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Power Architecture and Magnetics to Unlock the Potential of WBG Semiconductor Devices

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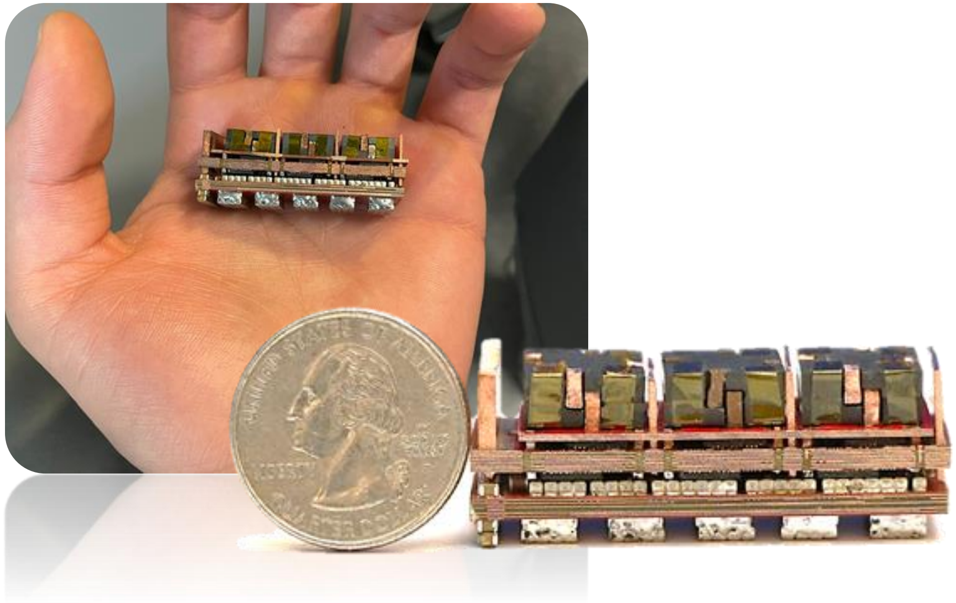

Princeton Power Electronics Research Lab

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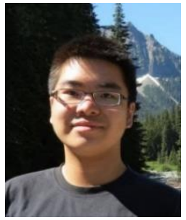

NSF

Google

arpa·e
CHANGING WHAT'S POSSIBLE

CENTER FOR STATISTICS AND MACHINE LEARNING

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ENERGY INSTITUTE

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A Murata Company

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Emerging Trends in Power Electronics

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Grid-Forming Inverters

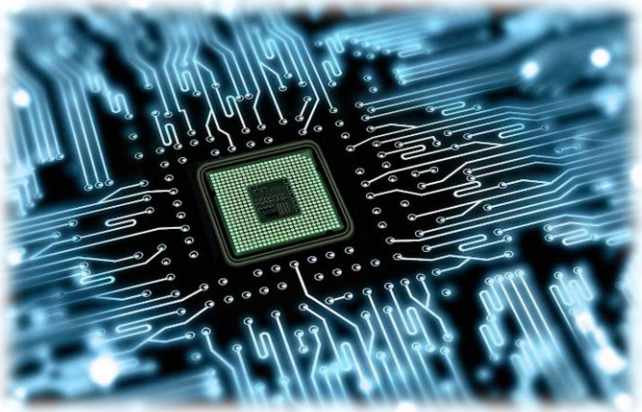
Cloud Computing and 5G

Power for Robotics

Extreme Performance and Complex Functions

Extreme High Density

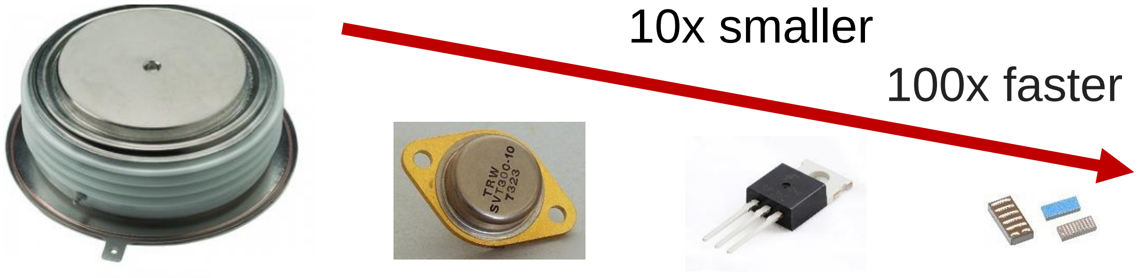
Very High Efficiency



Extreme Environment

Opportunities and Challenges in Power Electronics

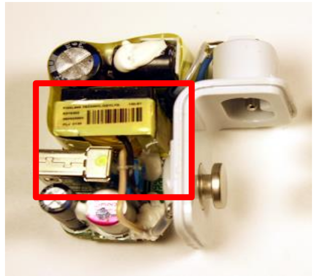
Opportunities - Rapid advances in semiconductors



Thyristor 1950s	BJT 1960s	MOSFET 1980s	GaNFET 2010s

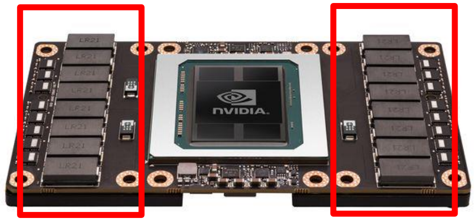
Challenges - Passive components dominating the size

Ac-Dc Adapter



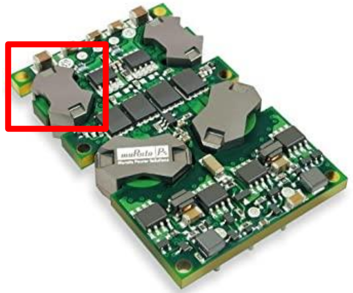
[Apple Ipad Adapter]

CPU Supply



[Nvidia Tesla V100]

Telecom Dc-Dc



[Synqor PQ Series]

Switching at higher frequencies

- Reduces energy storage requirements
- Reduces passive component size
- L, C values $\propto 1/f$

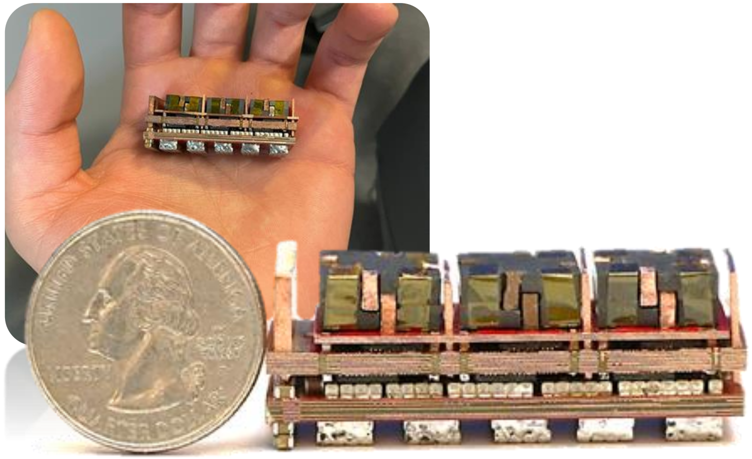
$$Z_L = j\omega L$$
$$Z_C = \frac{1}{j\omega C}$$

Limitations of higher frequencies

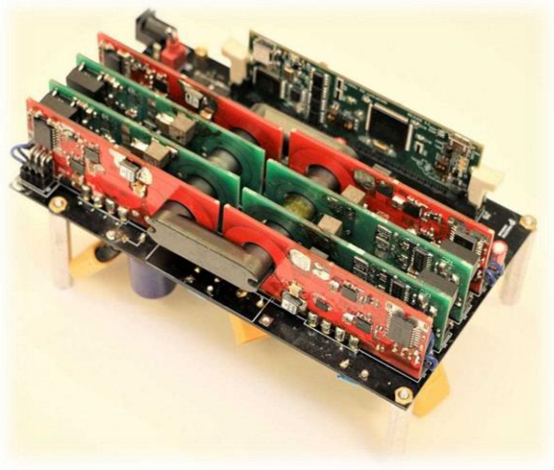
- Switching loss
- Core loss
- Material property
- Parasitics

Architectures to Unlock the Potential of WBG Devices

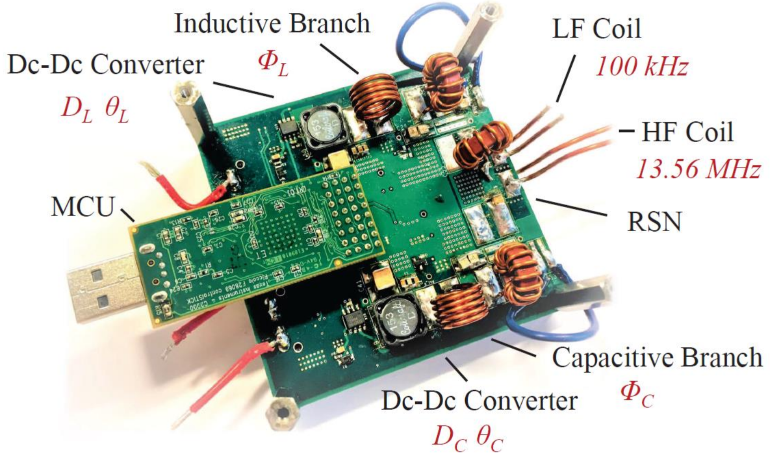
- **Extreme Performance: Hybrid-Switched-Capacitor Architecture**
  Extreme Performance CPU Voltage Regulators
- **Sophisticated Functions: Control of MIMO Power Flow**
  Modeling and Control of Multiport Energy Routers
- **Enabling New Applications: Dual Frequency Wireless Power Transfer**
  Compensate for Impedance Variation with Reactance Steering Network



CPU Voltage Regulator



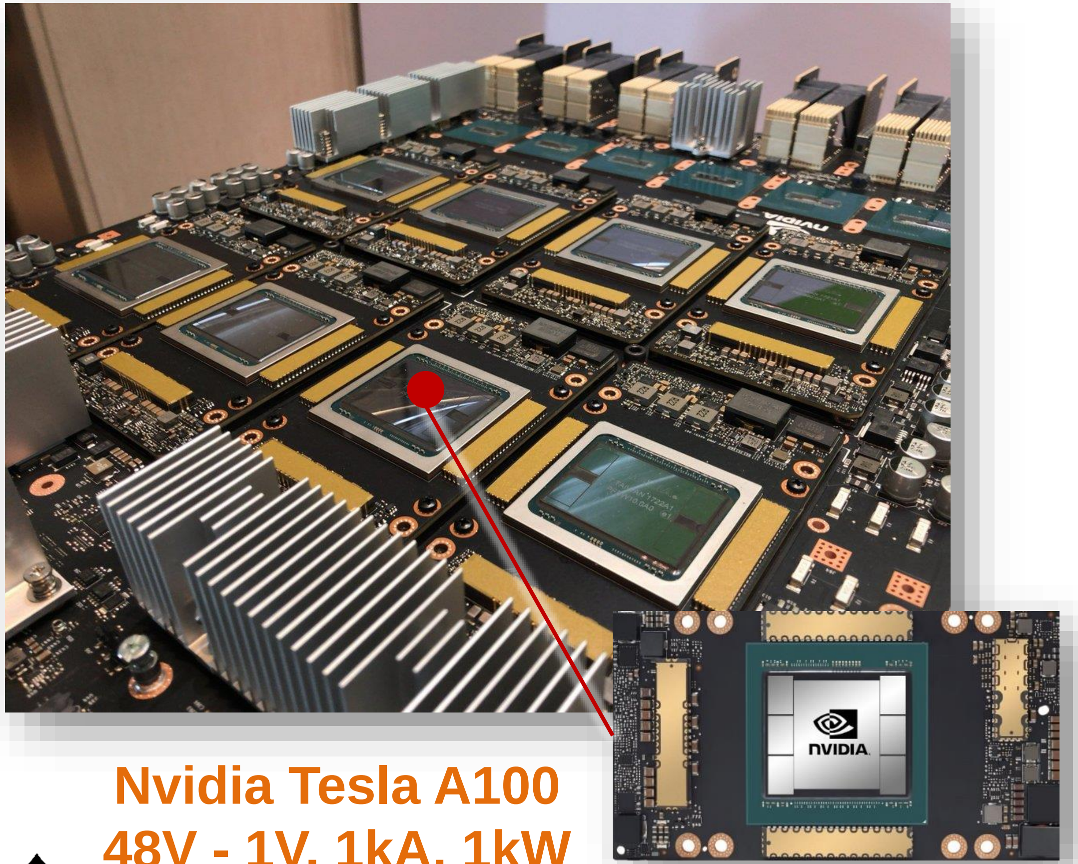
MIMO Energy Router



Dual-Band Wireless Power Transfer

Power Delivery for Future Computing

Nvidia 8 x GPU AI Server
$230V_{AC}$ - $400V_{DC}$ - $48V_{DC}$ - $1V_{DC}$, >10 kW



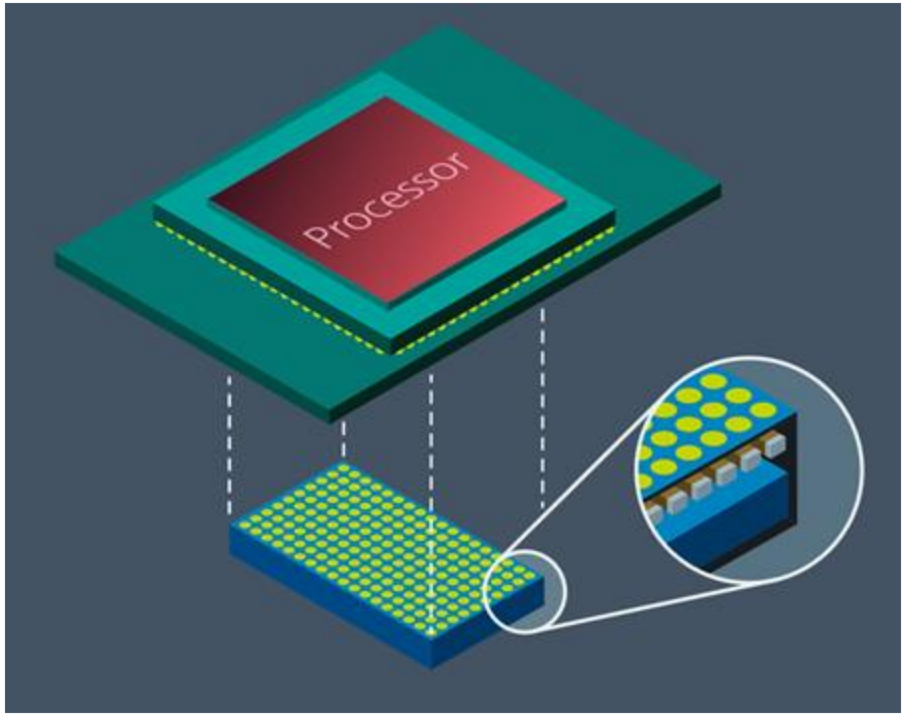
Nvidia Tesla A100
48V - 1V, 1kA, 1kW

Extreme performance 48V-1V PoL

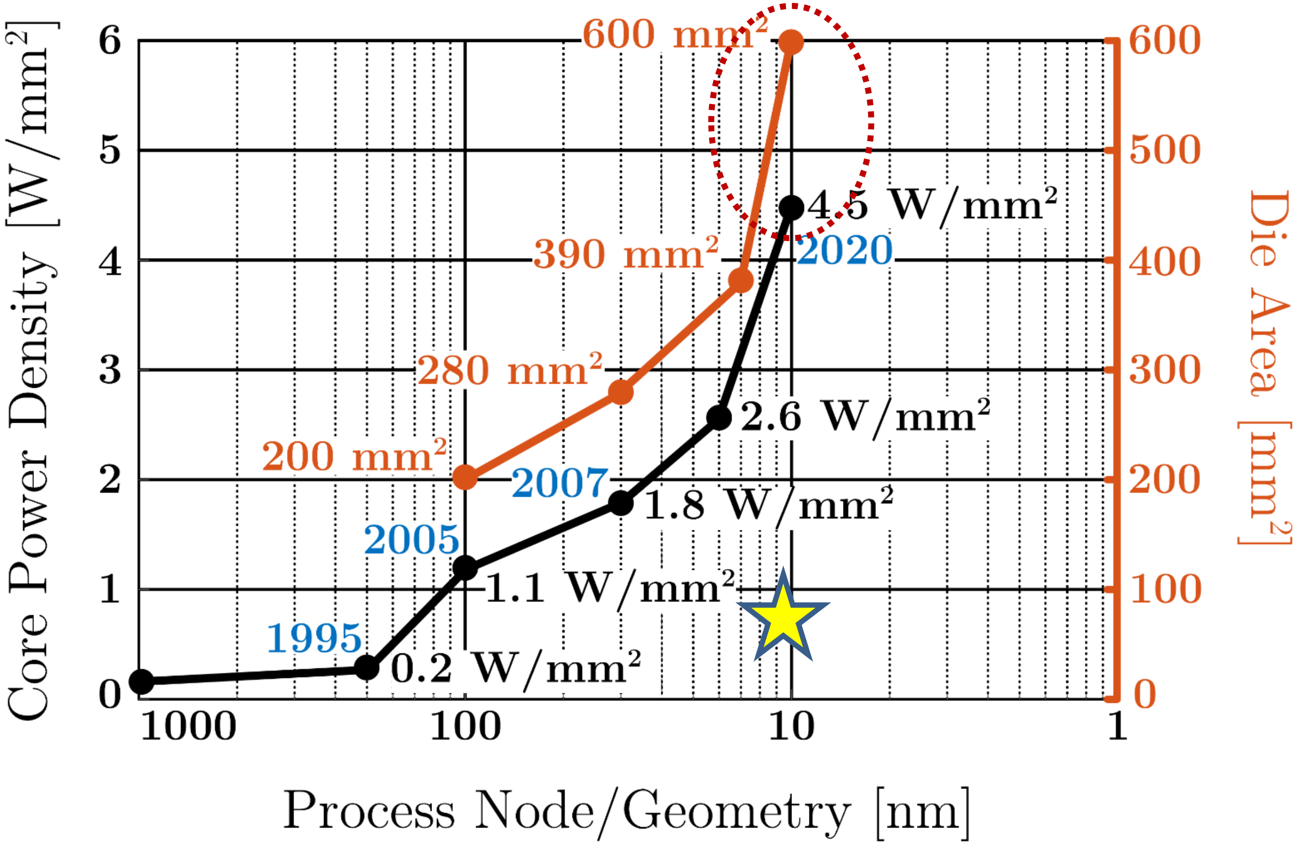
- **Processor-Level**
  - High current (>1,000 A/core)
  - High conversion ratio (48 V-1 V)
  - Fast control bandwidth (>1 A/ns)
  - High density (>100 A/cm^2)
  - High efficiency (>95%)
- **Server-Level**
  - Modular loads (up to 16 GPUs together)
  - Core-to-core communications

Vertical Power Delivery for Microprocessors

- Power consumption per core as high as 2 kW
- Silicon power density still rapidly growing …

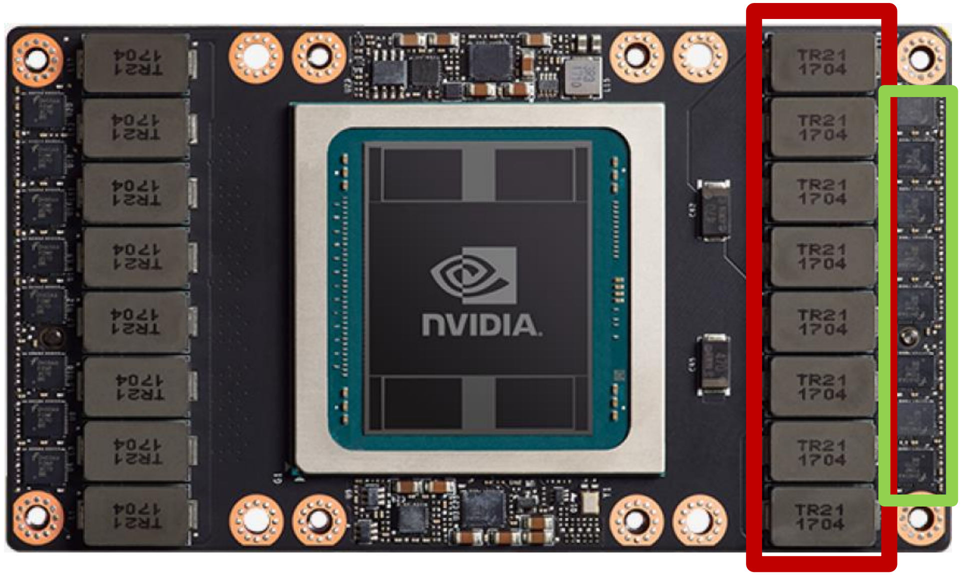


Vertical Power Delivery to Microprocessors

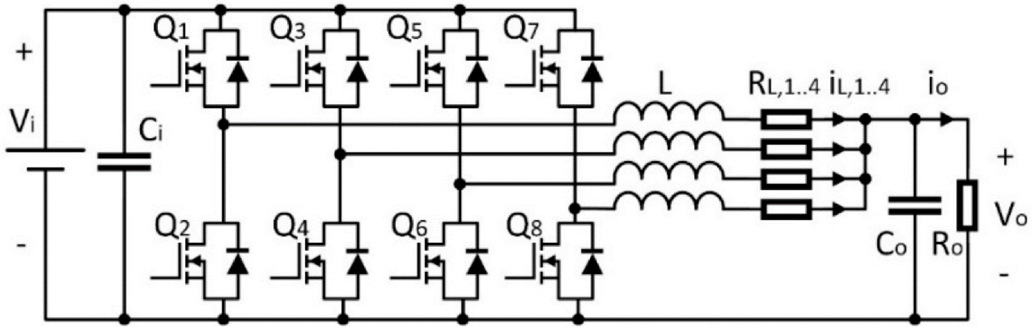


- J. Beak et al., "Vertical Stacked 48V-1V CPU Voltage Regulator with 91.1% Efficiency, 1 A/mm² Current Density and 1,000 W/in³ Power Density", IEEE Transactions on Power Electronics, in preparation.

