MSP-LEGO: Modular Series-Parallel (MSP) Architecture and LEGO Building Blocks for Non-isolated High Voltage Conversion Ratio Hybrid Dc-Dc Converters

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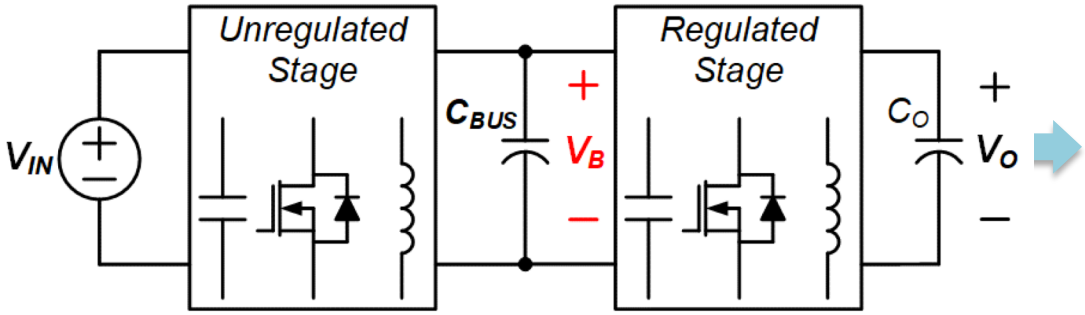
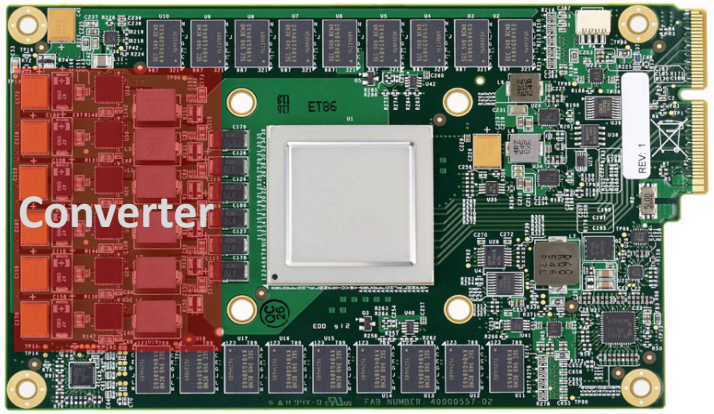
High Voltage Conversion Ratio

High voltage conversion ratio topologies





- **Two-stage transformer-based solutions**

  Low light load efficiency & low power density

  Narrow operation range

- **Single-stage hybrid-switched-capacitor-based solutions**

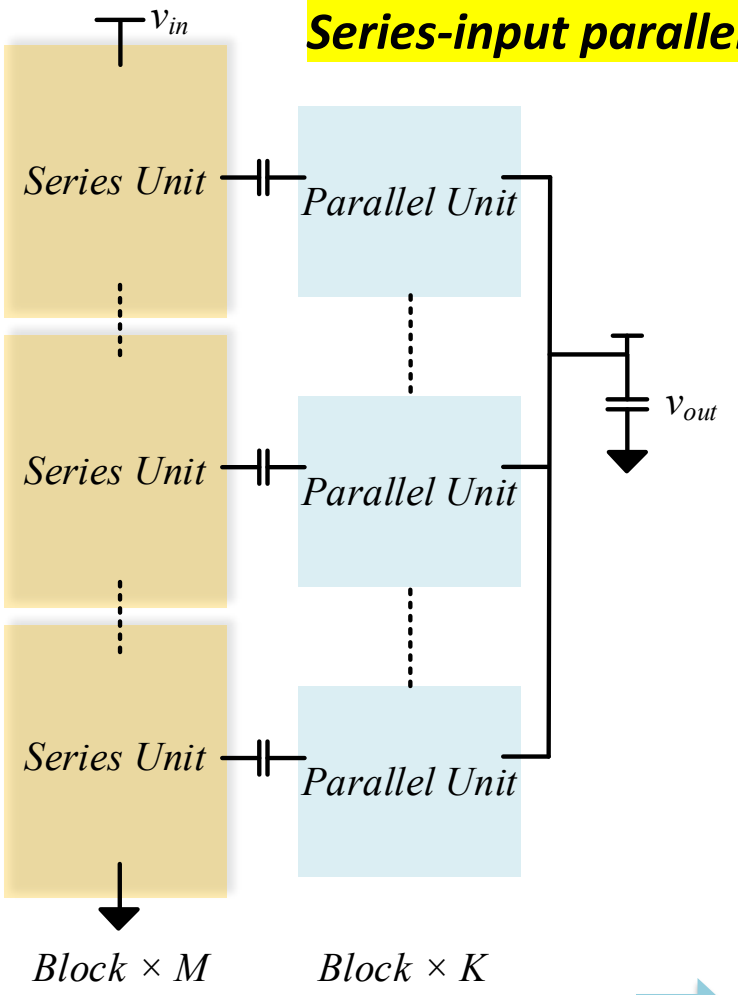
  Transformer-free & high modularity & non-isolated

