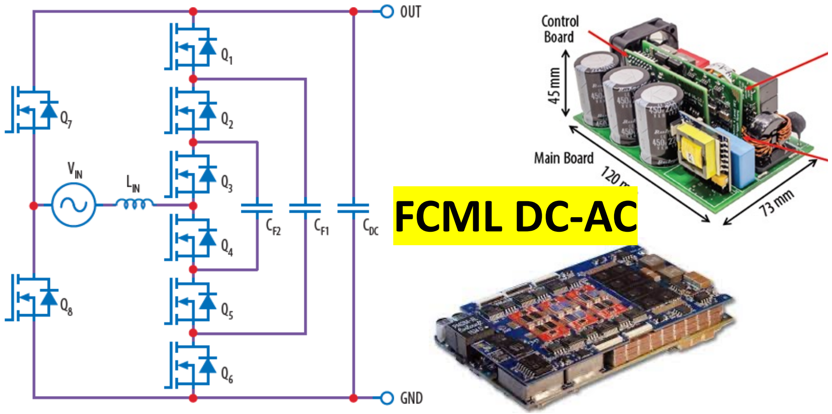


Control



FCML Converter is Attractive in Many Applications





- *J. S. Rentmeister and J. T. Stauth, "A 92.4% Efficient, 5.5V:0.4-1.2V, FCML Converter with Modified Ripple Injection Control for Fast Transient Response and Capacitor Balancing," CICC'20.*
- *J. Rodriguez et al., "Multilevel Converters: An Enabling Technology for High-Power Applications," Proceedings of the IEEE, vol. 97, no. 11, Nov. 2009.*
- *Q. Huang, Q. Ma, P. Liu, A. Q. Huang and M. A. de Rooij, "99% Efficient 2.5-kW Four-Level Flying Capacitor Multilevel GaN Totem-Pole PFC," JESTPE'21.*
- *Y. Lei et al., "A 2-kW Single-Phase Seven-Level Flying Capacitor Multilevel Inverter With an Active Energy Buffer," TPEL'17.*

- **Reduced switch rating + lower current ripple + smaller magnetic size + frequency multiplication**
- **Lots of potential for both high power (HVDC) and low power (PMIC) applications**
- **Voltage balancing is a MUST to make FCML practical**

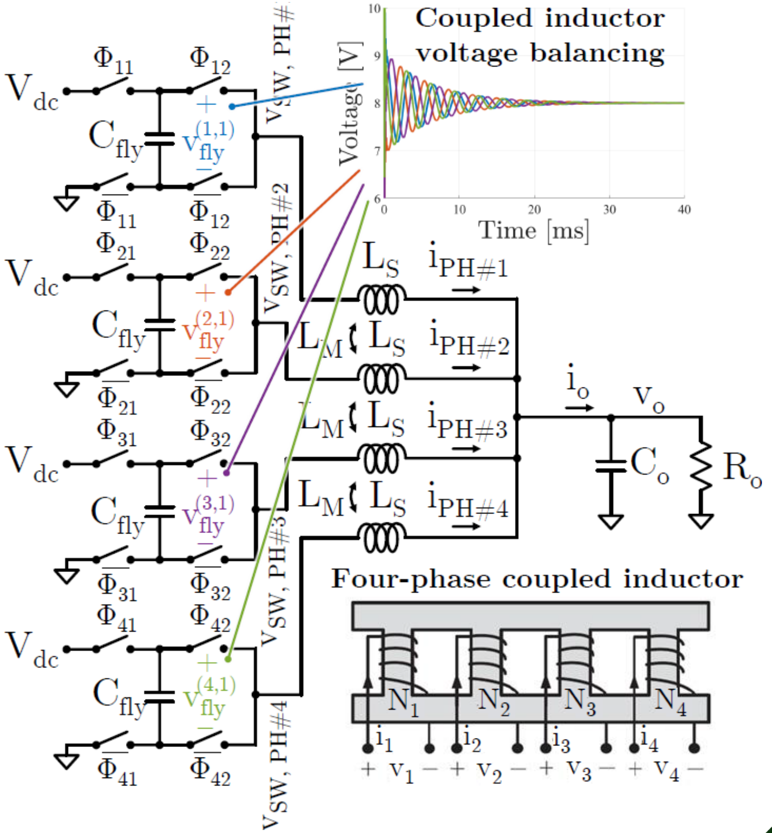
Synergy Between FCML and Coupled Inductors

Three "orthogonal" ways of improving performance and reducing inductor size

***Multiphase* interleaving**
- Ripple reduction, current sharing

***Multilevel* switching**
- Ripple reduction, switch stress reduction

***Coupled* inductors**
- Ripple reduction, smaller size, faster transient



- *D. H. Zhou, Y. Elasser, J. Baek and M. Chen, "Reluctance-Based Dynamic Models for Multiphase Coupled Inductor Buck Converters," TPEL'22.*
- *D. H. Zhou, A. Bendory, C. Li, and M. Chen, "Multiphase FCML Converter with Coupled Inductors for Ripple Reduction and Intrinsic Flying Capacitor Voltage Balancing," APEC'22.*
- *D. H. Zhou, J. Celikovic, Y. Elasser, D. Maksimovic, and M. Chen, "Balancing Limits of Flying Capacitor Voltages in Coupled Inductor FCML Converters," COMPEL'22*

