IEEE ENERGY CONVERSION CONGRESS & EXPO BALTIMORE, MD ▲ SEPT. 29 - OCT. 3

LEGO-MIMO Architecture:

A Universal Multi-Input Multi-Output (MIMO) Power Converter with Linear Extendable Group Operated (LEGO) Power Bricks

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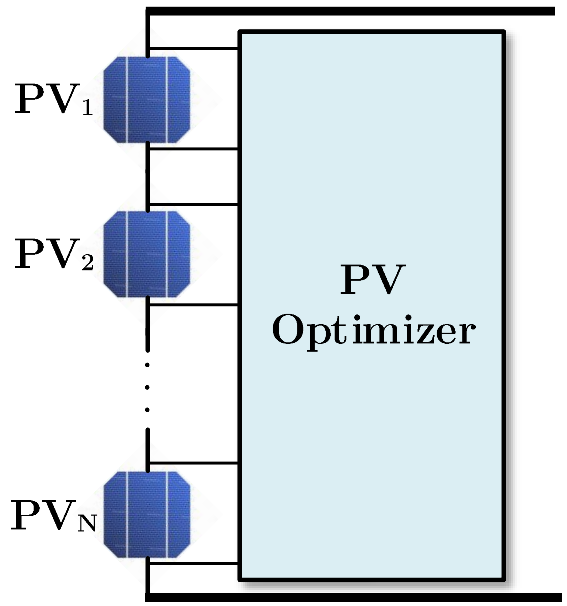
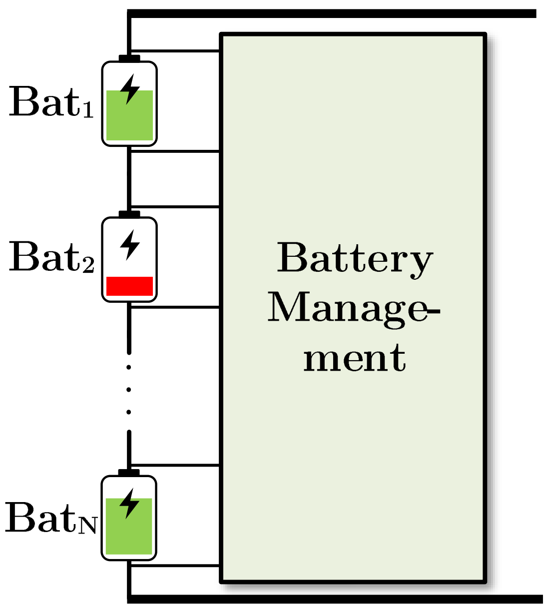
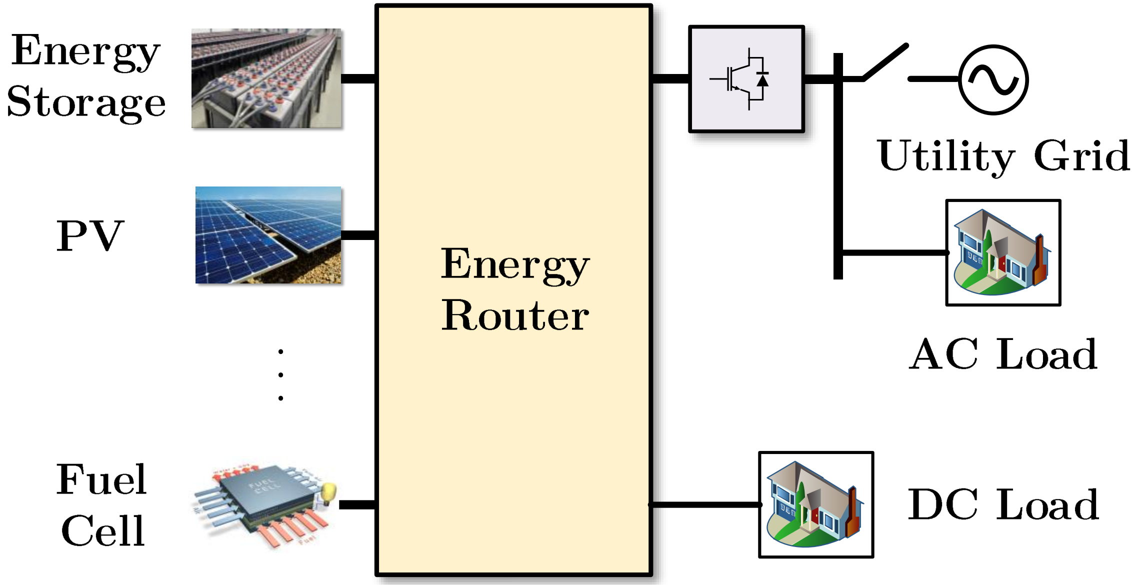
MIMO Applications







- Large number of modular cells
- MPPT, power balancing, SOC monitoring
- Multiple energy sources/loads
- Energy routing

MIMO Architectures

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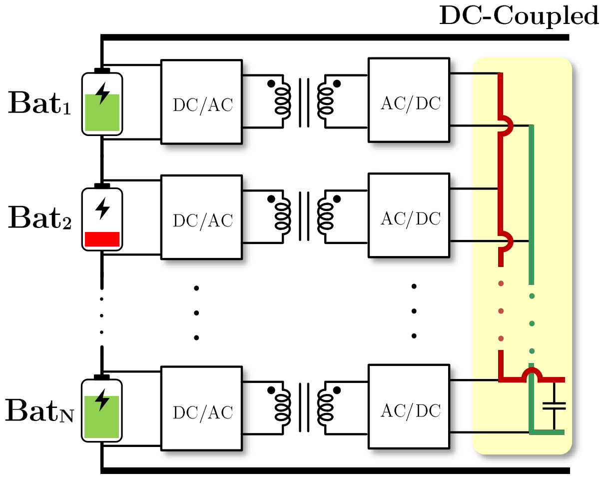
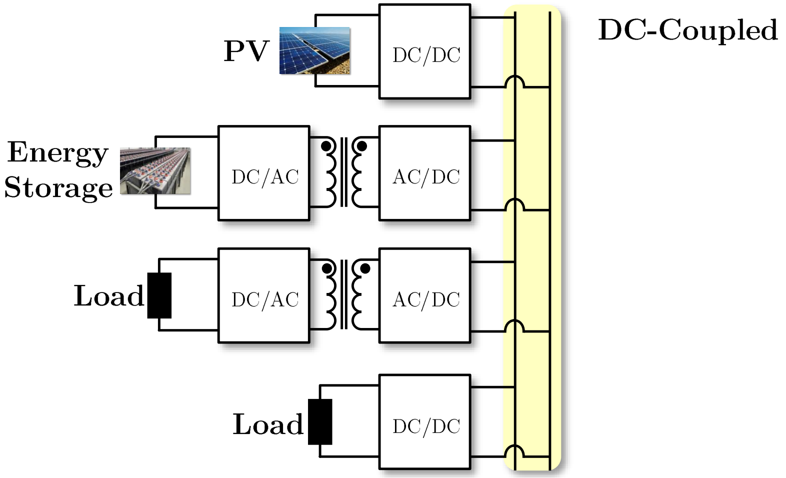
DC-Coupled MIMO

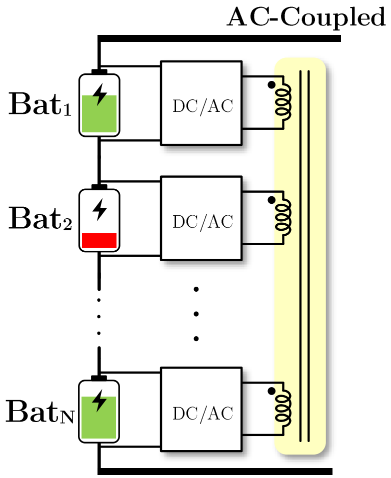
- ☺ Decoupled control
- ☹ Multiple conversion stages
- ☹ Low efficiency

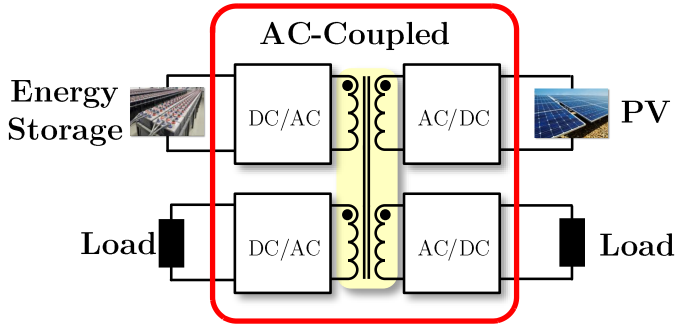




AC-Coupled MIMO

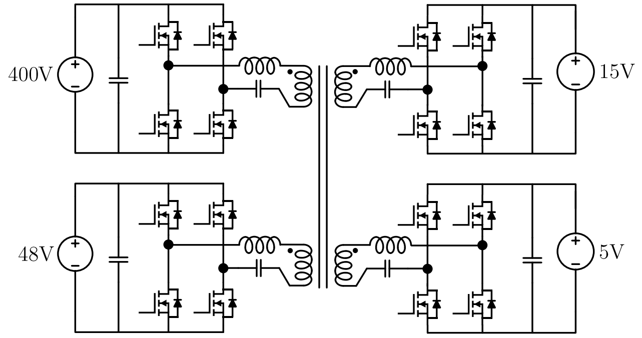
- ☺ Single-core multi-winding transformer
- ☺ Fewer conversion stages
- ☺ High efficiency
- ☹ Coupled power flow