  High light load efficiency & high power-density

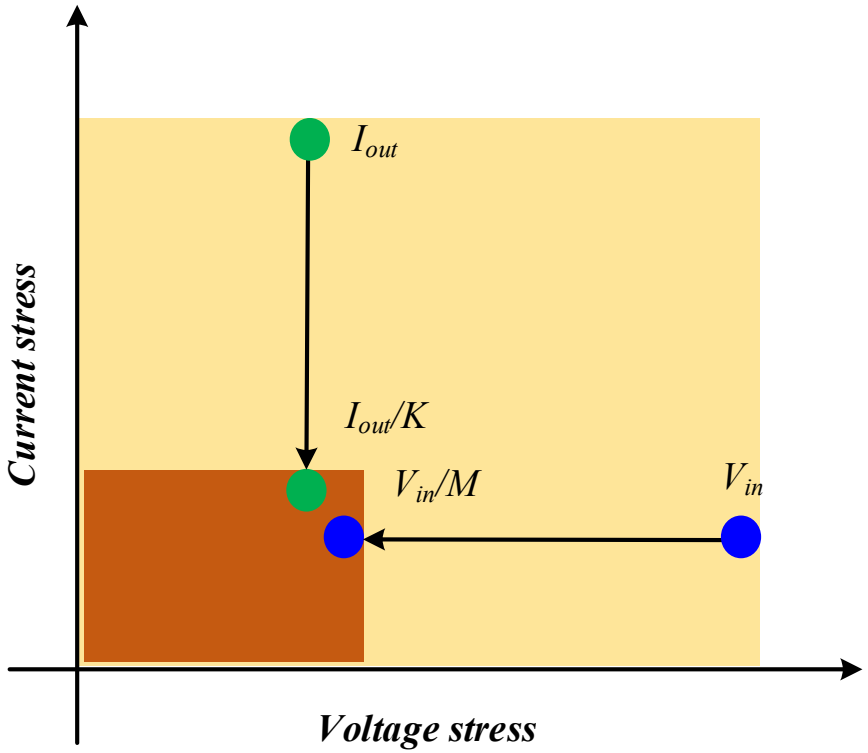
  High operating bandwidth

Modular Series-Parallel Architecture

Series-input parallel-output configuration



MSP architecture

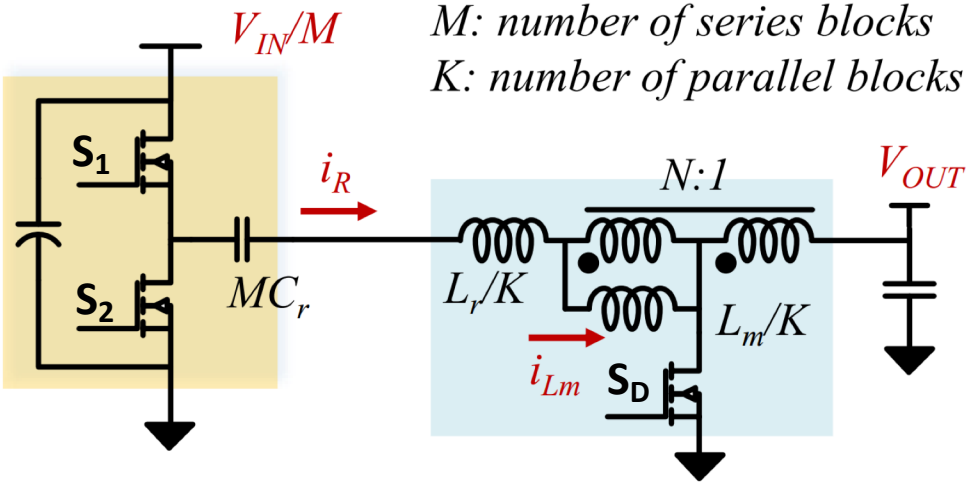


- Merged operation of the two units
- Reduced switch voltage stress
- Reduced switch current stress
- Reduced overall V*I ratings

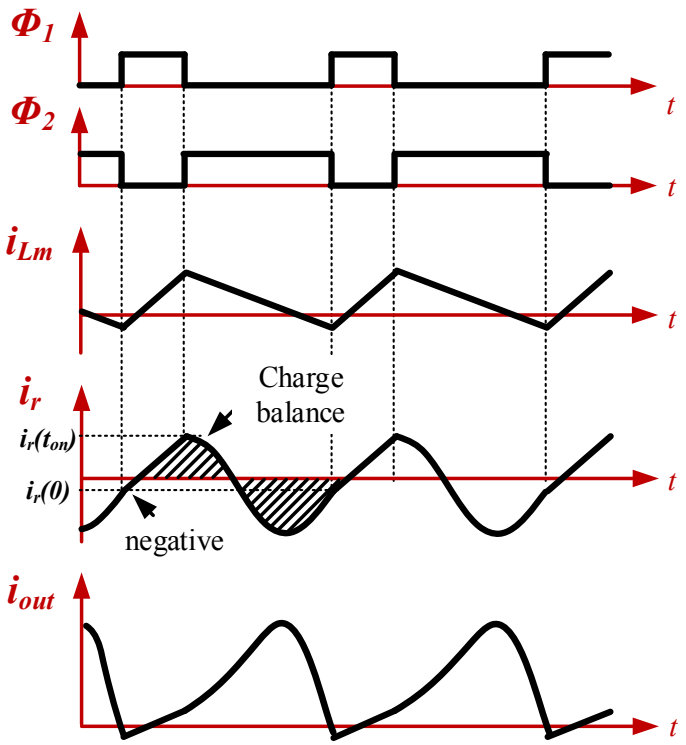
A SC-TaB Example Topology

Series Unit
a half bridge

Parallel Unit
a coupled inductor



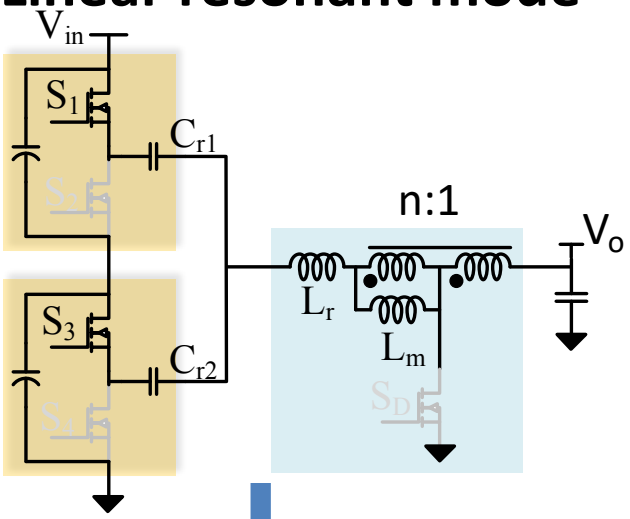
A Series-capacitor tapped buck (SC-TaB) converter