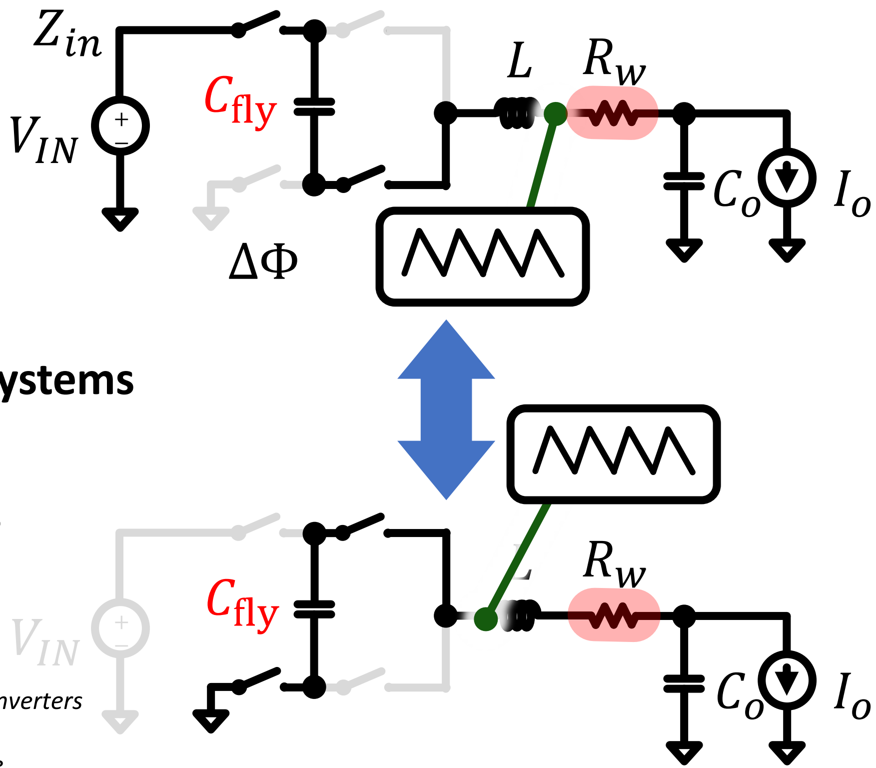
Previous Study on FCML Natural Balancing

Many factors may cause voltage imbalance
- Input impedance, timing, parasitics, etc.

Winding resistance helps with balancing
- Naturally exist in all FCML converters

Natural balancing is weak in low loss (high-Q) systems
- Low Q inductor -> weak natural balancing

Active balancing challenging / impractical at HF
- Current sensing, analog/digital delay, etc …



- *Z. Xia, B. L. Dobbins, J. T. Stauth, "Natural Balancing of Flying Capacitor Multilevel Converters at Nominal Conversion Ratios", COMPEL'19.*
- *Z. Ye, Y. Lei, Z. Liao, and R. C. N. Pilawa-Podgurski, "Investigation of Capacitor Voltage Balancing in Practical Implementations of Flying Capacitor Multilevel Converters," TPEL'21.*

Multi-Resonant Balancing with Coupled Inductors

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Imbalance in one capacitor leads to current imbalance in the coupled inductor

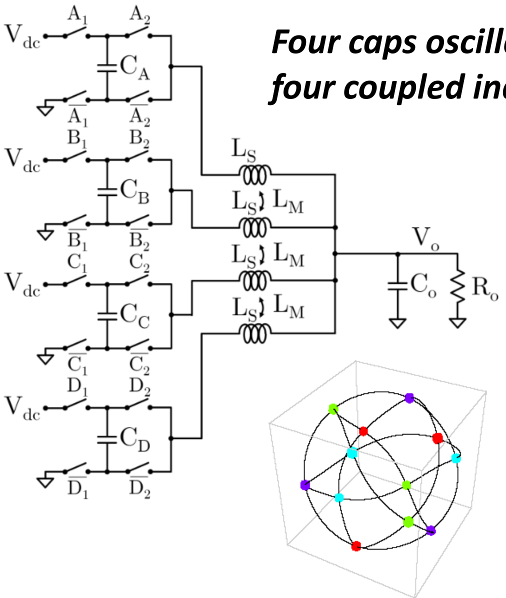
- Independent from winding resistance

Current imbalance in the coupled inductor helps to pull the other capacitor back

- Negative feedback mechanism to "pull" the capacitor voltages together

Automatic voltage balancing and multi-resonant of the flying capacitor voltages

- Two capacitor "resonate" with the coupled inductor and reach a balance



Four caps oscillate with four coupled inductors

Daniel Zhou

Janko Celikovic (with Prof. Maksimovic)

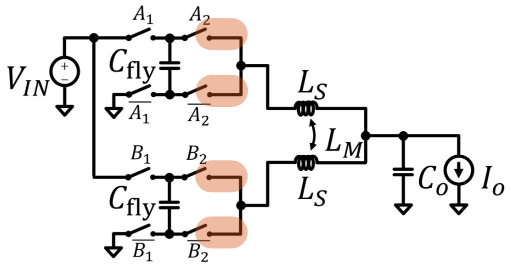
How to approach this multi-resonant problem?

