Power Flow Control in Multi-Active-Bridge Converters: Theories and Applications

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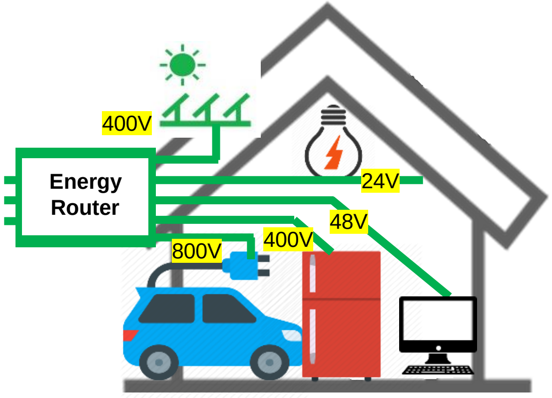
Multiport Power Conversion Applications

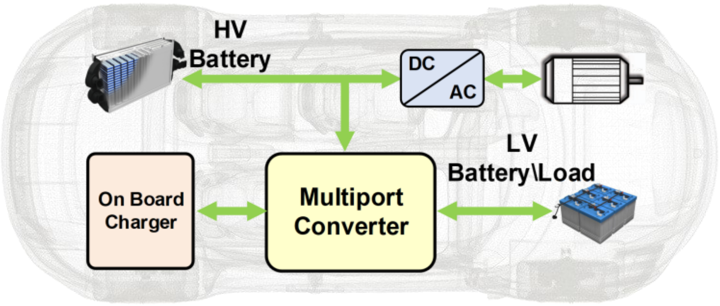
- Solar energy system

- Battery system

- Smart home

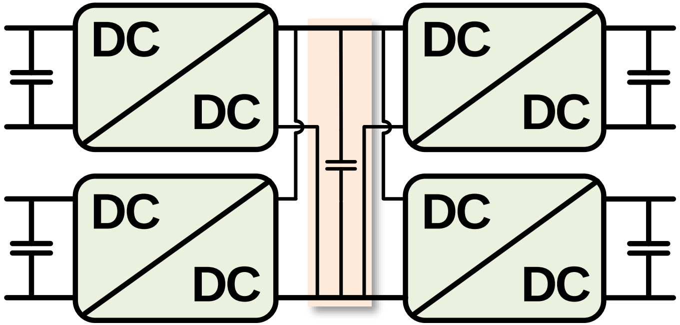


- Electric vehicle



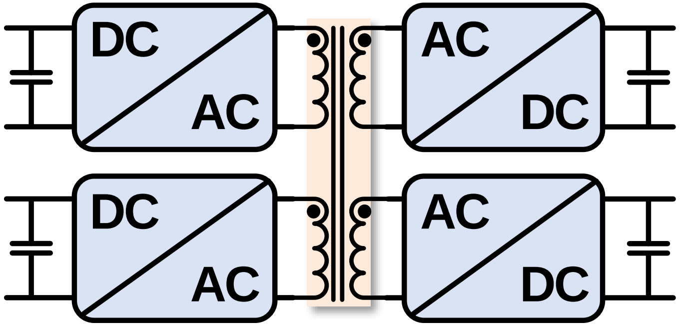
Multiport Architecture

- Dc coupled



☺ Decoupled control
☹ Low efficiency

- Ac coupled

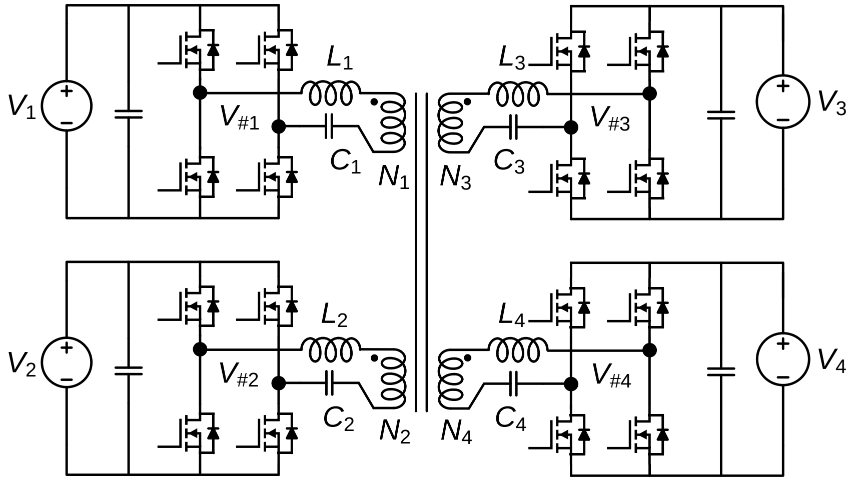


☺ Higher efficiency & power density
☹ Coupled control

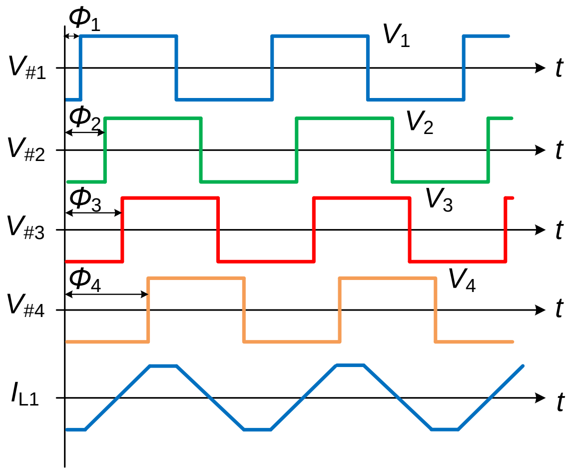
Multi-Active-Bridge Converter

- Ac coupled: single magnetic core
- One "dc-ac-dc" stage between two arbitrary ports
- Control the power flow by changing the phase-shift

$$P = \frac{1}{2\pi f_s} \frac{V_{in} V_o}{N_{in} N_o L} \Phi \left(1 - \frac{|\Phi|}{\pi}\right)$$