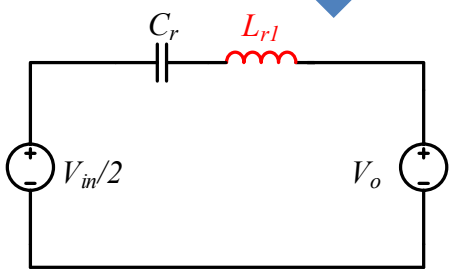


Interleaved operation to reduce the output current ripple

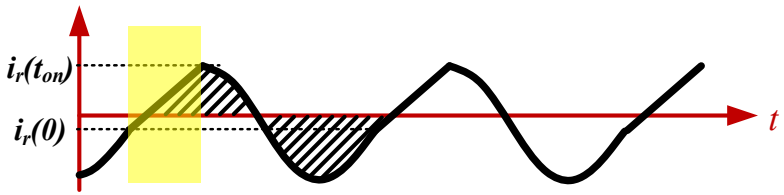
Semi-Resonant Operation

Linear resonant mode

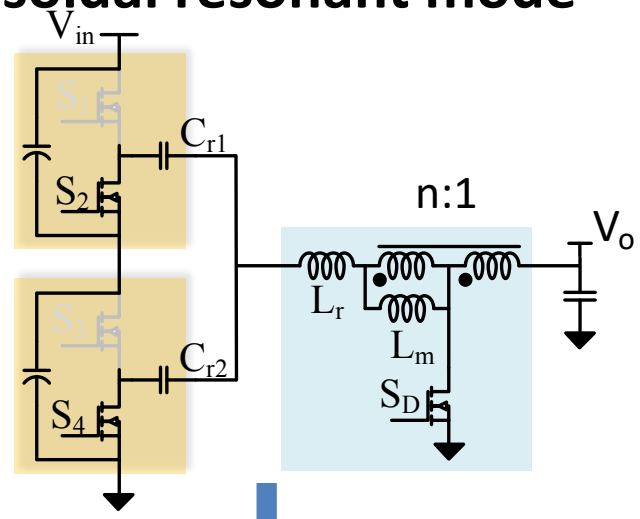


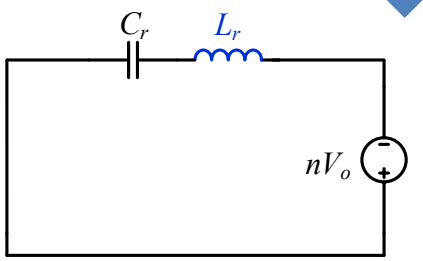


Approximately linear operation

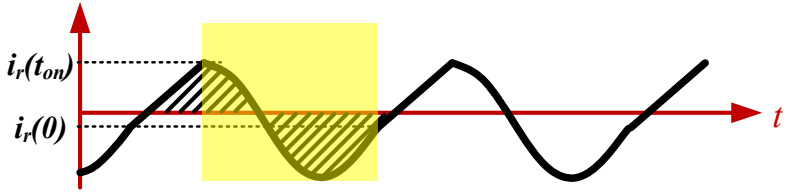


Sinusoidal resonant mode





Three quarters of sinusoidal resonant operation

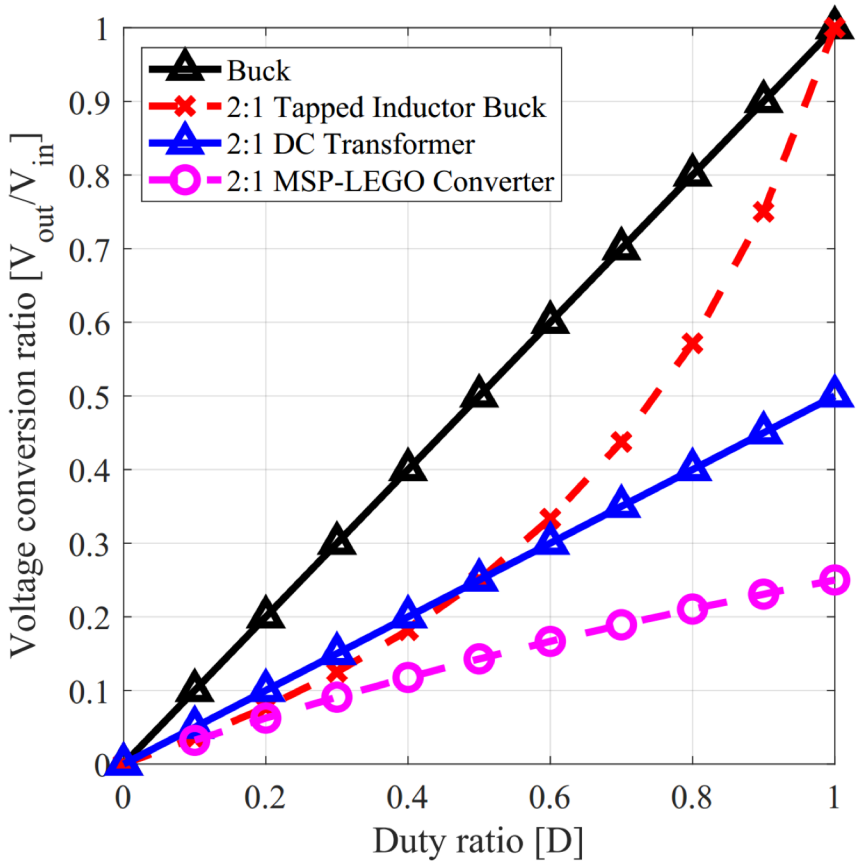


Extended Voltage Gain

$$\frac{V_o}{V_{in}} = \frac{1}{1+n} \frac{\sin\left(\omega_r T_s (1-D)\right) + \frac{N}{M}\left(\cos\left(\omega_r T_s (1-D)\right) - 1\right)}{\sin\left(\omega_r T_s (1-D)\right) + \frac{N}{M}\left(\cos\left(\omega_r T_s (1-D)\right) - 1\right) - \omega_r T_s (1-D)}$$

Simplification
(linear operation)

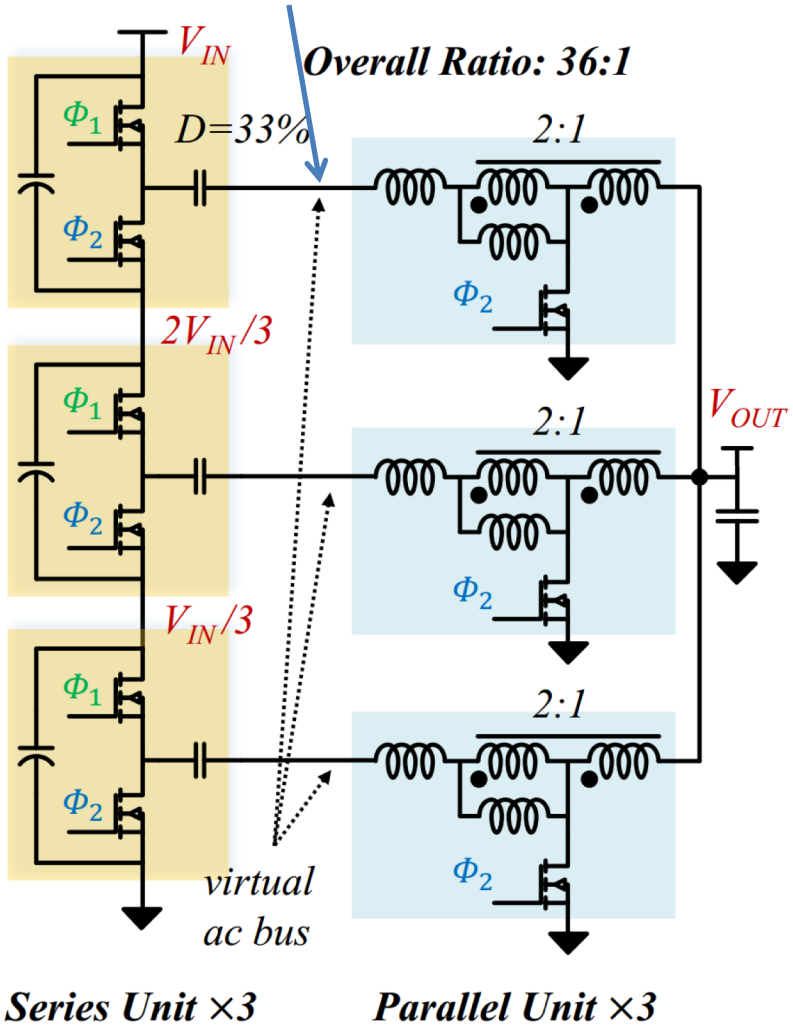
$$\frac{V_{out}}{V_{in}} = \frac{1}{M} \frac{(N+1) D L_m}{(N+1)^2 L_m - N^2 L_r}$$



- Soft-switching operation
- High voltage conversion ratio
- Extend the voltage conversion ratio by 3x compared with Buck

MSP-LEGO Converter (split ac bus)

Split virtual ac bus



Operation Principles

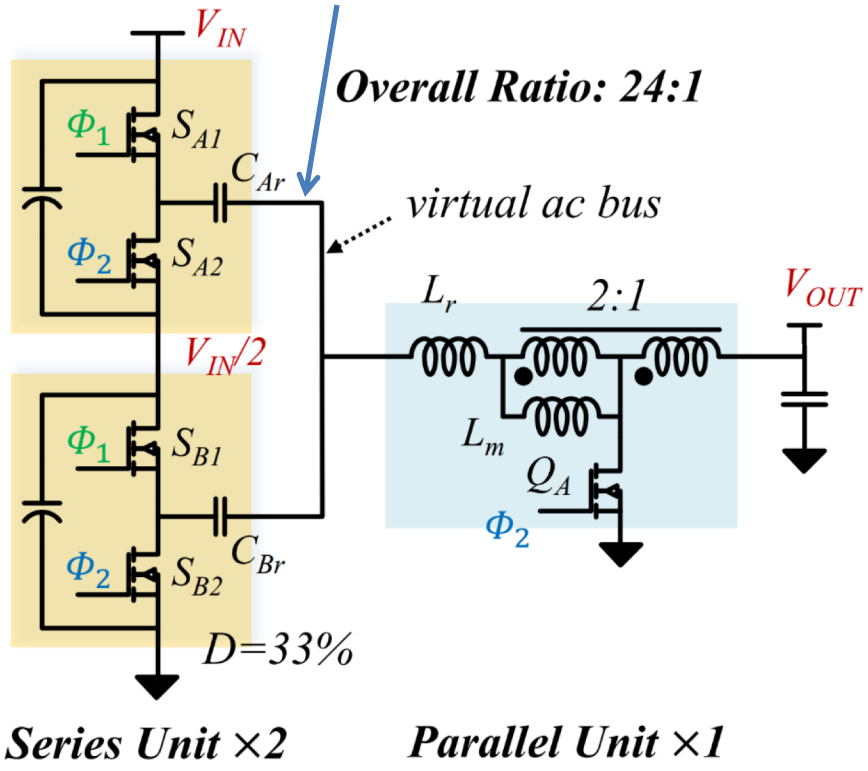
- Linear Extendable Group Operated
- Switched capacitor building block
- Switched inductor building block
- Automatic current sharing
- Low component count