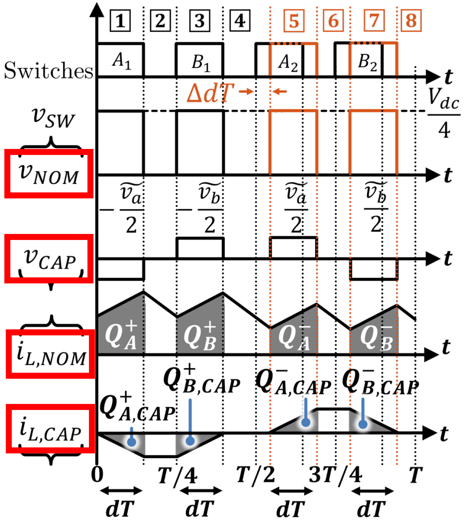
Four state variables: v_1, v_2, i_1, i_2

Sensitive to d_1, d_2, d_3, d_4

- *D. H. Zhou, A. Bendory, C. Li, and M. Chen, "Multiphase FCML Converter with Coupled Inductors for Ripple Reduction and Intrinsic Flying Capacitor Voltage Balancing," APEC'22.*
- *D. H. Zhou, J. Celikovic, Y. Elasser, D. Maksimovic, and M. Chen, "Balancing Limits of Flying Capacitor Voltages in Coupled Inductor FCML Converters," COMPEL'22.*

Three-Level Multiphase Coupled FCML Converter





Balancing Q — Disturbance Q — Balancing matrix — Disturbance factors

$$\mathbf{Q}_{\mathbf{BAL,ALL}} + \mathbf{Q}_{\mathbf{DIST,ALL}} = \mathbf{A}\mathbf{v} + \mathbf{u} = 0.$$

$$\mathbf{v} = \begin{bmatrix} v_{fly}^{(1,1)} & v_{fly}^{(2,1)} & v_{fly}^{(3,1)} & \cdots & v_{fly}^{(M,1)} \end{bmatrix}^T$$

$$\mathbf{A}_{M\text{-phase}} = (dT)^2 \frac{\mathcal{R}_C}{N^2} \begin{bmatrix} 0 & 1 & 1 & \cdots & 1 \\ -1 & 0 & 1 & \cdots & 1 \\ -1 & -1 & 0 & \cdots & 1 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -1 & -1 & -1 & \cdots & 0 \end{bmatrix}_{M\times M}$$

- *Non-invertible for odd M*
- *Invertible for even M*
- ***Even phases (2,4,6,…) better***
- *Three-phase coupled inductor FCML not attractive (5,7,9,…)*

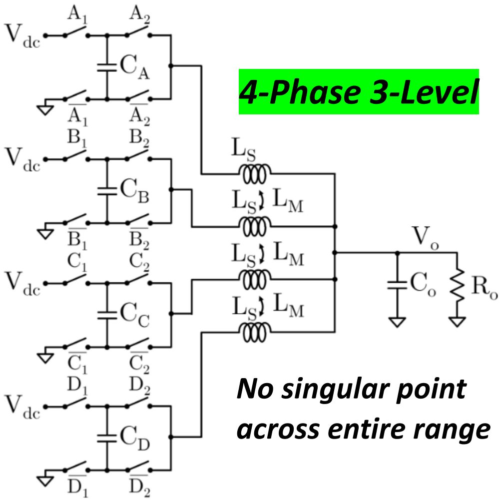
$$\mathbf{v} = \begin{bmatrix} \tilde{v}_{\text{fly}}^{(1,1)} \\ \tilde{v}_{\text{fly}}^{(2,1)} \\ \tilde{v}_{\text{fly}}^{(3,1)} \\ \tilde{v}_{\text{fly}}^{(4,1)} \end{bmatrix} = -\mathbf{A}^{-1}\mathbf{u} = V_{\text{dc}} \times \frac{\Delta t}{T} \times \frac{\mathcal{R}_L + 4\mathcal{R}_C}{\mathcal{R}_C} \begin{bmatrix} 1 \\ -1 \\ 1 \\ -1 \end{bmatrix}$$

Inverse coupling coefficient

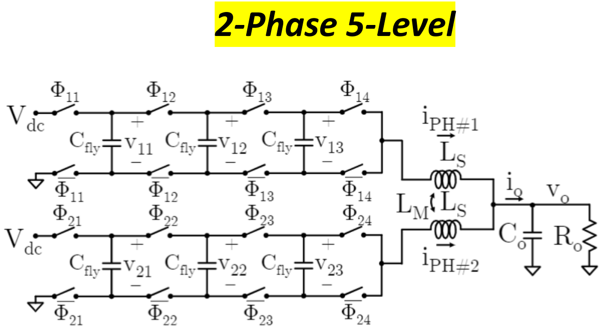
- *Higher coupling coefficient*
- *Lower voltage imbalance*
- ***Stronger coupling better***