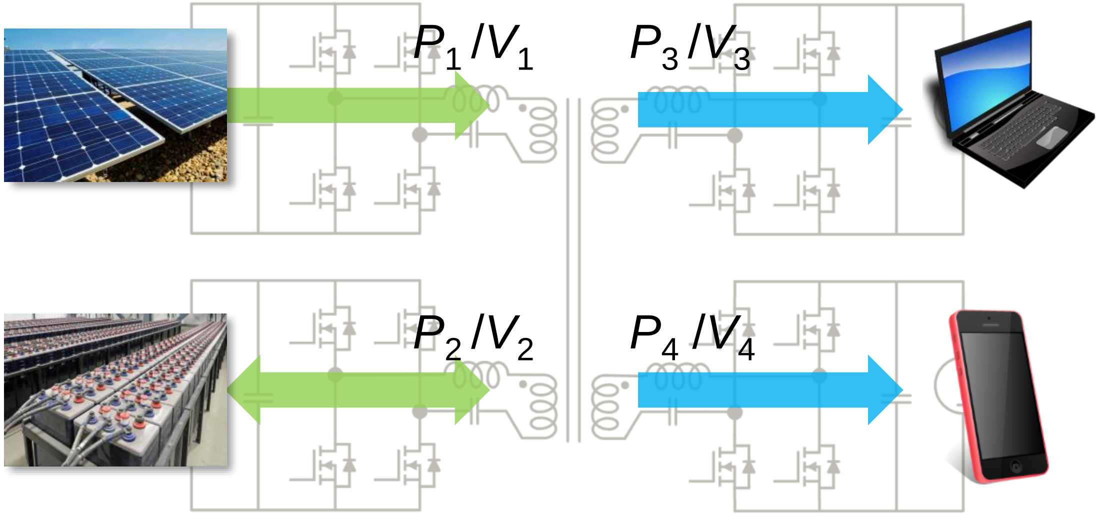


- MAB converter



- Full-bridge output voltage and current

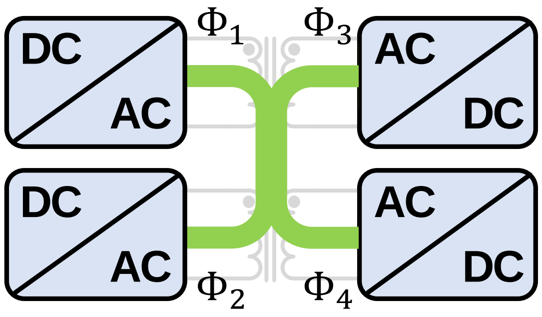
Power Flow Control and Voltage Regulation



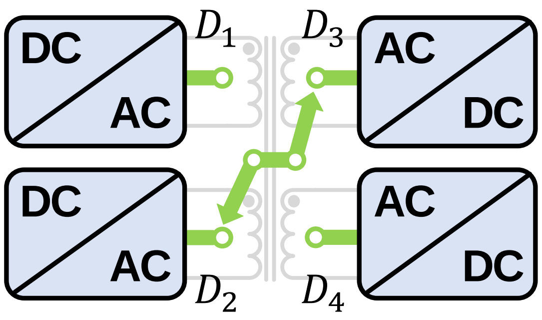
- Power flow control:
  - Energy price
  - Power fluctuation
- Voltage regulation:
  - Different load

Power Flow Control and Voltage Regulation of the MAB Converter

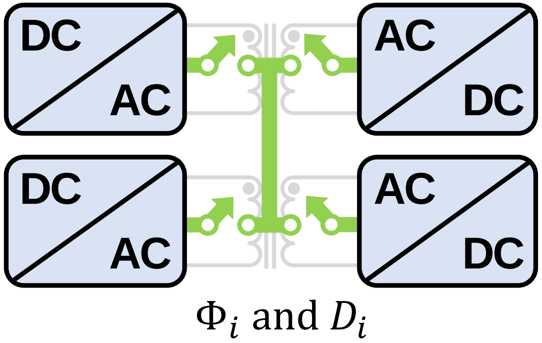
- Phase-shift



- Time-sharing



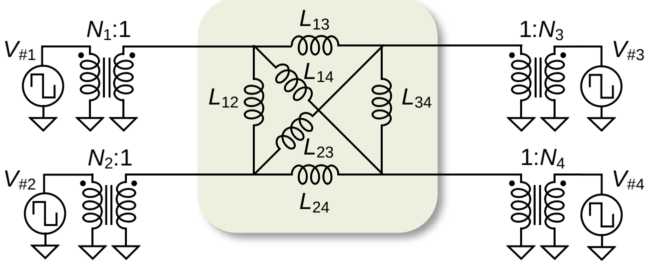
- Hybrid



- How do we control the power flow of multiple ports ?
- How do we regulate the voltage of multiple ports ?
- How do we achieve high efficiency across wide operation range ?

Principles of Phase-Shift Control

- Large signal model for power flow



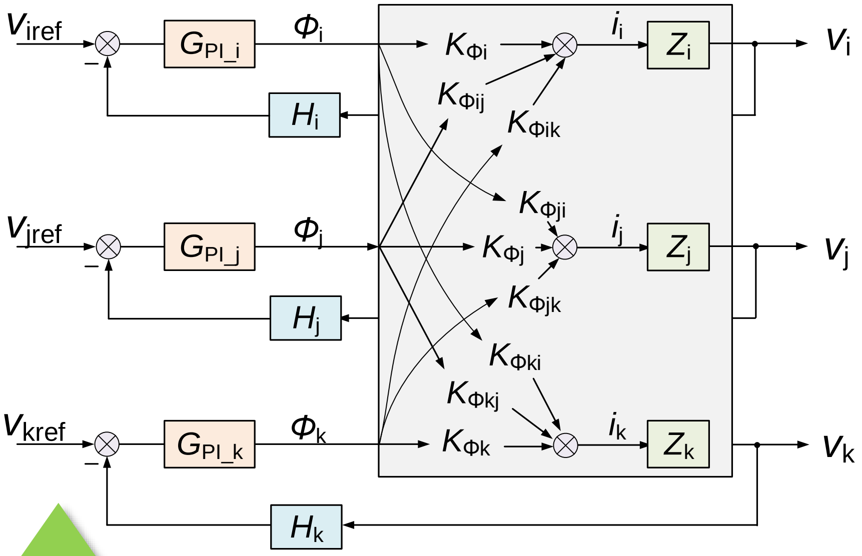
$$P_i = \frac{1}{2\pi f_s}\sum_{j\neq i}\frac{V_iV_j}{N_iN_jL_{ij}}(\Phi_i-\Phi_j)\left(1-\frac{|\Phi_i-\Phi_j|}{\pi}\right)$$

$$V_i = \frac{R_i}{2\pi f_s}\sum_{j\neq i}\frac{V_j}{N_iN_jL_{ij}}(\Phi_i-\Phi_j)\left(1-\frac{|\Phi_i-\Phi_j|}{\pi}\right)$$

- Small signal model for stability

$$\hat{v}_i = \left(K_{\phi i}\hat{\phi}_i + \sum_{j\neq i}(K_{\phi ij}\hat{\phi}_j)\right)Z_i$$