A Problem that Cannot be Simply Solved by WBG



Nvidia Tesla V100 Accelerator – 16 Phase Buck



Traditional PoL Architectures

➢ **Buck Derived Solutions**

- High conversion ratio (48:1)
- Narrow ON/OFF
- Low duty ratio
- Poor inductance utilization
- Almost impossible to control

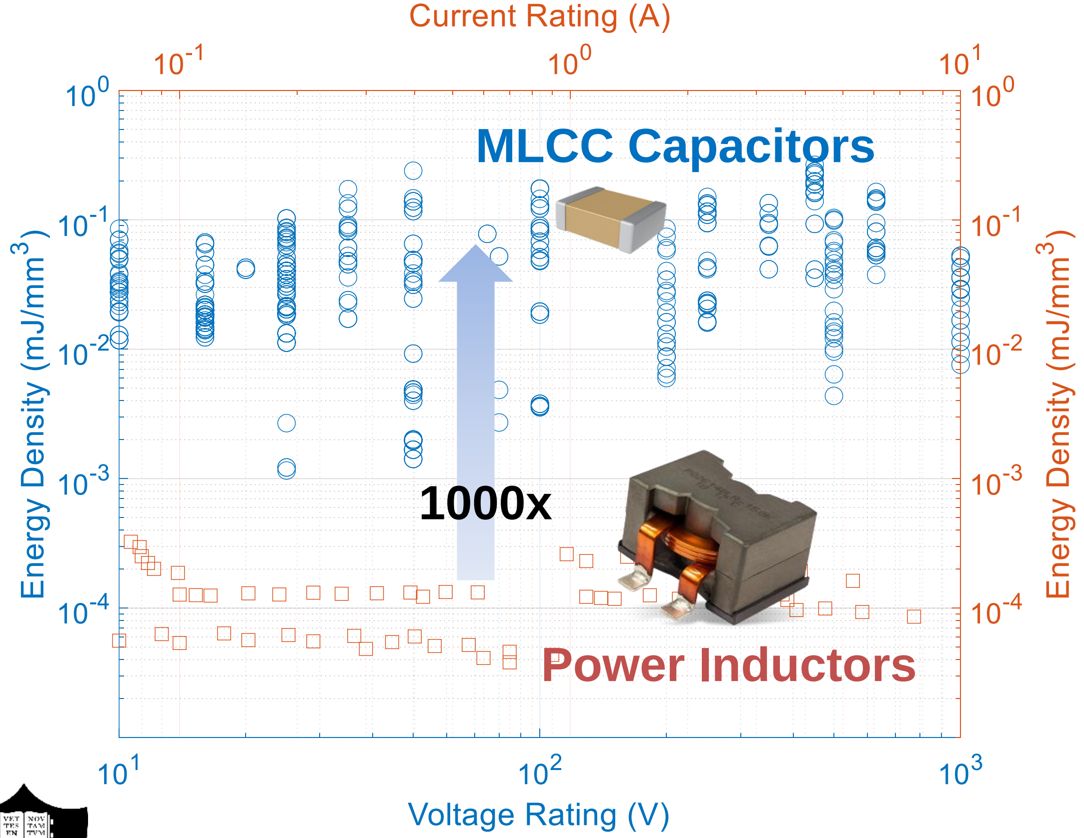
➢ **Transformer Based Solutions**

- High turns ratio (48:1)
- Complicated dynamics
- Difficult to do current mode control
- Transformer leakage and parasitics
- Lack of magnetics in MHz range

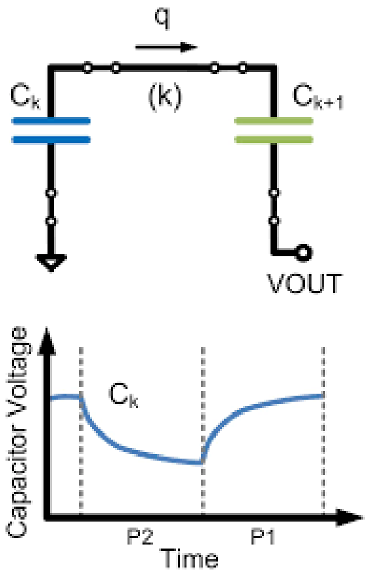
Hybrid Switched-Capacitor-Magnetics Approach

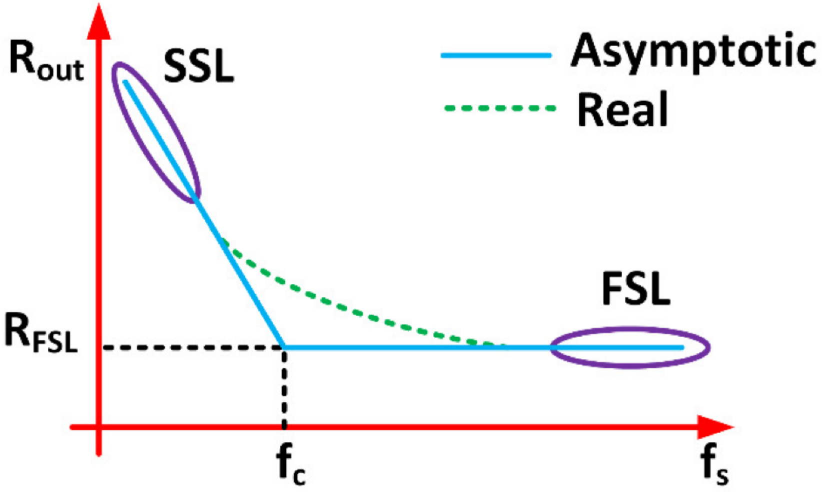
➢ Energy Density of Capacitors vs. Inductors

- Capacitors are 100x denser than inductors
- Switched capacitor circuit suffers loss and regulation



➢ Charge Sharing Loss of Switched Caps



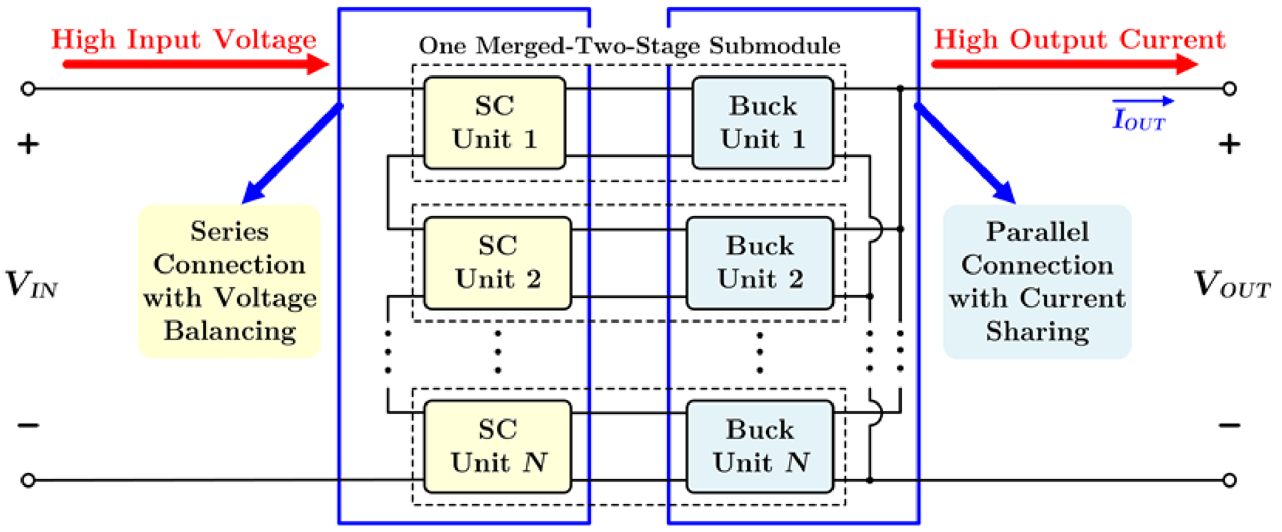


Hybrid inductive and capacitive energy transfer

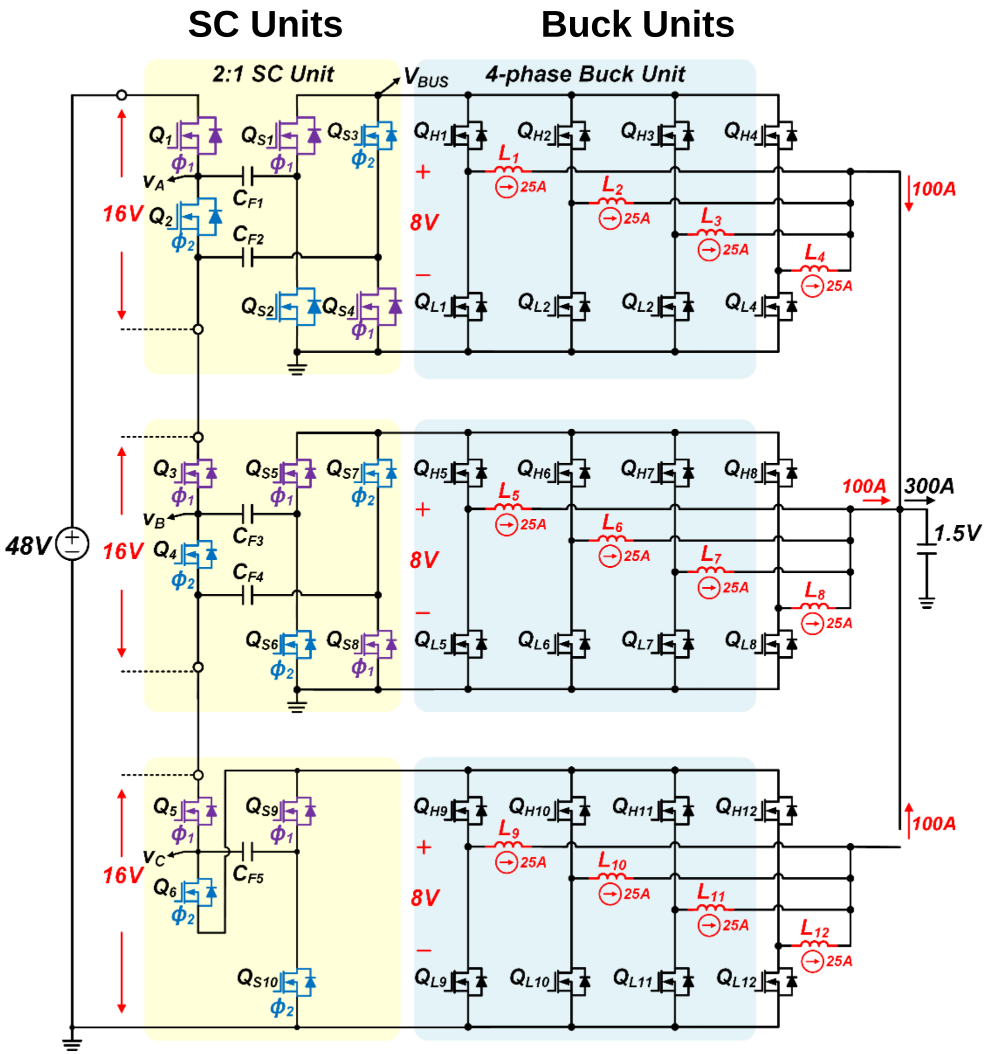
- Capacitive energy transfer for power density
- Inductive energy transfer for efficiency and regulation

- M. D. Seeman and S. R. Sanders, "Analysis and Optimization of Switched-Capacitor DC–DC Converters," in *IEEE Transactions on Power Electronics*, vol. 23, no. 2, pp. 841-851, March 2008.

LEGO-PoL: Granular Building Block Approach for PoL



Submodules ➔ Linear Extendable & Group Operated (LEGO)



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

• J. Baek, Y. Elasser, and M. Chen, “3D LEGO-PoL: A 93.3% Efficient 48V-1.5V 450A Merged-Two-Stage Hybrid Switched-Capacitor Converter with 3D Vertical Coupled Inductors,” APEC 2021.

Merged Two Stage Operation with Mutual Benefits

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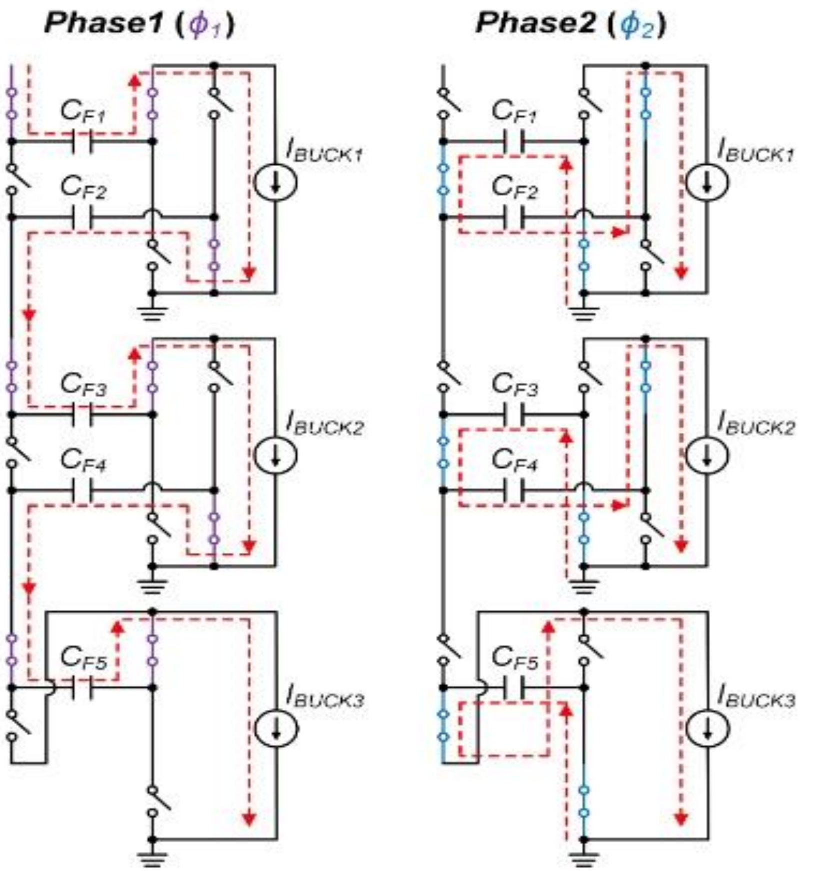
➢ Soft-Charging Operation of SC Circuit

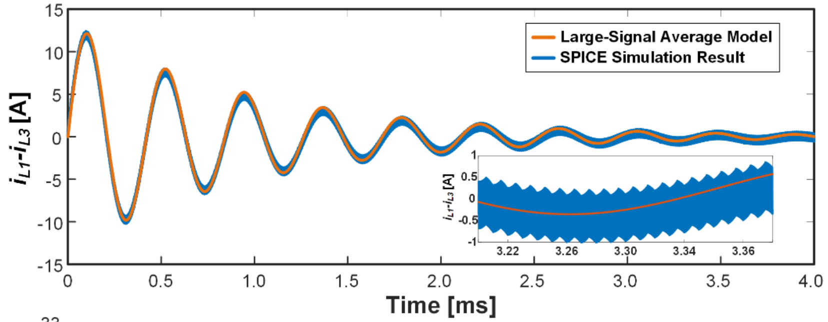


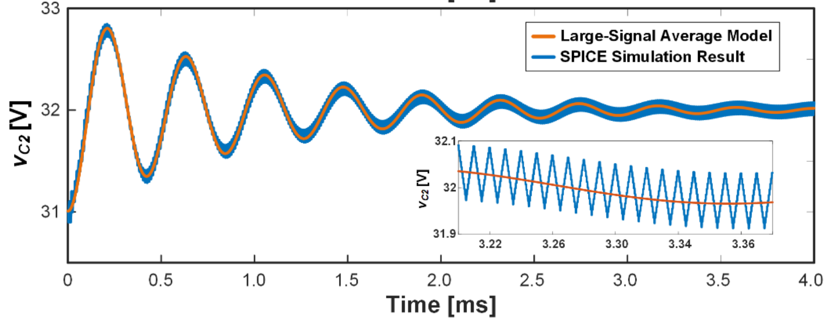
➢ Dynamics of Current Balancing

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

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

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

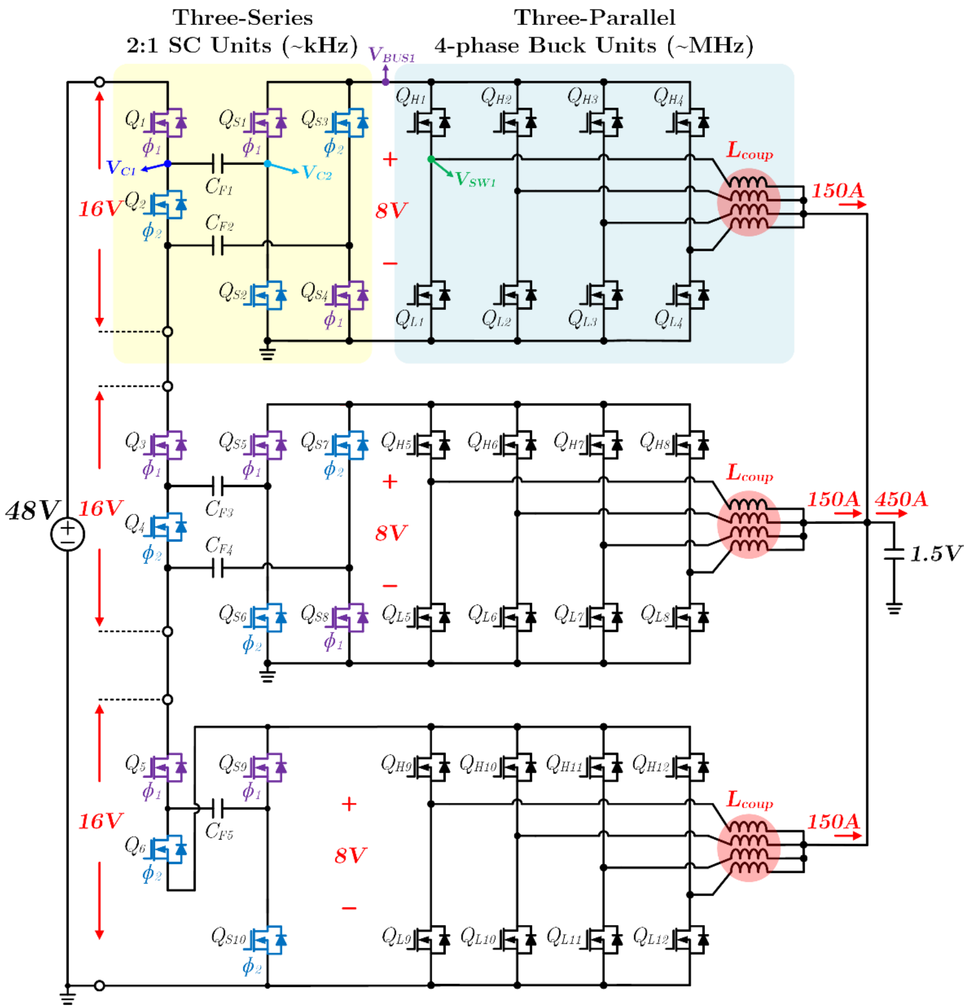


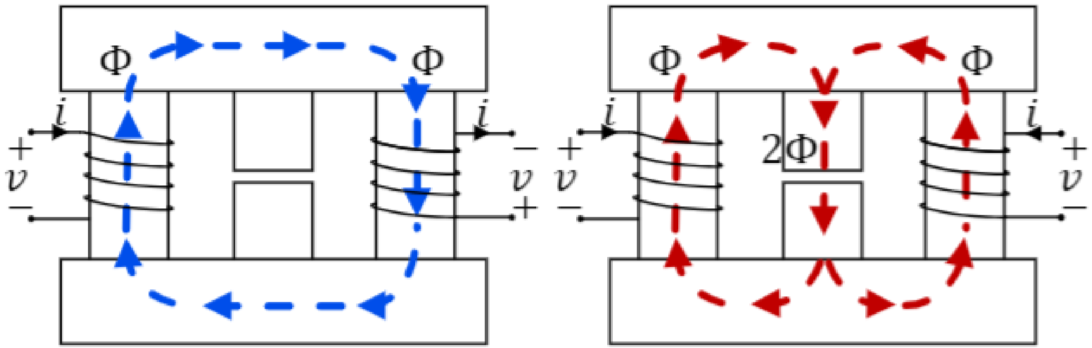


- Inductors soft-charge the switched capacitors
- Automatic current balancing of switched-capacitor circuits
- Low frequency voltage conversion & high frequency regulation

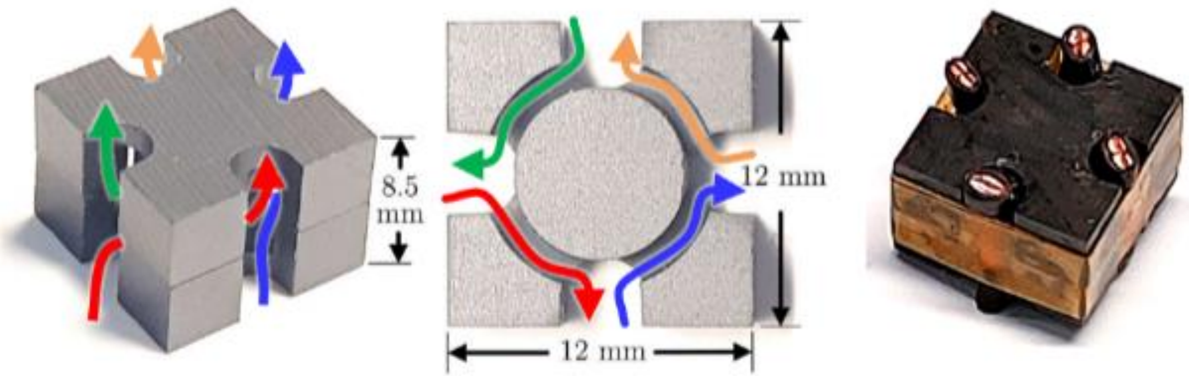
- J. Baek, Y. Elasser, and M. Chen, “3D LEGO-PoL: A 93.3% Efficient 48V-1.5V 450A Merged-Two-Stage Hybrid Switched-Capacitor Converter with 3D Vertical Coupled Inductors,” APEC 2021.

Multiphase Coupled Inductor for Voltage Regulation



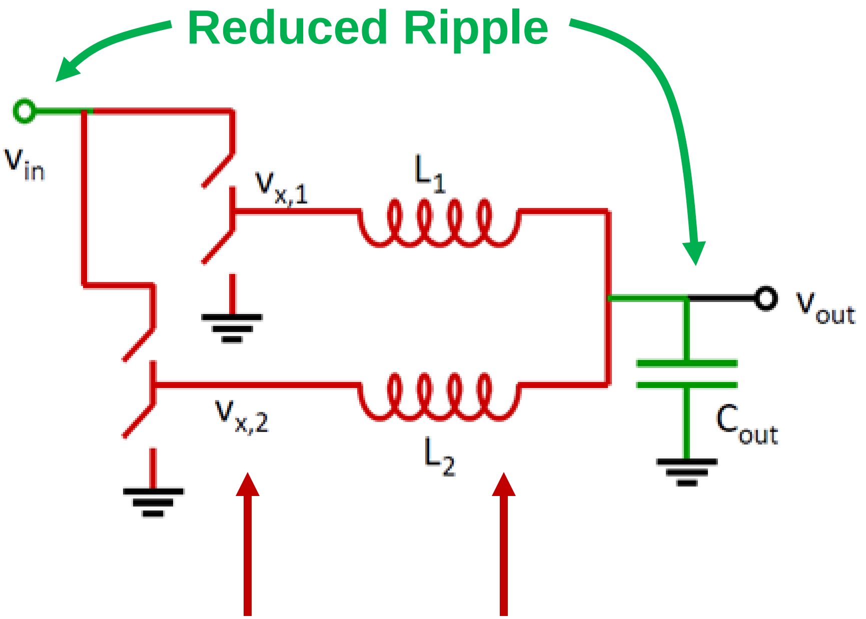


Four Phase Vertical Coupled Inductor

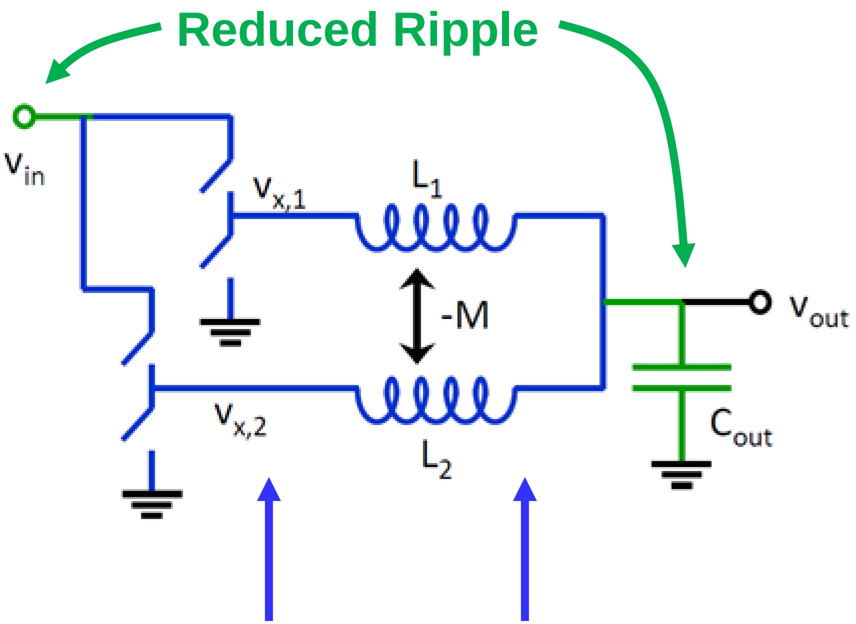


- J. Baek, Y. Elasser, and M. Chen, "3D LEGO-PoL: A 93.3% Efficient 48V-1.5V 450A Merged-Two-Stage Hybrid Switched-Capacitor Converter with 3D Vertical Coupled Inductors," APEC 2021.