- *D. H. Zhou, J. Celikovic, Y. Elasser, D. Maksimovic, and M. Chen, "Balancing Limits of Flying Capacitor Voltages in Coupled Inductor FCML Converters," COMPEL'22.*

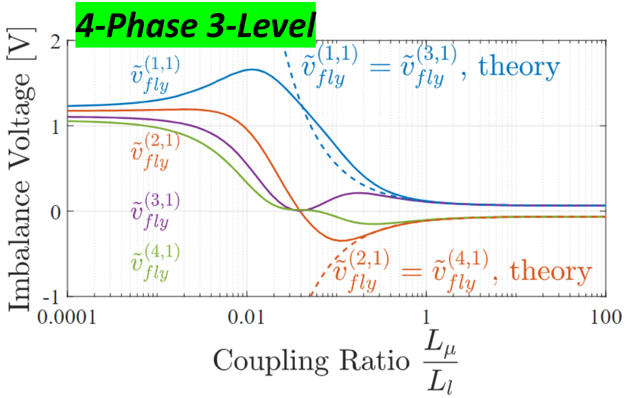
How about Multilevel and Multiphase?

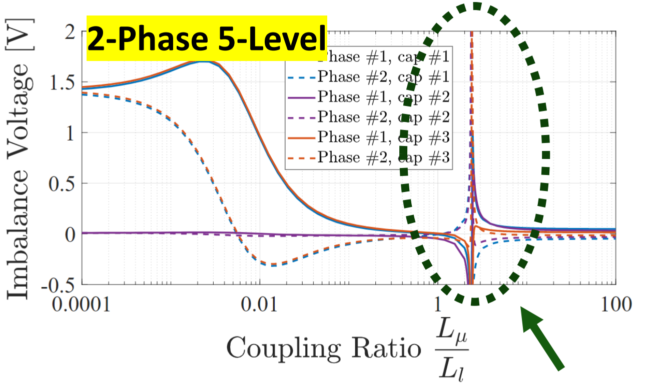


No singular point across entire range



No singular point for duty ratio
One singular point for coupling coefficient

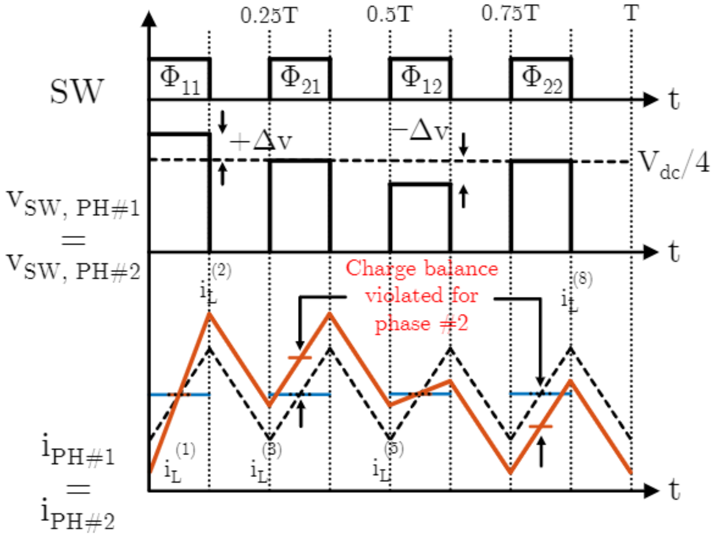




- Asymmetry in circuits and magnetics removes singularity
- High enough coupling coefficient removes singularity
- Good models and active control removes singularity

- *D. H. Zhou, J. Celikovic, Y. Elasser, D. Maksimovic, and M. Chen, "Balancing Limits of Flying Capacitor Voltages in Coupled Inductor FCML Converters," COMPEL'22.*

Findings with Piece-Wise Linear Model (Janko)



Even Phase, Fully Coupled, Arbitrary Level

Levels	Coupled Inductor Singularities, $0 < d < 1$	Discrete Inductor Singularities, $0 < d < 1$ [16]
3	0	4
4	0	0
5	0	8
6	0	0
7	0	12
8	0	0
9	0	16
10	0	0
11	0	20

Credit: Janko Celikovic, Daniel Zhou

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University of Colorado Boulder

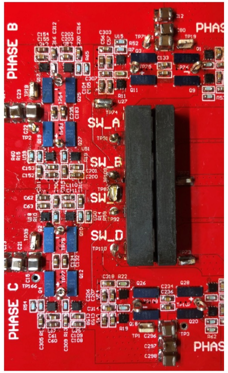
- With even phases, fully coupled inductors can remove all singularity, system robust;
- If partially coupled, singularities emerge at special duty ratio and coupling coefficient combos.