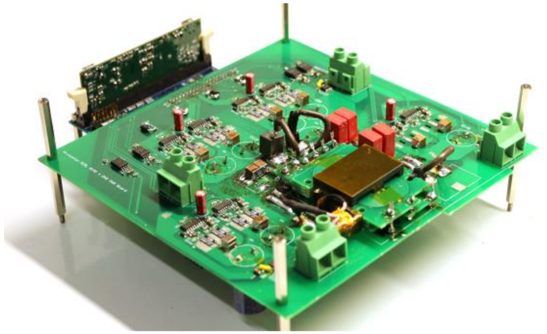


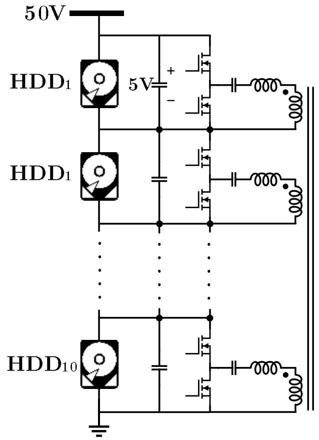


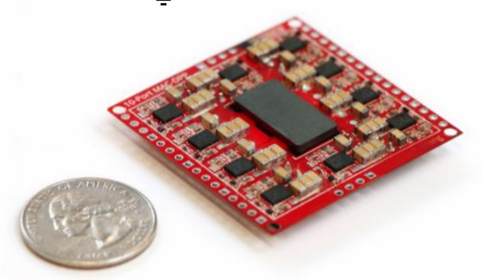
Energy Router

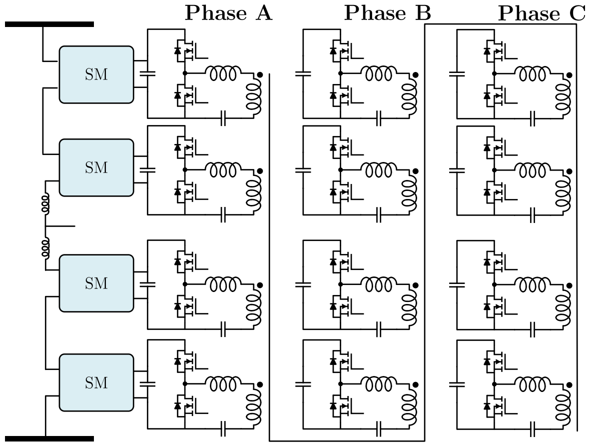
AC-Coupled MIMO: Previous Work

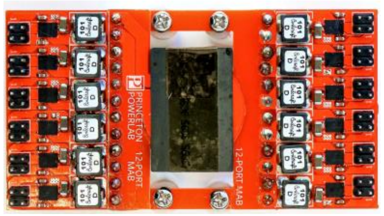












- **400V-48V-15V-5V 4-Port** converter for DC power distribution in smart home[1]
- **50V-5V 10-Port** converter for data center[2]
- **12-Port** converter for submodule capacitor balancing in 3-Phase MMC inverter[3]

❑ Large number of ports with single magnetic core

❑ Cover wide voltage & current range

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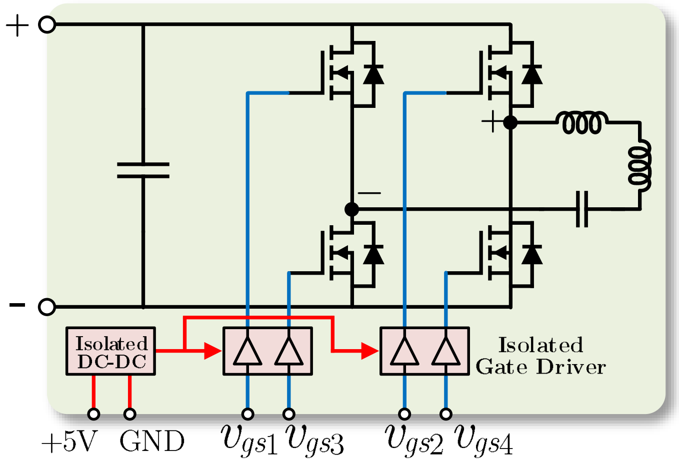
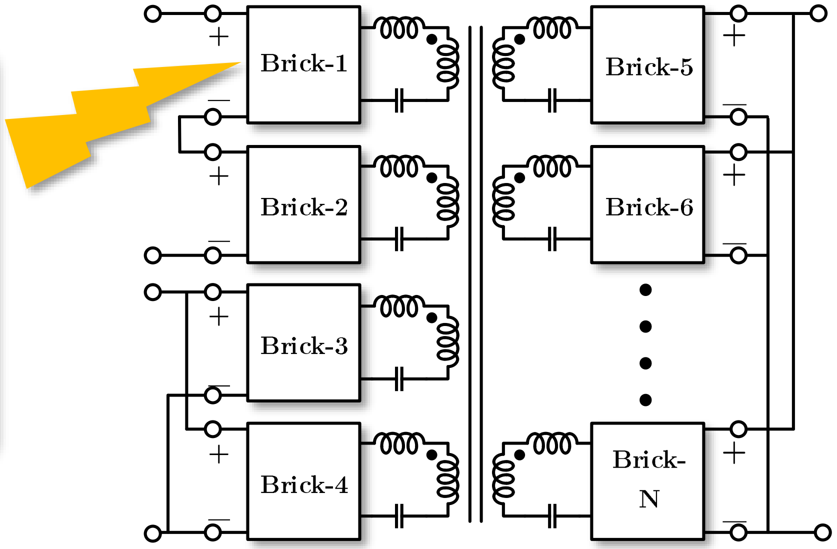
LEGO-MIMO Concept

Linear
Extendable
Group
Operated

LEGO Power Brick (Active-Bridge)



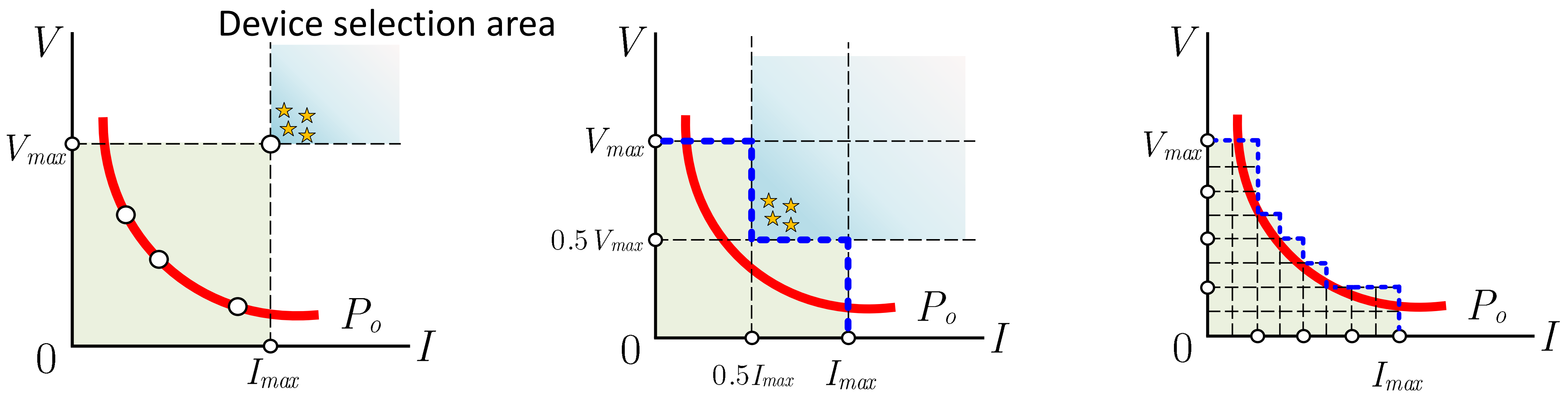
LEGO-MIMO Converter



- ❑ **Identical active-bridge unit: LEGO toy bricks**

- ❑ **Series/parallel connecting for wide voltage/current range**
- ❑ **Modular design, reconfiguration**

Power Rating of LEGO Bricks



- Traditional converter
  $P_{max} = V_{max} \times I_{max} >> P_o$

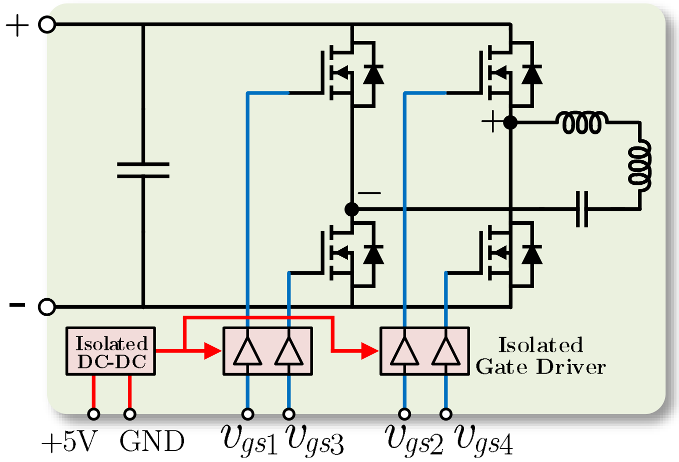
- 2 LEGO bricks
- $V_{max} - 0.5I_{max}$
- $0.5V_{max} - I_{max}$
  $P_{max} = 2 \times 0.5V_{max} \times 0.5I_{max}$