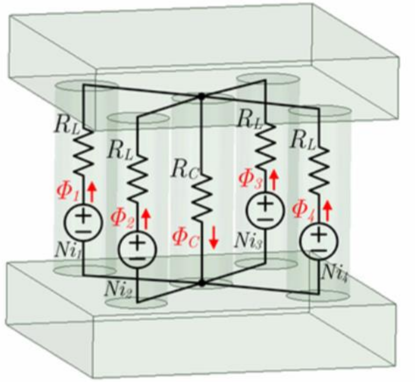
Unified Model for Multiphase Coupled Inductors

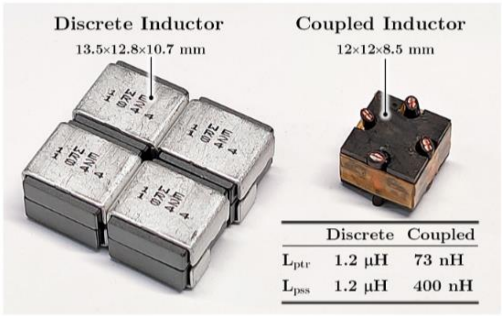


Uncoupled, Same Ripple



Coupled, Reduced Ripple





- Benefits of interleaving

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

- Coupling Coefficient

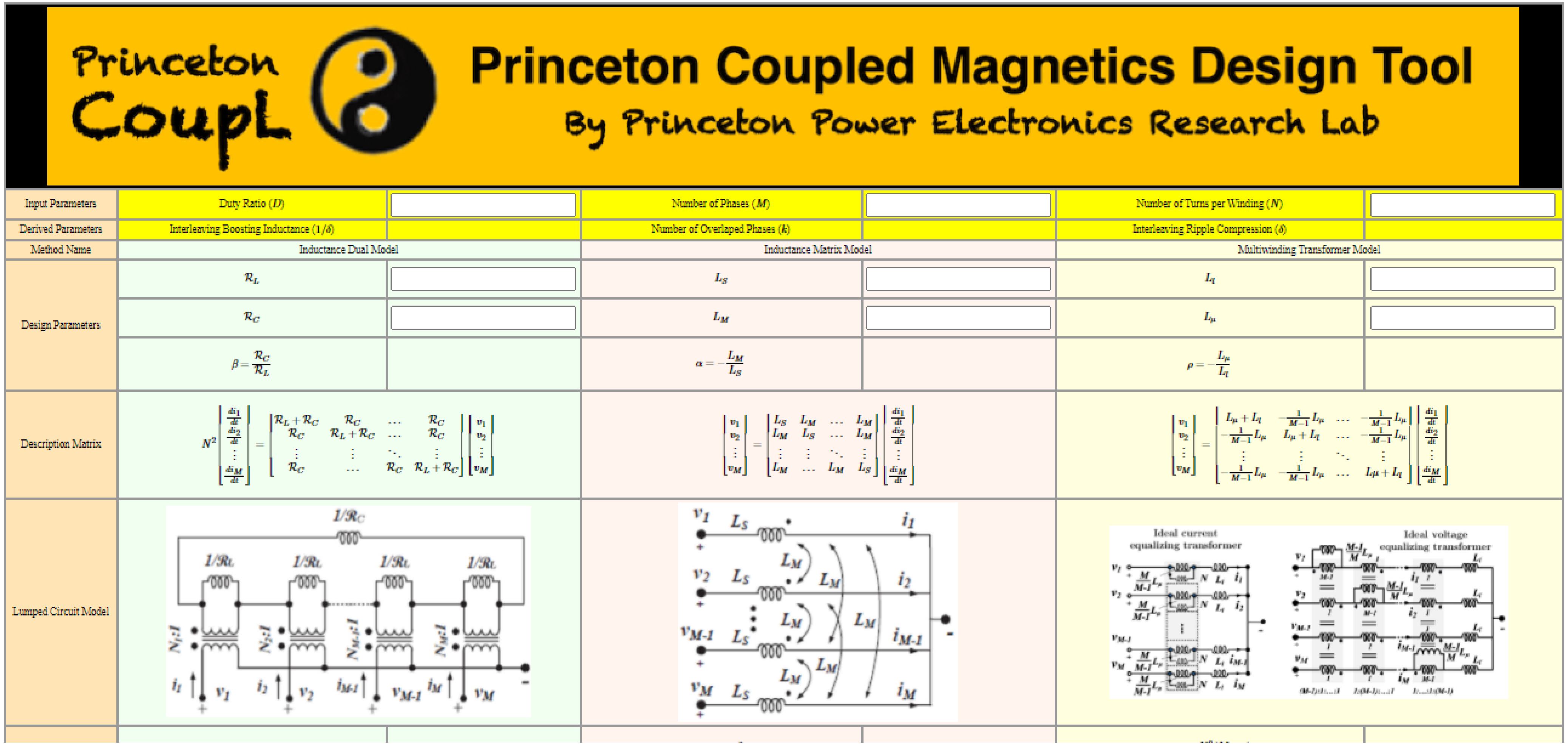
$$\beta = \frac{MR_C}{R_L}$$

- Benefits of Multiphase Coupling

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

- M. Chen and C. R. Sullivan, “Unified Models for Coupled Inductors Applied to Multiphase PWM Converters,” IEEE Transactions on Power Electronics, accepted.

Software Tool for Coupled Inductor Design



- M. Chen and C. R. Sullivan, "Unified Models for Coupled Inductors Applied to Multiphase PWM Converters," IEEE Transactions on Power Electronics, accepted.

3D Stacked Packaging for Vertical Power Delivery

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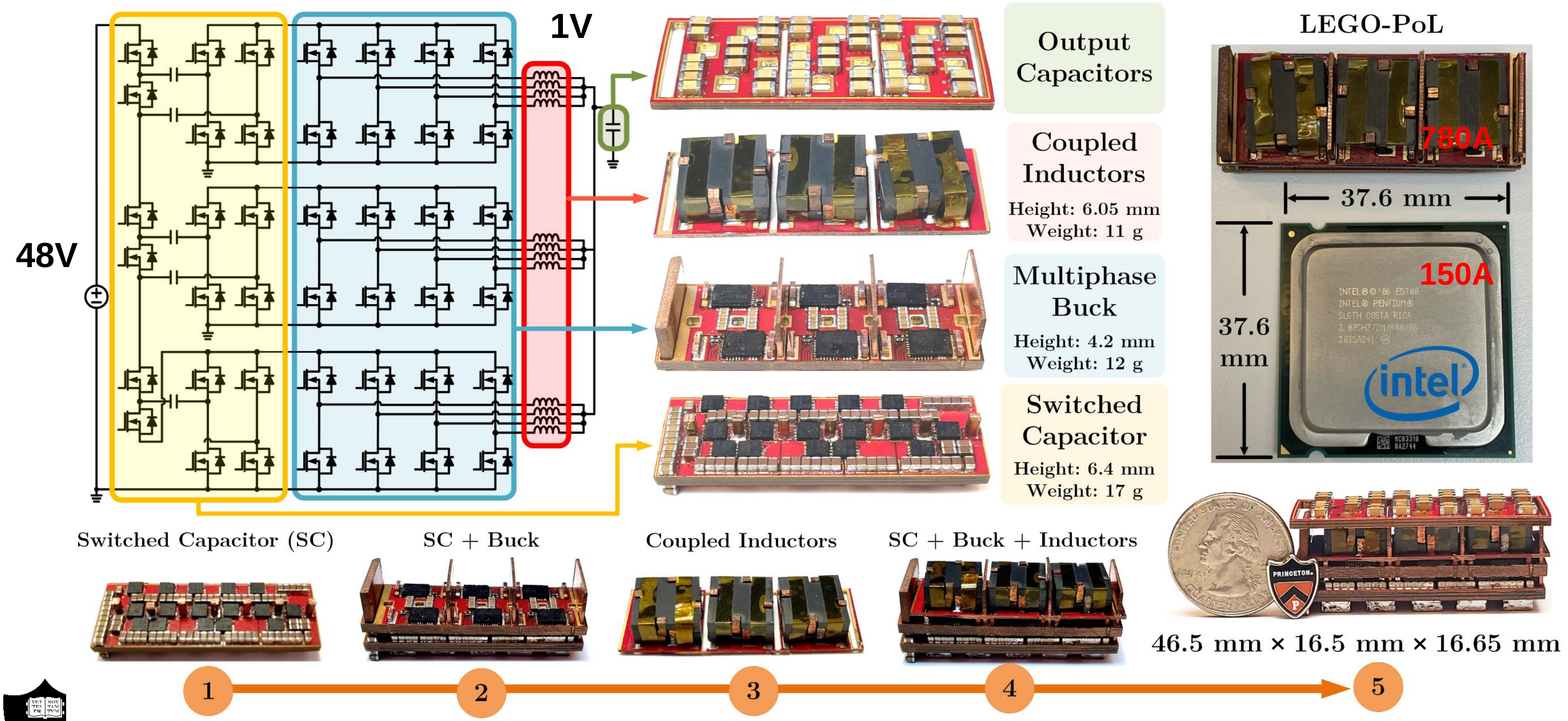
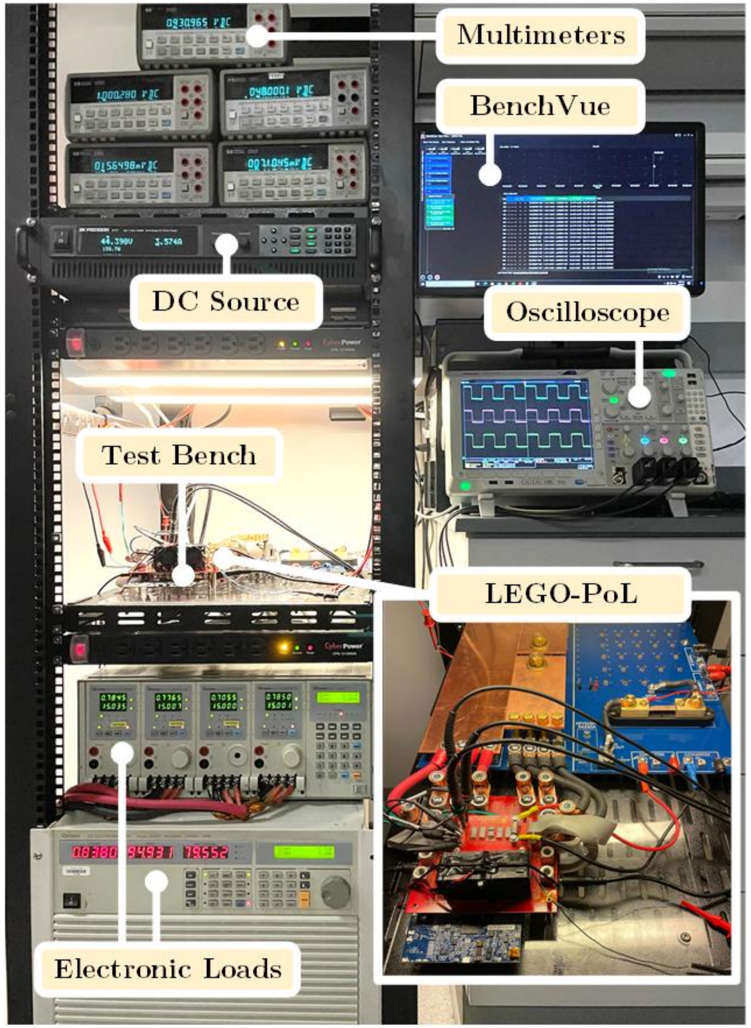
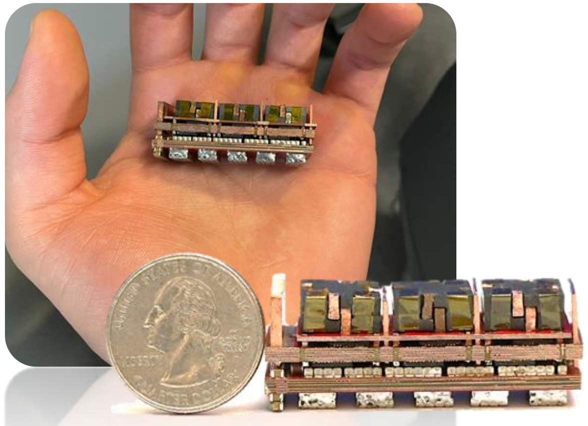


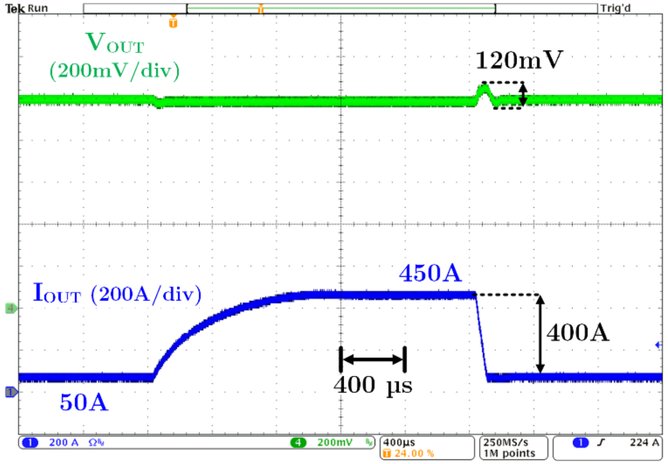
- J. Beak et al., "Vertical Stacked 48V-1V CPU Voltage Regulator with 91.1% Efficiency, 1 A/mm^2 Current Density and 1,000 W/in^3 Power Density", IEEE Transactions on Power Electronics, in preparation.

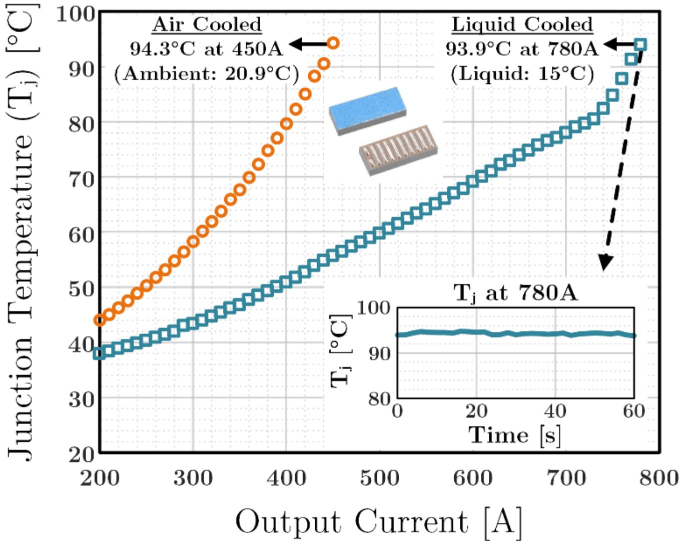
Performance Summary

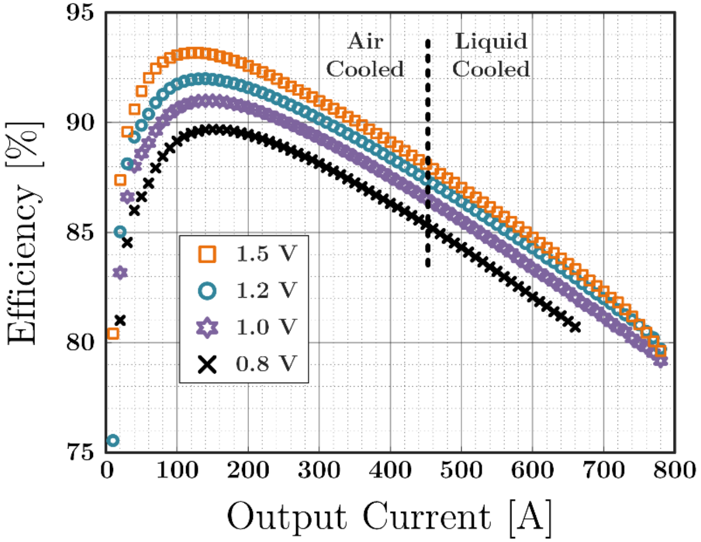




780 A, 1 V, 1 A/mm^2, 1,000 W/in^3







- J. Beak et al., "Vertical Stacked 48V-1V CPU Voltage Regulator with 91.1% Efficiency, 1 A/mm^2 Current Density and 1,000 W/in^3 Power Density", IEEE Transactions on Power Electronics, in preparation.

780 A, 91.1% Peak Efficiency, 1000 W/in^3, 1A/mm^2

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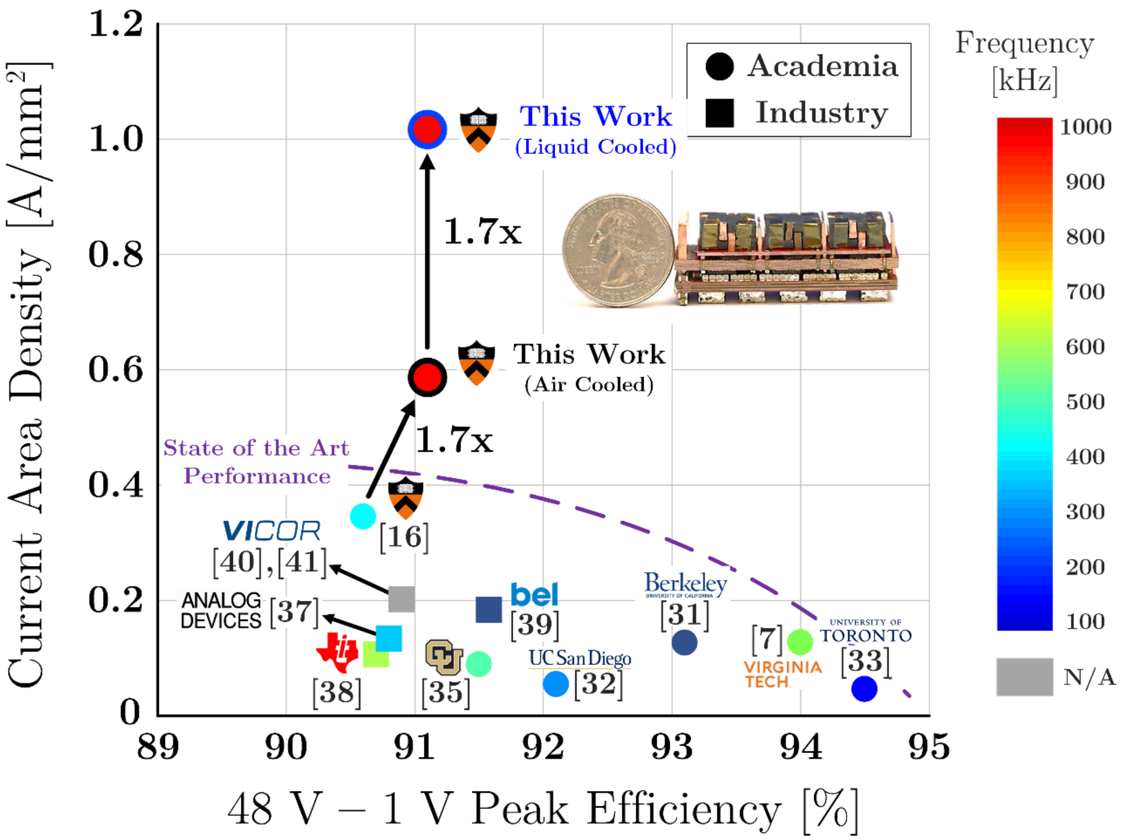
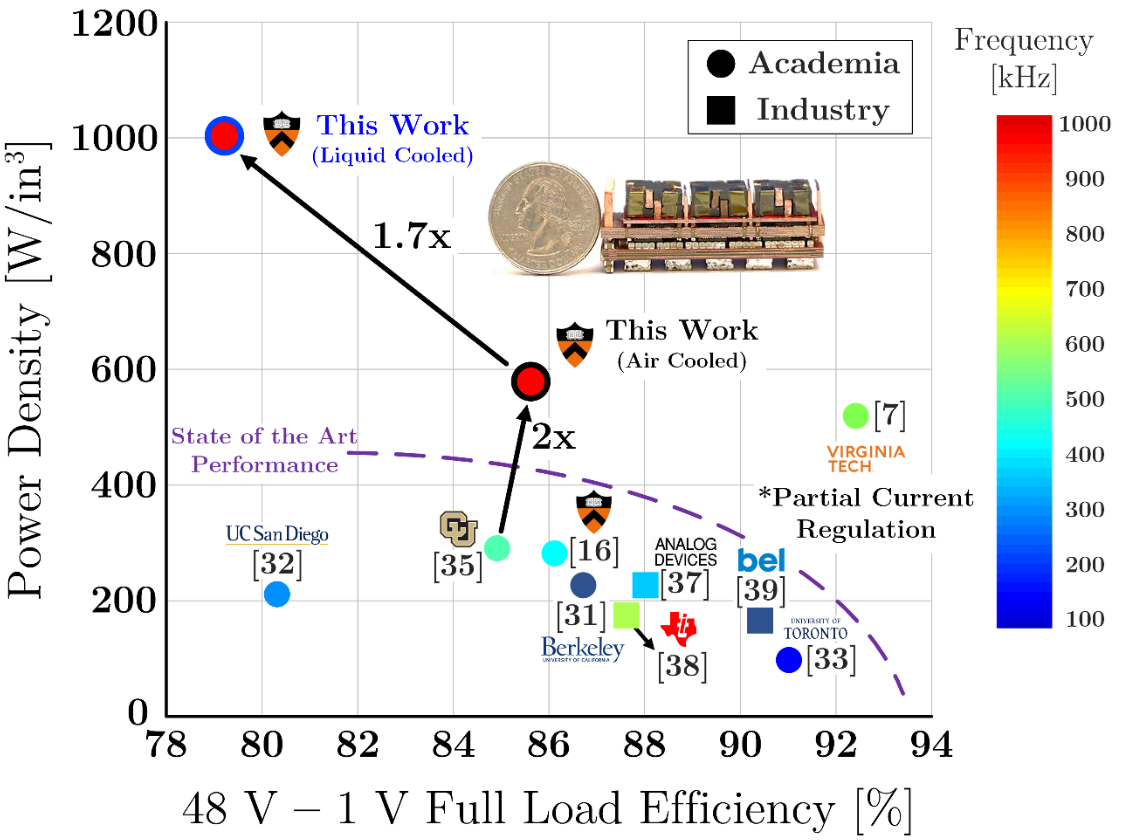
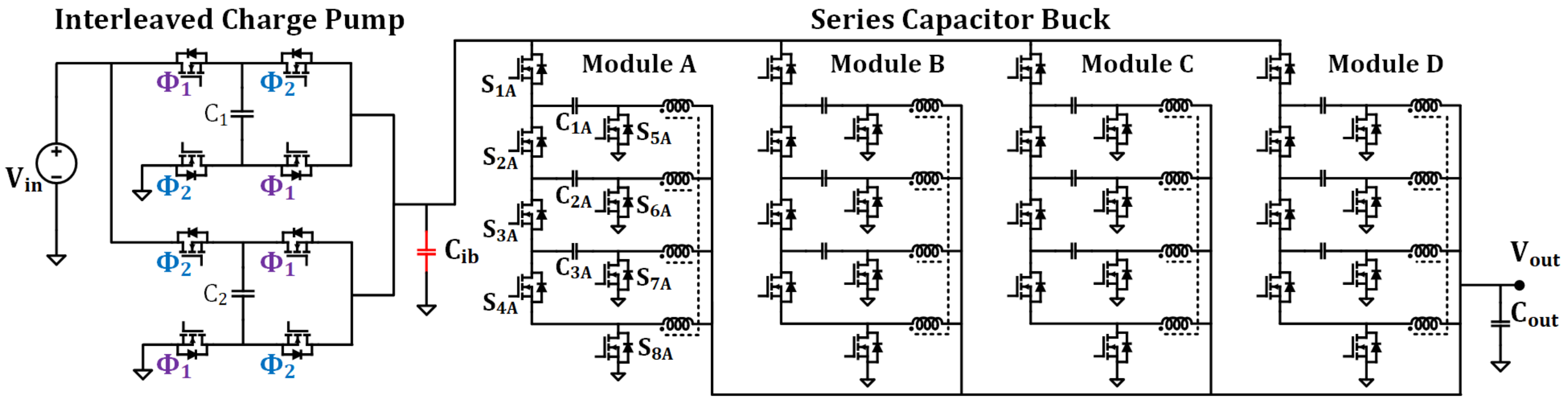


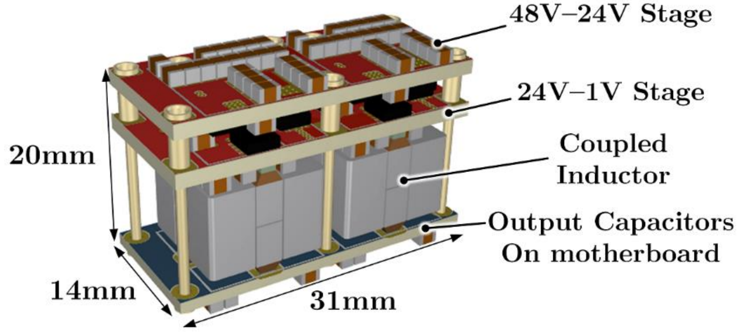


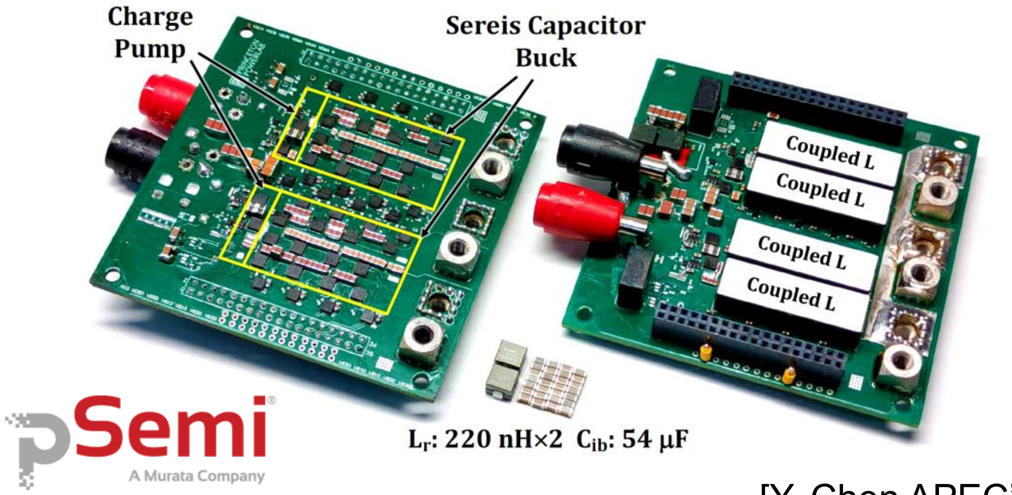
Sponsors & Collaborators: Google intel Dartmouth

- J. Beak et al., "Vertical Stacked 48V-1V CPU Voltage Regulator with 91.1% Efficiency, 1 A/mm^2 Current Density and 1,000 W/in^3 Power Density", IEEE Transactions on Power Electronics, in preparation.