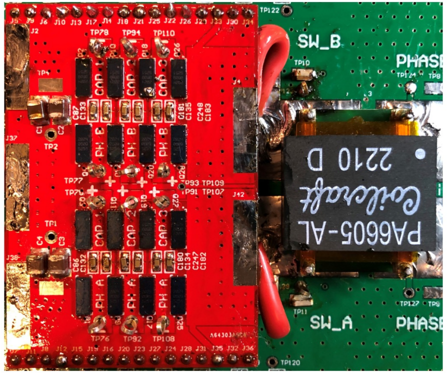
Robust FCML = Even Phase, Even Level Strong Coupling

- *D. H. Zhou, J. Celikovic, Y. Elasser, D. Maksimovic, and M. Chen, "Balancing Limits of Flying Capacitor Voltages in Coupled Inductor FCML Converters," COMPEL'22.*
- *J. Celikovic, R. Das, H.-P. Le, and D. Maksimovic, "Modeling of Capacitor Voltage Imbalance in Flying Capacitor Multilevel DC-DC Converters," COMPEL'19.*

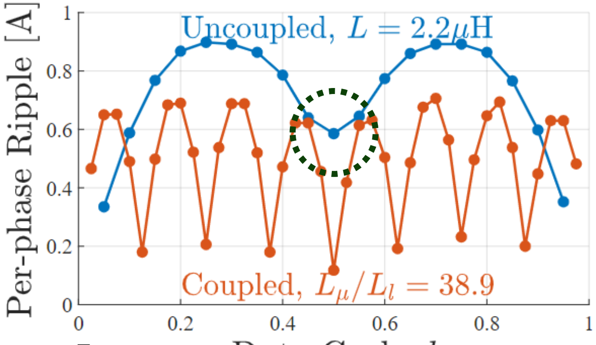
Experimental Verification of the FCML+CoupL Theory

4-Phase 3-Level *2-Phase 5-Level*

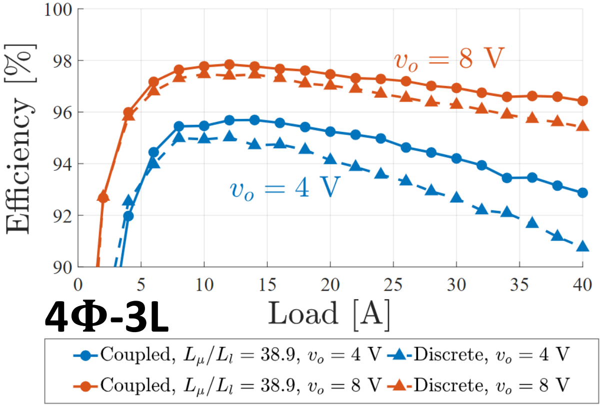




Parameter/Component	Value
f_{sw}	500 kHz
V_{dc}	16 V
C_{fly}	1206 10 μF $\times$ 4
Custom Coupled Inductor L_l	192 nH
Custom Coupled Inductor L_μ	7.44 uH
Off-the-shelf Coupled Inductor	Eaton CL1108-4-50TR-R
Two-phase Coupled Inductor	Coilcraft PA6605-AL
Discrete Inductor	Coilcraft XAR7030-222MEB
Switches	EPC2024
Controller	TMS320F28379D



4Φ-3L



4Φ-3L

Two prototypes

- **One 4Φ-3L**
- **One 2Φ-5L**

Ripple Reduction

Unbalanced FCML voltage leads to increased current ripple

Efficiency Benefits

Ripple reduction improves the efficiency

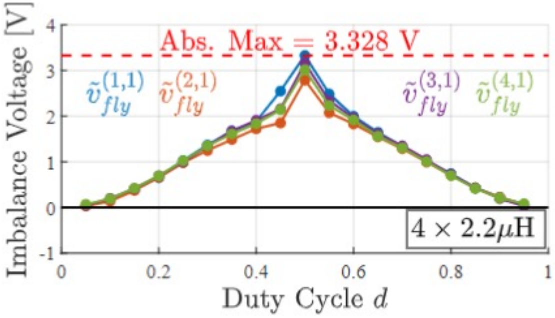
- *M. Chen and C. R. Sullivan, "Unified Models for Coupled Inductors Applied to Multiphase PWM Converters," TPEL'21.*

Voltage Balancing with Coupled Inductors

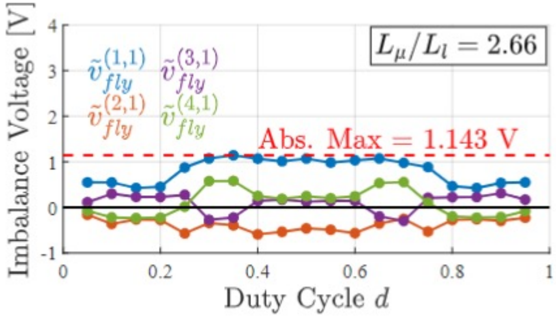
4-Phase 3-Level , Similar total L_μ, Nominal Flying Capacitor Voltage: 8V

Uncoupled

4× discrete 2.2 µH inductors



(a)



(b)