- N LEGO bricks
- $\boldsymbol{P_{max} \approx P_o}$

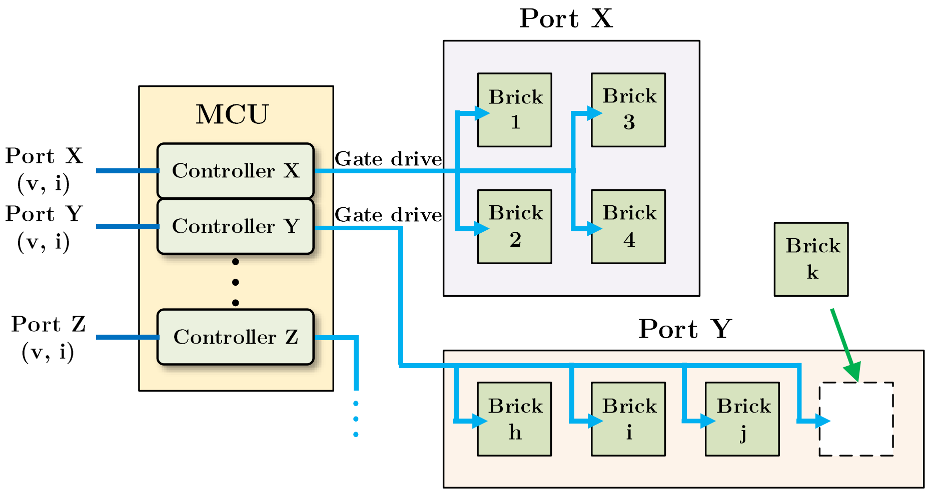
Group Operated Control

Linear
Extendable
Group
Operated

LEGO Power Brick (Active-Bridge)



Group Control Strategy



- ❑ **LEGO bricks in the same group (port): same gate driver**
- ❑ **Plug-and-play, simpler controller, fewer sensors**

Reduced Order Control Model

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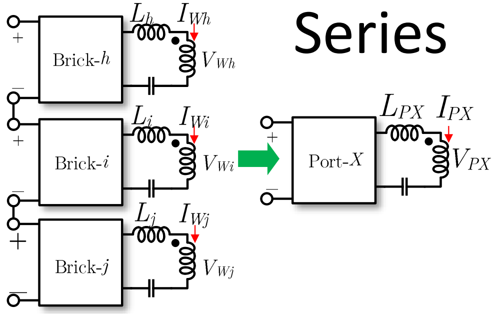
Brick power: $P_i = \dfrac{N_i V_i}{2\pi^2 f_s} \sum_{j \neq i} \dfrac{N_j V_j (\Phi_i - \Phi_j)(\pi - |\Phi_i - \Phi_j|)}{N_i^2 N_j^2 L_{ij} + N_j^2 L_i + N_i^2 L_j}$

N bricks and **M** ports: **N** ≥ **M**

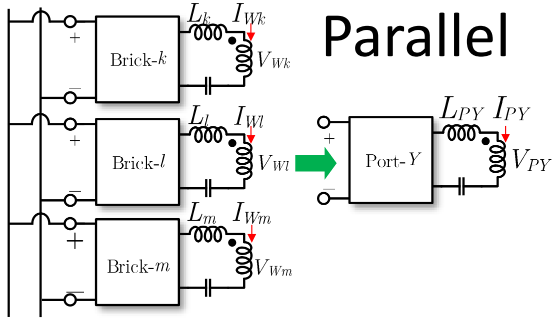
Series



$$I_{PX} = I_{Wh} = I_{Wi} = I_{Wj}$$

$$V_{PX} = V_{Wh} + V_{Wi} + V_{Wj}$$

Parallel



$$I_{PY} = I_{Wk} + I_{Wl} + I_{Wm}$$

$$V_{PY} = V_{Wk} = V_{Wl} = V_{Wm}$$

$$\begin{bmatrix} \hat{v}_{P1} \\ \hat{v}_{P2} \\ \vdots \\ \hat{v}_{Pm} \end{bmatrix} = \boldsymbol{G_{Pi}} \begin{bmatrix} \hat{\imath}_{P1} \\ \hat{\imath}_{P2} \\ \vdots \\ \hat{\imath}_{Pm} \end{bmatrix} + \boldsymbol{G_{P\phi}} \begin{bmatrix} \hat{\phi}_{P1} \\ \hat{\phi}_{P2} \\ \vdots \\ \hat{\phi}_{Pm} \end{bmatrix}$$

Voltage conversion

$$\begin{bmatrix} V_{P1} \\ \vdots \\ V_{Pm} \end{bmatrix} = \underbrace{\begin{bmatrix} Q_{V11} & \cdots & Q_{V1n} \\ \vdots & \ddots & \vdots \\ Q_{Vm1} & \cdots & Q_{Vmn} \end{bmatrix}_{m\times n}}_{\boldsymbol{Q_V}} \begin{bmatrix} V_{W1} \\ \vdots \\ V_{Wn} \end{bmatrix}$$

Current conversion

$$\begin{bmatrix} I_{W1} \\ \vdots \\ I_{Wn} \end{bmatrix} = \underbrace{\begin{bmatrix} Q_{C11} & \cdots & Q_{C1n} \\ \vdots & \ddots & \vdots \\ Q_{Cn1} & \cdots & Q_{Cnm} \end{bmatrix}_{n\times m}}_{\boldsymbol{Q_C}} \begin{bmatrix} I_{P1} \\ \vdots \\ I_{Pm} \end{bmatrix}$$

Impedance matrix simplification

$$\begin{bmatrix} V_{W1} \\ \vdots \\ V_{Wn} \end{bmatrix} = j\omega \boldsymbol{M_{W2W}} \begin{bmatrix} I_{W1} \\ \vdots \\ I_{Wn} \end{bmatrix} \Rightarrow \begin{bmatrix} V_{P1} \\ \vdots \\ V_{Pm} \end{bmatrix} = j\omega \boldsymbol{Q_V M_{W2W} Q_C} \begin{bmatrix} I_{P1} \\ \vdots \\ I_{Pm} \end{bmatrix}$$

- ***M* × *M*** transfer matrix
- For port *P*/*V* regulation

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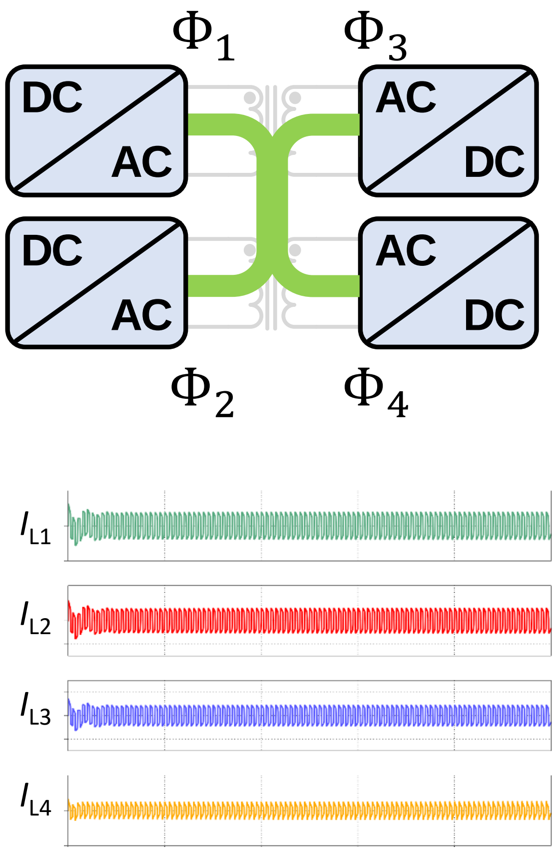
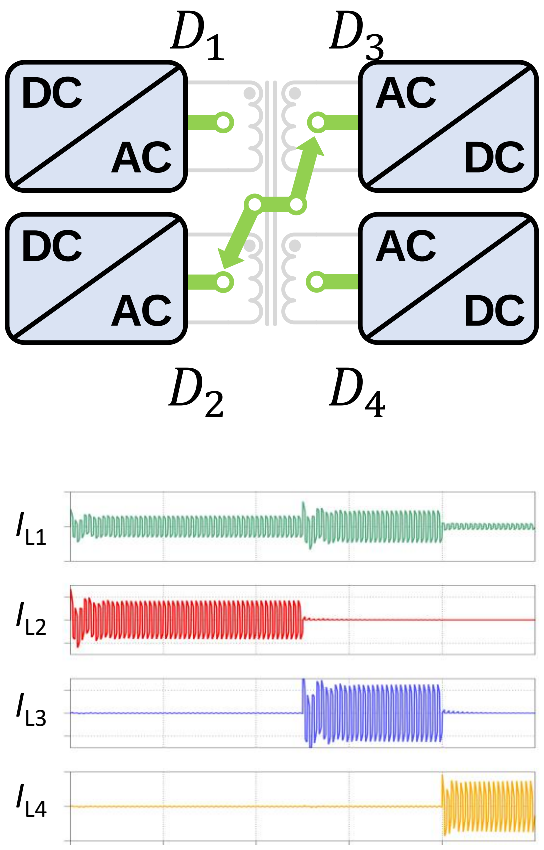
Control Methods