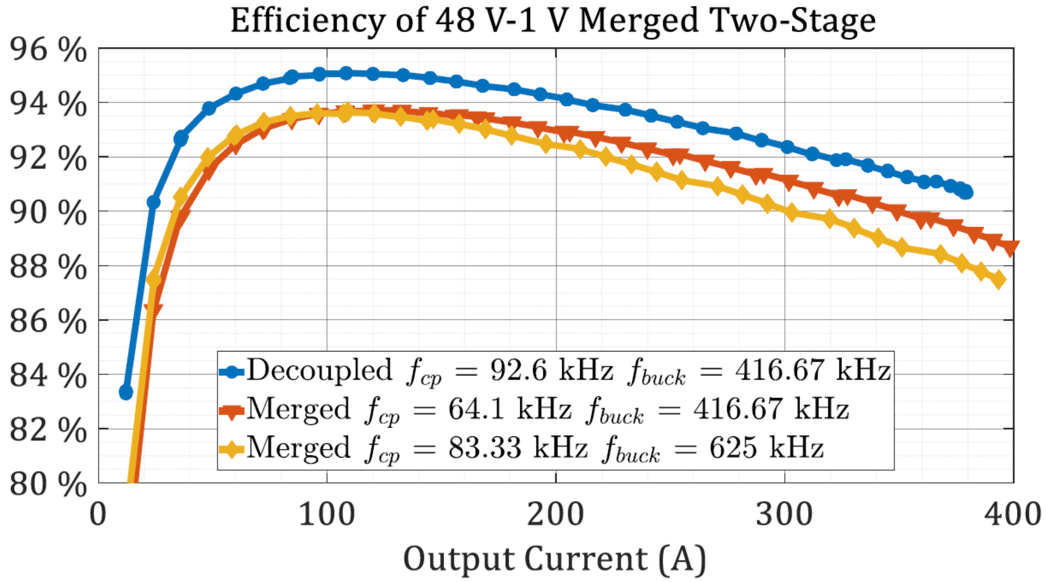
Alternative Designs for Extreme Efficiency







[Y. Chen APEC'21]



A GaN version to further shrink the size

- Y. Chen, H. Cheng, D. Giuliano, M. Chen, "A 93.7% Efficient 400A 48V-1V Merged-Two-Stage Hybrid Switched-Capacitor Converter with 24V Virtual Intermediate Bus and Coupled Inductors," APEC 2021.

Architectures to Unlock the Potential of WBG Devices

- **Extreme Performance: Hybrid-Switched-Capacitor Architecture**
  Extreme Performance CPU Voltage Regulators
- **Sophisticated Functions: Control of MIMO Power Flow**
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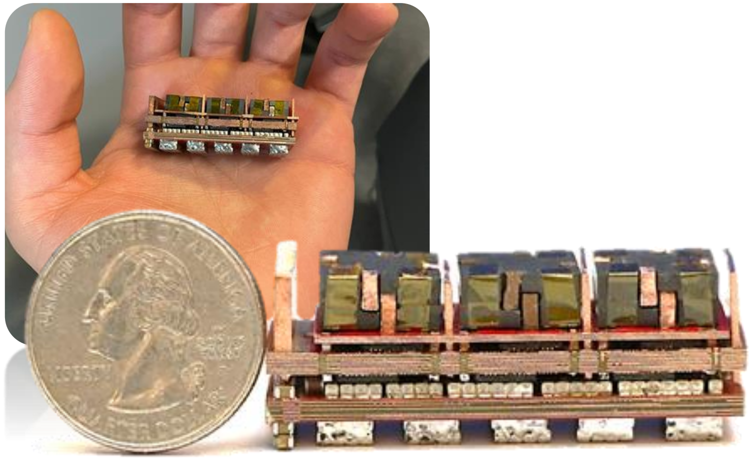
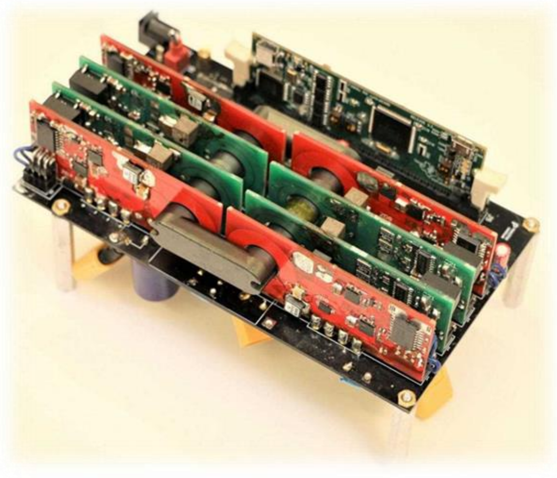
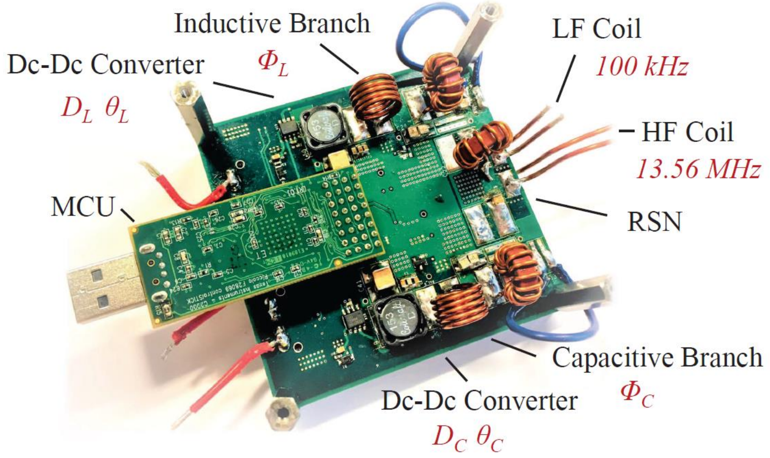


CPU Voltage Regulator



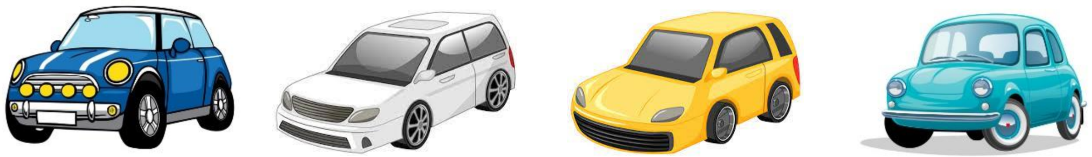
MIMO Energy Router



Dual-Band Wireless Power Transfer

Large Scale Modular Energy Systems

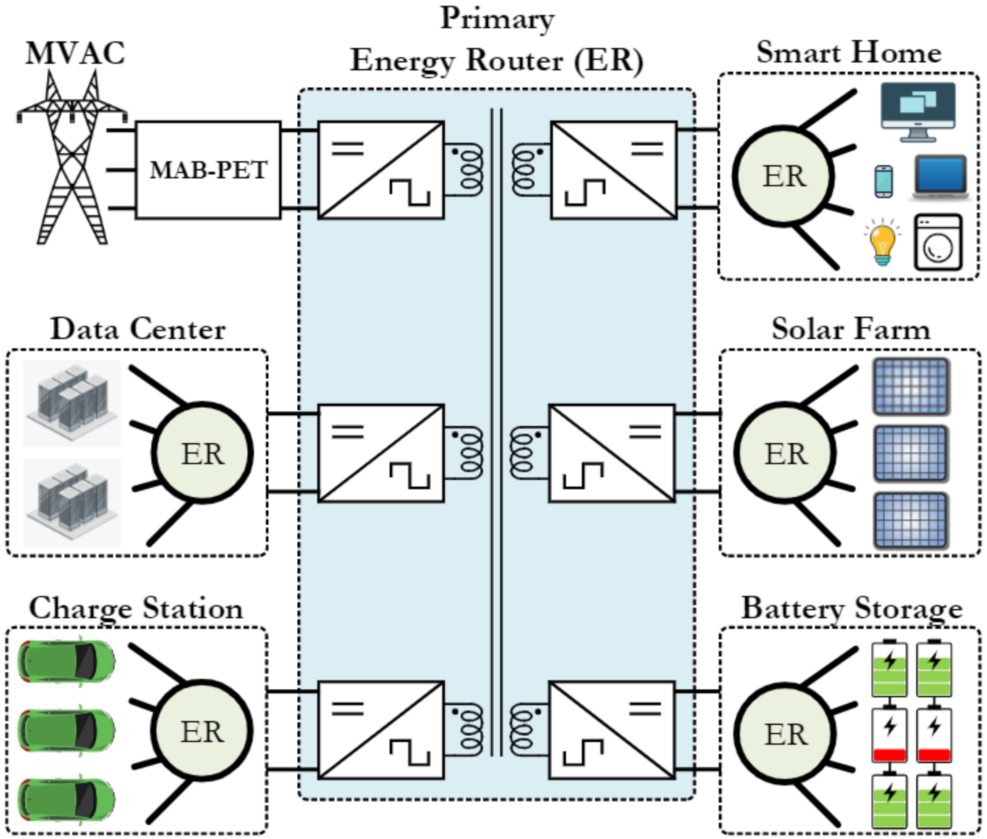
Individual Converters



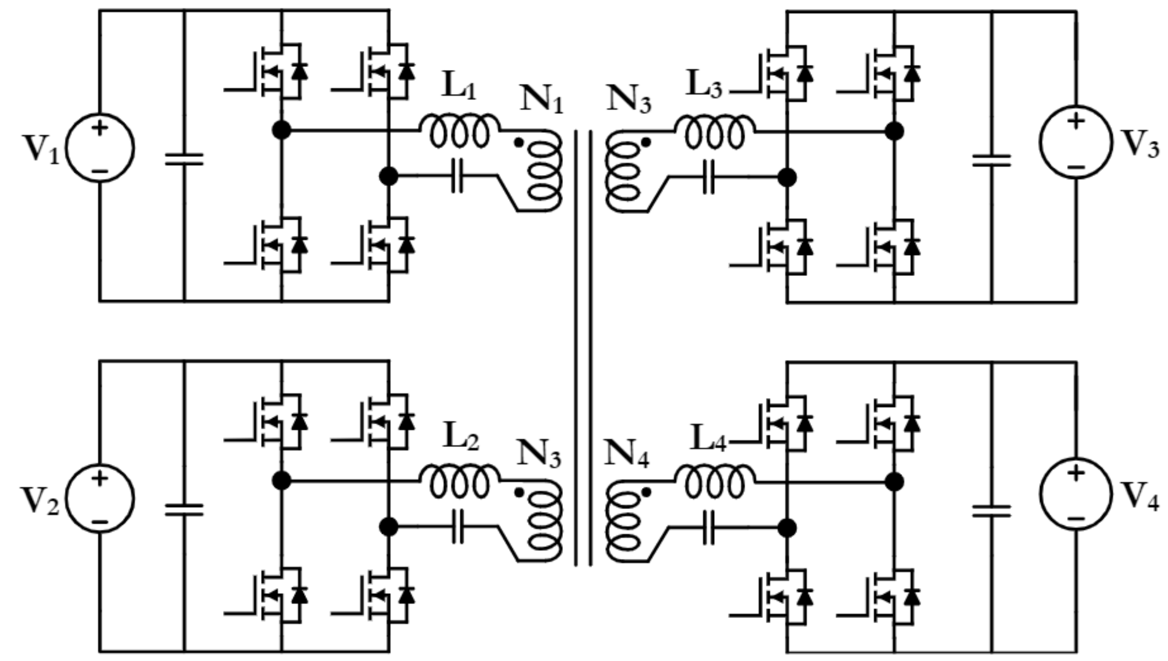
MIMO Power Management

- Efficiency
- Density
- Weight
- Cost

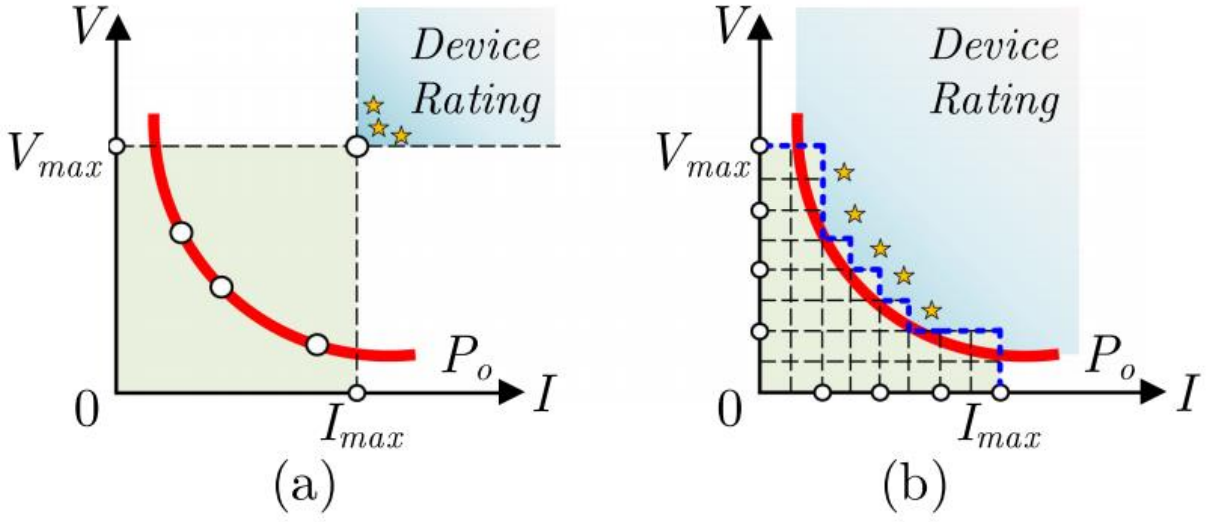
MIMO Energy Router (ER) for Modular Loads



Flexible Programmable Granular Adaptive (FPGA)



Flexible Programmable Granular Adaptive (FPGA)

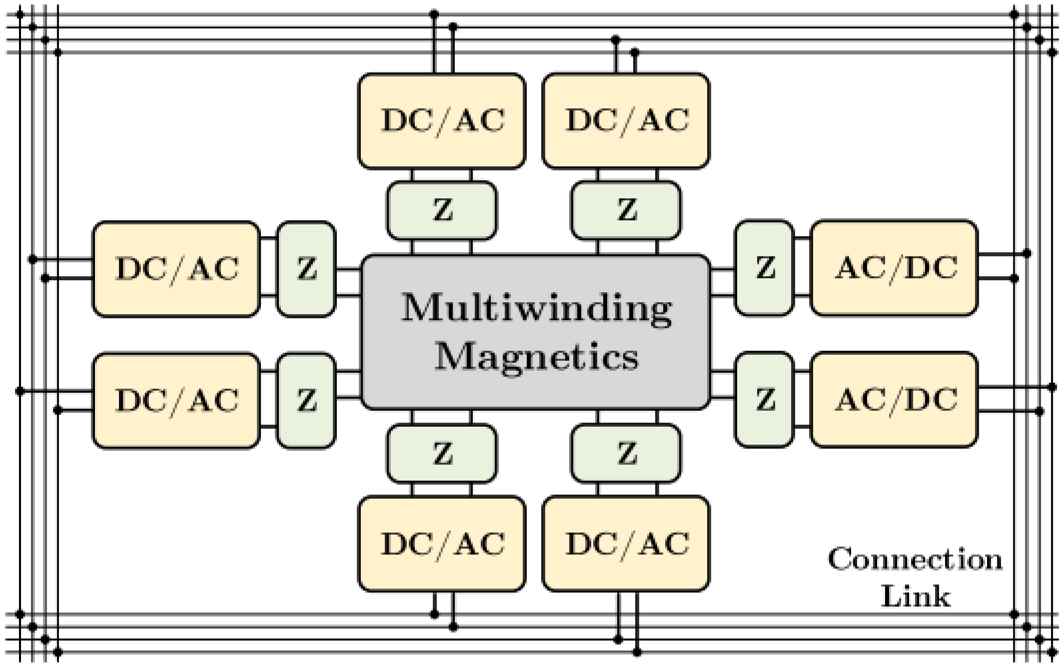


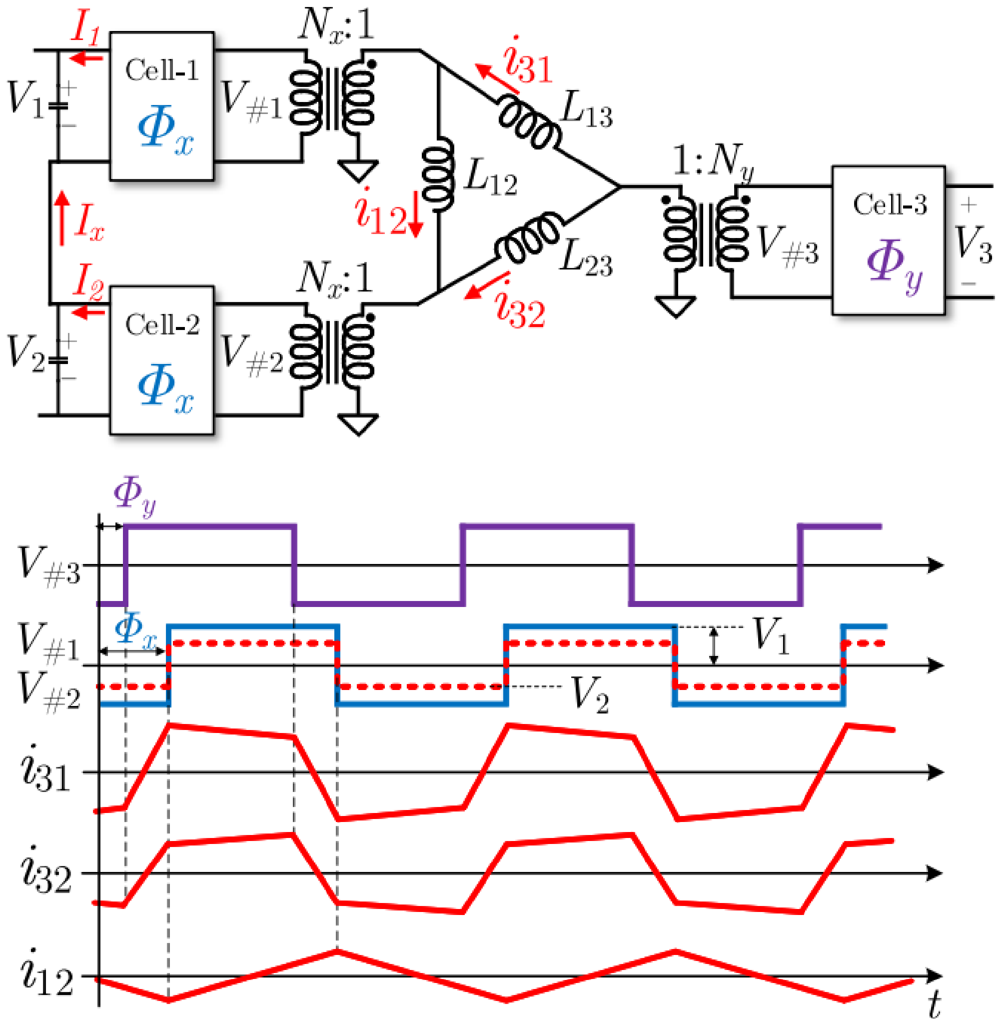
- MIMO power flow are highly dynamic
- Dynamically allocate power processing capability to different ports?

- Reconfiguration cells
- Sophisticated power flow
- Precise modeling and control

- P. Wang and M. Chen, “Towards Power FPGA: Architecture, Modeling and Control of Multiport Power Converters,” IEEE COMPEL, Padua, Italy, June 2018.

Reconfigurable Multicell MIMO Energy Router

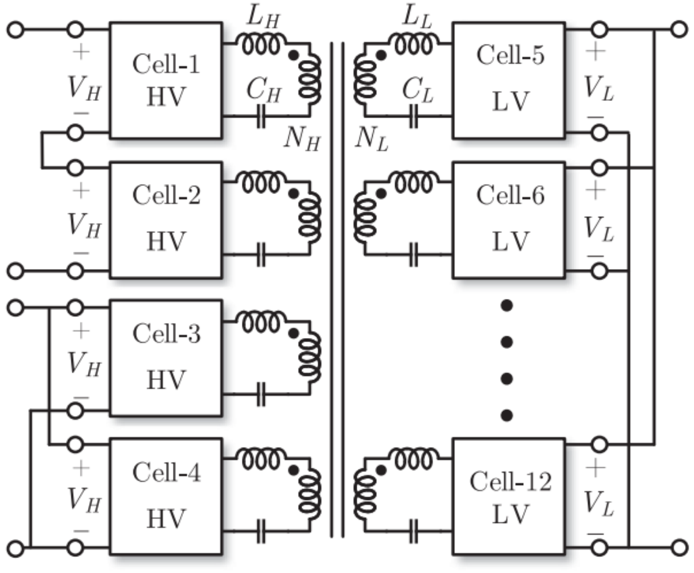


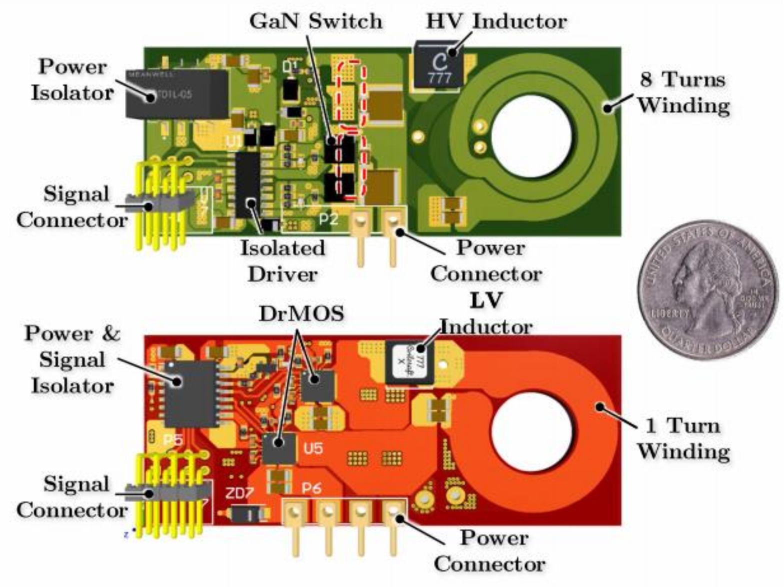


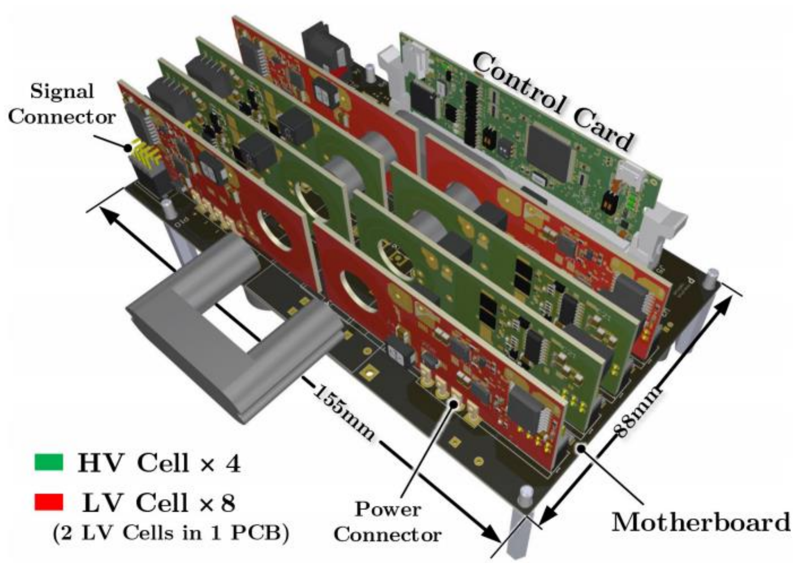
- Granular dc-ac building blocks as the "core"
- Magnetics as a central power processor "memory"
- Manage power in dc-domain instead of ac-domain
- Switch timing is important – WBG devices

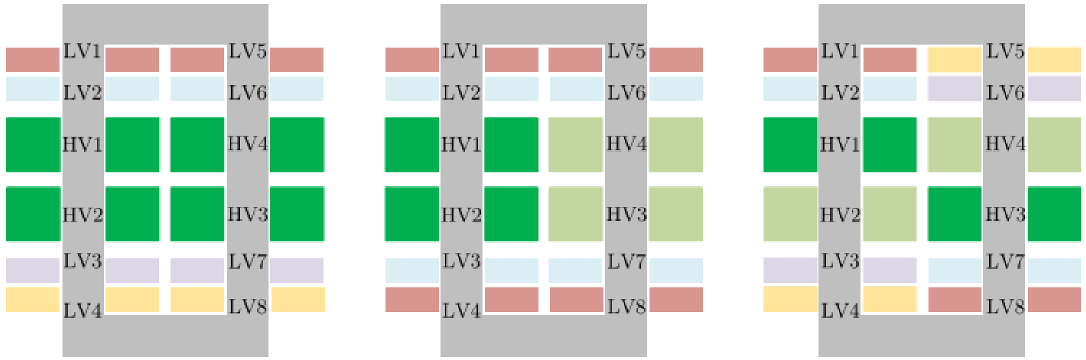
- Y. Chen, P. Wang, Y. Elasser, M. Chen, "Multicell Reconfigurable Multi-Input Multi-Output Energy Router Architecture," IEEE Transactions on Power Electronics, Dec. 2020.