Conversion Ratio Breakdown

- 3:1 from the series input stack
- 3:1 from the duty ratio
- 4:1 from the semi-resonant operation
- 3 × 3 × 4 = 36:1

MSP-LEGO converter (merged ac bus)

Merged virtual ac bus



Key principles:

- C_{Ar} and C_{Br} effectively connected in parallel
- Automatic voltage balancing of series units

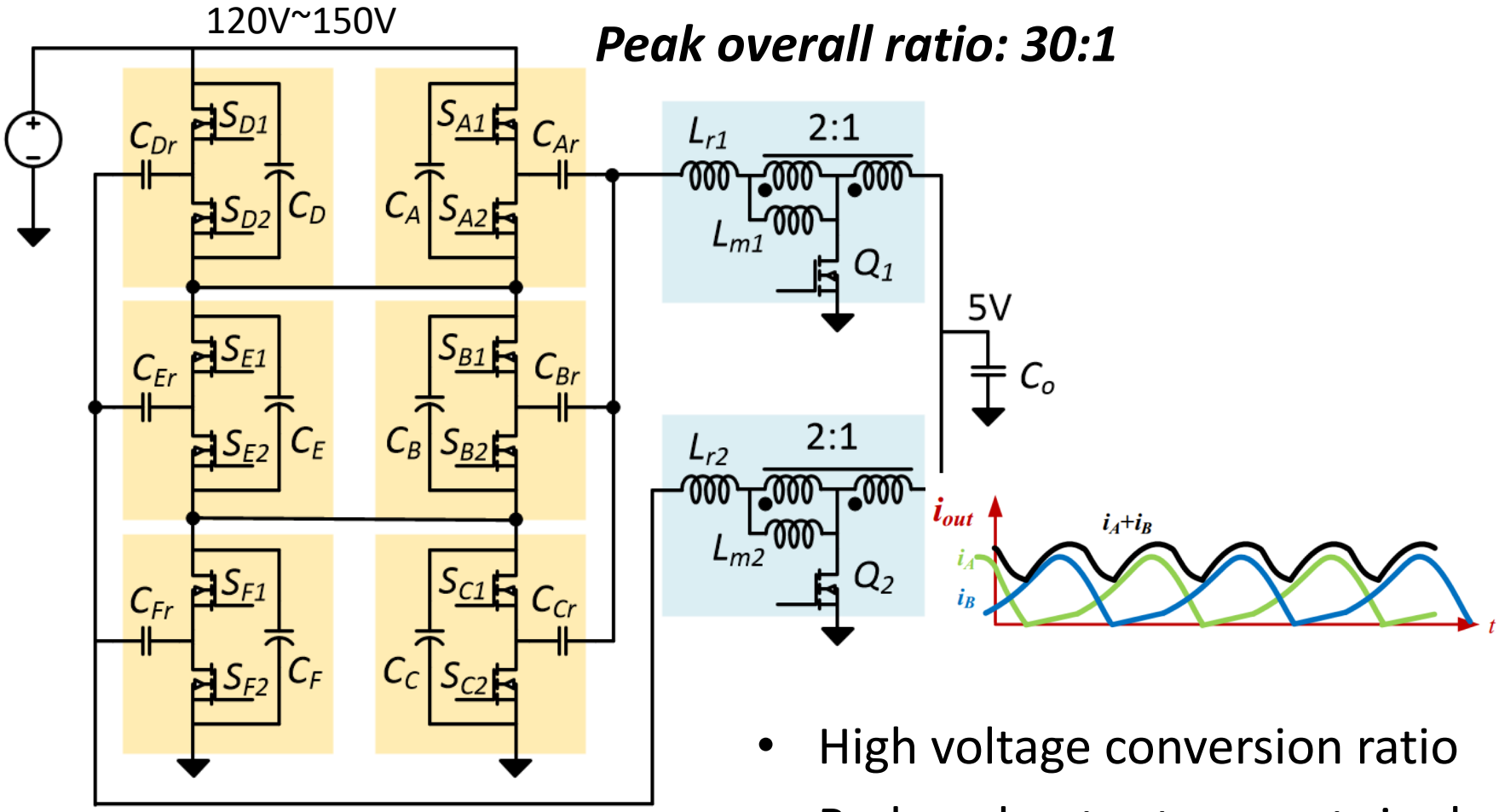
Advantages:

- Flexible series-parallel combinations

Disadvantages:

- Current sharing not guaranteed

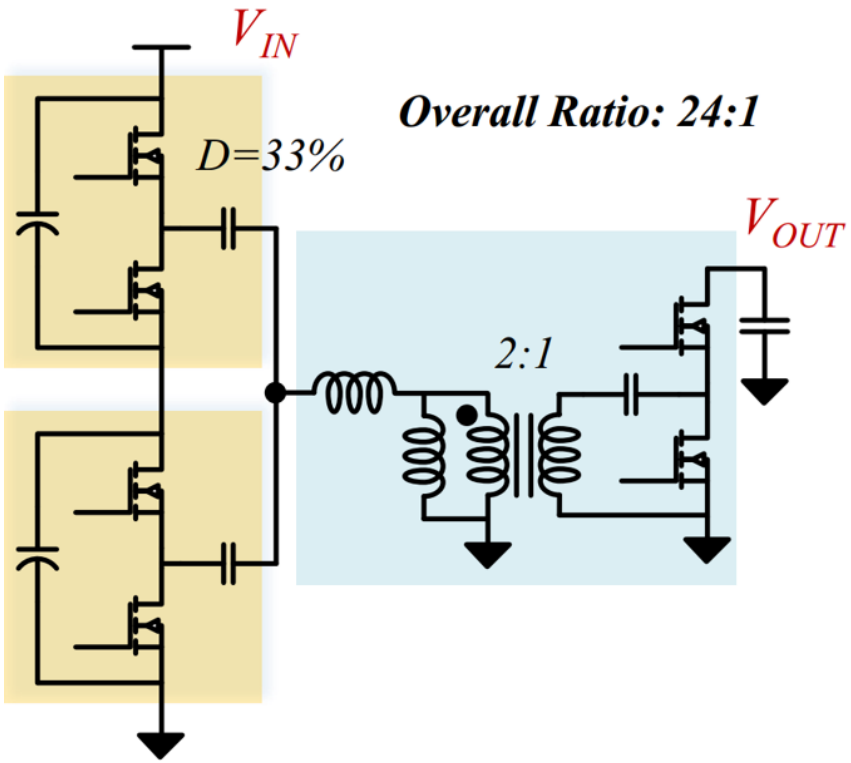
Interleaved MSP-LEGO converter



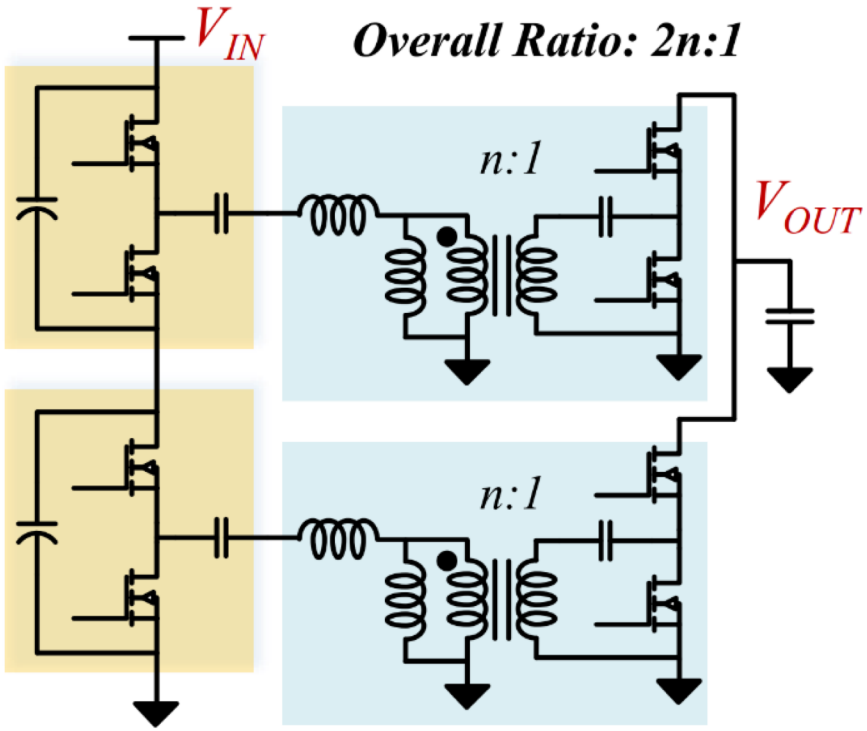
MSP-LEGO converter with two interleaved modules

- High voltage conversion ratio
- Reduced output current ripple
- Reduced input capacitor size

Other Isolated MSP-LEGO Options

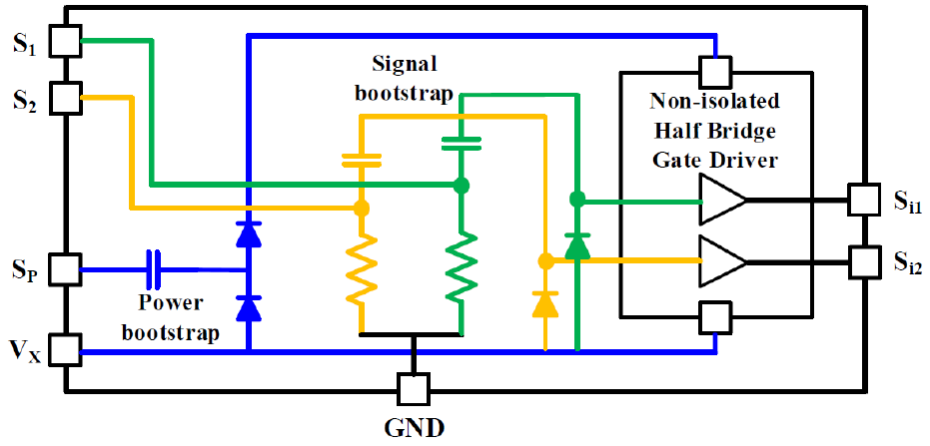


Isolated half-bridge (merged ac bus)



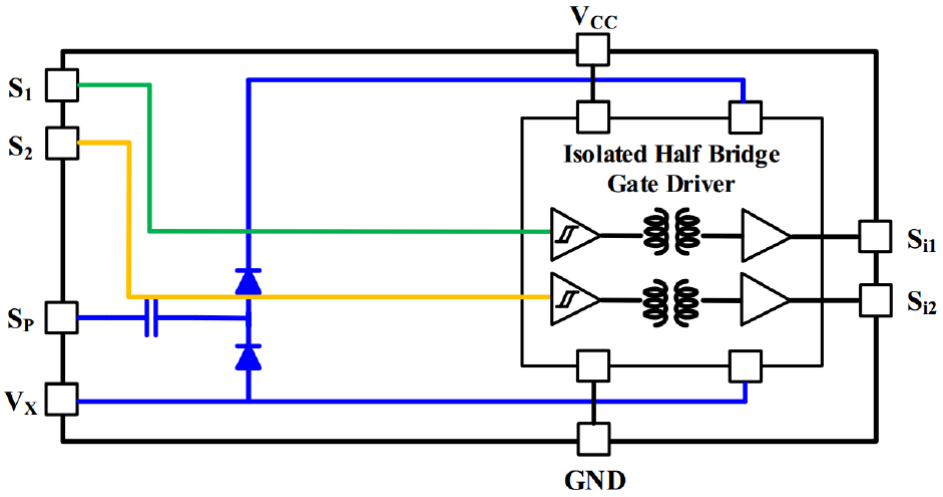
Isolated half-bridge (split ac bus)

Modular Gate Drive Circuits



Boot-strap gate driver

- Signal bootstrap
- Power bootstrap
- Adopted in prototype



Capacitive isolated gate driver

- Power bootstrap
- IL711 isolated coupler

A 110W/in^3 MSP-LEGO prototype

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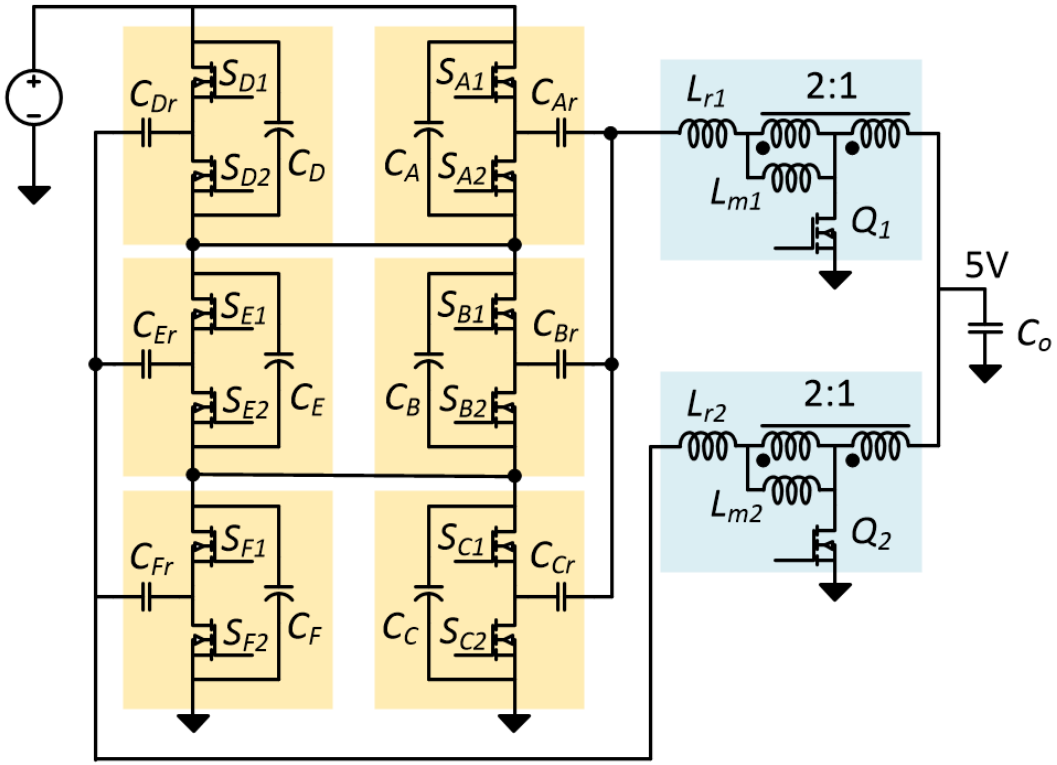
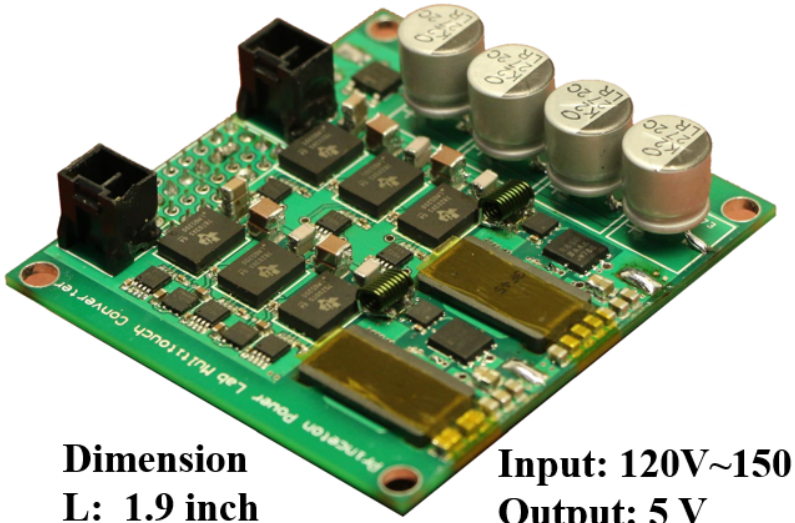
Peak overall ratio: 30:1