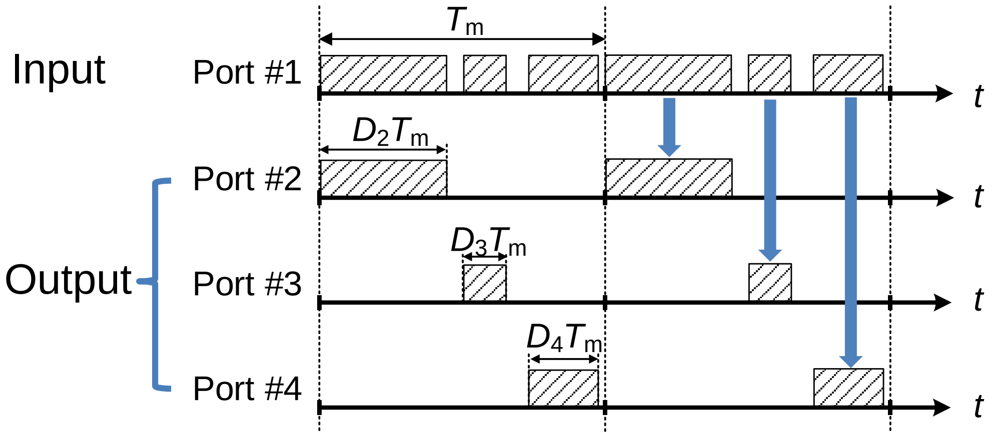
Port voltage control loop



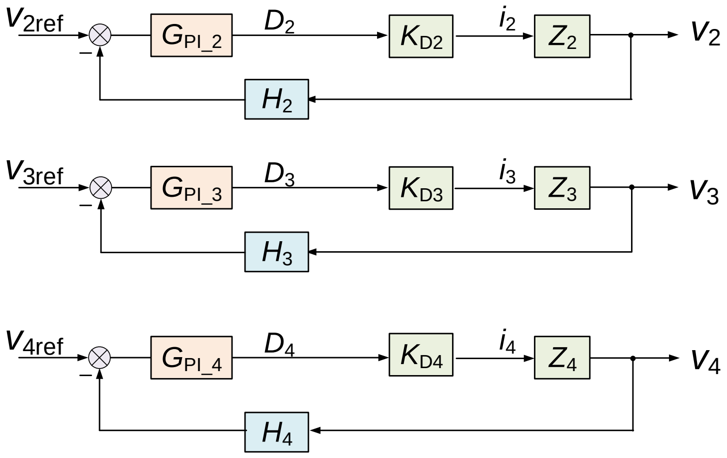
Principles of Time-Sharing Control

- Low efficiency with **PS** control in light load
- Fixed phase-shift Φ_i
- $T_m >> T_s$

$D_2 + D_3 + D_4 \leq 1$



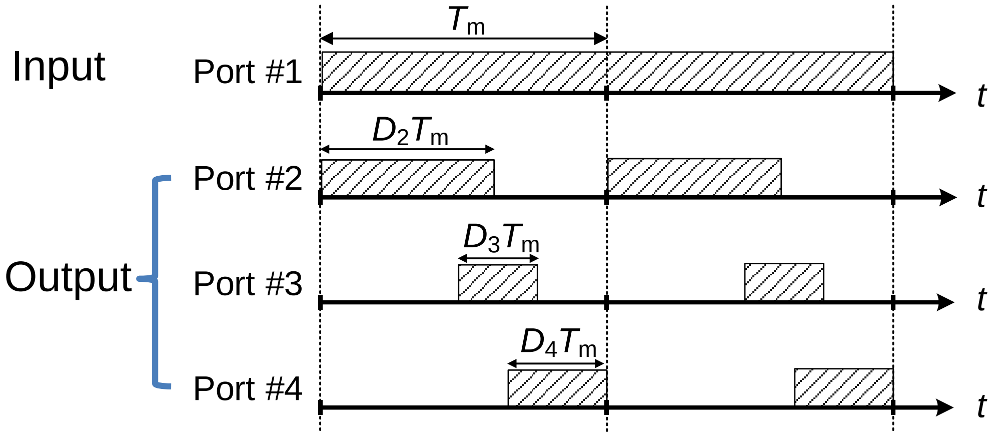
- Audible noise
- Higher voltage ripple



Decoupled PI control of D

Hybrid Phase-Shift & Time-sharing Control

- Low transformer utilization, higher voltage ripple with **TS** control
- $D_2 + D_3 + D_4 \neq 1$



- Two control parameters:

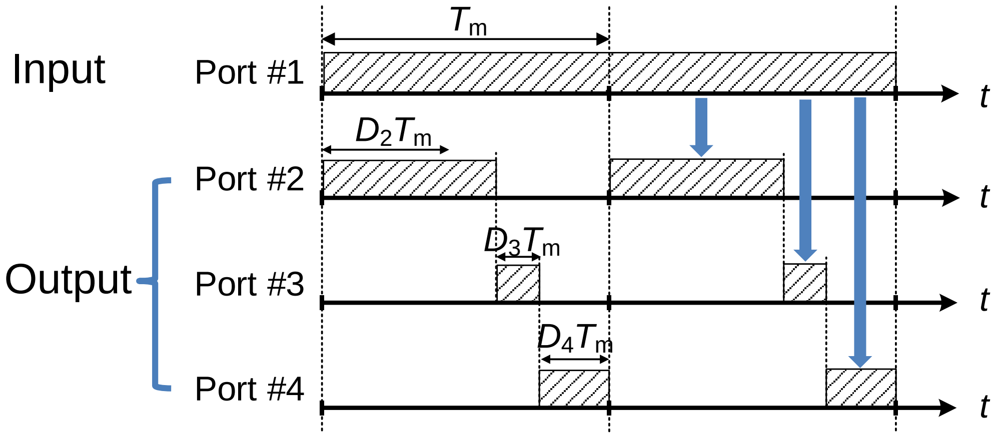
  Duty ratio D

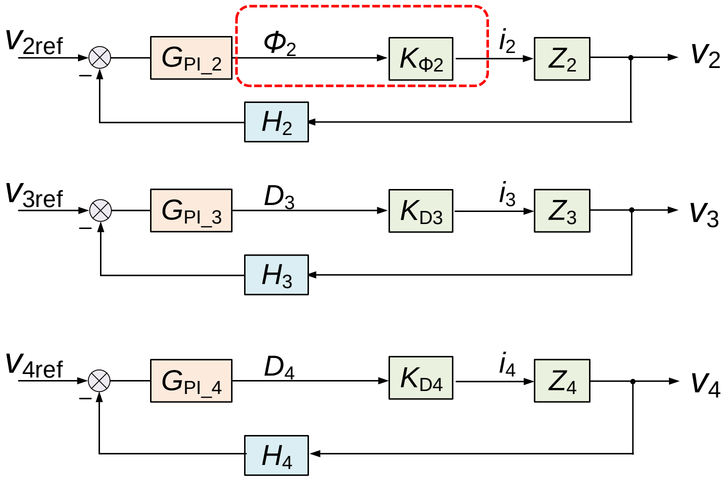
  Phase-shift Φ

- No audible noise
- Lower voltage ripple than TS

Simplified Hybrid Control

- $D_2 + D_3 + D_4 = 1$
- Fixed D + changing Φ or Fixed Φ + changing D

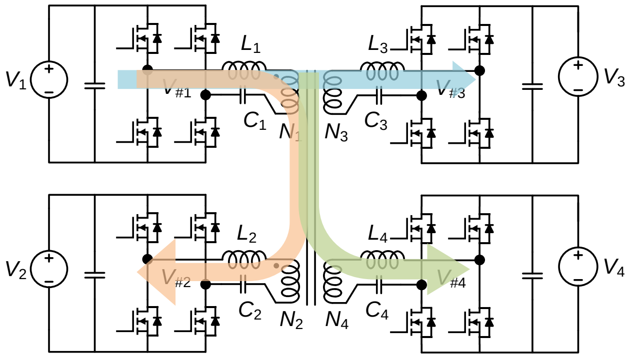




- No audible noise
- Lower voltage ripple than TS

Decoupled PI control of D and Φ

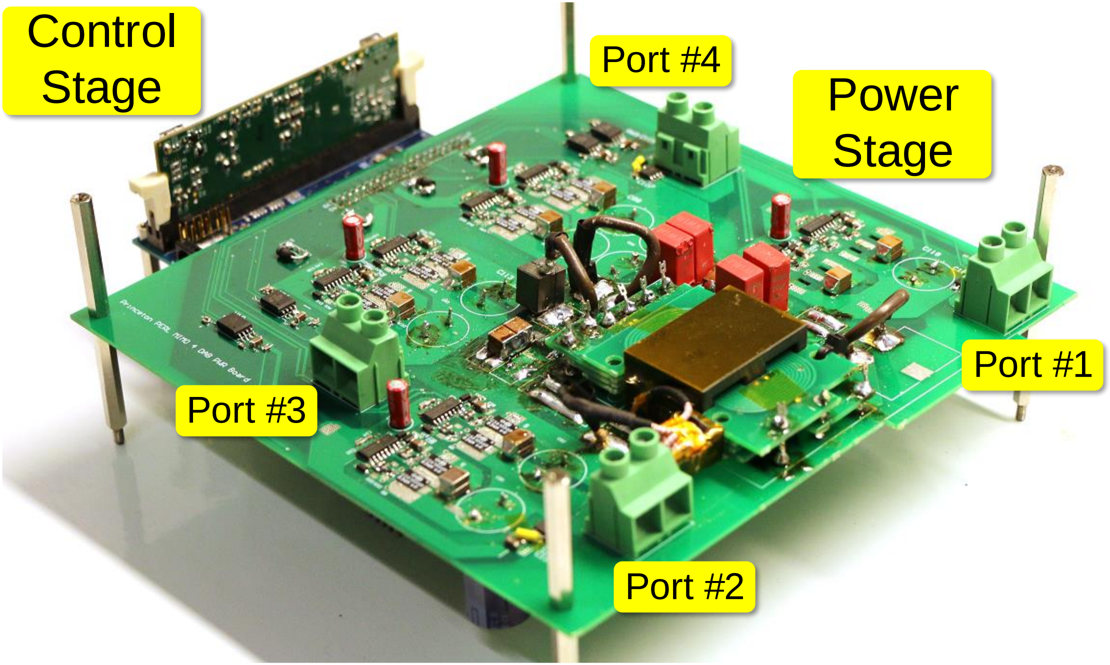
Summary of Control Methods

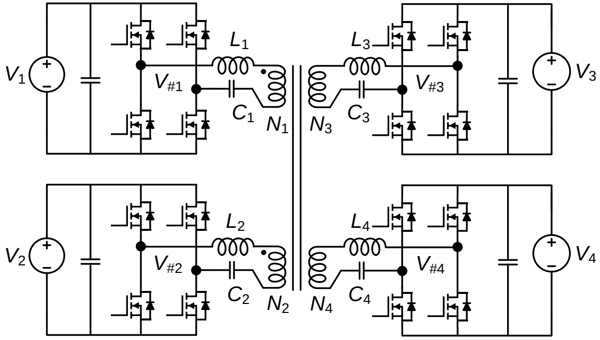


	Phase-shift	Time-sharing	Hybrid
Control Loops	coupled	uncoupled	partially coupled
Power Capability	high	lowest	medium
Light Load Efficiency	low	high	??
Voltage Ripple	low	high	medium