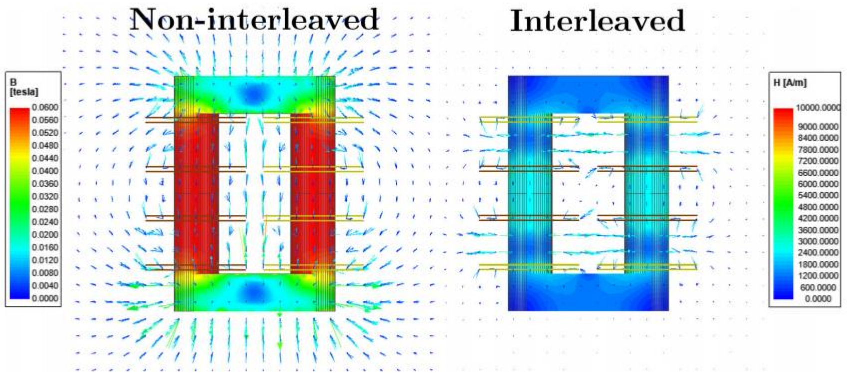
Reconfigurable Multicell MIMO Energy Router





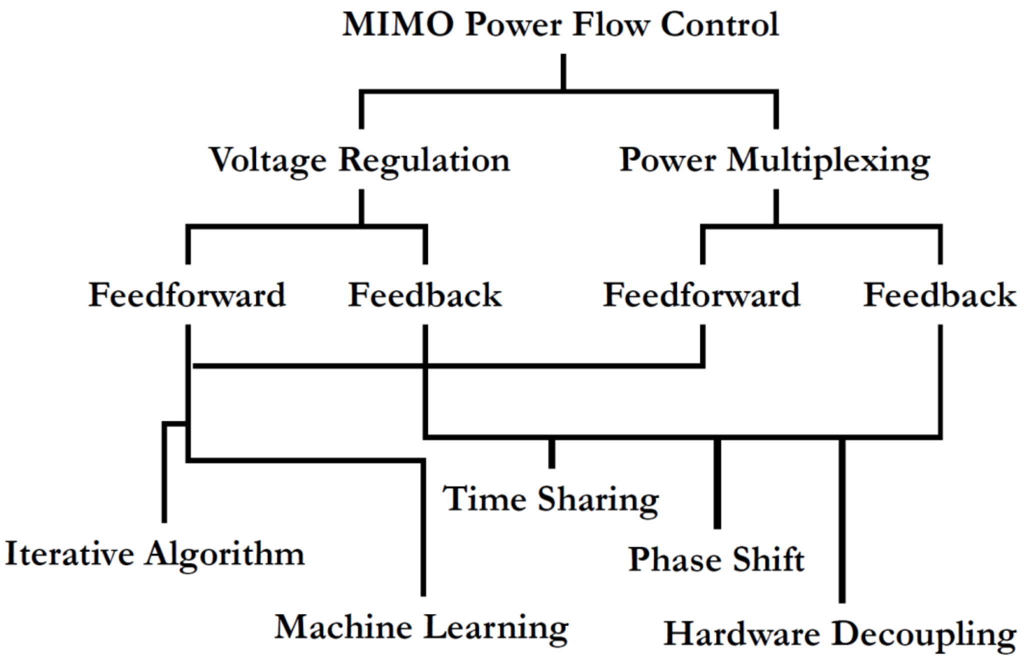


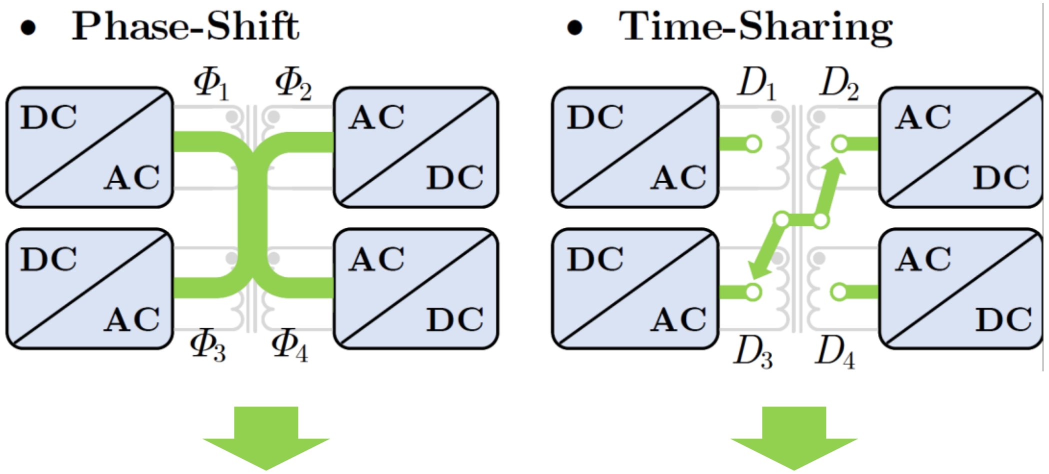




- Y. Chen, P. Wang, Y. Elasser, M. Chen, “Multicell Reconfigurable Multi-Input Multi-Output Energy Router Architecture,” IEEE Transactions on Power Electronics, Dec. 2020.

MIMO Power Flow Control Strategy



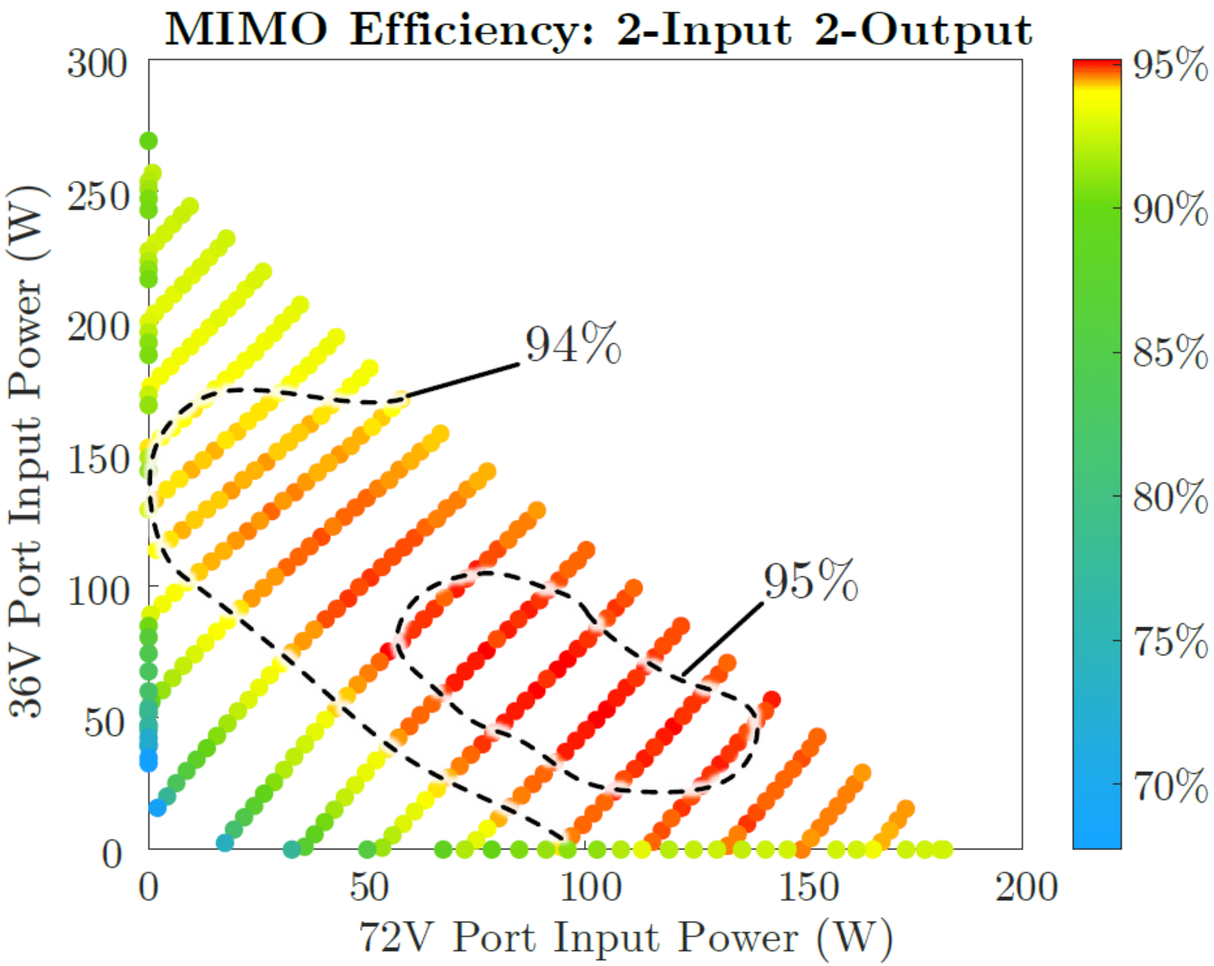


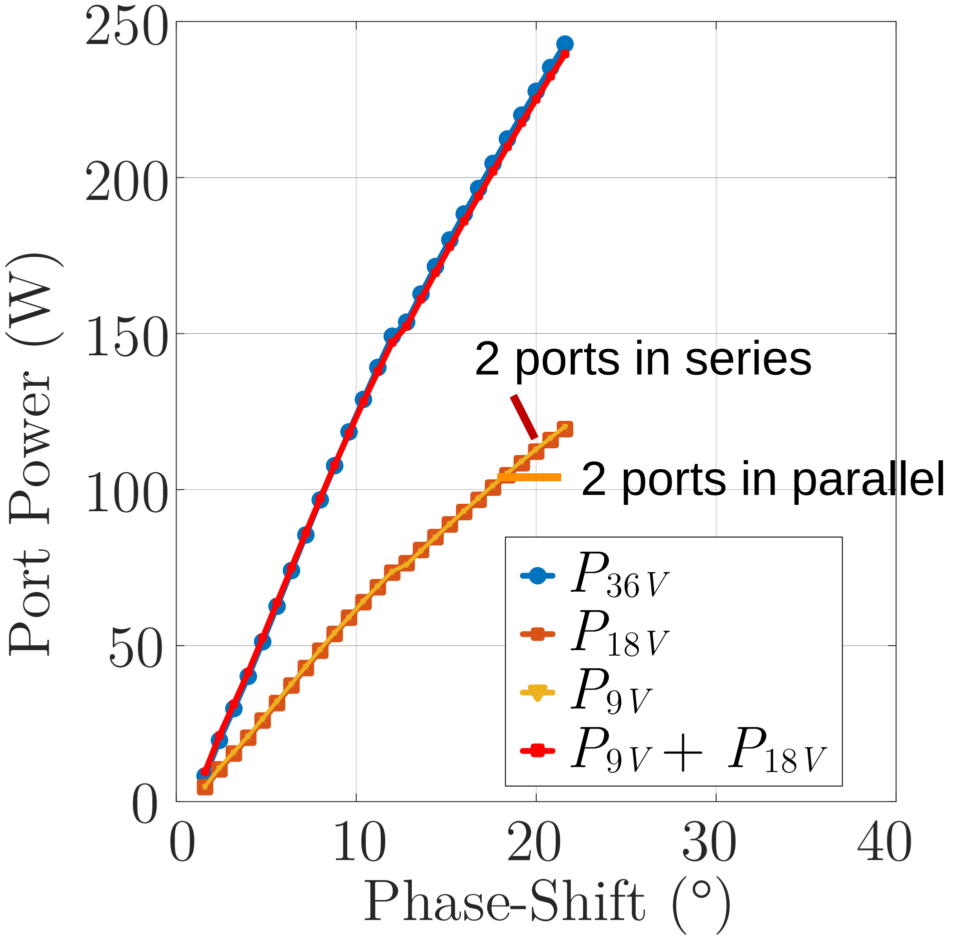
- Partly decoupled
- High scalability
- High power throughput

- Fully decoupled
- Limited scalability
- Limited power throughput

- P. Wang and M. Chen, “Towards Power FPGA: Architecture, Modeling and Control of Multiport Power Converters,” IEEE 19th Workshop on Control and Modeling for Power Electronics (COMPEL), Padova, 2018, pp. 1-8.
- Y. Chen, P. Wang, H. Li and M. Chen, “Power Flow Control in Multi-Active-Bridge Converters: Theories and Applications,"2019 IEEE Applied Power Electronics Conference and Exposition (APEC), Anaheim, CA, USA, 2019, pp. 1500-1507.
- Bhattacharjee, A. K., Kutkut, N., and Batarseh, I. “Review of Multiport Converters for Solar and Energy Storage Integration,” IEEE Transactions on Power Electronics, 2007, 34, (2), pp. 1431-1445.

Performance of the MIMO Energy Router





- Y. Chen, P. Wang, Y. Elasser, M. Chen, "Multicell Reconfigurable Multi-Input Multi-Output Energy Router Architecture," IEEE Transactions on Power Electronics, Dec. 2020.

Operation Sensitive to Switch Timing

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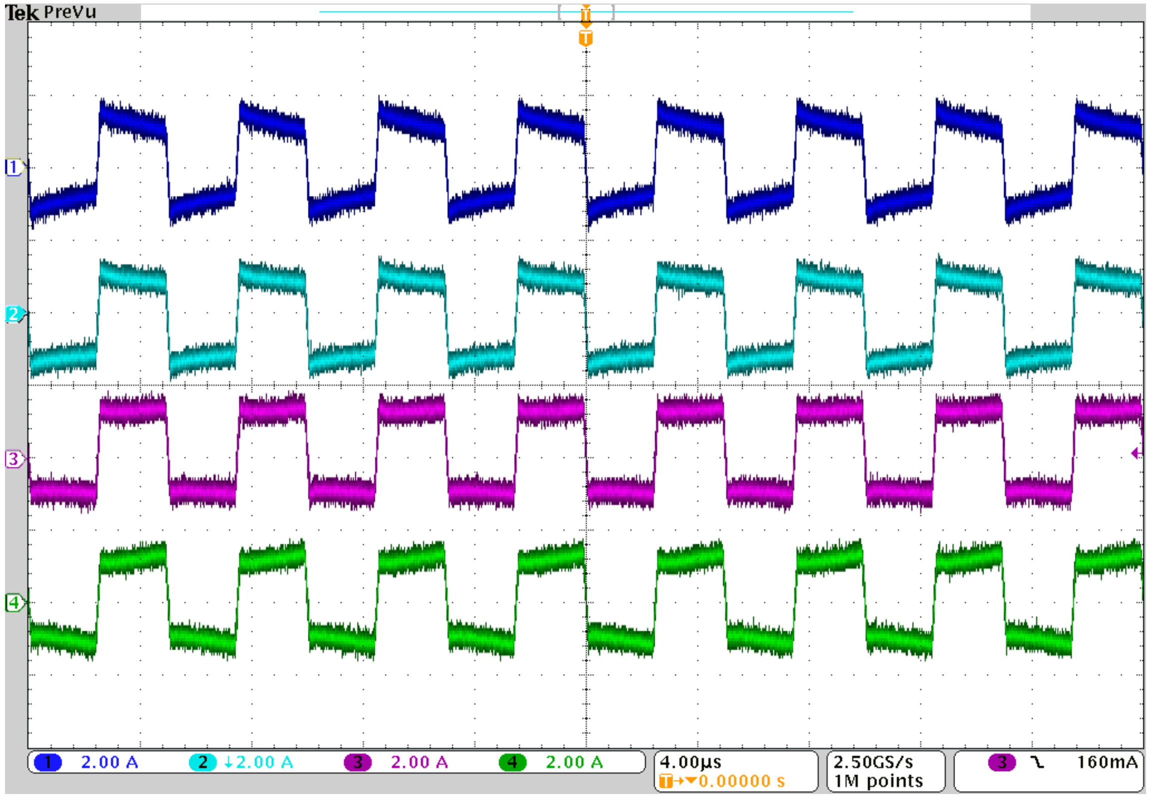
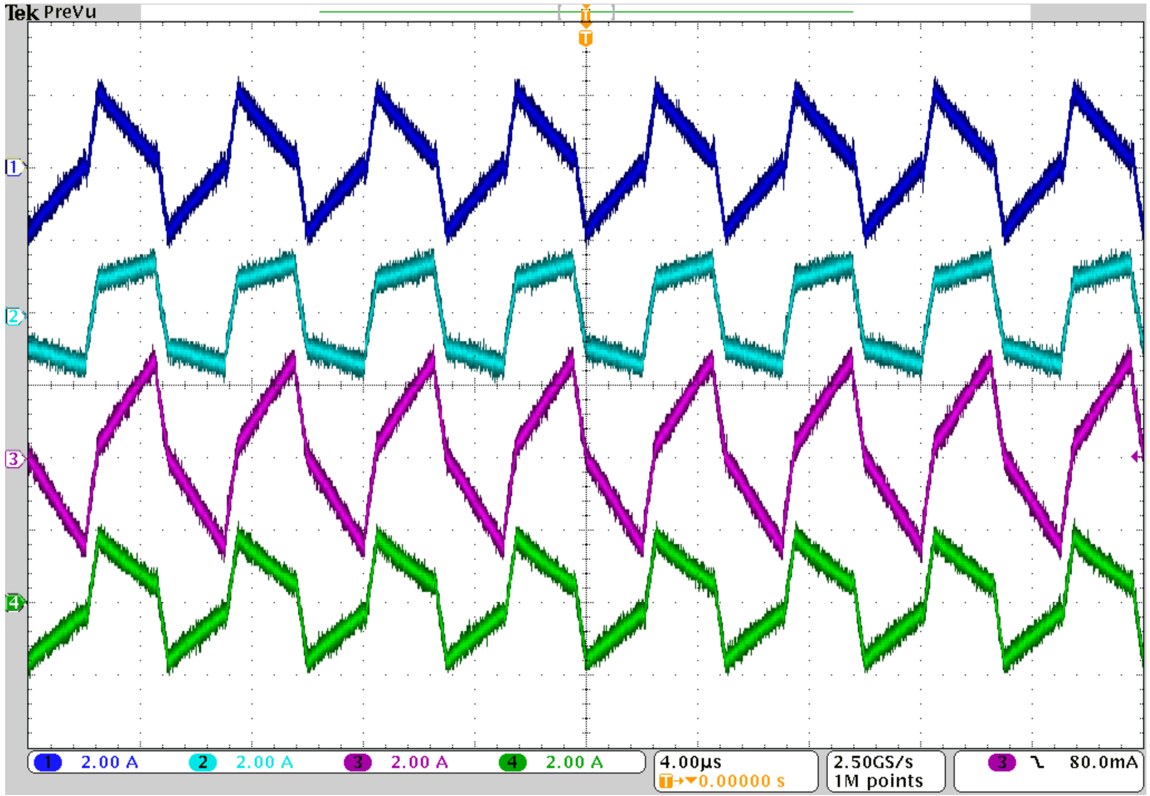
Operating Condition #1



Operating Condition #2

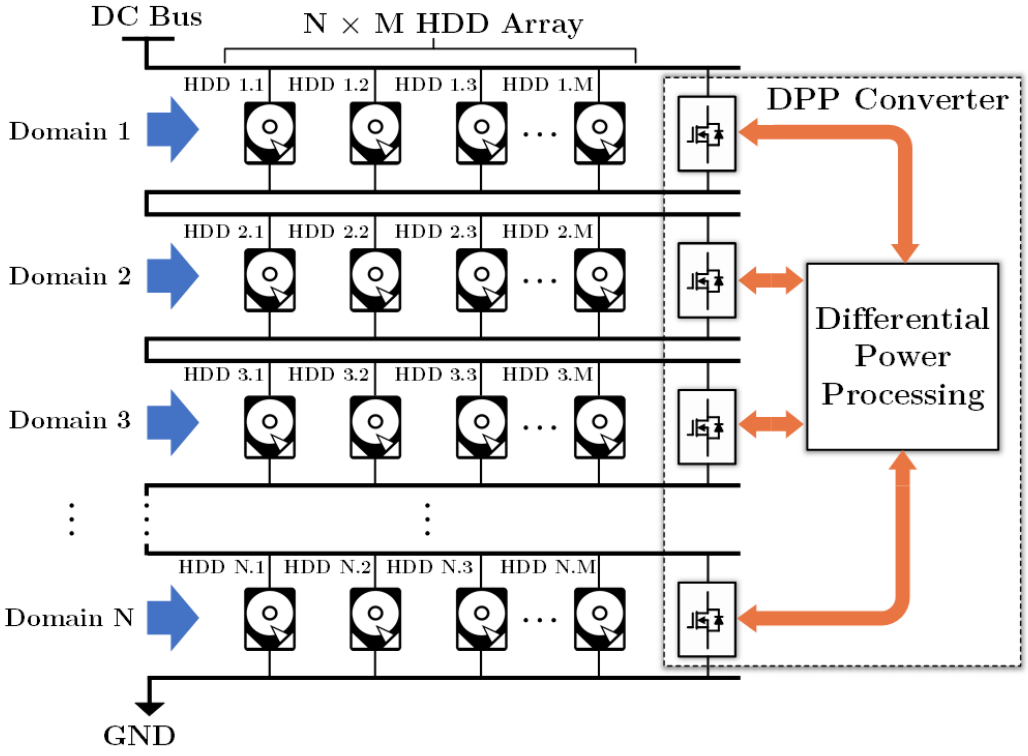


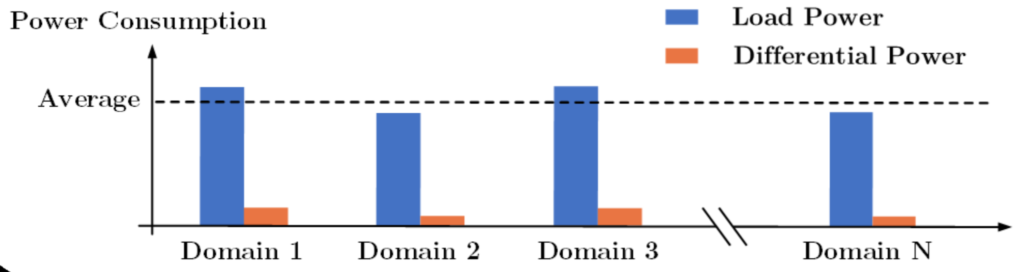
Switching Frequency: 200 kHz

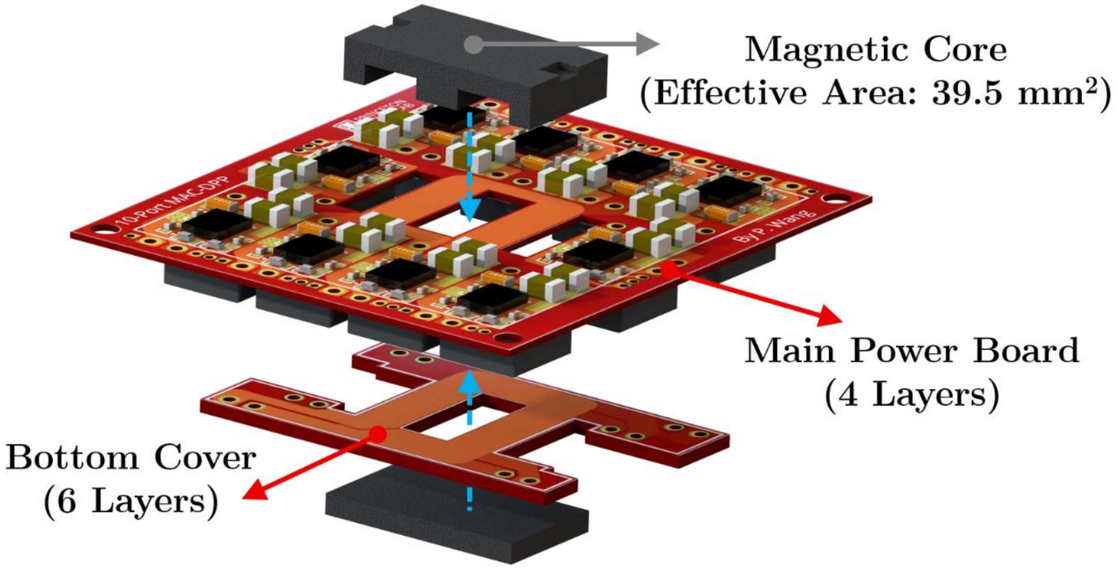
- Y. Chen, P. Wang, Y. Elasser, M. Chen, “Multicell Reconfigurable Multi-Input Multi-Output Energy Router Architecture,” IEEE Transactions on Power Electronics, Dec. 2020.