Six input units and two output units



Dimension
L: 1.9 inch
W: 1.6 inch
H: 0.3 inch

Input: 120V~150 V
Output: 5 V
Power: 100 W
Efficiency: 91.5%

Switched Capacitors **Coupled Inductors**

- Power density: 110 W/in^3
- Switching frequency: 600kHz
- All gate-drive & boot-strap circuit included

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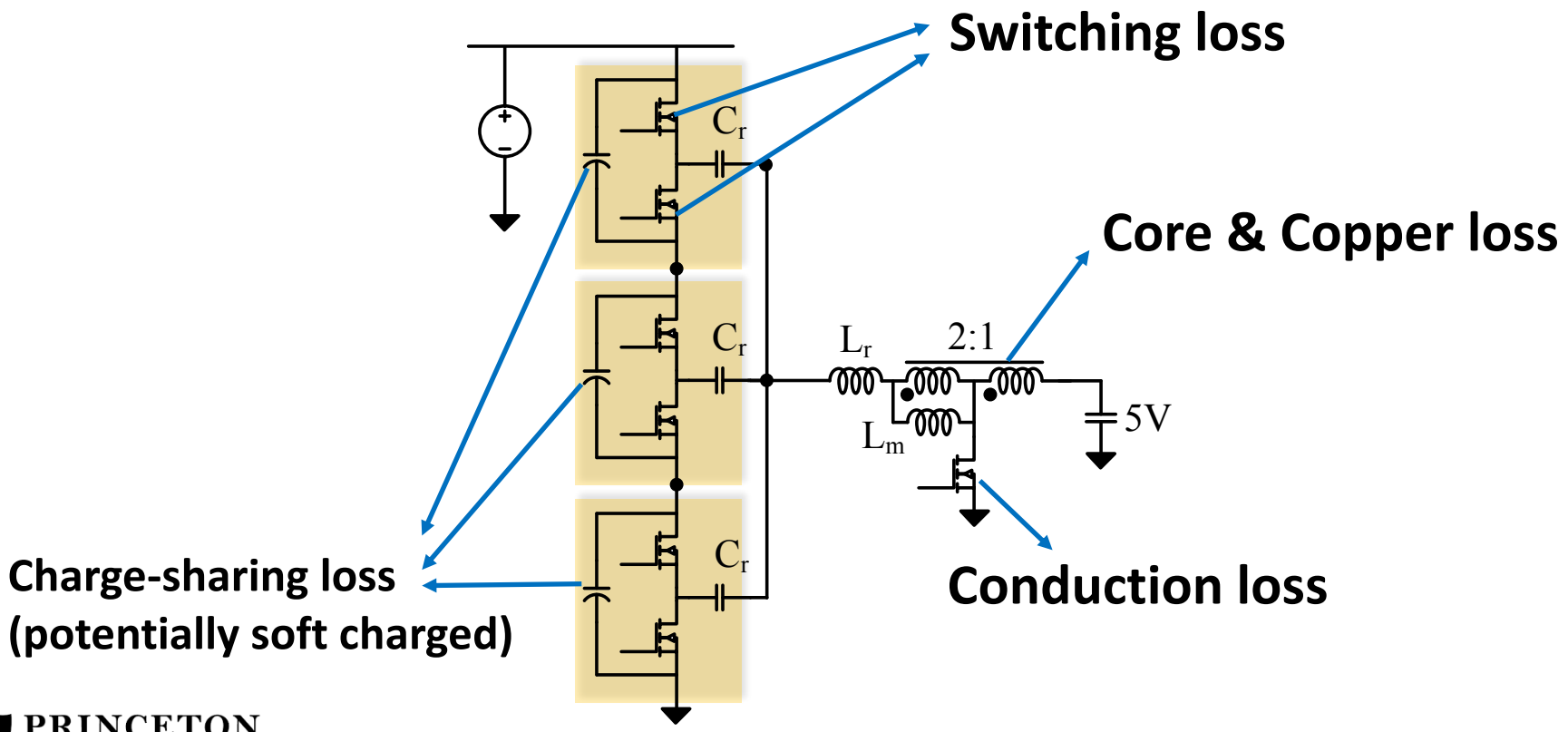
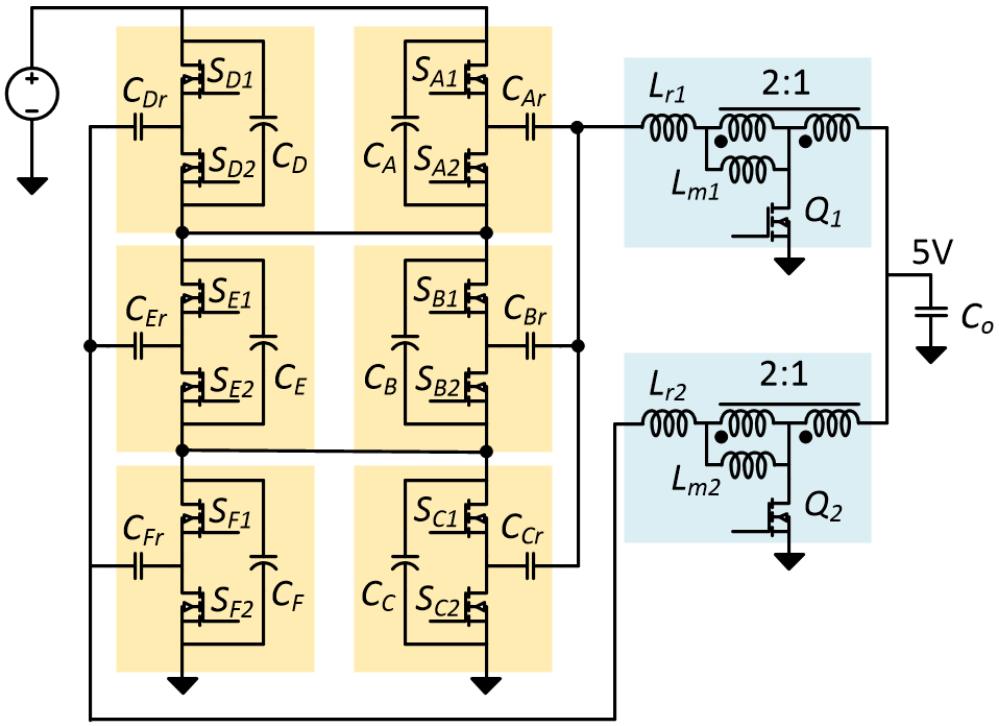
Converter Parameter Design