Weakly Coupled

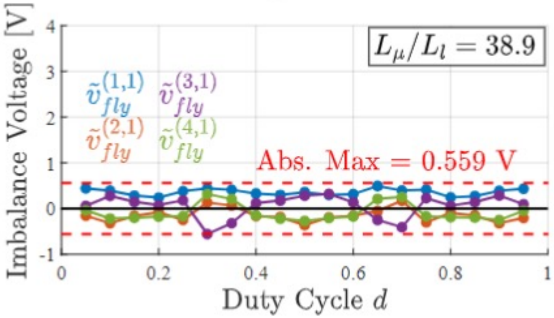
Four phases

$$\frac{L_\mu}{L_l} = 2.66$$

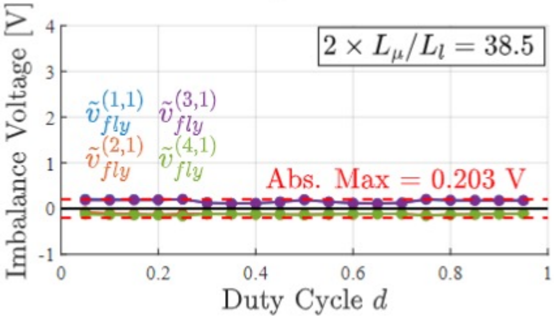
Tightly Coupled

Four phases

$$\frac{L_\mu}{L_l} = 38.9$$



(c)



(d)