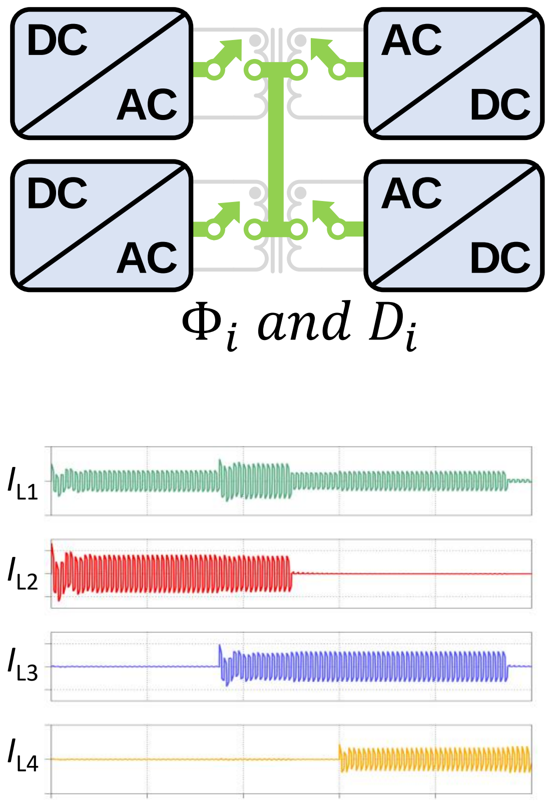
- **Phase-shift**



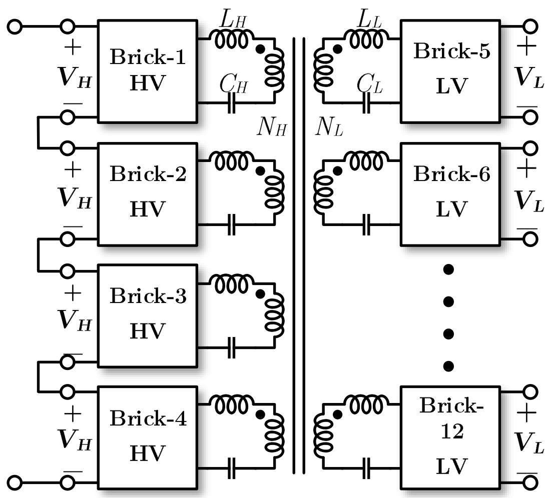
- **Time-sharing**

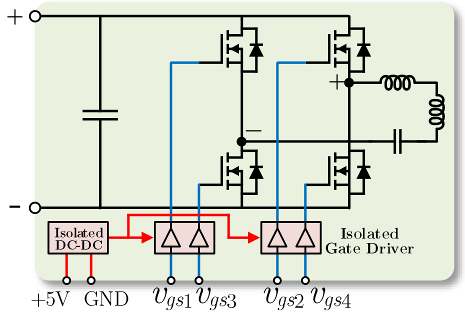


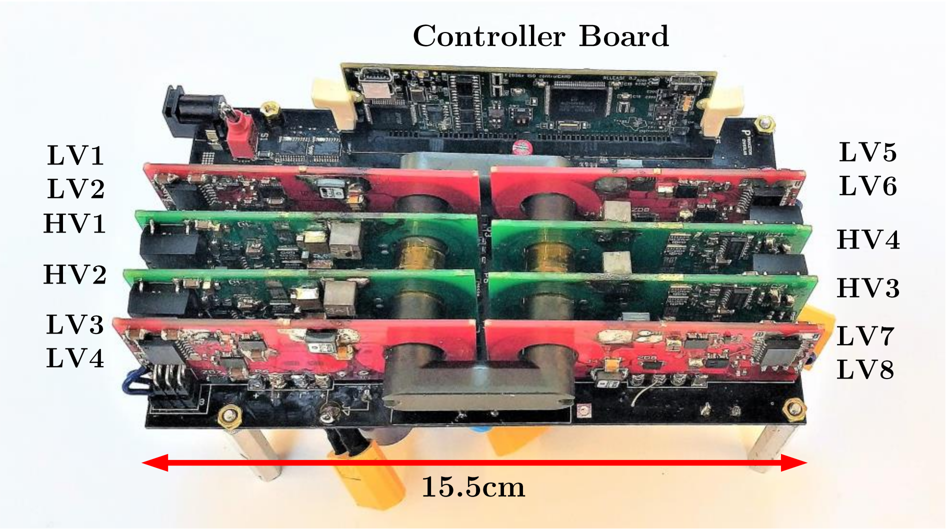
- **Hybrid**



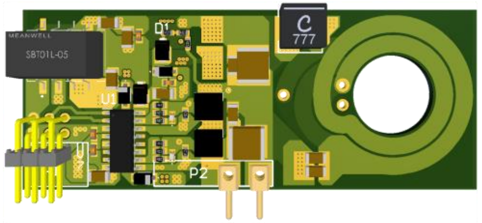
LEGO-MIMO Design Example

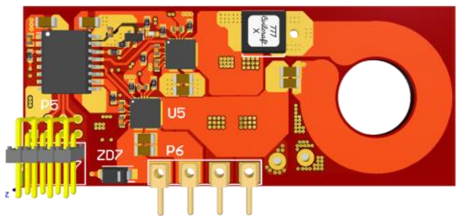






- ❑ 1 magnetic core
- ❑ Air-cooling
- ❑ No heatsink





- HV PCB (1 HV brick)
- V_H = 72V, N_H = 8
- P_{max} = 200W, f_s = 200kHz
- GaN GS1004B/100V

- LV PCB (2 LV bricks)
- V_L = 9V, N_L = 1
- P_{max} = 2×100W, f_s = 200kHz
- DrMOS SIC632/24V

Multi-Winding Transformer Design

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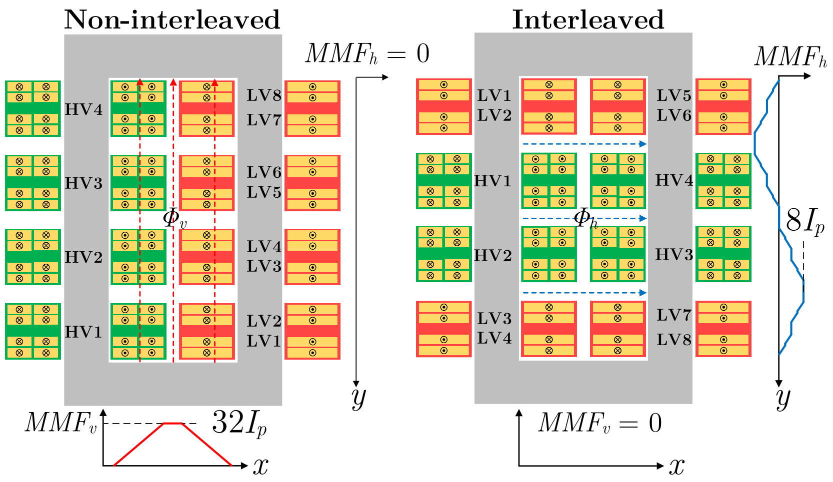
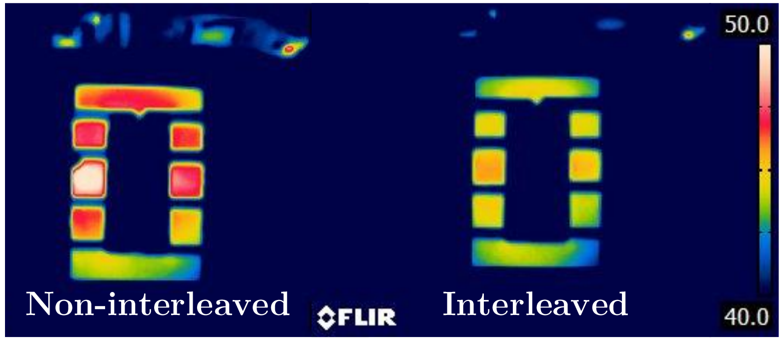
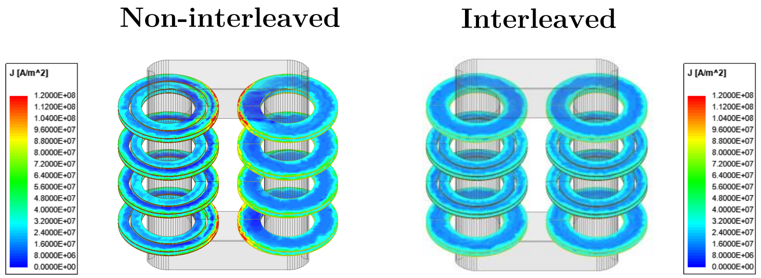