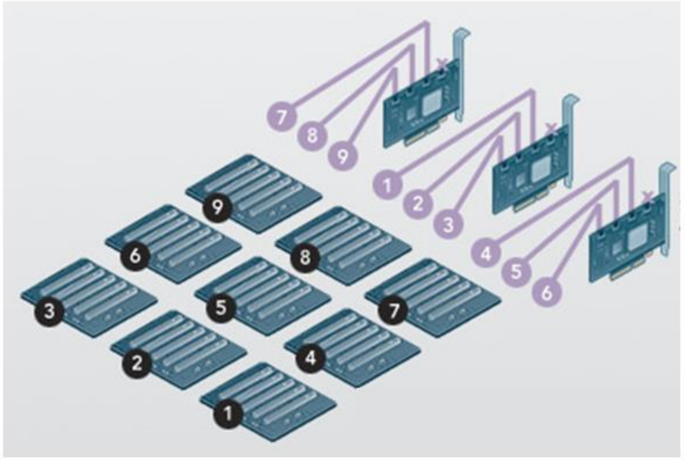
Differential Power Processing for Data Storage

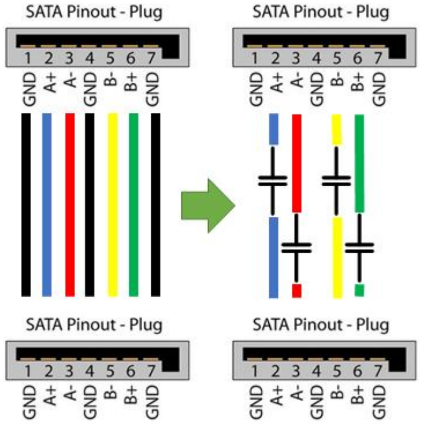
PRINCETON UNIVERSITY







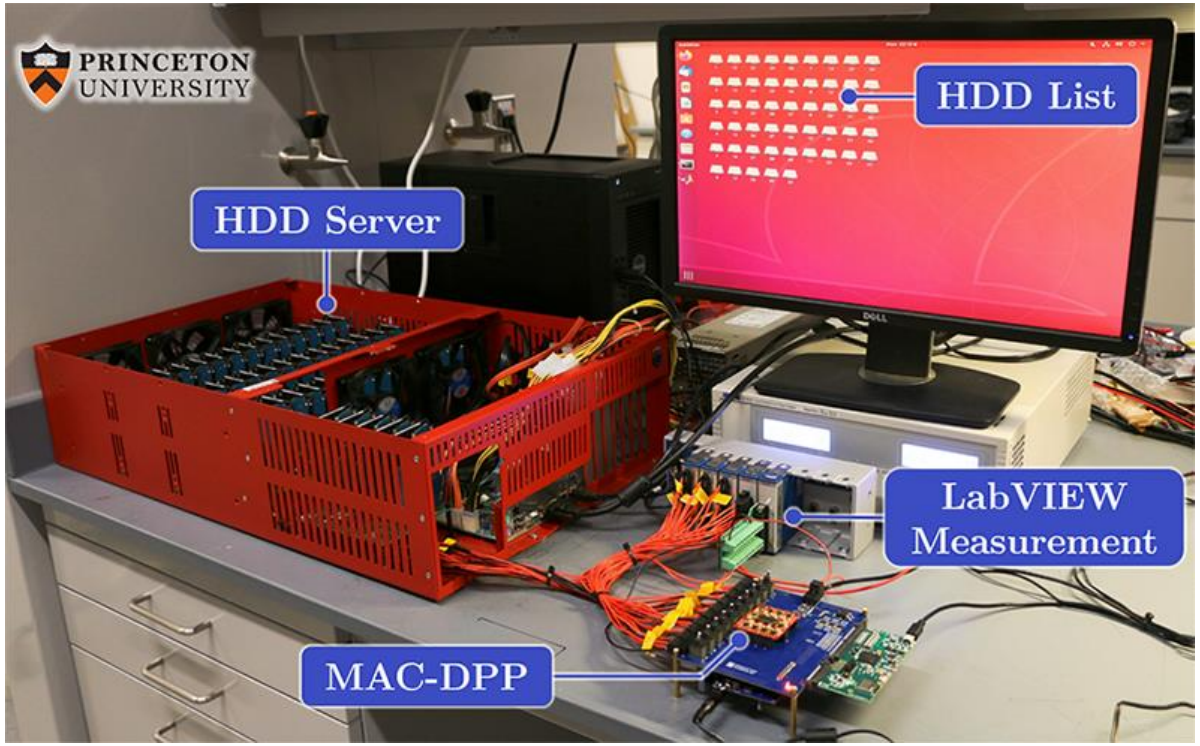


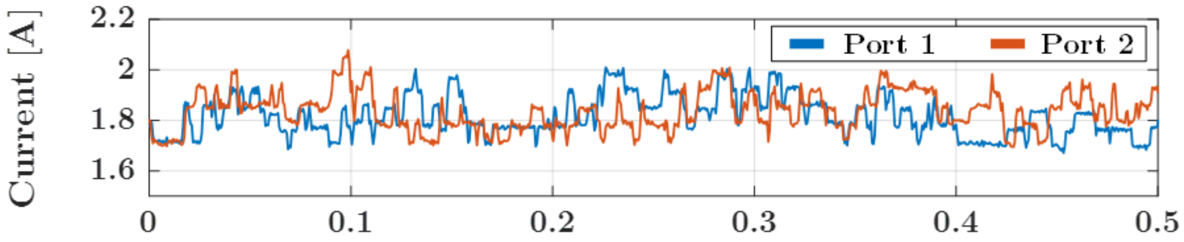


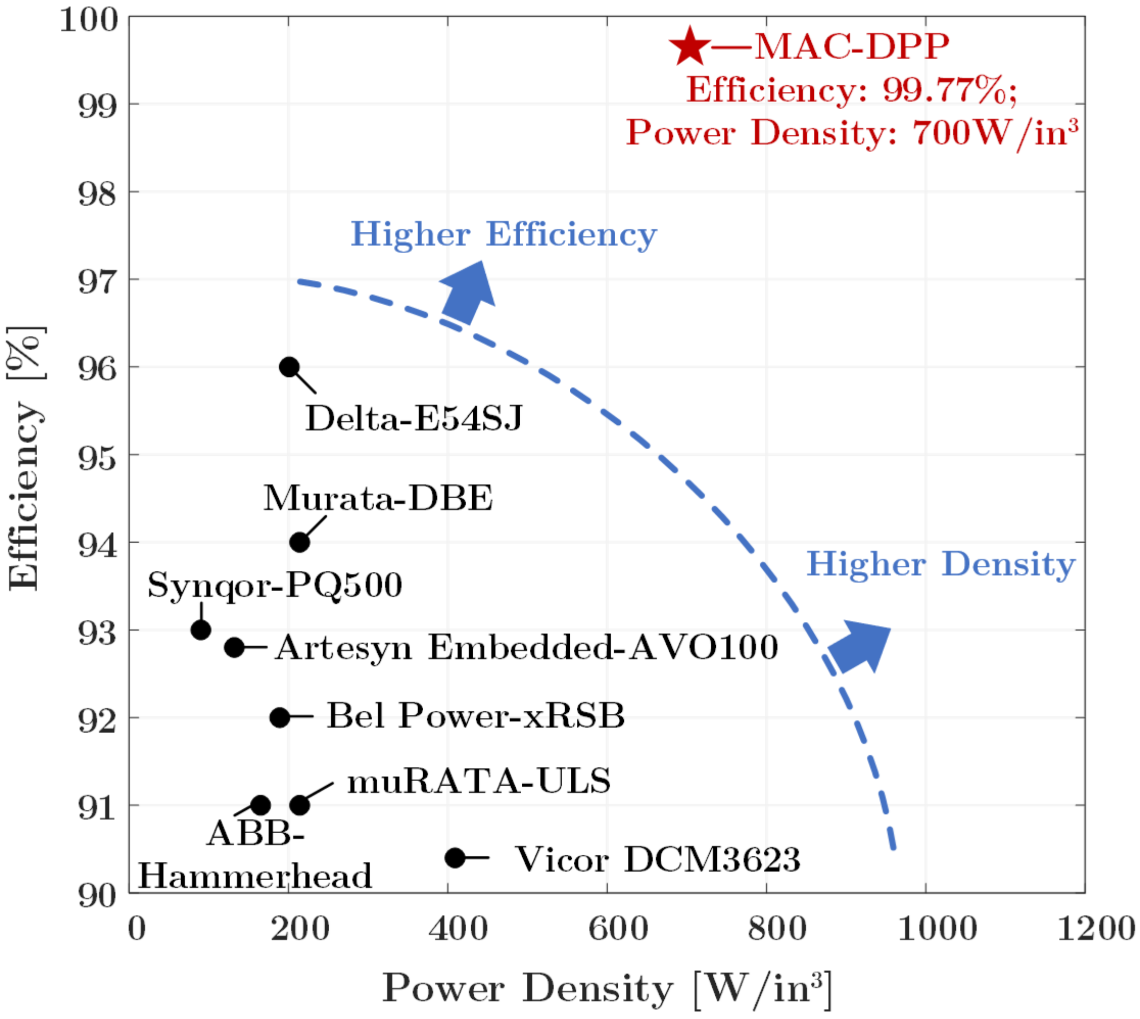
- P. Wang, Y. Chen, J. Yuan, R. C. N. Pilawa-Podgurski, M. Chen, "Differential Power Processing for Ultra-Efficient Data Storage," IEEE Transactions on Power Electronics, April 2021.

Differential Power Processing for Data Storage

PRINCETON UNIVERSITY

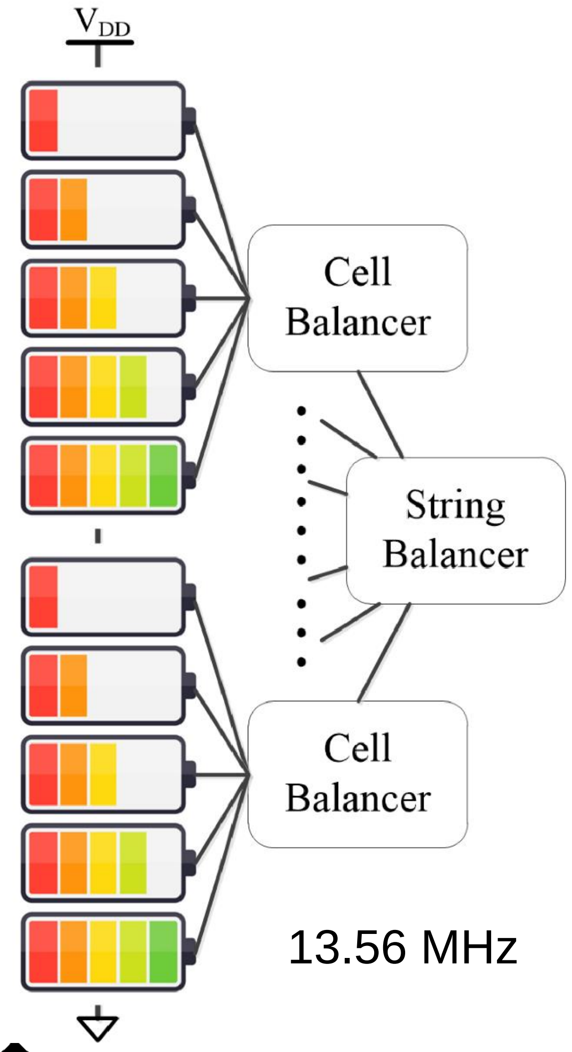


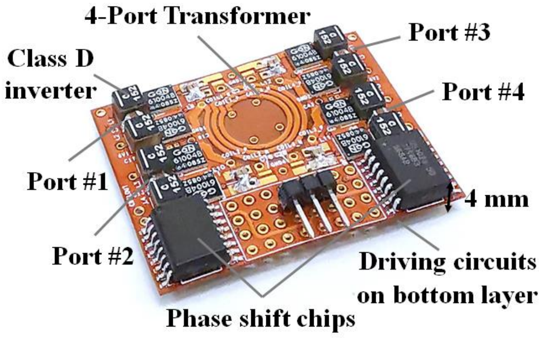


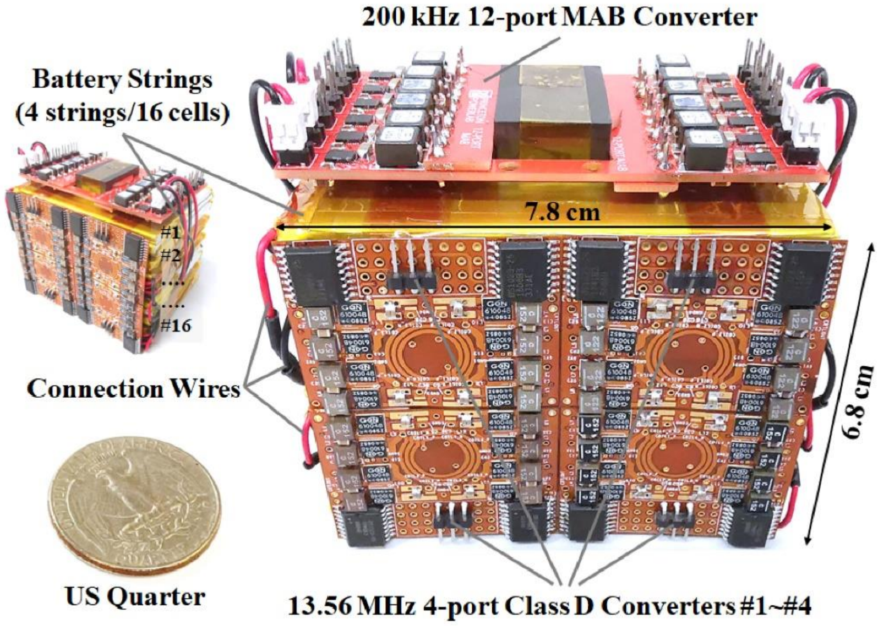


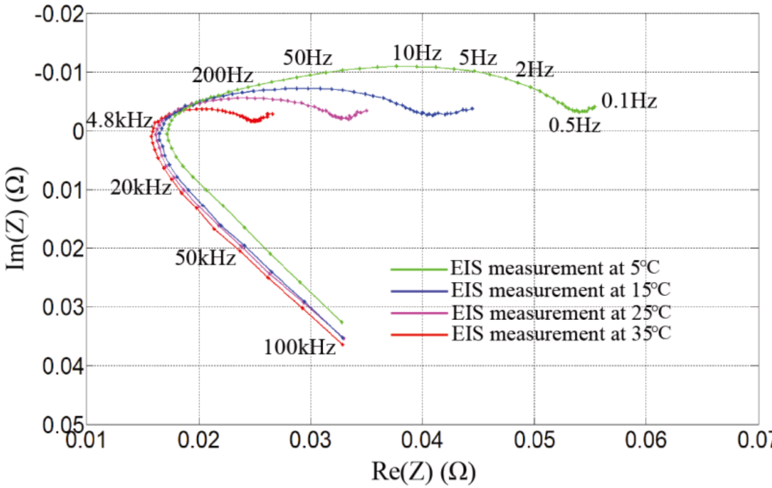
- P. Wang, Y. Chen, J. Yuan, R. C. N. Pilawa-Podgurski, M. Chen, "Differential Power Processing for Ultra-Efficient Data Storage," IEEE Transactions on Power Electronics, April 2021.

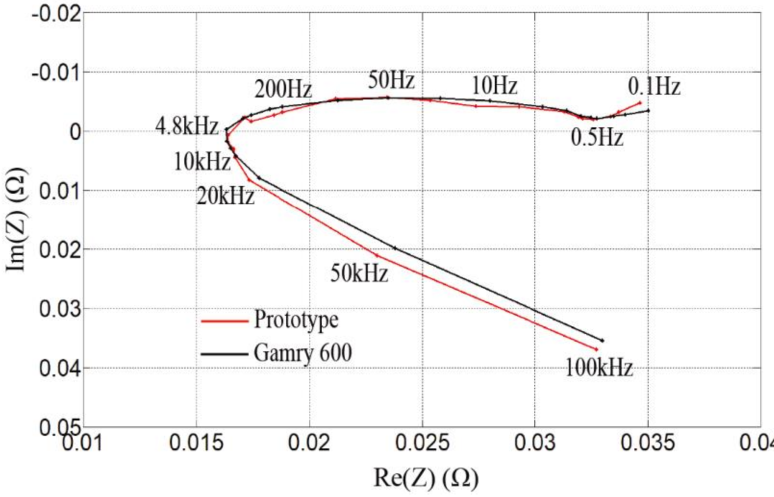
Battery Balancer with On-line Impedance Spectroscopy











- M. Liu, Y. Chen, Y. Elasser, M. Chen, "Dual Frequency Hierarchical Modular Multilayer Battery Balancer Architecture," IEEE Transactions on Power Electronics, March 2021.

MIMO Energy Management for Large Scale Systems

PRINCETON UNIVERSITY

Grid Scale Energy Storage

Solar Photovoltaic

High Power LED Lighting

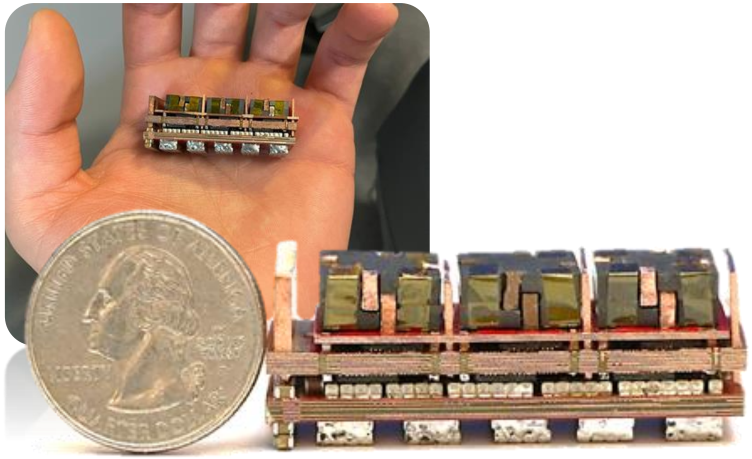
- Hardware, software, communication, thermal, algorithm and power co-design.
- Multi-input multi-output power management and grid interface.
- Efficiency, power density, reliability, cost, thermal.

Architectures to Unlock the Potential of WBG Devices

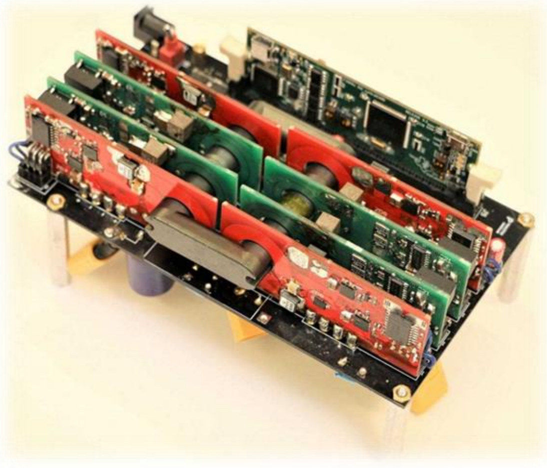
- **Extreme Performance: Hybrid-Switched-Capacitor Architecture**
  Extreme Performance CPU Voltage Regulators

- **Sophisticated Functions: Control of MIMO Power Flow**
  Modeling and Control of Multiport Energy Routers

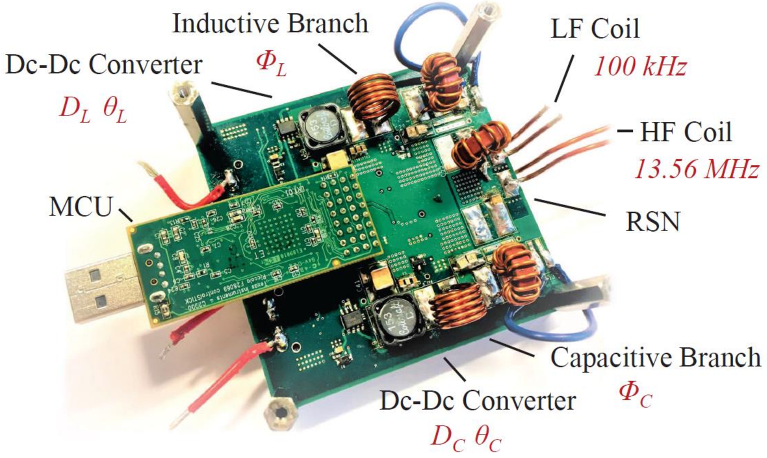
- **Enabling New Applications: Dual Frequency Wireless Power Transfer**
  Compensate for Impedance Variation with Reactance Steering Network