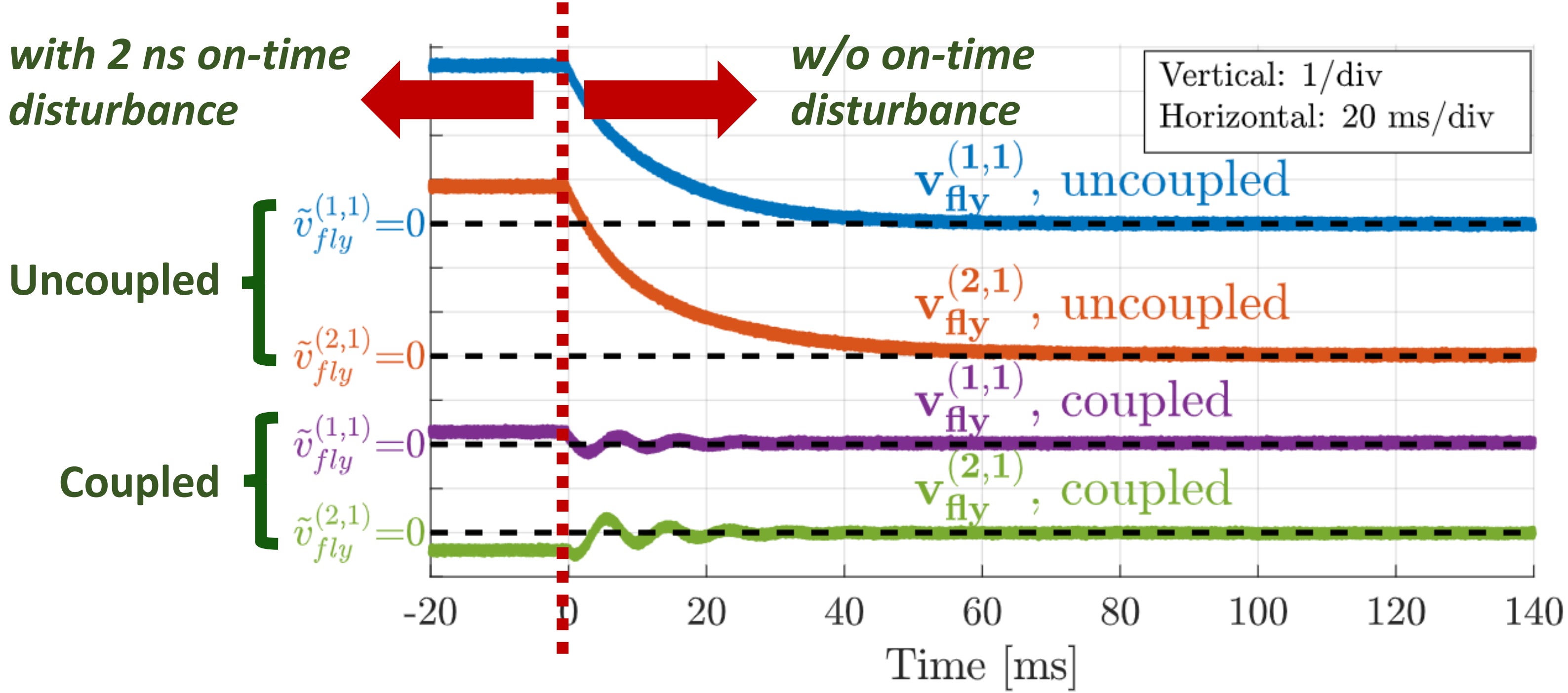
Pairly Coupled

2×2 phases

$$\frac{L_\mu}{L_l} = 38.9$$

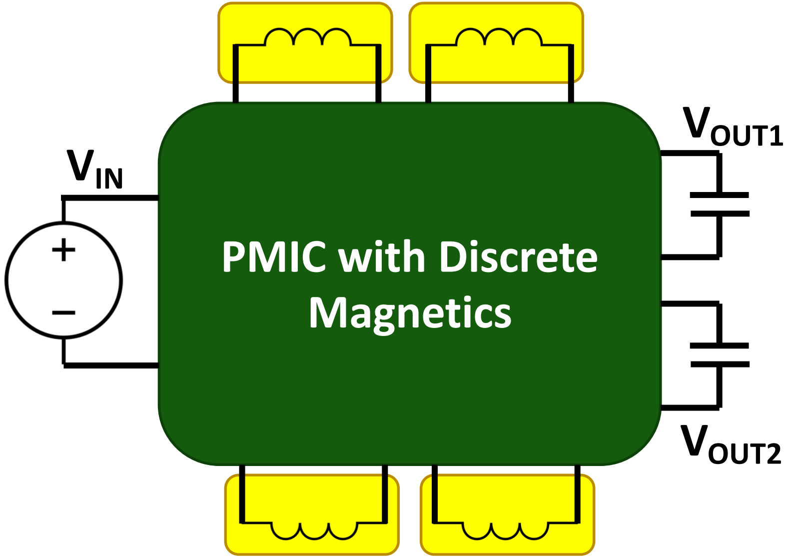
Dynamics of the Balancing Mechanism

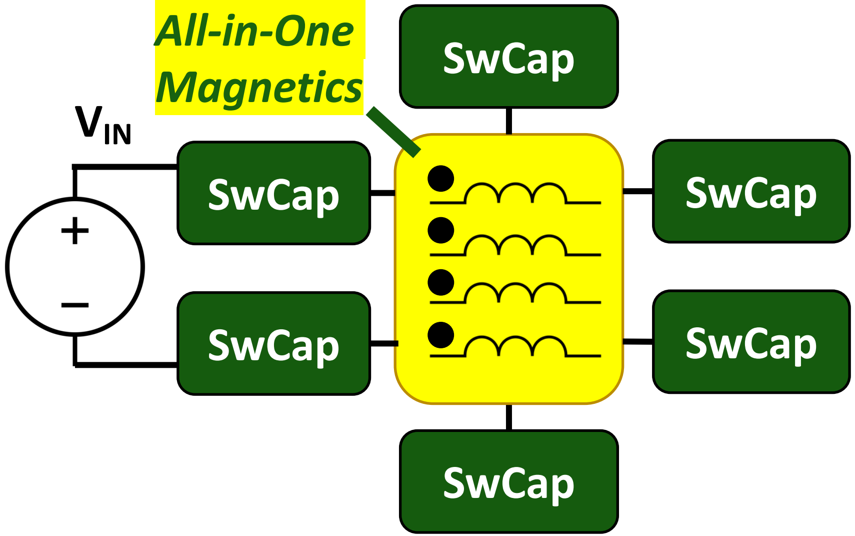
- Coupled inductors considerably reduce imbalance
- Flying capacitor alternation causes oscillations during dynamic balancing



Hybrid Switched-Cap Circuits with All-in-One Magnetics

Single IC, multiple magnetics → **Multiple ICs, All-in-ONE magnetics**





Hybrid switched capacitor magnetics power conversion:

Circuit architecture + novel magnetics + precise models + advanced control

Switched Capacitor Circuits and All-in-One Magnetics

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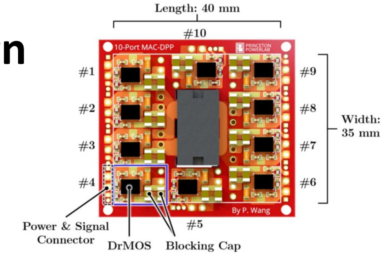
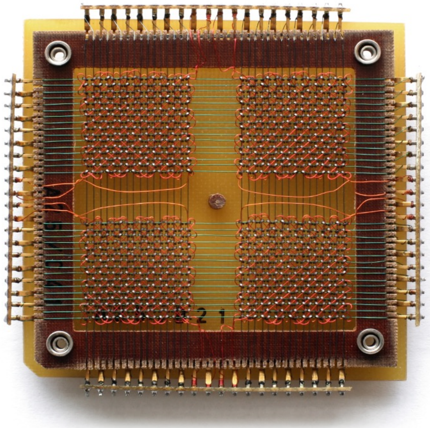
Switched capacitor circuits and all-in-one magnetics co-design

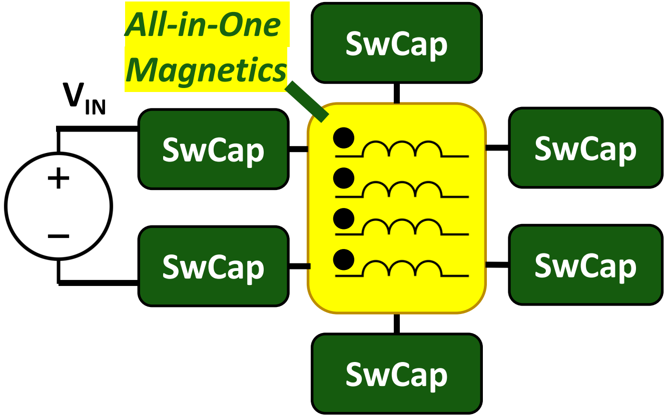


Magnetic (Information) Memory

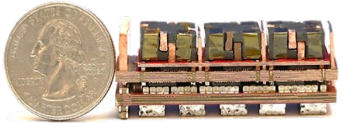


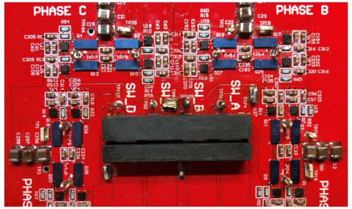
1960s, MIT Museum Servomechanisms Lab

Magnetic (Energy) Memory



2020s, Princeton Power Electronics Research Lab





Princeton MagNet
Princeton Power Electronics Research Lab

Related Publications

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- **Hybrid Switched Capacitor Circuit Architecture and Design Methods**