Prototype Specifications

- DC power delivery architecture for smart home

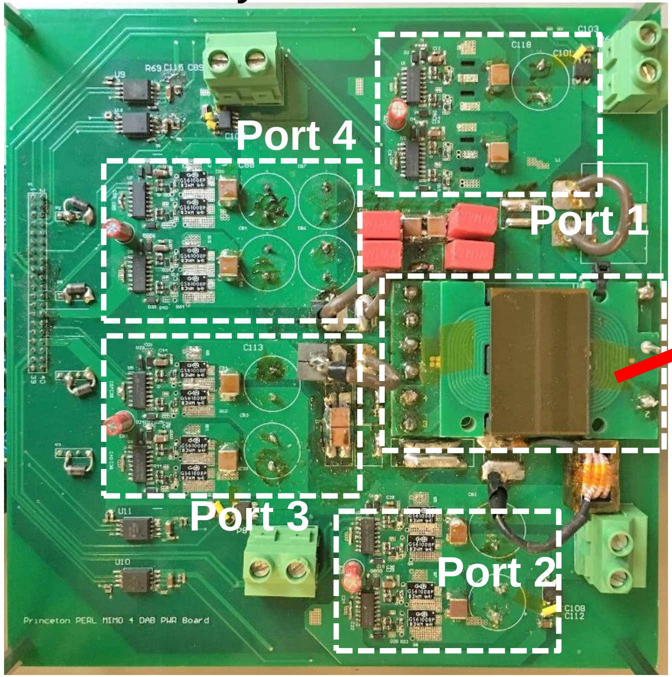




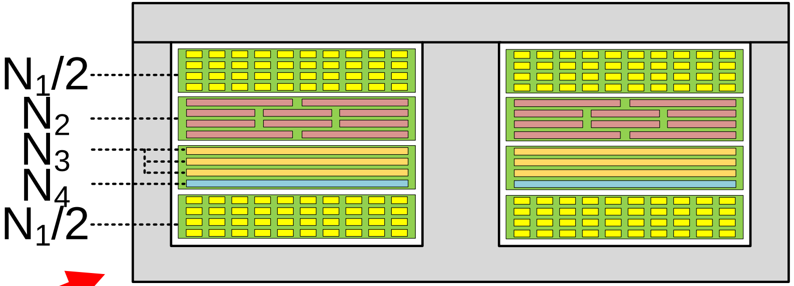
- 400V: PV, PFC to grid
- 48V: battery, high power appliances
- 15V & 5V: consumer electronics

Hardware

- PCB layout



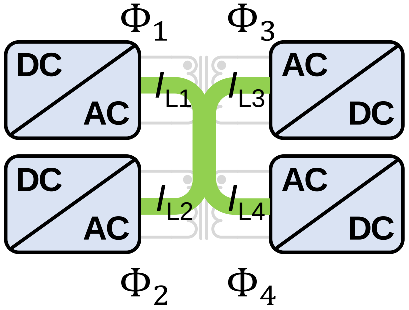
- Cross section view of transformer

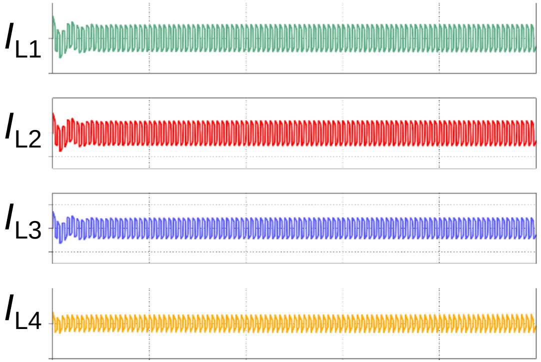


- Ferroxcube E38/8/25, 3F36
- N_1 = 80, N_2 = 10, N_3 = 3, N_4 = 1
- All GaN switches: 650 V/30 A & 100 V/90 A