- Design capacitors to balance the charge sharing loss and size
- Design coupled inductor to achieve ZVS and minimize core loss
- Select switches to minimize the switching and conduction losses
- Select the optimal operating frequency (600kHz)



Prototype Specifications

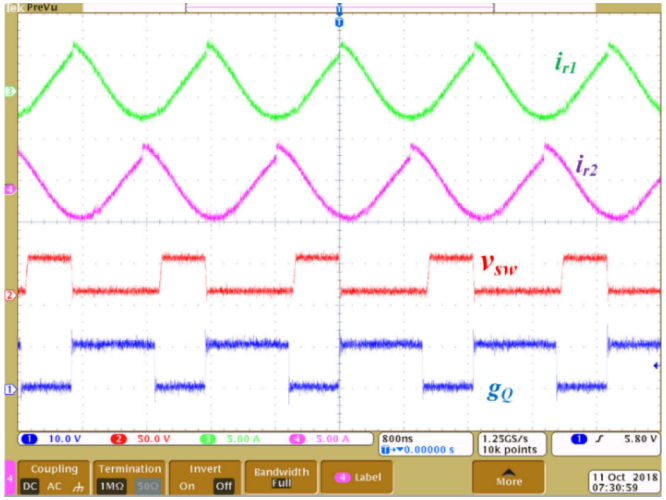


BOM of the prototype converter

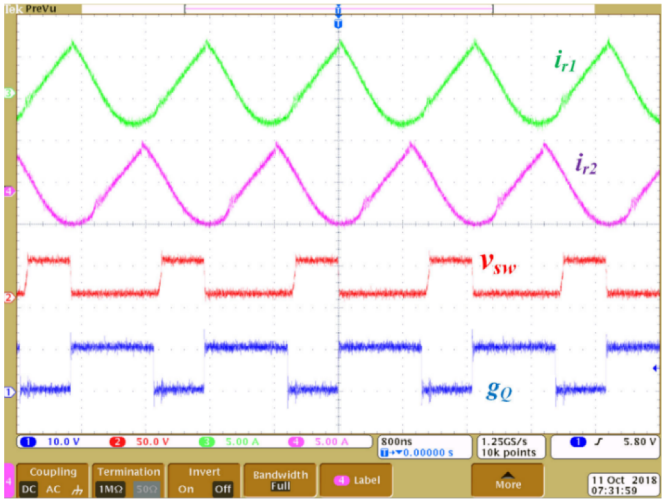
Device Symbol	Component Description
C_{Ar}, C_{Dr}	C0G Ceramic, 200V, 100 nF+39 nF+2x22 nF
C_{Br}, C_{Er}	C0G Ceramic, 100V, 100 nF+39 nF+2x22 nF
C_{Cr}, C_{Fr}	C0G Ceramic, 50V, 100 nF+39 nF+2x22 nF
L_{r1}, L_{r2}	173 nH
L_{m1}, L_{m2}	1.1 μH
$S_{A1,A2}$–$S_{F1,F2}$	TI LMG5200 integrated GaN half-bridge modules
Q_1, Q_2	2x Vishay SIR890DP silicon MOSFETs
C_A–C_F	2x X5R Ceramic, 50V, 10 μF
C_o	36x X5R Ceramic, 6.3V, 22 μF
Inductor	Ferroxcube ER18, Core material 3F45, turns ratio 2:1, 4-layer PCB

- **The half-bridge module is implemented with TI GaN LMG5200**
- **The coupled inductor is implemented as a PCB planar inductor**

Experimental Results

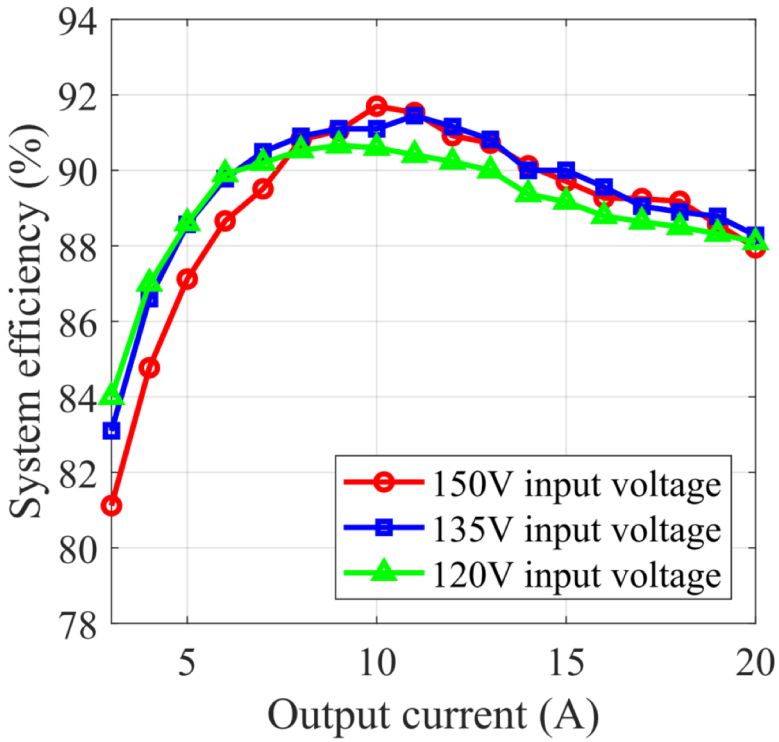


3A output current



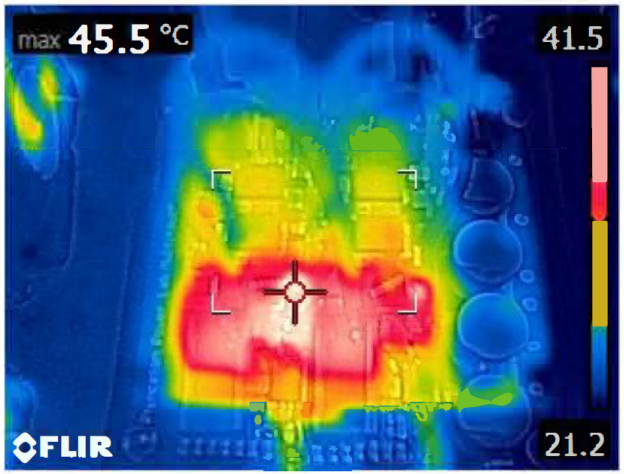
10A output current

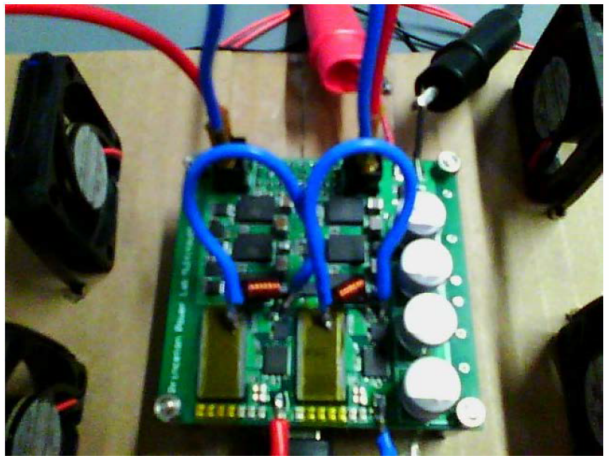
Input: 120V-150V, Output: 5V, Current, 20A