- Thermal measurement: HV input, LV output
- P = 80W, T_a = 20°C, no air-cooling

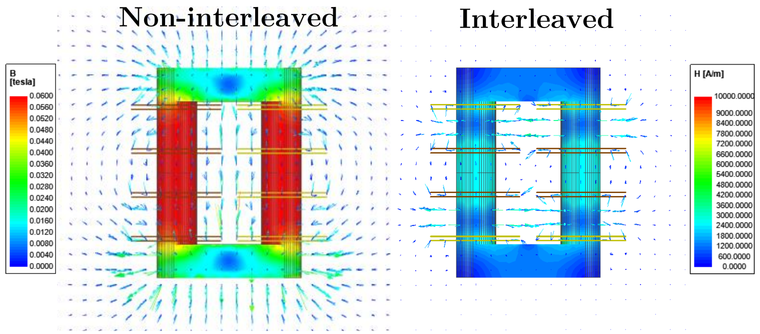


PCB copper current density



- HV windings as primary side, LV windings as secondary side
- Current excitation: I_p = 4A, I_s = 16A

Magnetic field strength and core flux density



Interleaved structure:

- **Lower B and H**
- **Smaller ac resistance (56% of non-interleaved structure)**

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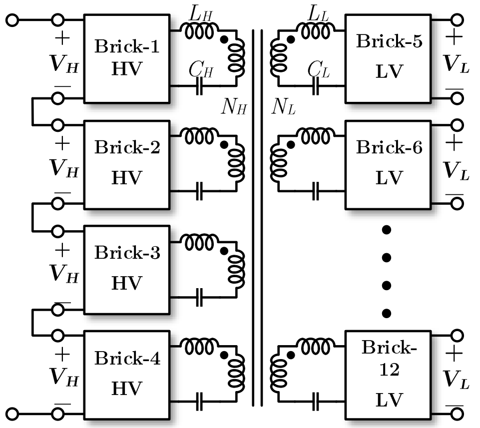
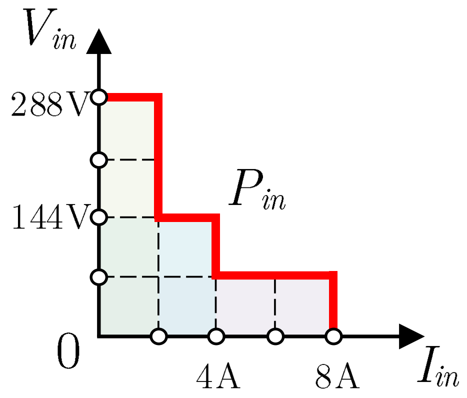
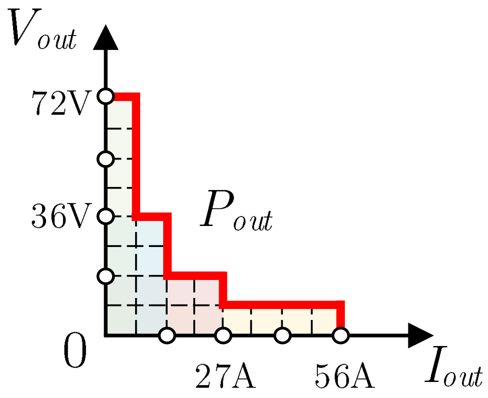
Port Configuration