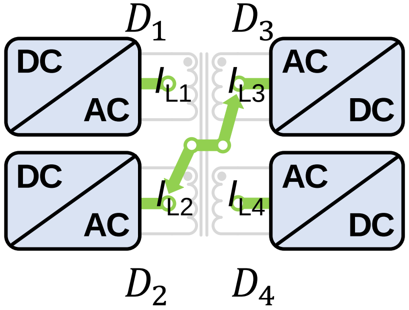
Simulation Results

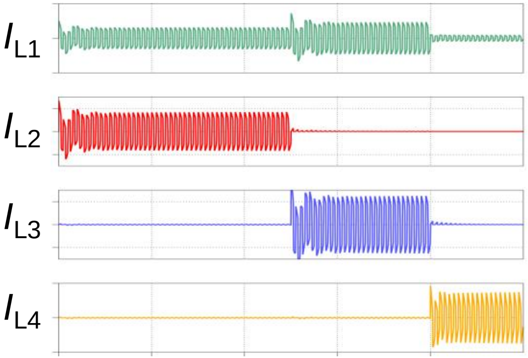
- Phase-shift



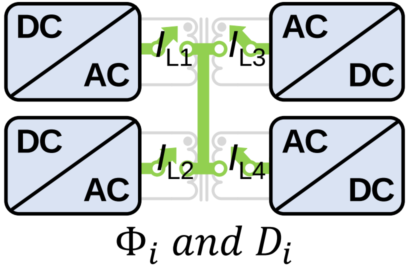


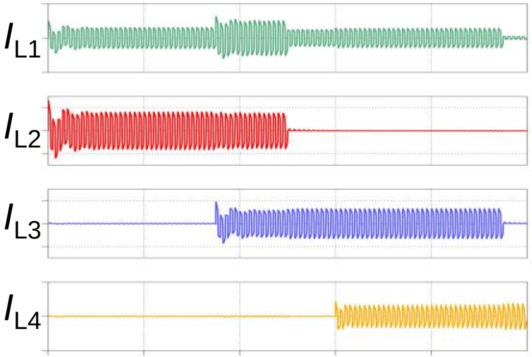
- Time-sharing



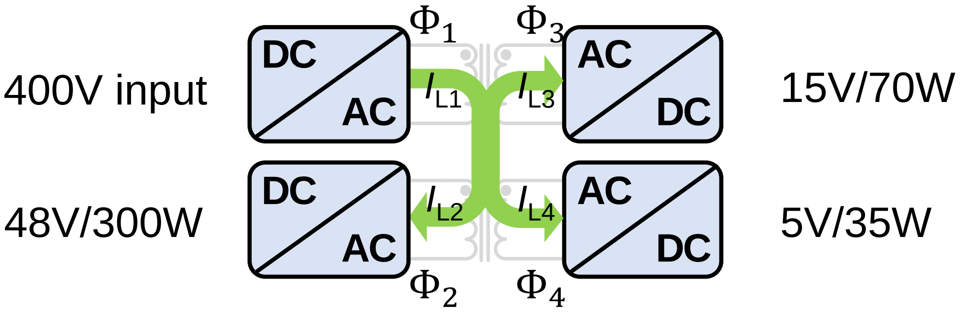


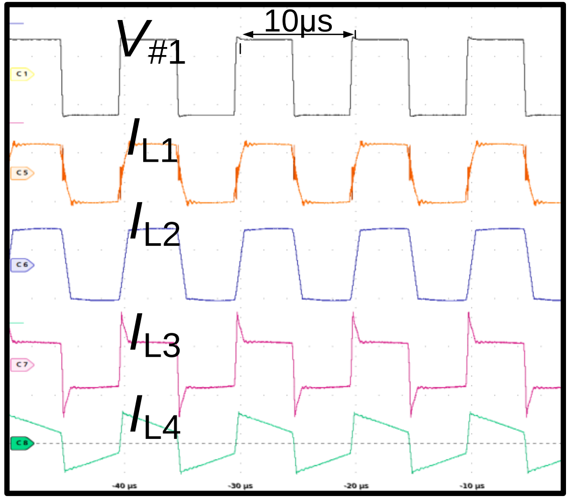
- Hybrid

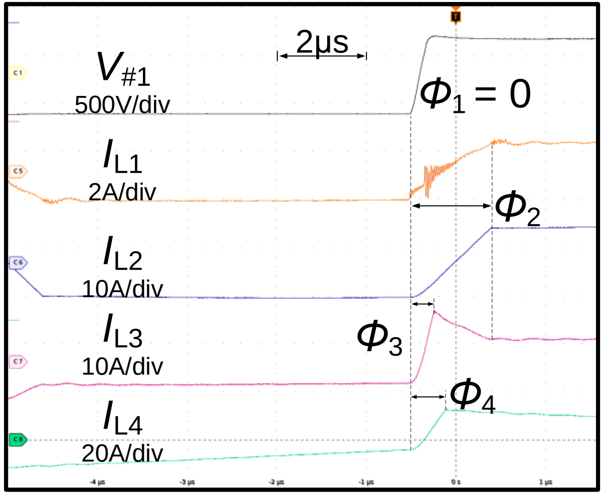




Phase-Shift Control

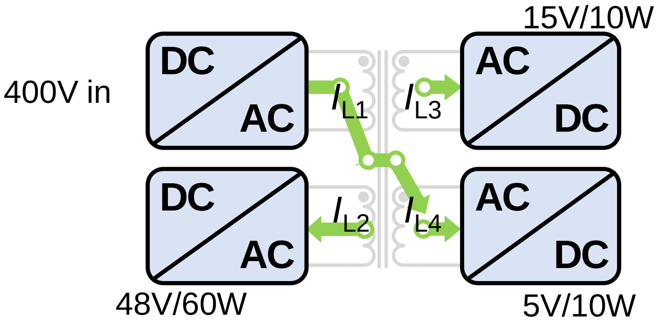


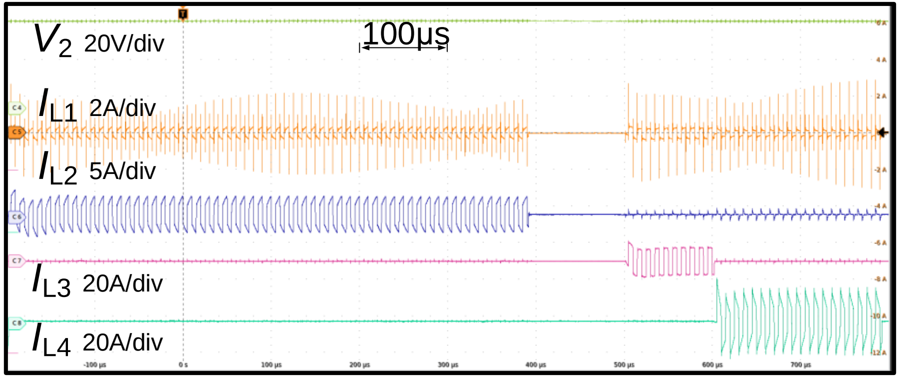




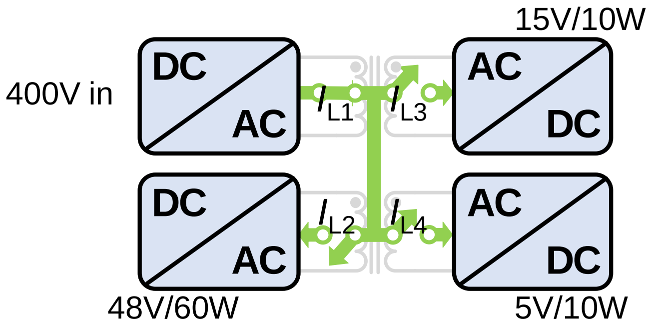
Experiment Results