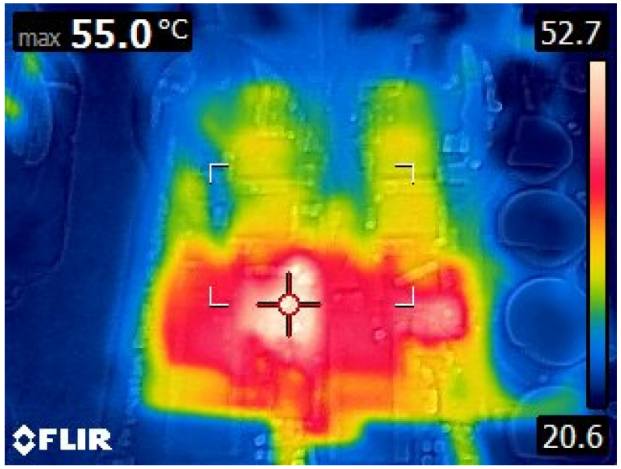
- Peak efficiency 91.5% with 10 A output current
- Over 88% efficiency across a wide voltage/power range

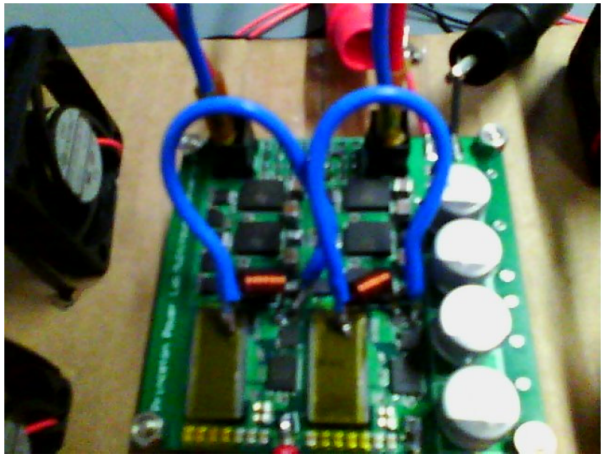
Converter Thermal Images





3A output current (200LFM)

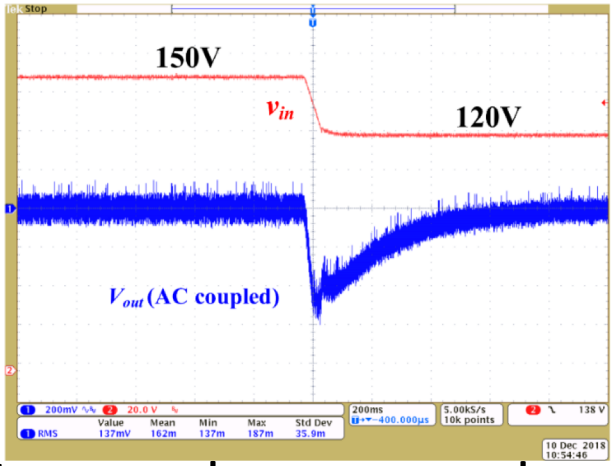




10A output current (200LFM)

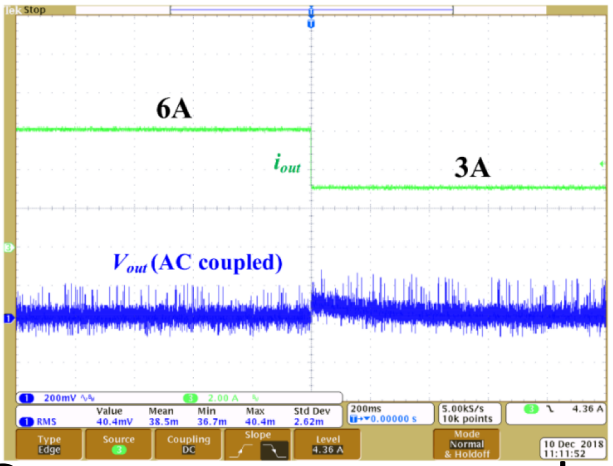
The coupled inductor is still the hottest component

Transient response



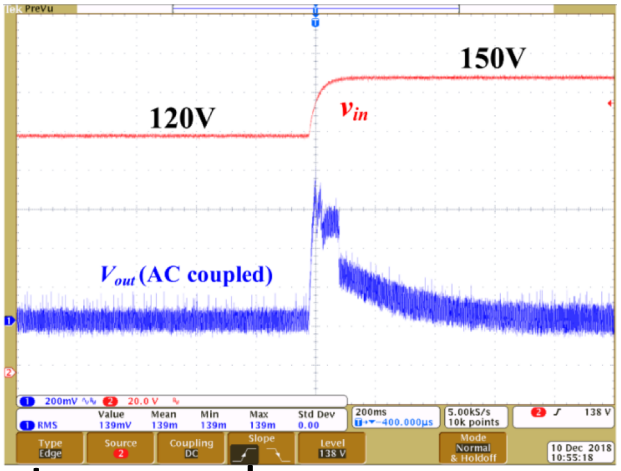
400mV

Input voltage steps down



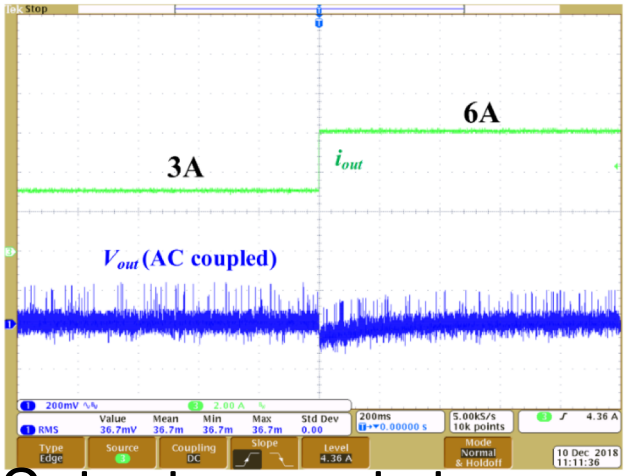
40mV

Output current steps down



400mV

Input voltage steps up



40mV

Output current steps up

Improving dynamic response in future work

Conclusion

- MSP architecture and LEGO building blocks
- Linear extendable with reduced voltage/current stresses
- Hybrid switched-capacitor magnetic operation
- Achieve high efficiency and power density across wide operation range

Thank you!

References

1. Y. Lei, W. Liu and R. C. N. Pilawa-Podgurski, “An Analytical Method to Evaluate and Design Hybrid Switched-Capacitor and Multilevel Converters,” IEEE Transactions on Power Electronics, vol. 33, no. 3, pp. 2227-2240, March 2018.
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5. K. I. Hwu, W. Z. Jiang and Y. T. Yau, “Ultrahigh Step-Down Converter,” IEEE Transactions on Power Electronics, vol. 30, no. 6, pp. 3262-3274, June 2015.