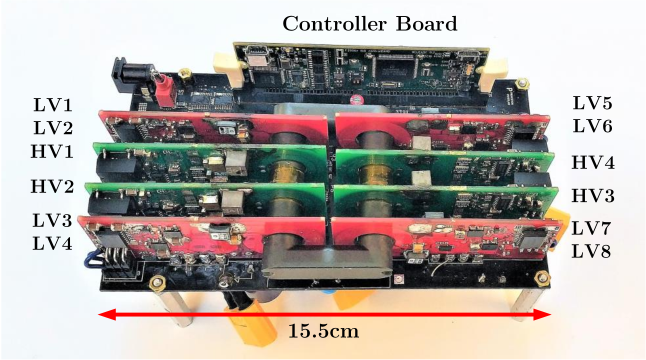


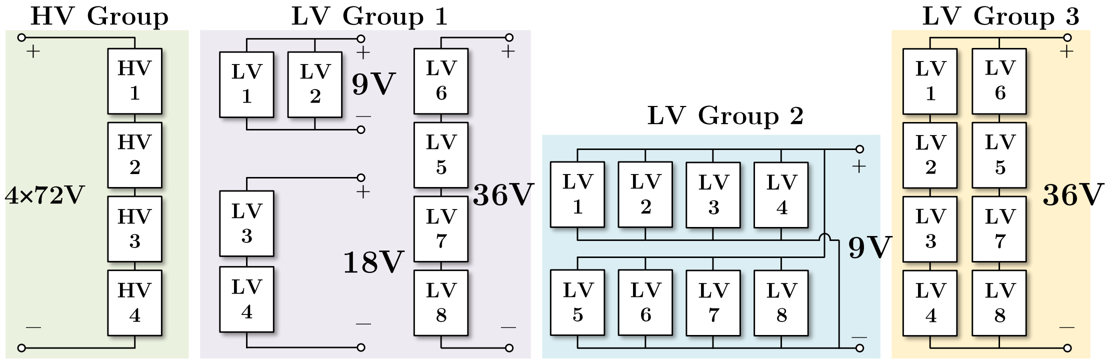


Input operation range



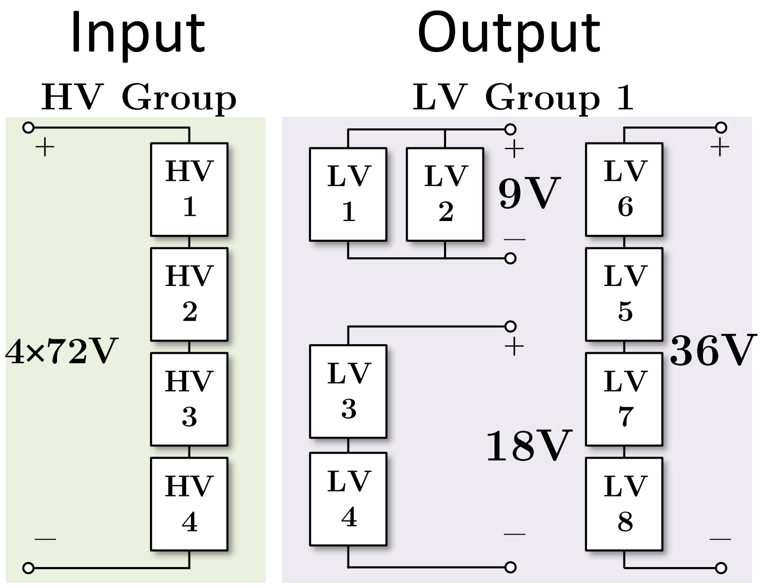
Output operation range



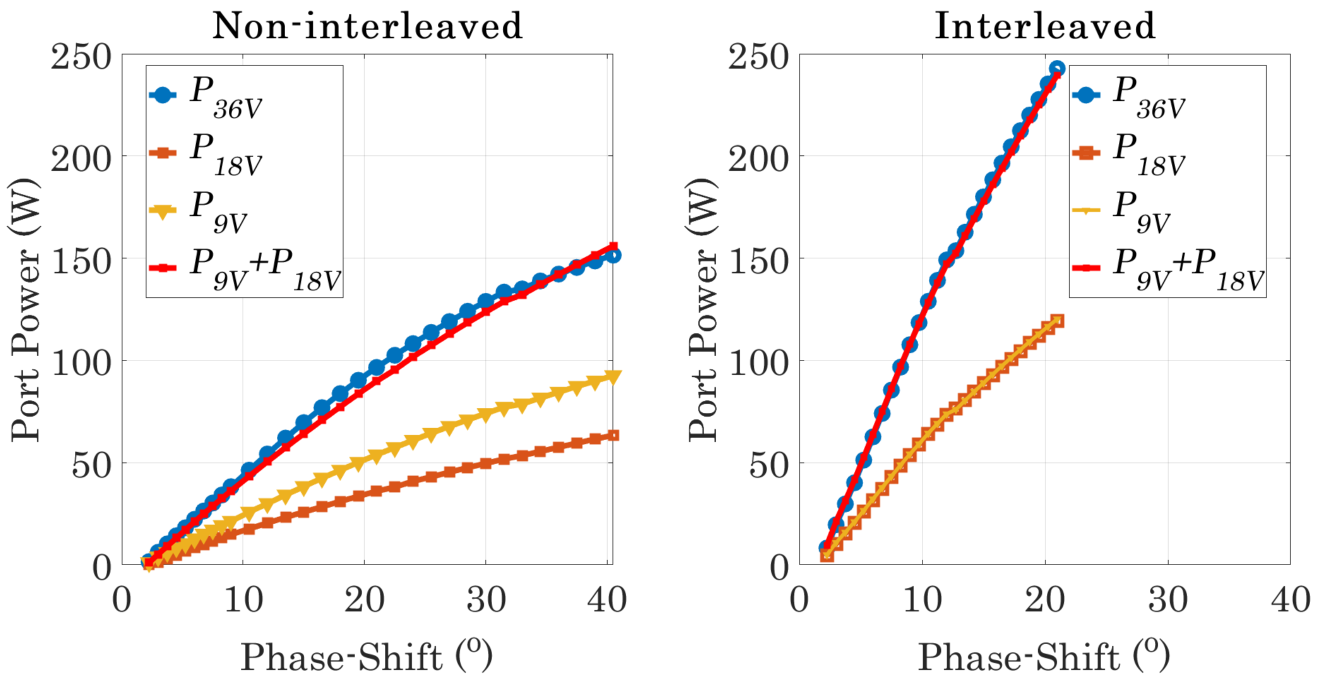


- System maximum power: 500W
- Experiment Setup

Power Distribution



Measured power of the 9V, 18V and 36V ports with same Φ



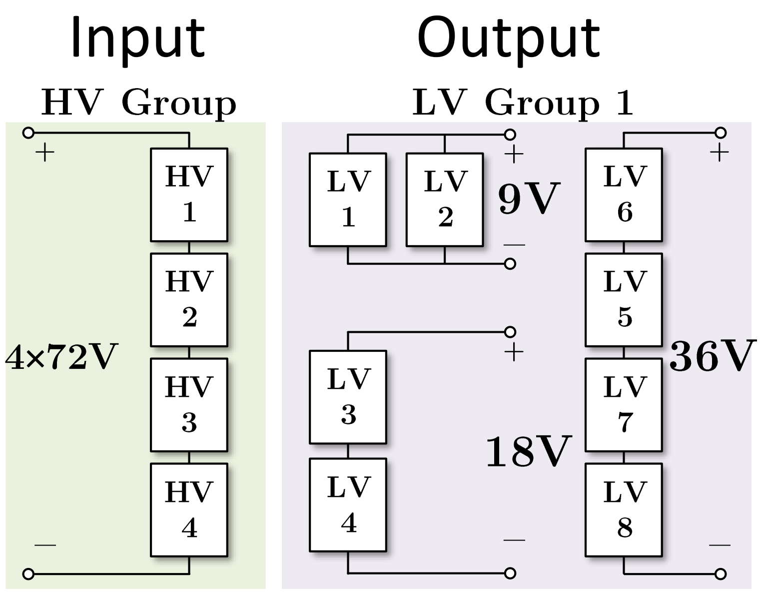
Interleaved structure:

- **Balanced power distribution**
- **Able to be linearly extended**

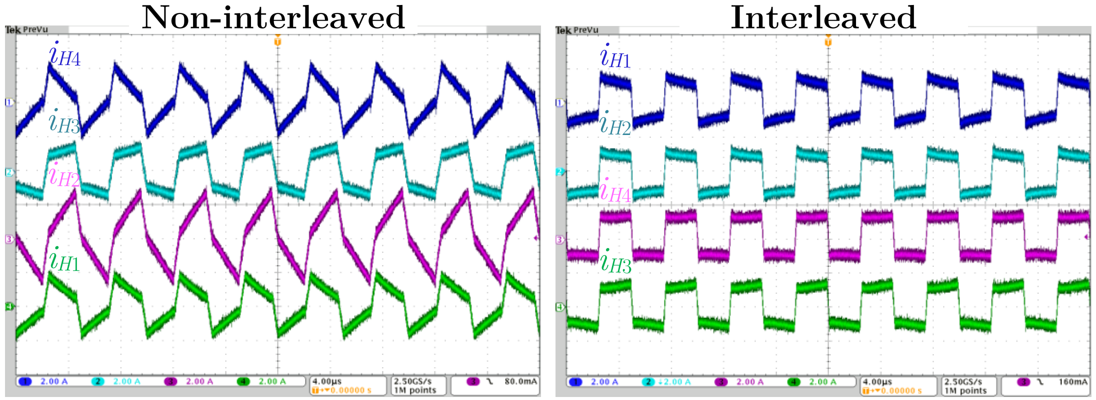
Non-interleaved:
- $P_{9V} \neq P_{18V}$
- $P_{9V} + P_{18V} \neq P_{36V}$

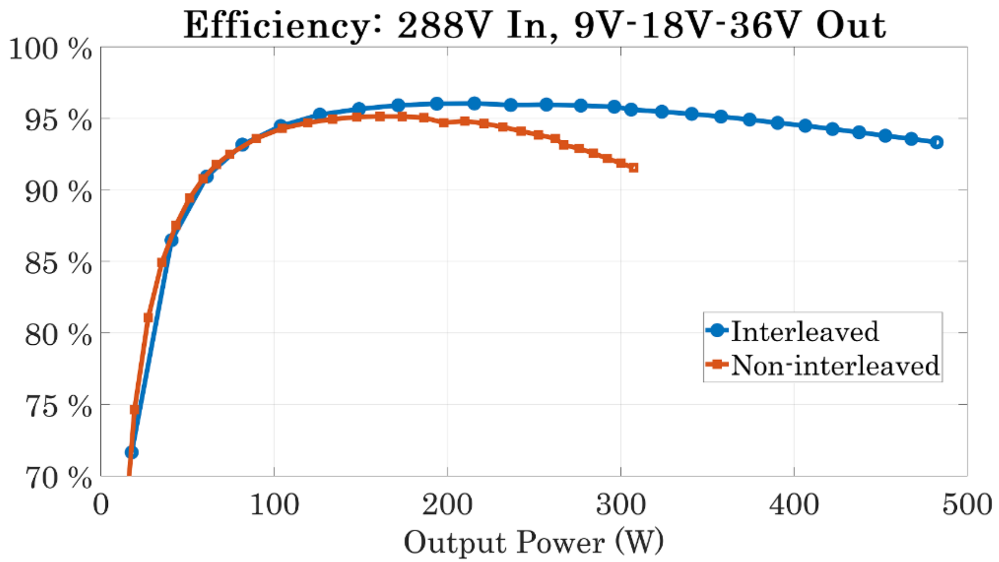
Interleaved:
- $P_{9V} \approx P_{18V}$
- $P_{9V} + P_{18V} \approx P_{36V}$

Efficiency with Different Winding Structures



Winding currents in the HV bricks, P_o = 300W

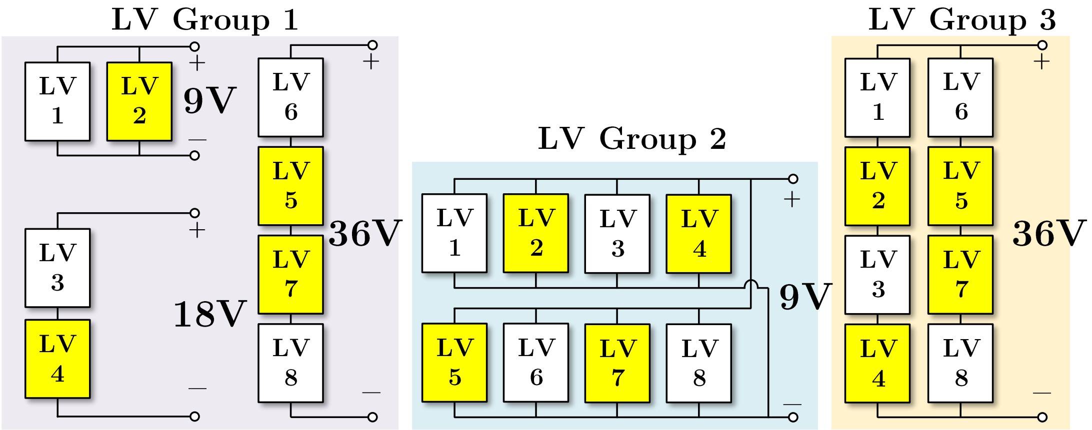


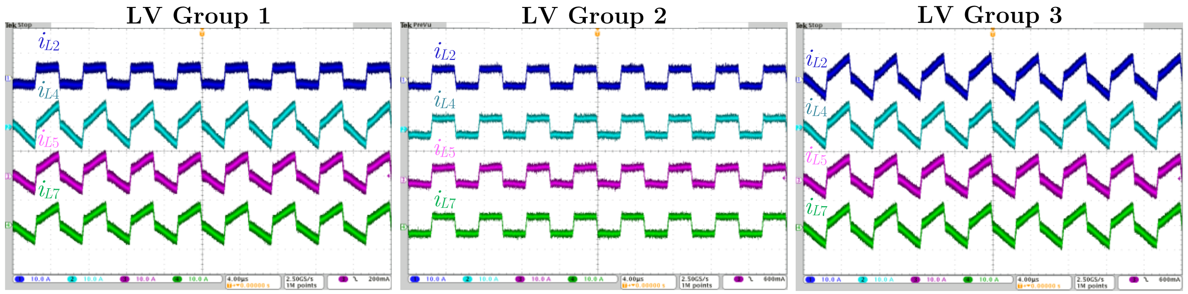


Interleaved structure:

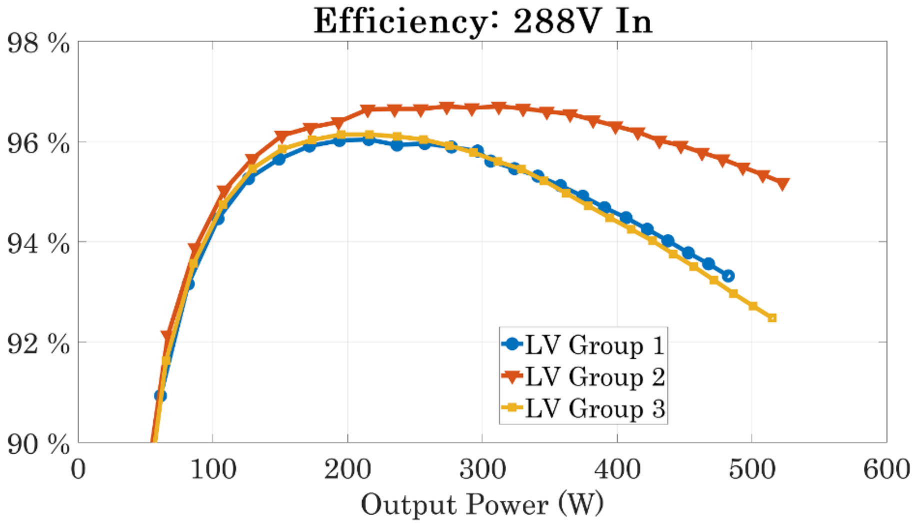
- **Lower current peak**
- **Higher efficiency**

Efficiency with Different Port Structures





Winding currents in the LV bricks with interleaved structure, P_o = 300W



- **96.7% @ 288V - 9V /300W**
- **Voltage slightly unbalanced among series bricks**
- **Tradeoff: cost vs. efficiency**

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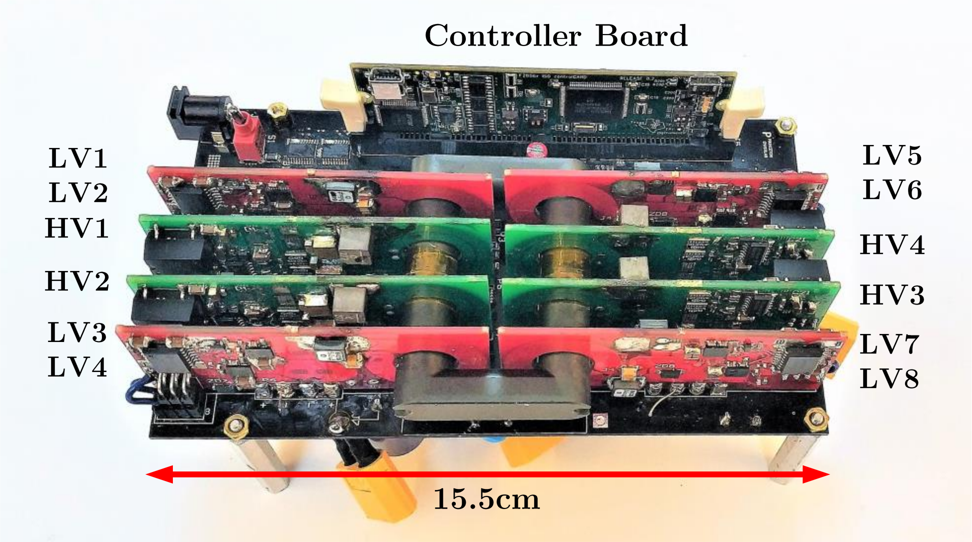
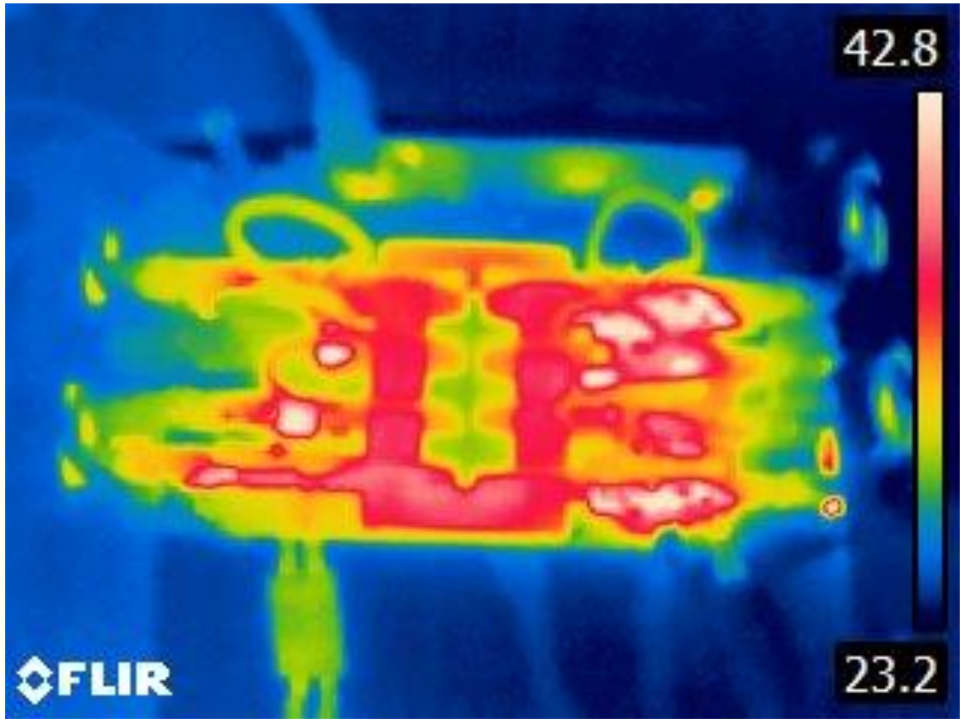
Thermal Measurement

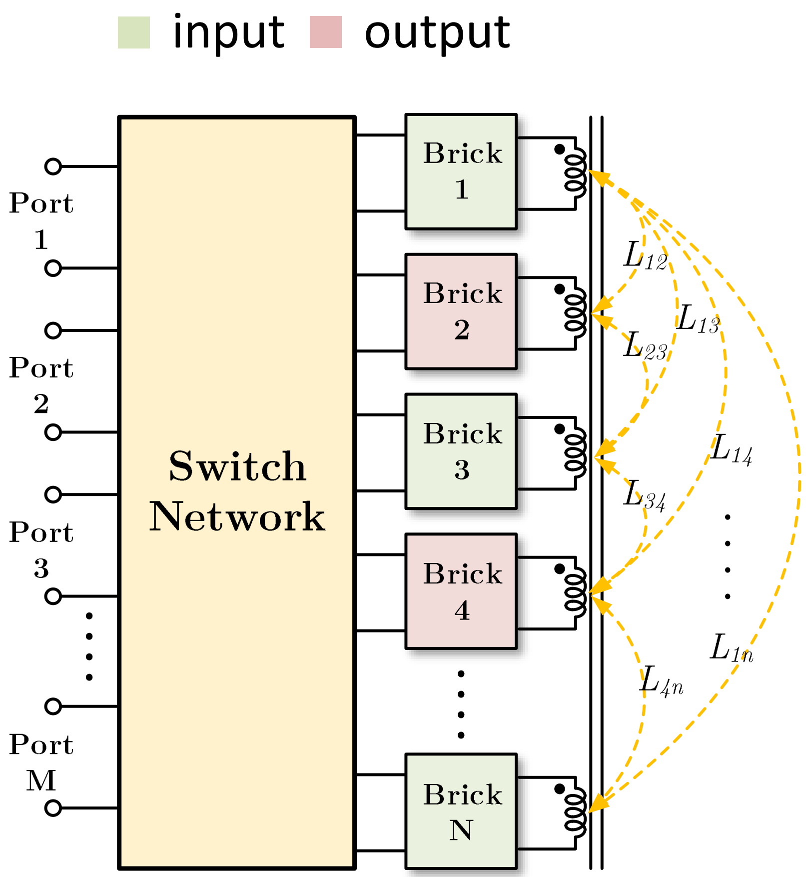
- LV Group 1: 9V-18V-36V output
- P = 500W, T_a = 23°C
- Airflow = 21.9 CFM





- ❑ **Hottest components: HV inductors and LV DrMOS**
- ❑ **Natural distribution of heat**
- ❑ **No heatsink**

Design Guideline

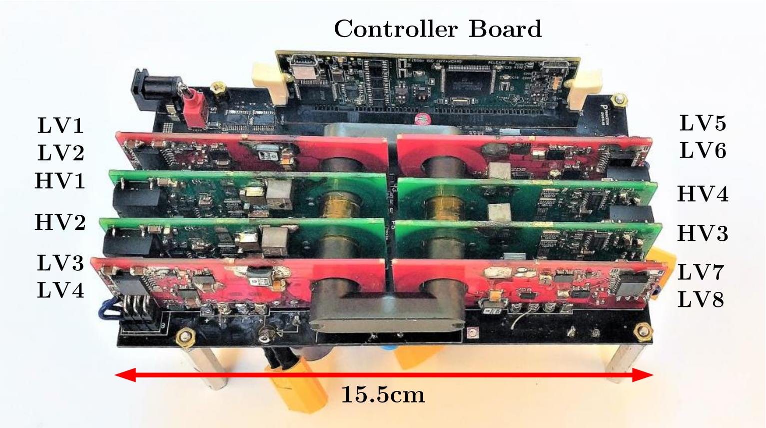


For equal power distribution

- Interleaving the input bricks (windings) and output bricks (windings)
- Using bricks with similar linkage inductance L_{ij} for the same port