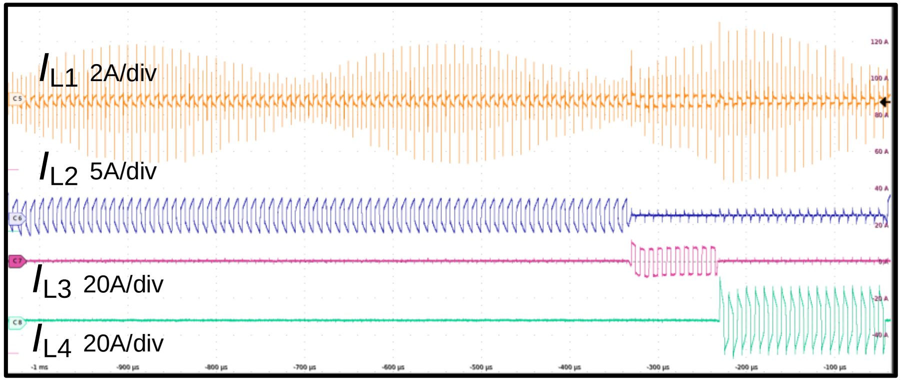
- **Time-sharing**



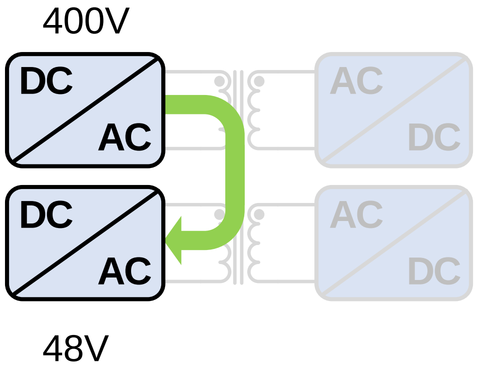


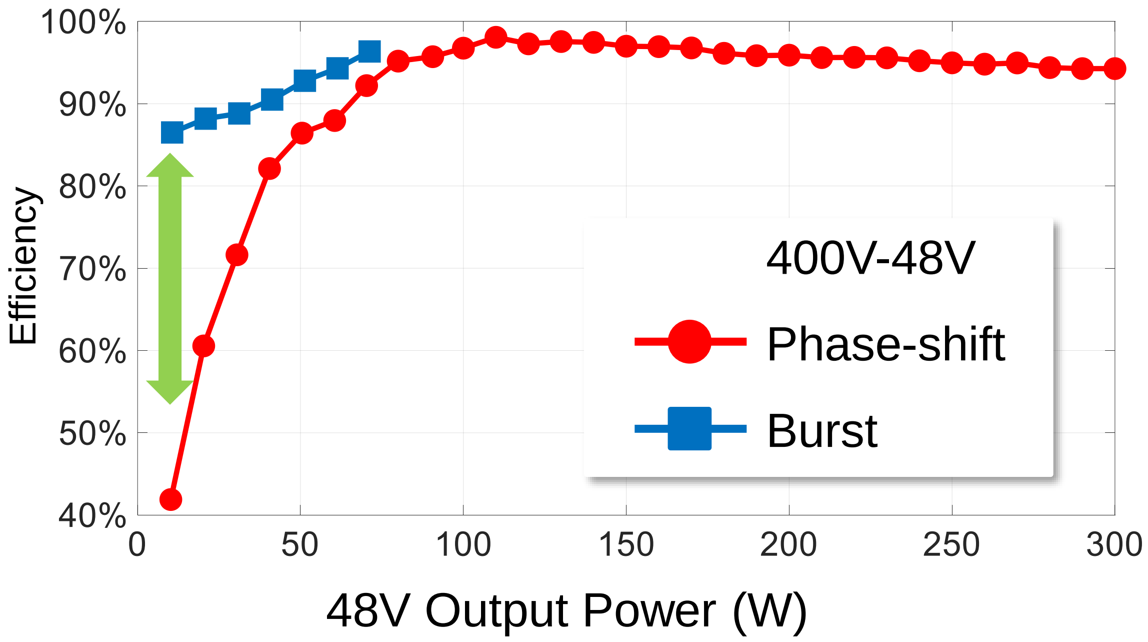
- **Simplified hybrid**





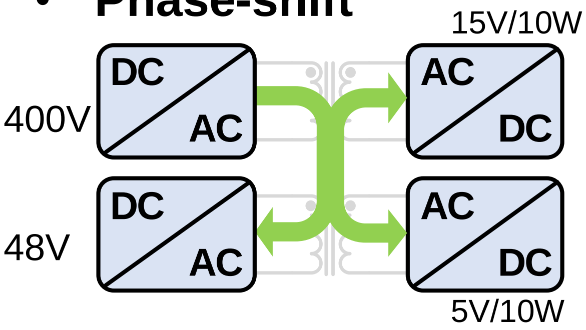
Single-Input Single-Output Efficiency



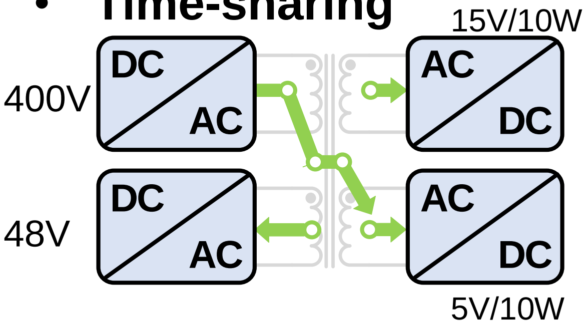


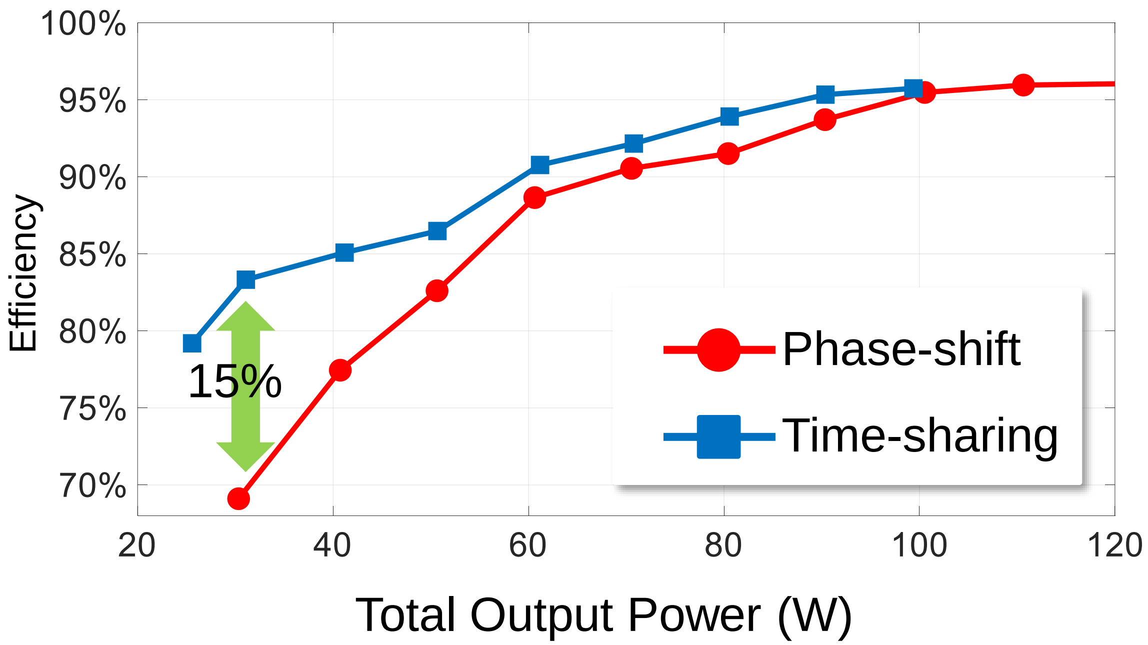
MAB Efficiency

- **Phase-shift**



- **Time-sharing**

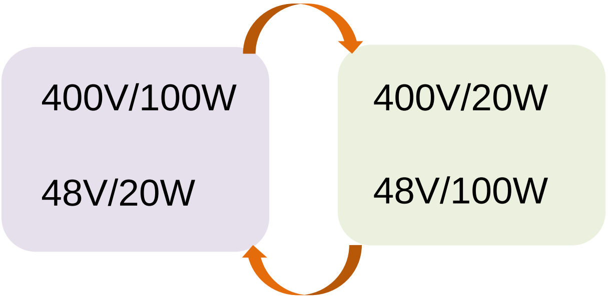


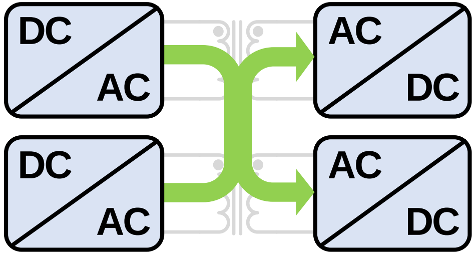


Power Flow Control: 2 Input 2 Output

Input 1 (PV)

Input 2 (battery)