- J. Baek, Y. Elasser, K. Radhakrishnan, H. Gan, J. Douglas, H. K. Krishnamurthy, X. Li, S. Jiang, C. R. Sullivan, and M. Chen, “Vertical Stacked LEGO-PoL CPU Voltage Regulator,” IEEE Trans. on Power Electron., vol. 37, no. 6, pp. 6305-6322, June 2022.
- Y. Chen, P. Wang, H. Cheng, G. Szczeszynski, S. Allen, D. M. Giuliano, and M. Chen, “Virtual Intermediate Bus CPU Voltage Regulator,” IEEE Trans. on Power Electron., vol. 37, no. 6, pp. 6883-6898, June 2022.

- **Coupled Inductor Models, FCML, and Dynamic Analysis**

- M. Chen and C. R. Sullivan, “Unified Models for Coupled Inductors Applied to Multiphase PWM Converters,” IEEE Transactions on Power Electronics, vol. 36, no. 12, pp. 14155-14174, Dec. 2021.
- C. R. Sullivan and M. Chen, “Coupled Inductors for Fast-Response High-Density Power Delivery: Discrete and Integrated,” IEEE Custom Integrated Circuits Conference (CICC), April 2021.
- D. H. Zhou, Y. Elasser, J. Baek, and M. Chen, “Reluctance-Based Dynamic Models for Multiphase Coupled Inductor Buck Converters,” IEEE Trans. on Power Electronics, vol. 37, no. 2, pp. 1334-1351, Feb. 2022.
- P. Wang, Y. Elasser, V. Yang,and M. Chen, “WAN Converter: A Family of Multicell PWM Converter with All-in-One Magnetics,” IEEE Applied Power Electronics Conference (APEC), Houston, March 2022.
- P. Wang, D. H. Zhou, V. Yang and M. Chen, “ Matrix Coupled All-in-One Magnetics for PWM Power Conversion,” IEEE Workshop on Control and Modeling of Power Electronics (COMPEL), Cartagena de Indias, Colombia, 2021.
- D. H. Zhou, A. Bendory, C. Li, and M. Chen, “Multiphase FCML Converter with Coupled Inductors for Ripple Reduction and Intrinsic Flying Capacitor Voltage Balancing,” APEC’22.

Related Publications

- **Machine Learning and Magnetics Core Loss Modeling**

- H. Li, D. Serrano, T. Guillod, E. Dogariu, A. Nadler, S. Wang, M. Luo, V. Bansal, Y. Chen, C. R. Sullivan, and M. Chen, "MagNet: an Open-Source Database for Data-Driven Magnetic Core Loss Modeling," IEEE Applied Power Electronics Conference (APEC), Houston, March 2022.
- E. Dogariu, H. Li, D. Serrano López, S. Wang, M. Luo and M. Chen, "Transfer Learning Methods for Magnetic Core Loss Modeling," IEEE Workshop on Control and Modeling of Power Electronics (COMPEL), Colombia, 2021.
- H. Li, S. Lee, M. Luo, C. R. Sullivan, Y. Chen and M. Chen, "MagNet: A Machine Learning Framework for Magnetic Core Loss Modeling," IEEE Workshop on Control and Modeling of Power Electronics (COMPEL), Aalborg, Denmark, 2020.

- **Wireless Power Transfer, Energy Router, Differential Power Processing, and Robotics**

- M. Liu, Y. Chen, Y. Elasser, and M. Chen, "Dual Frequency Hierarchical Modular Multilayer Battery Balancer Architecture," IEEE Trans. on Power Electronics, vol. 36, no. 3, pp. 3099-3110, March 2021.
- P. Wang, Y. Chen, J. Yuan, R. C. N. Pilawa-Podgurski, M. Chen, "Differential Power Processing for Ultra-Efficient Data Storage," IEEE Transactions on Power Electronics, vol. 36, no. 4, pp. 4269-4286, April 2021.
- P. Wang, R. C. N. Pilawa-Podgurski, P. Krein and M. Chen, "Stochastic Power Loss Analysis of Differential Power Processing," IEEE Trans. on Power Electronics, vol. 37, no. 1, pp. 81-99, Jan. 2022.
- Y. Chen, P. Wang, Y. Elasser, and M. Chen, "Multicell Reconfigurable Multi-Input Multi-Output Energy Router Architecture," IEEE Transactions on Power Electronics, vol. 35, no. 12, pp. 13210-13224, Dec. 2020.
- Z. Zheng, P. Kumar, Y. Chen, H. Cheng, S. Wagner, M. Chen, N. Verma, and J. Sturm, "Scalable Simulation and Demonstration of Jumping Piezoelectric 2-D Soft Robots," IEEE International Conference on Robotics and Automation (ICRA), 2022.