Summary

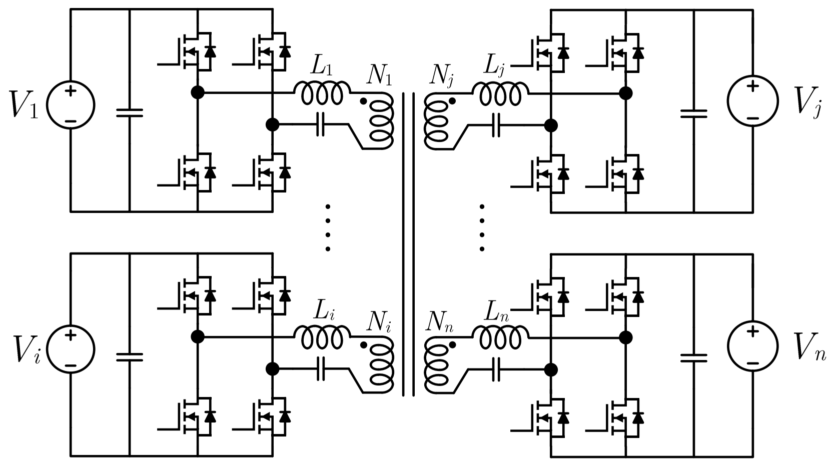
- LEGO-MIMO: Linear Extendable Group Operated Multi-Input Multi-Output
- Applicable to wide operation range multiport dc-dc applications
  - Battery balancer, energy router, PV MPPT
- Design example: 500W 12-Brick MIMO dc-dc converter
- Wide operation range: 72V/8A-288V/2A input, 9V/56A-72V/7A output
- Multi-winding single-core transformer design
- 96.7% peak efficiency @ 288V-9V/250W
- Natural heat distribution



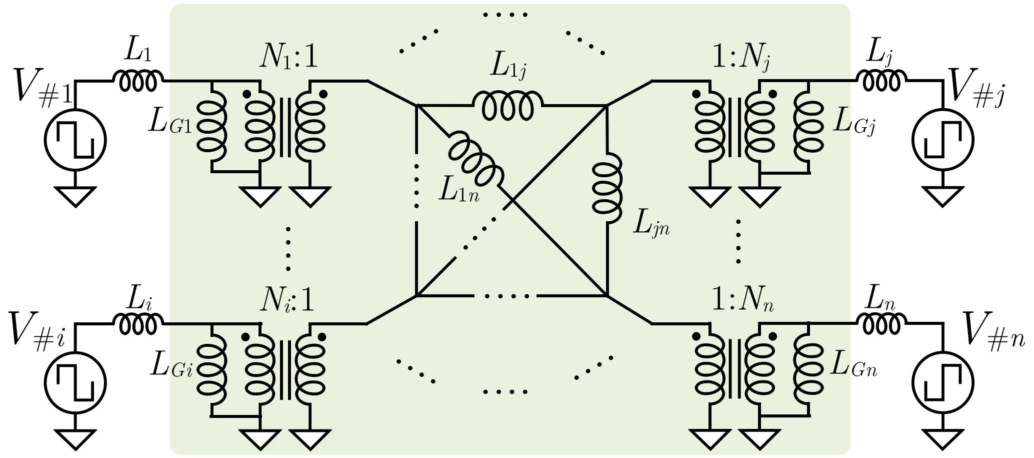
References

1. 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.
2. P. Wang, Y. Chen, Y. Elasser and M. Chen, "Small Signal Model for Very-Large-Scale Multi-Active-Bridge Differential Power Processing (MAB-DPP) Architecture," *2019 20th Workshop on Control and Modeling for Power Electronics (COMPEL)*, Toronto, ON, Canada, 2019, pp. 1-8.
3. Y. Chen, Y. Elasser, P. Wang, J. Baek and M. Chen, "Turbo-MMC: Minimizing the Submodule Capacitor Size in Modular Multilevel Converters with a Matrix Charge Balancer," *2019 20th Workshop on Control and Modeling for Power Electronics (COMPEL)*, Toronto, ON, Canada, 2019, pp. 1-8.
4. R. W. Erickson and D. Maksimovic, “A multiple-winding magnetics model having directly measurable parameters," *PESC 98 Record. 29th Annual IEEE Power Electronics Specialists Conference (Cat. No.98CH36196)*, Fukuoka, 1998, pp. 1472-1478 vol.2.

Control Model for Multi-Active-Bridge



- N-Brick multi-active-bridge converter



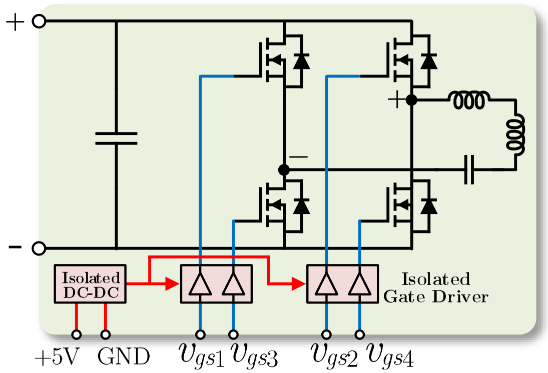
- Cantilever model for an N-winding transformer[4]

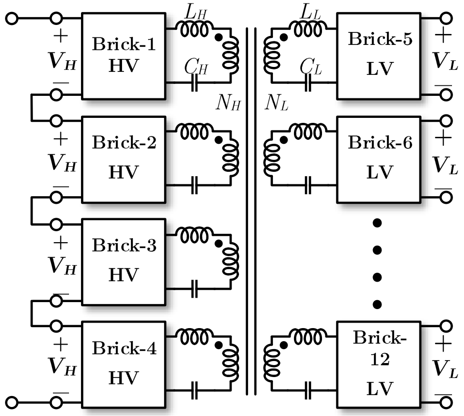
Average power of Brick *i*: $$P_i = \frac{N_i V_i}{2\pi^2 f_s} \sum_{j \neq i} \frac{N_j V_j (\Phi_i - \Phi_j)(\pi - |\Phi_i - \Phi_j|)}{N_i^2 N_j^2 L_{ij} + N_j^2 L_i + N_i^2 L_j}$$

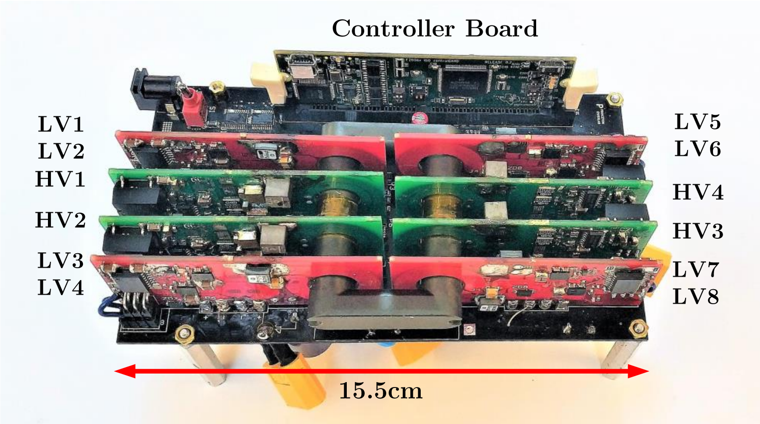
Small signal model[1][2]: $$\begin{bmatrix} \hat{v}_1 \\ \hat{v}_2 \\ \vdots \\ \hat{v}_n \end{bmatrix} = \boldsymbol{G_i} \begin{bmatrix} \hat{i}_1 \\ \hat{i}_2 \\ \vdots \\ \hat{i}_n \end{bmatrix} + \boldsymbol{G_\phi} \begin{bmatrix} \hat{\phi}_1 \\ \hat{\phi}_2 \\ \vdots \\ \hat{\phi}_n \end{bmatrix}$$

- G_i and G_ϕ: ***n* × *n*** transfer matrix
- For independent P/V regulation

Prototype Parameters







Specifications & Symbol	Description
HV Bus Voltage V_H	72V
HV Winding Turns N_H	8
HV Branch Inductor L_H	Coilcraft XEL6060 – 2.7μH
HV Blocking Capacitor C_H	200μF
HV Switch	GS61004B 100V
LV BUS Voltage V_L	9V
LV Winding Turns N_L	1
LV Branch Inductor L_L	Coilcraft SLC7530S – 64nH
LV Blocking Capacitor C_L	440μF
LV DrMOS	SIC632 24V
Switching Frequency f_s	200kHz
Transformer Core	0P4413UC, $\mu_r = 2500$

- System maximum power: 500W