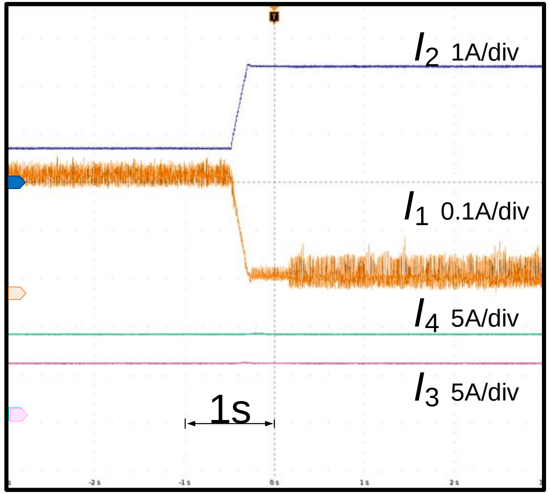


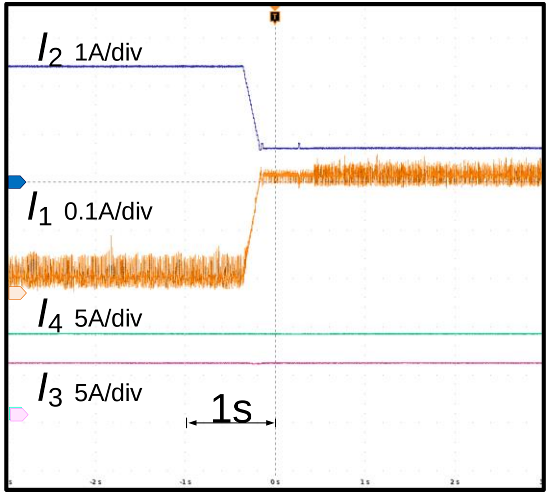
15V/75W

5V/45W

Input 2

Input 1





Input 2

Input 1

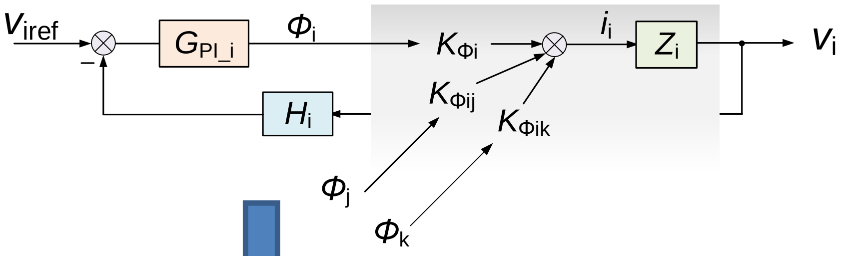
Conclusion

- **Design and validate three control methods**
- **Optimize efficiency:**
  - Time-sharing with low power
  - Phase-shift with high power
- **Future work:**
  - Optimize hybrid control

Thank you !

PI Control of Phase-Shift

- Single port voltage control loop

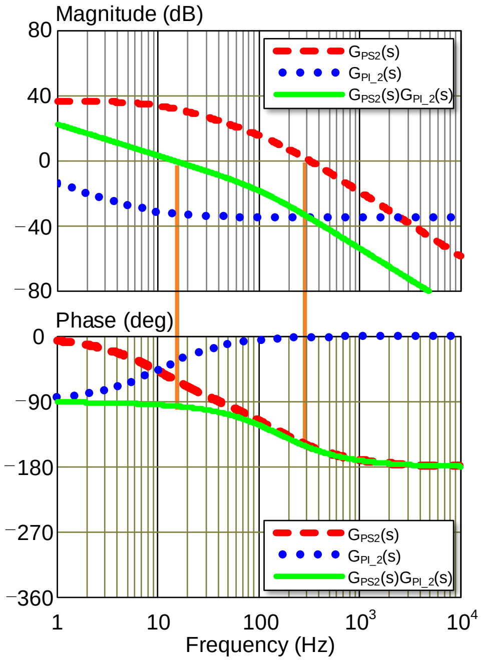


$$\frac{v_i(s)}{v_{iref}(s)} = \frac{G_{PI\_i}(s)K_{\phi i}(s)Z_i(s)}{1 + H_i(s)G_{PI\_i}(s)K_{\phi i}(s)Z_i(s)}$$

$$\frac{v_i(s)}{\phi_j(s)} = \frac{K_{\phi ij}(s)Z_i(s)}{1 + H_i(s)G_{PI\_i}(s)K_{\phi i}(s)Z_i(s)}$$

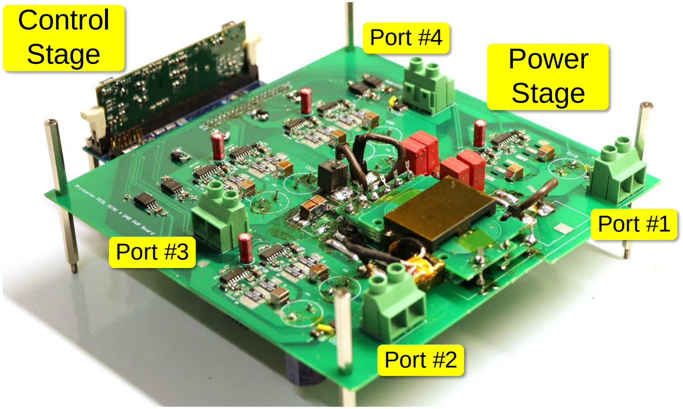
$$G_{PSi}(s) = H_i(s)K_{\phi i}(s)Z_i(s)$$

Same loop gain function



- Increase system stability and immunity to disturbance of ϕ_j
- Slower dynamic response

Prototype Design



- Maximum flux density

$$B_{max} = \frac{V_1 T_s}{4 N_1 A_e}$$

- Power rating

$$P_{imax} \approx \frac{V_o^2}{8 f_s} \sum_{j \neq i} \frac{1}{L_{ij}}$$

- Voltage ripple

$$\triangle v_i \leq \frac{P_{imax} T_m}{4 C_i V_i}$$

Parameters	Description
Switching Frequency: f_s	100 kHz
Port #1 Switches	GS66508T 650 V/30 A/50 mΩ
Port #2–#4 Switches	GS61008P 100 V/90 A/7 mΩ
Transformer	Ferroxcube E38/8/25, 3F36 80:10:3:1, 4×4-layer PCB
Leakage Inductance: L_{lk1} − L_{lk4}	18.2 µH, 0.81 µH, 84.1 nH, 26.4 nH
External Inductors: L_{ext1} − L_{ext4}	0, 4.2 µH, 200 nH, 100 nH
Bus Capacitors: C_1 − C_4	120 µF, 2 mF, 20 mF, 40 mF
DC Blocking Capacitors: C_{b1} − C_{b4}	10 µF, 20 µF, 134 µF, 154 µF

MAB Efficiency: PS Control