CPU Voltage Regulator



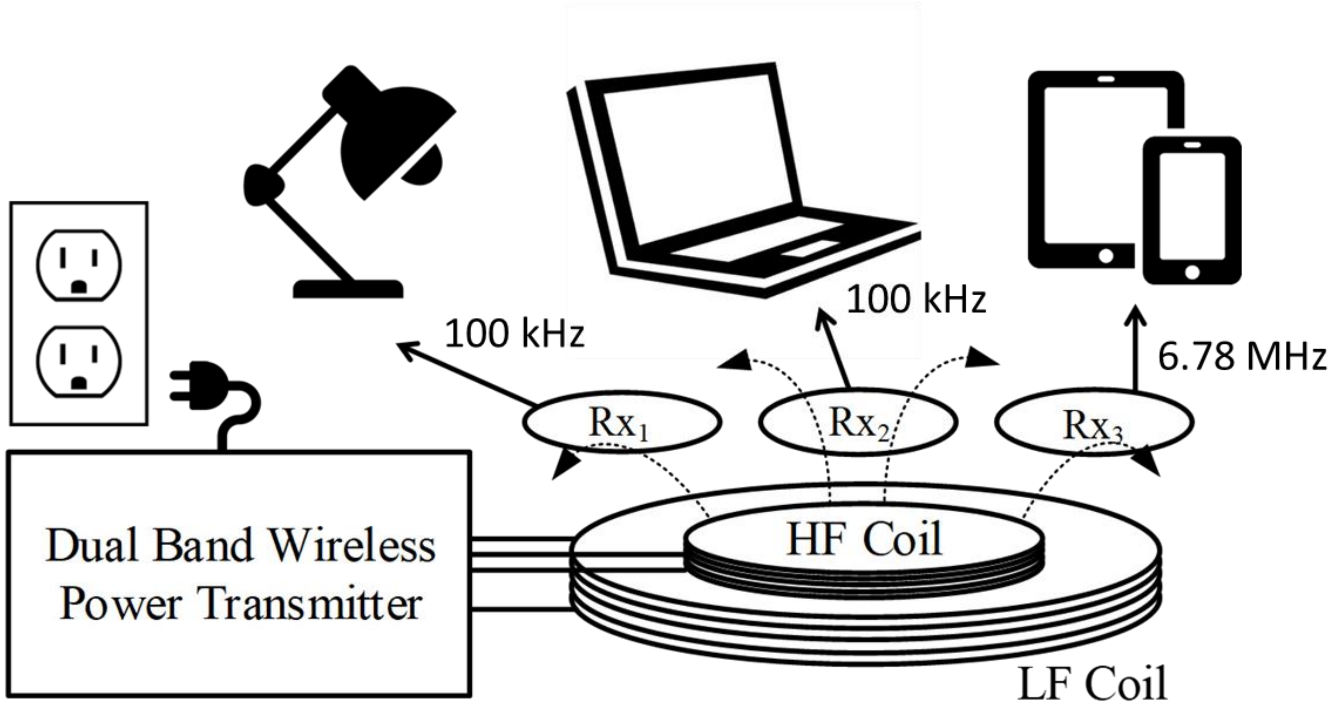
MIMO Energy Router



Dual-Band Wireless Power Transfer

Future Wireless Power Transfer Applications

Dual-Band Multi-Receiver Wireless Power Transfer



kHz wireless power transfer

- Higher efficiency
- Higher power transfer capability
- Large coil size
- Low tolerant to misalignment

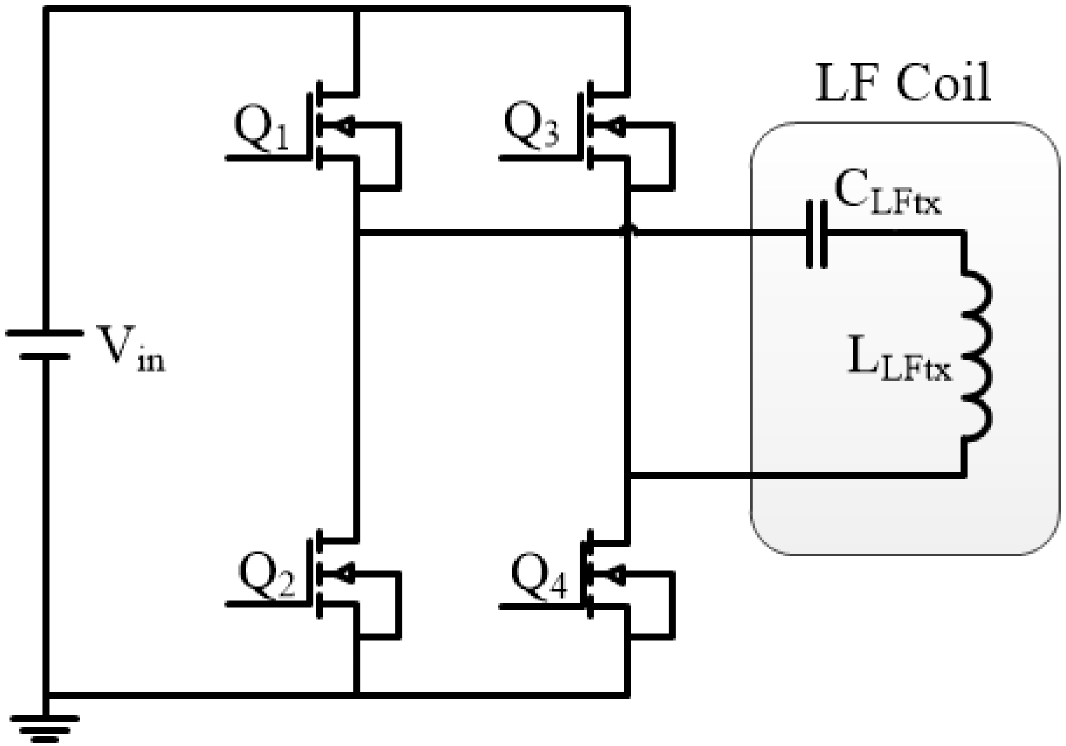
MHz wireless power transfer

- Lower efficiency
- Lower power transfer capability
- Small coil size
- High tolerance to misalignment

Support multiple frequency bands with wide impedance variation

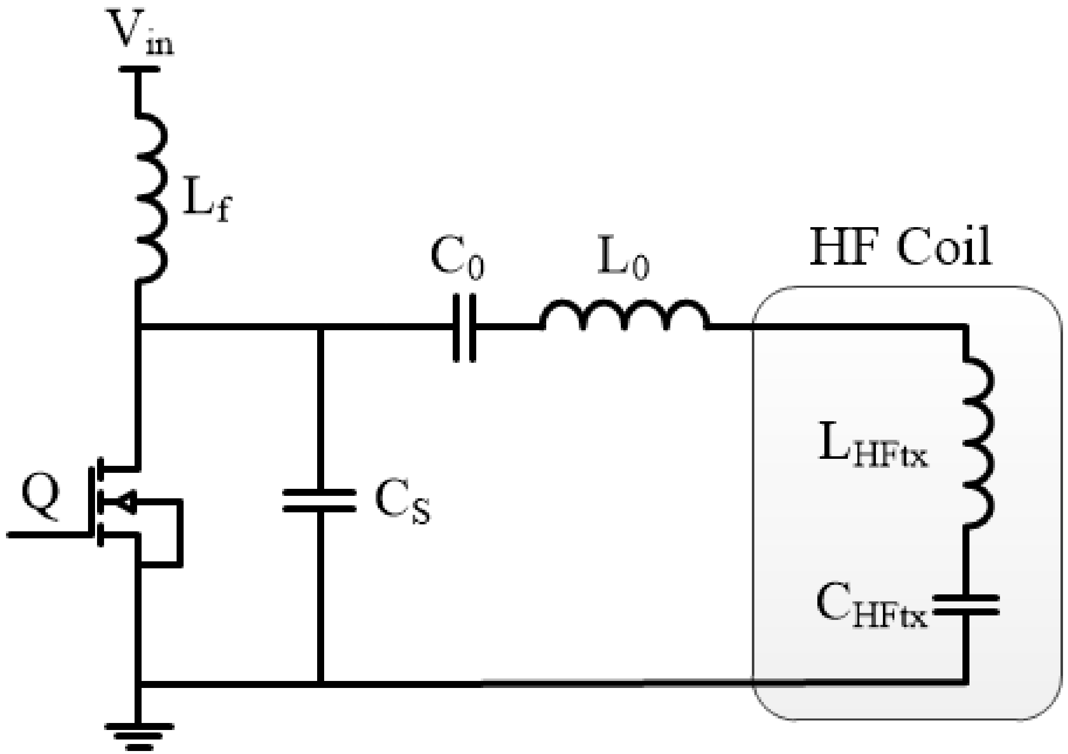
Topology Candidates for Dual-Band WPT

Typical kHz WPT Transmitter



(Full bridge inverter)

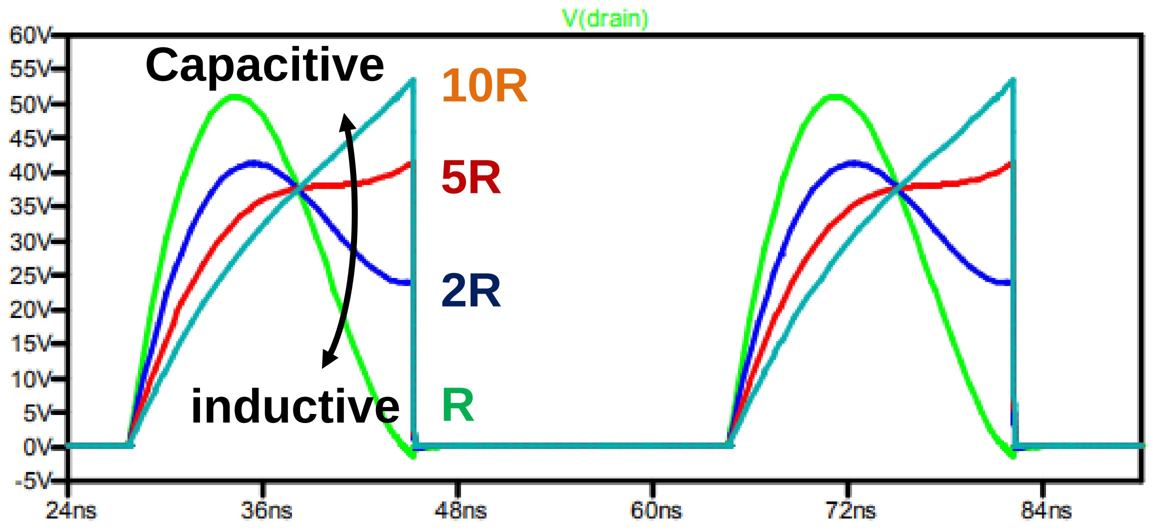
Typical MHz WPT Transmitter



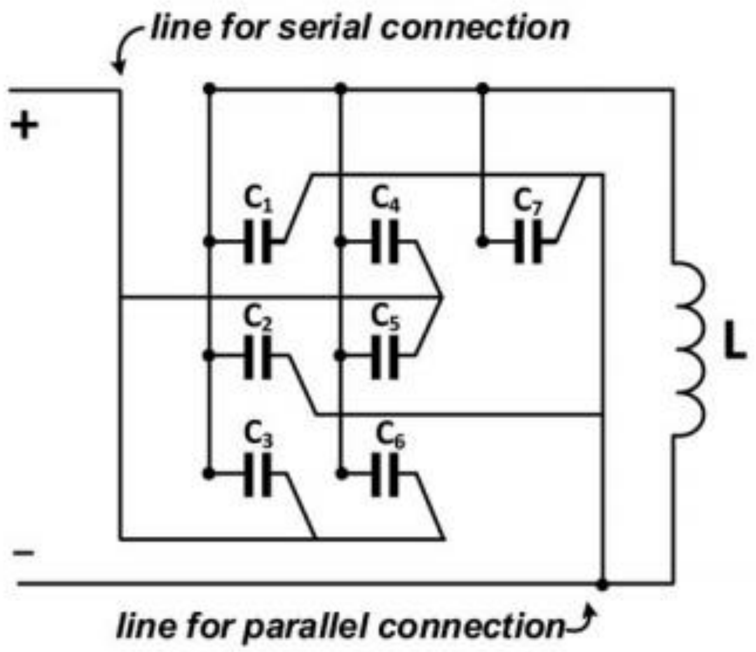
(Class E inverter)

Challenges of HF WPT with Single Switch PAs

- Co-location of multiple receivers induces large impedance variation
- Class-E PAs are sensitive to load impedance variation (resistive and reactive)



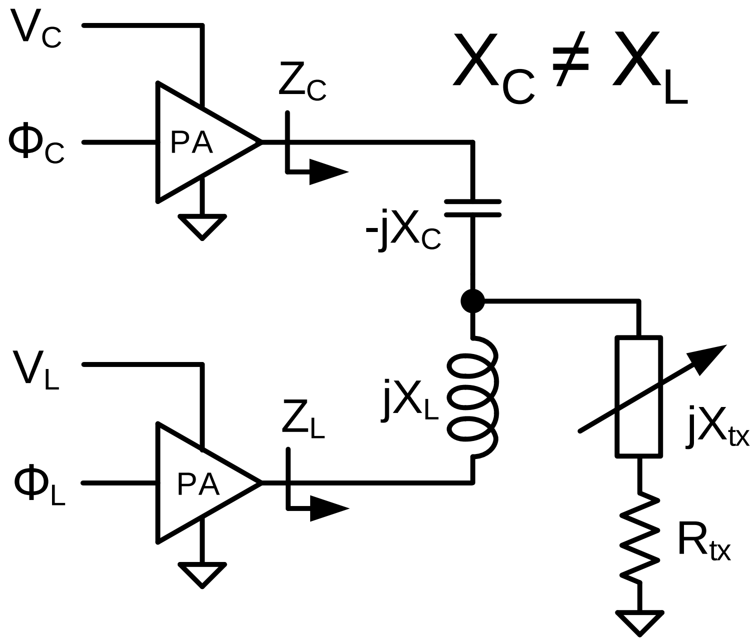
Drain voltage of Class-E PAs with impedance/resistance variation

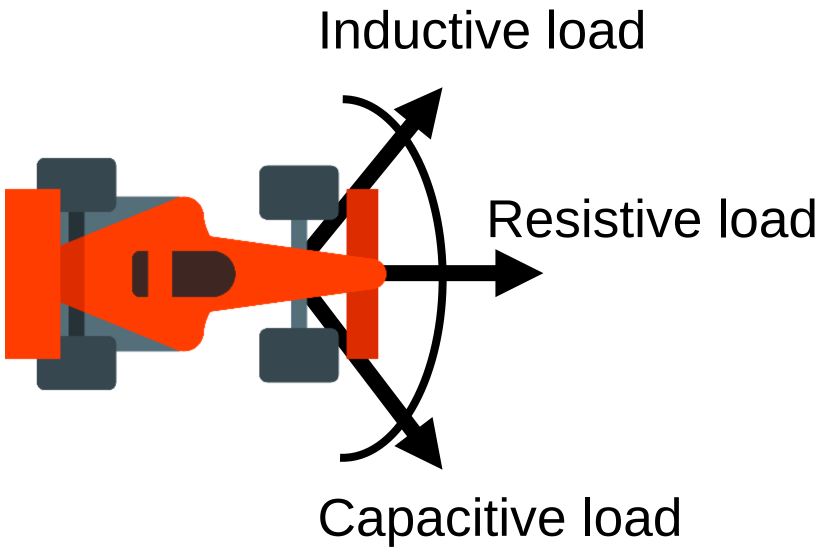


A tunable switched-capacitor matching network

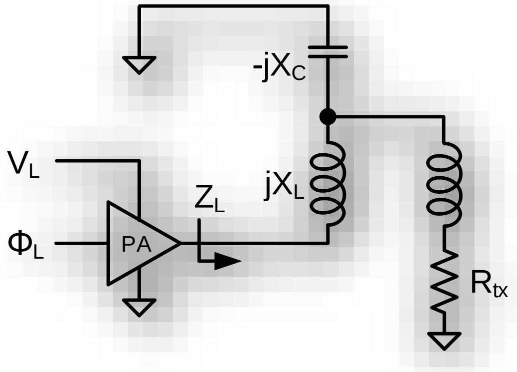
Principles of Reactance Steering Network

Maintain pure resistive load for both PAs

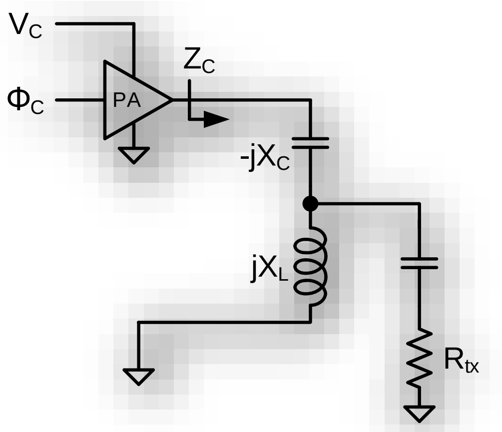




Inductive load



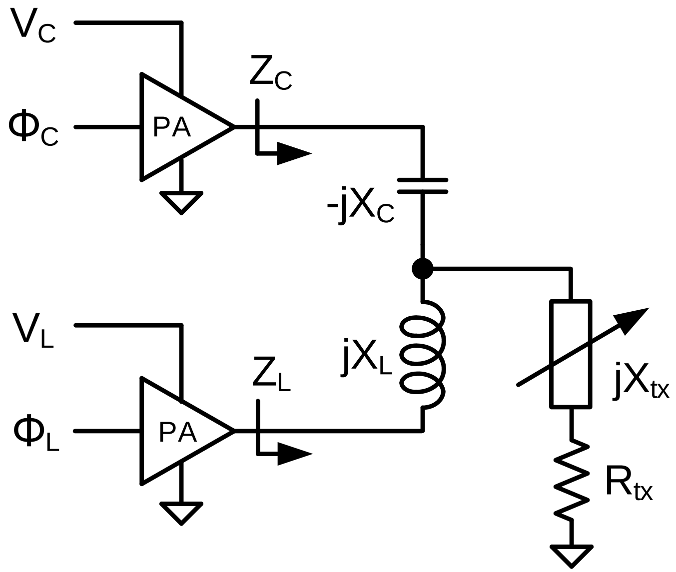
Capacitive load



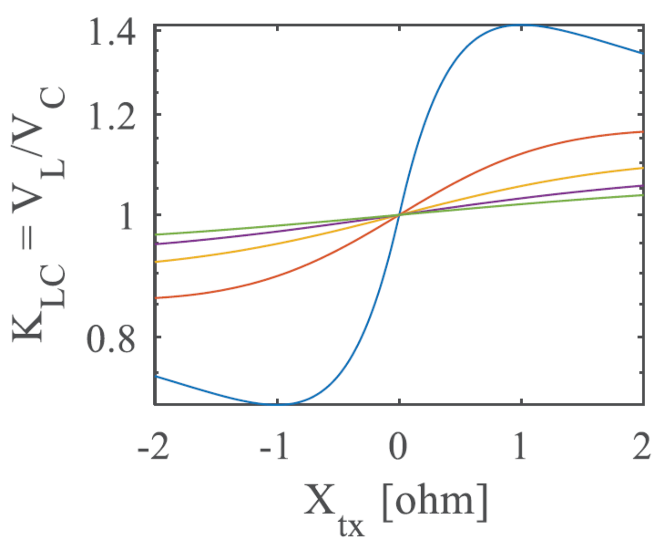
- Steering towards capacitive branch with inductive load
- Steering towards inductive branch with capacitive load
- Compensate for large reactance with small X_L and X_C

- M. Liu, M. Chen, "Dual-Band Wireless Power Transfer with Reactance Steering Network and Reconfigurable Receivers," IEEE Transactions on Power Electronics, Jan. 2020.

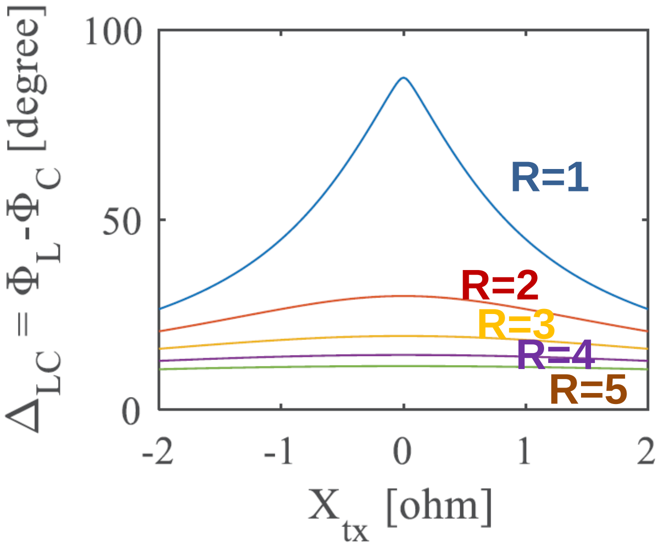
Control of the Reactance Steering Network



Amplitude Ratio



Phase Difference



Amplitude Ratio

$$K_{LC} = \left|\frac{V_L}{V_C}\right| = \frac{X_O + X_{tx}}{X_{tx}\cos(\Delta_{LC}) + R_{tx}\sin(\Delta_{LC})}$$

$$\frac{1}{\sqrt{2}} < K_{LC} < \sqrt{2}$$

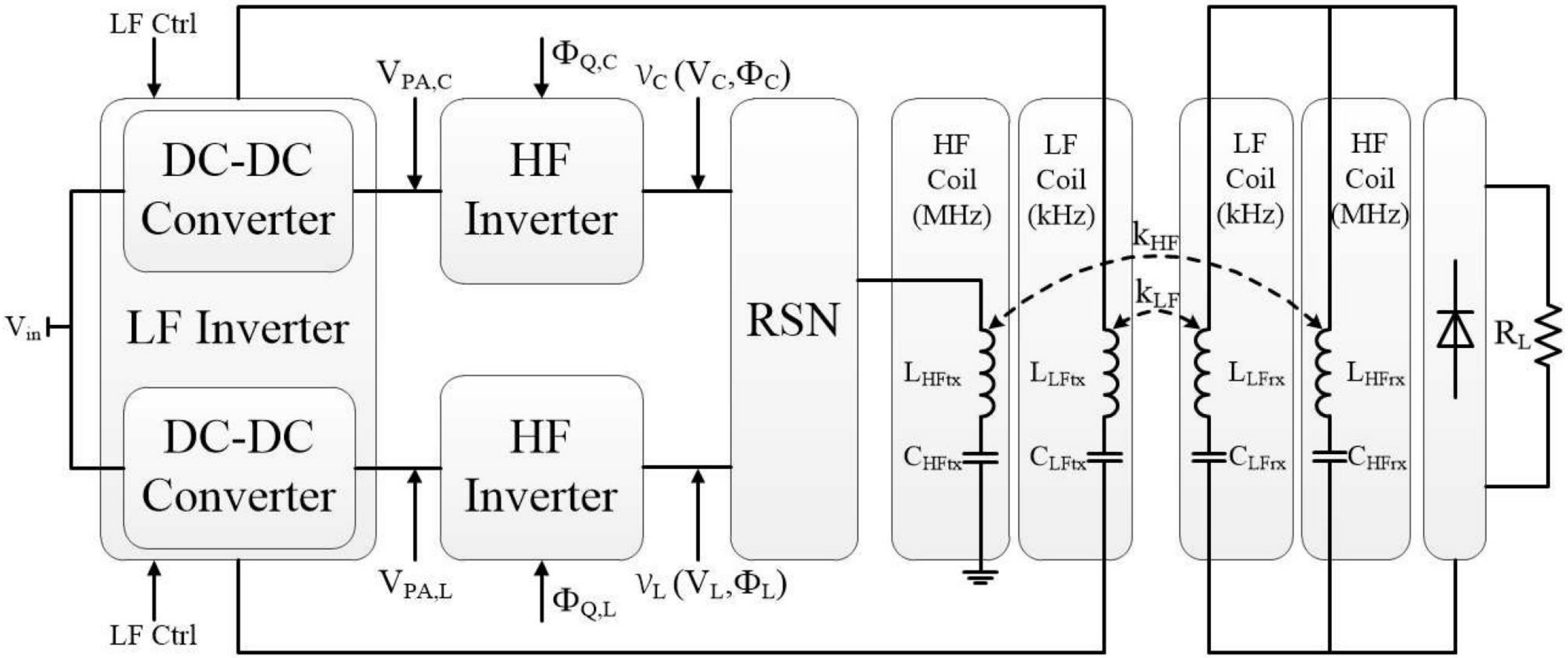
Phase Difference

$$\Delta_{LC} = \Phi_L - \Phi_C = \arcsin\sqrt{\frac{X_O^2}{X_{tx}^2 + R_{tx}^2}}$$

$$0° < \Delta_{LC} < 90°$$

- M. Liu, M. Chen, “Dual-Band Wireless Power Transfer with Reactance Steering Network and Reconfigurable Receivers,” IEEE Transactions on Power Electronics, Jan. 2020.

Dual-Band Multi-Receiver WPT Architecture with RSN

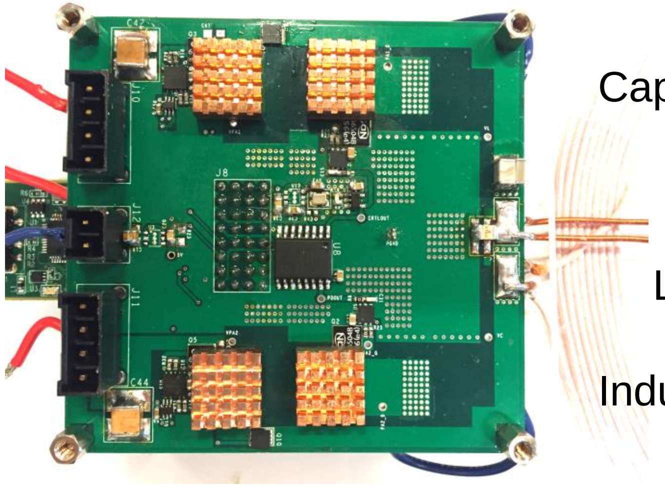


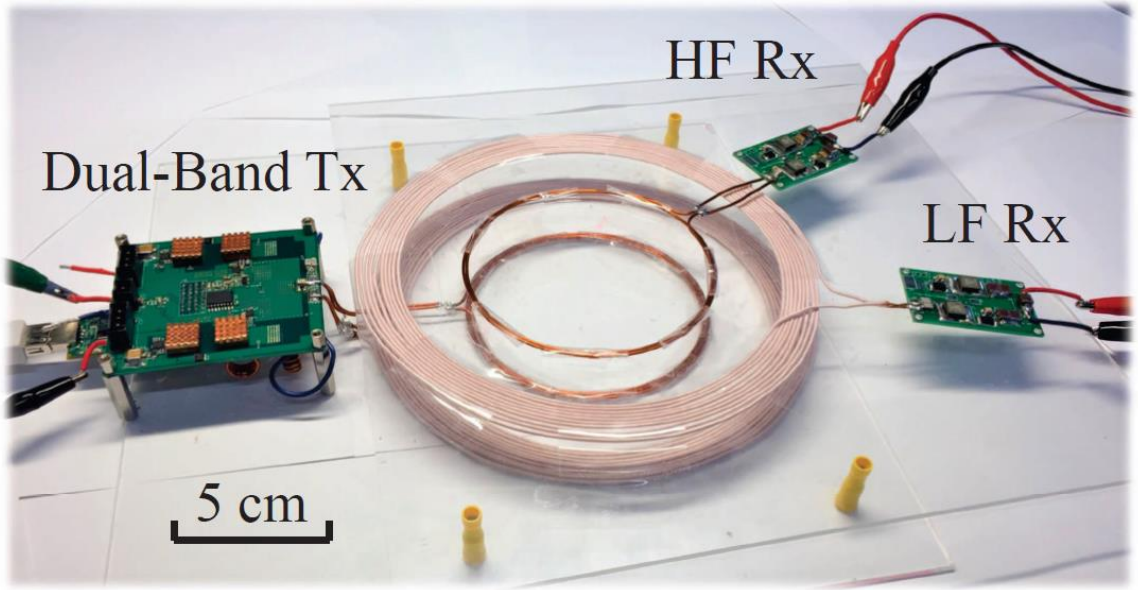
Merge LF and HF Transmitters, and create mutual advantages

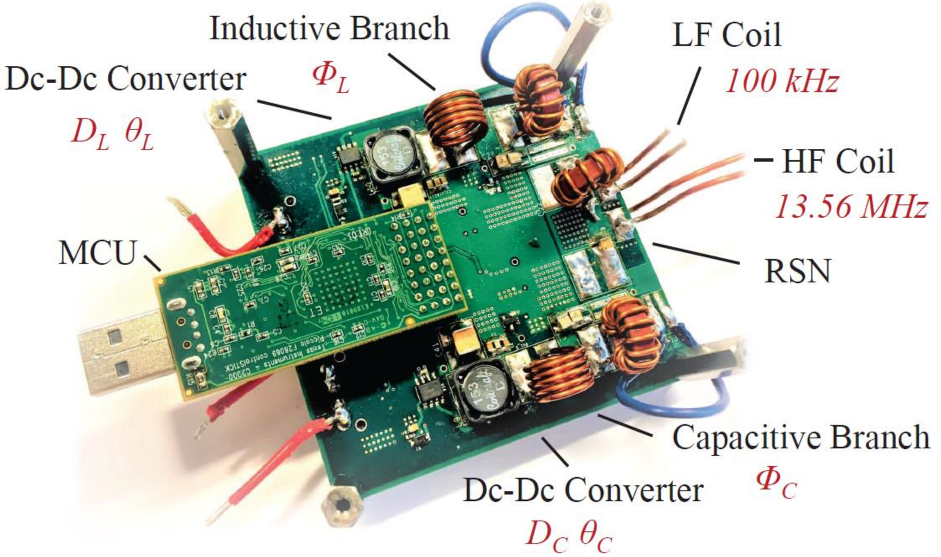
- M. Liu, M. Chen, "Dual-Band Wireless Power Transfer with Reactance Steering Network and Reconfigurable Receivers," IEEE Transactions on Power Electronics, Jan. 2020.

A Dual-Band Multi-Receiver WPT Prototype

Dual Band Operation: 100 kHz and 13.56 MHz
Power Rating: 65 W@100 kHz, 65 W@13.56 MHz
Input Voltage: 50 V (up to 80 V)
Output Voltage: 30 V@100 kHz, 30 V@13.56 MHz
Spacing: 2.8 cm distance, up to 3 cm misalignments
Coil size: Coil_HF (D=10 cm), Coil_LF (D=20 cm)

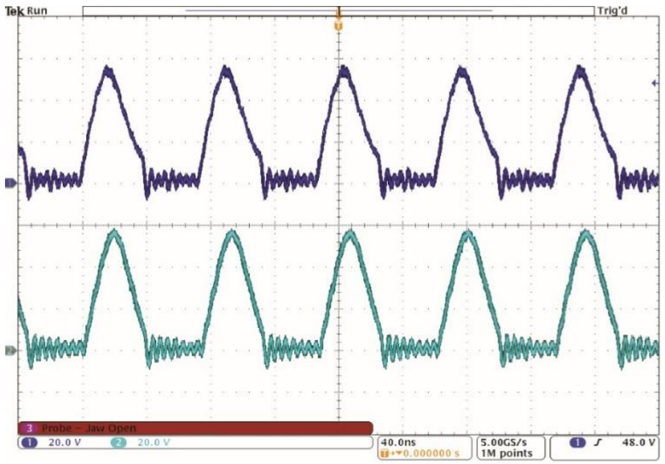




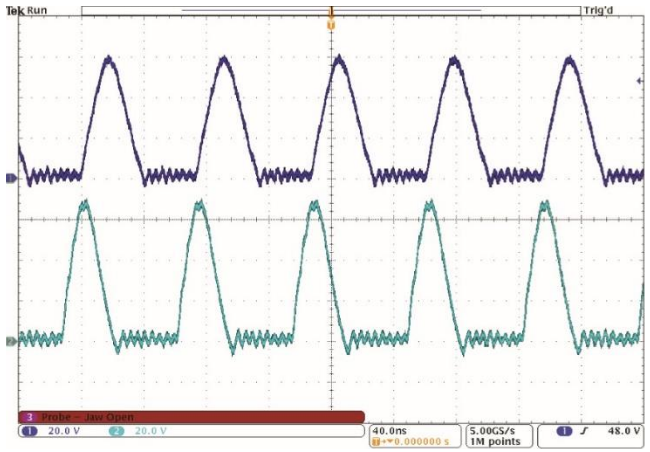


• M. Liu, M. Chen, "Dual-Band Wireless Power Transfer with Reactance Steering Network and Reconfigurable Receivers," IEEE Transactions on Power Electronics, Jan. 2020.

ZVS of Both Class-E PAs across Very Wide Range

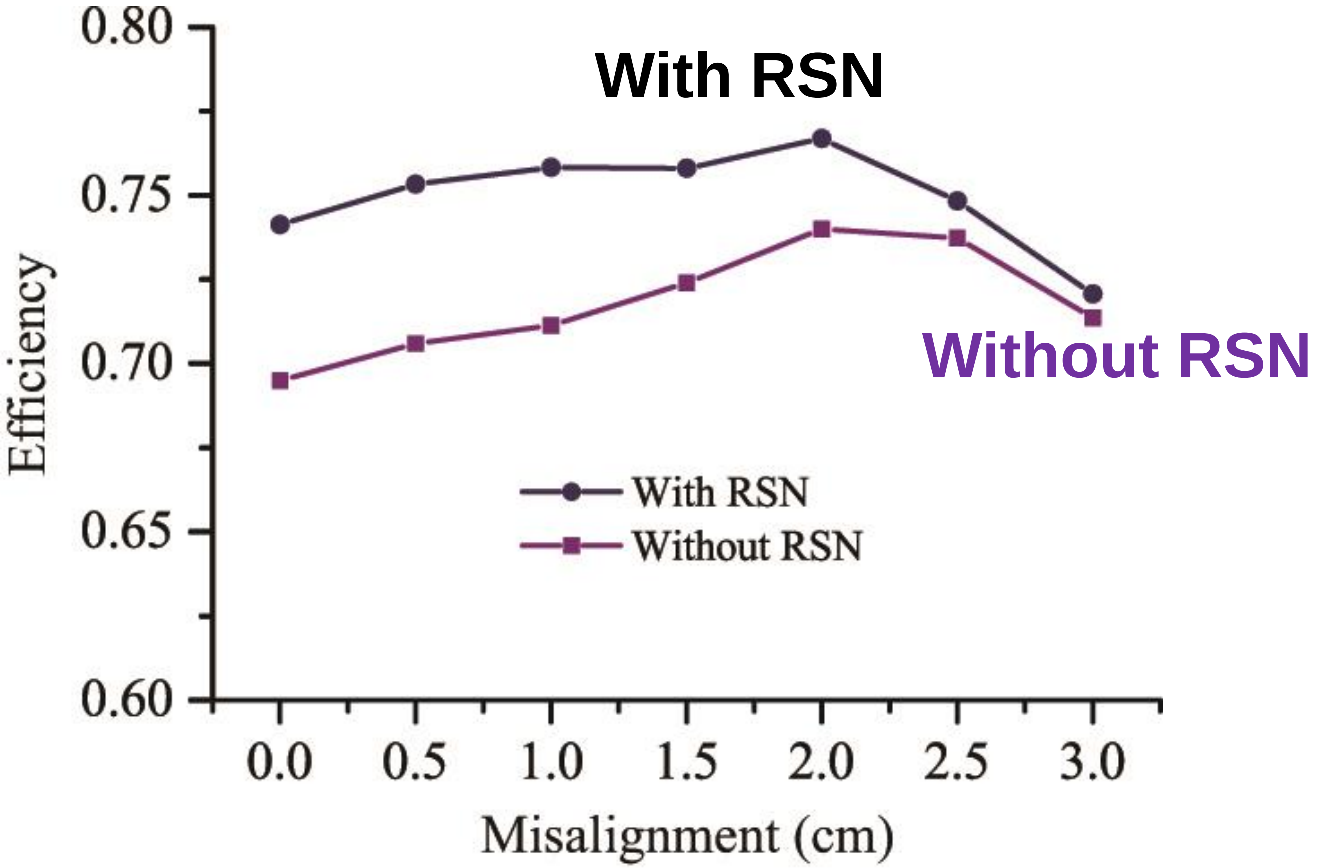


Example drain voltage without RSN



Example drain voltage with RSN

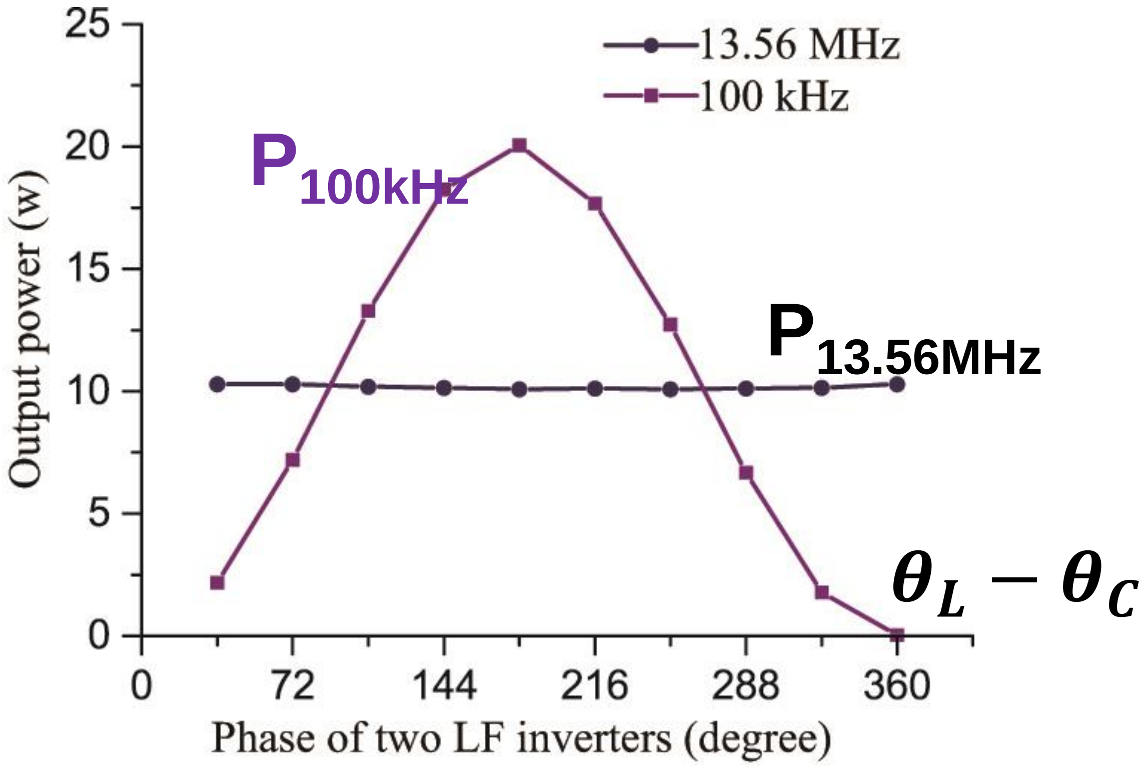
- Efficiency vs. misalignment (0 ~ 3 cm)
- Fixed output power 30W
- Reactance range from 0j Ω to 80j Ω



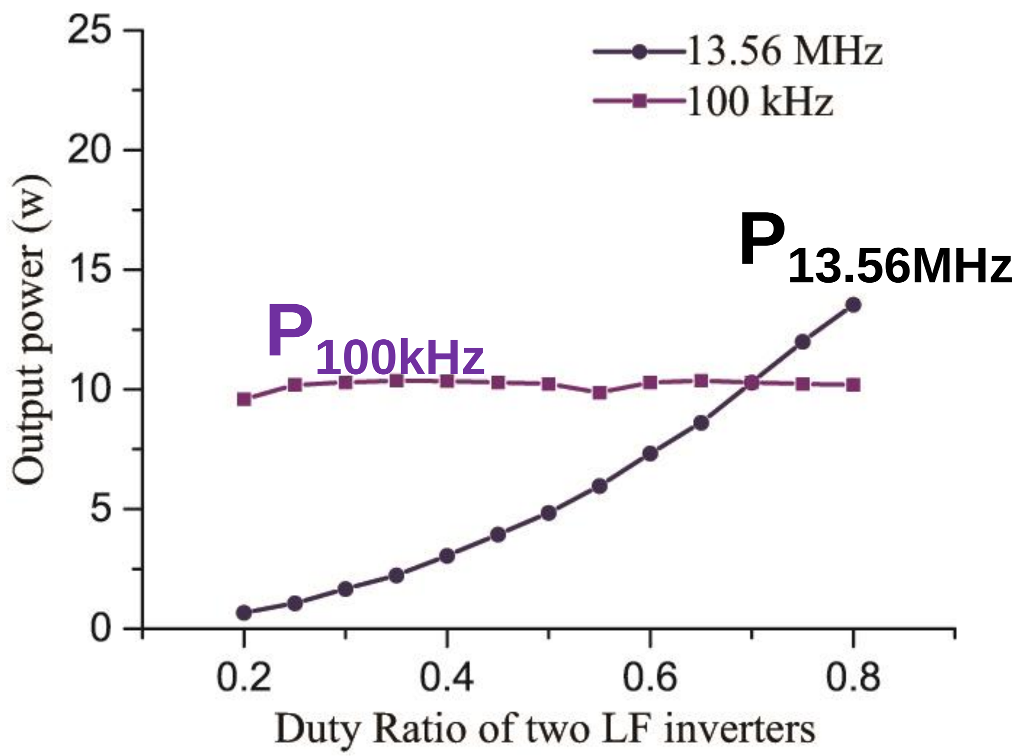
- M. Liu, M. Chen, "Dual-Band Wireless Power Transfer with Reactance Steering Network and Reconfigurable Receivers," IEEE Transactions on Power Electronics, Jan. 2020.

Decoupled Modulation of the Two Frequency Bands

- Modulating power at 100 kHz
- Maintaining 10 W at 13.56 MHz



- Modulating power at 13.56 MHz
- Maintaining 10 W at 100 kHz



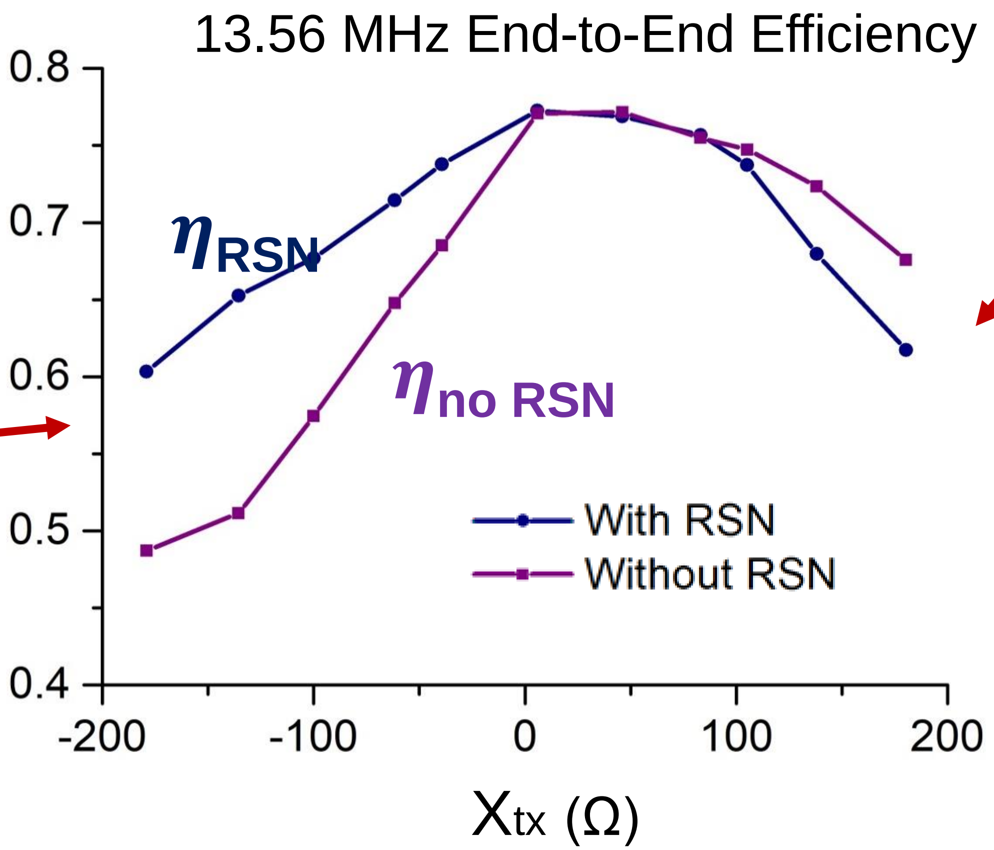
- M. Liu, M. Chen, “Dual-Band Wireless Power Transfer with Reactance Steering Network and Reconfigurable Receivers,” IEEE Transactions on Power Electronics, Jan. 2020.

HF WPT Efficiency with “Very” Reactive Load

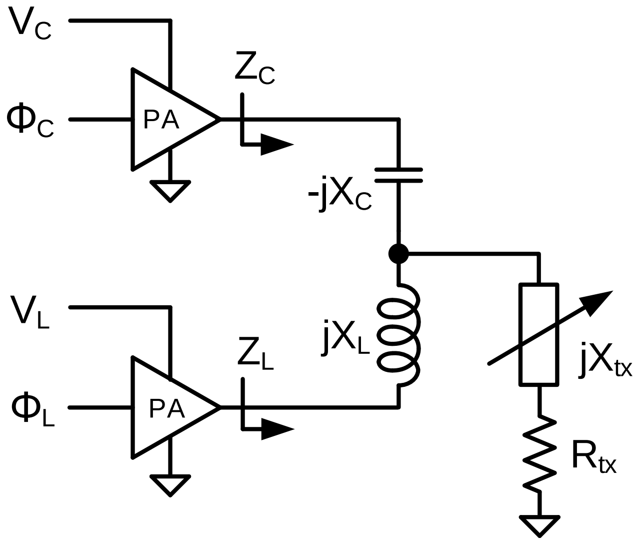
- RSN significantly improves the HF WPT efficiency with capacitive X_{tx}.
- RSN sacrifices more loss with very inductive load (due to circulating current).

R: 50 Ω
X: -200 Ω to +200 Ω

12% higher efficiency with “very” capacitive load



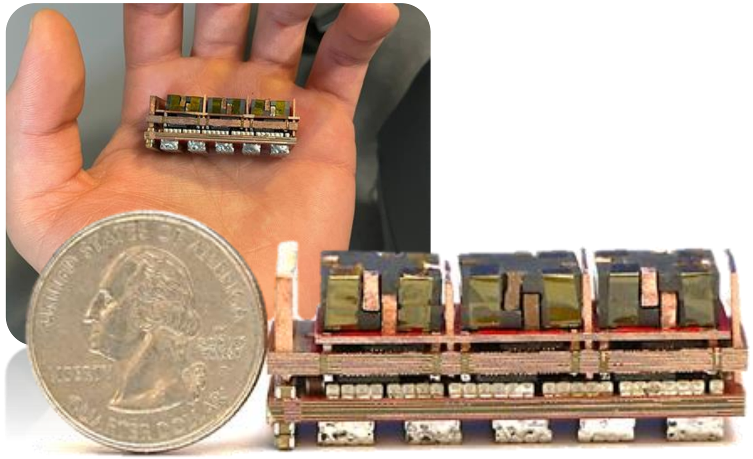
4% lower efficiency with “very” inductive load



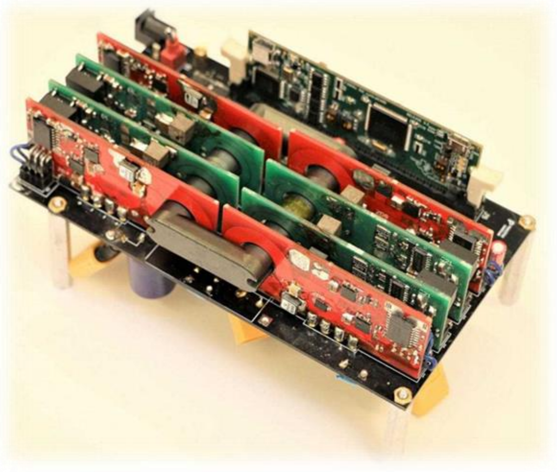
• M. Liu, M. Chen, “Dual-Band Wireless Power Transfer with Reactance Steering Network and Reconfigurable Receivers,” IEEE Transactions on Power Electronics, Jan. 2020.

Unlock the Potential of WBG Semiconductor Devices

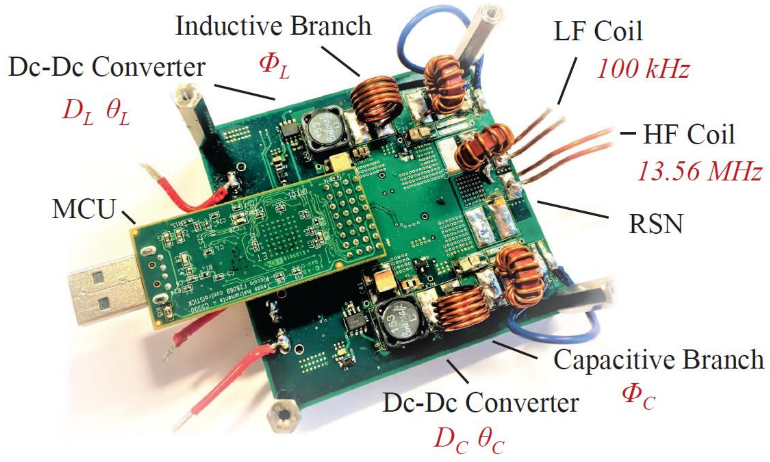
- "Drop and replace" designs only leverage the "efficiency" benefits
- WBG devices enables architectural level innovations, including:
  - ➢ Very-small-footprint: more compact packaging and better thermal
  - ➢ Ultra-fast-switching: more precise control and timing, smaller passives
  - ➢ Extended-design-space: reusing devices for multiple purposes at HF



CPU Voltage Regulator



MIMO Energy Router



Dual-Band Wireless Power Transfer

Related Publications

48V-1V CPU Voltage Regulator

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