Modular AC-DC Converters for Medium Voltage Applications

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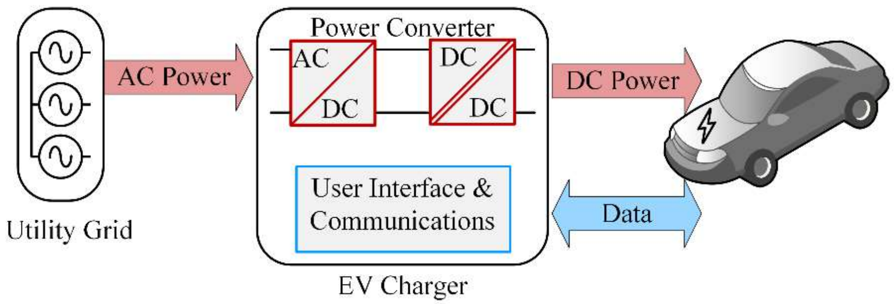
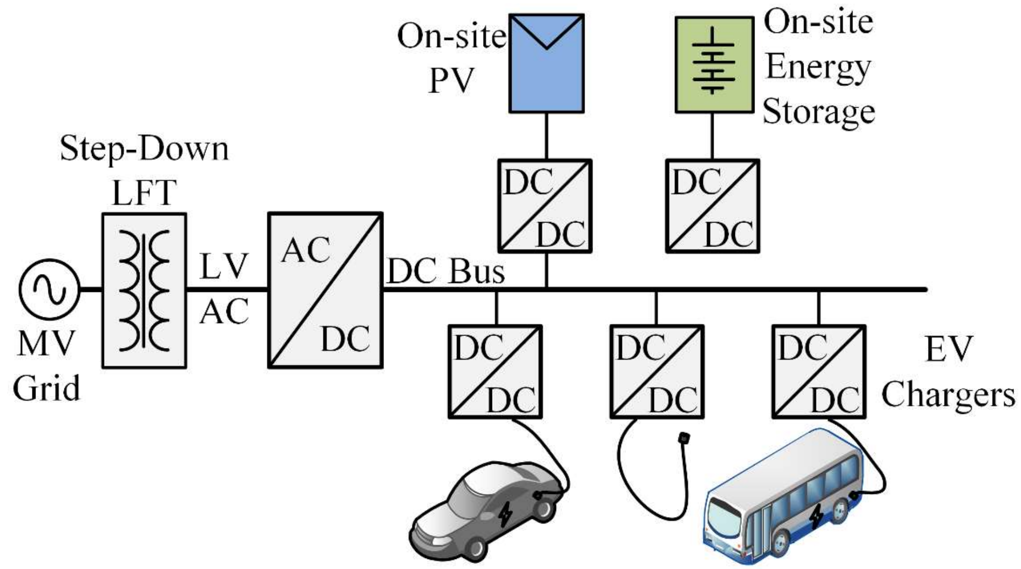
Need for High Power AC-DC Converters

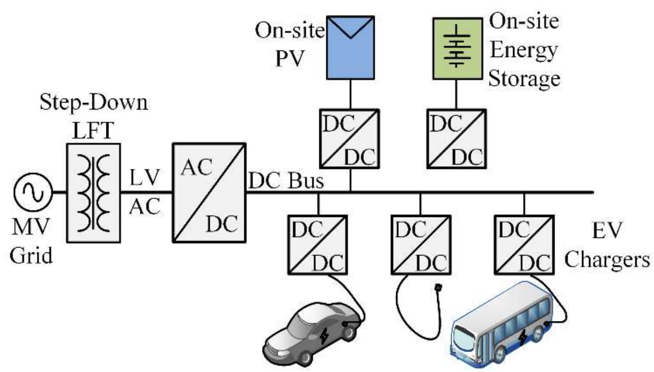
- A significant amount of electrical energy is generated by three-phase AC machines
- Most of electrical power is transmitted and distributed using existing three-phase AC systems
- Most modern and emerging loads are DC
- DC loads are increasing in power levels e.g., EV charging



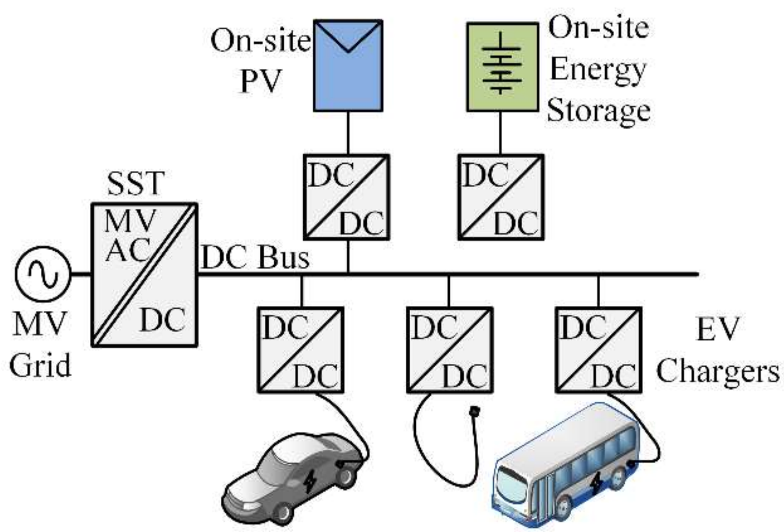


MV AC to DC Converter for EV Charging Stations:

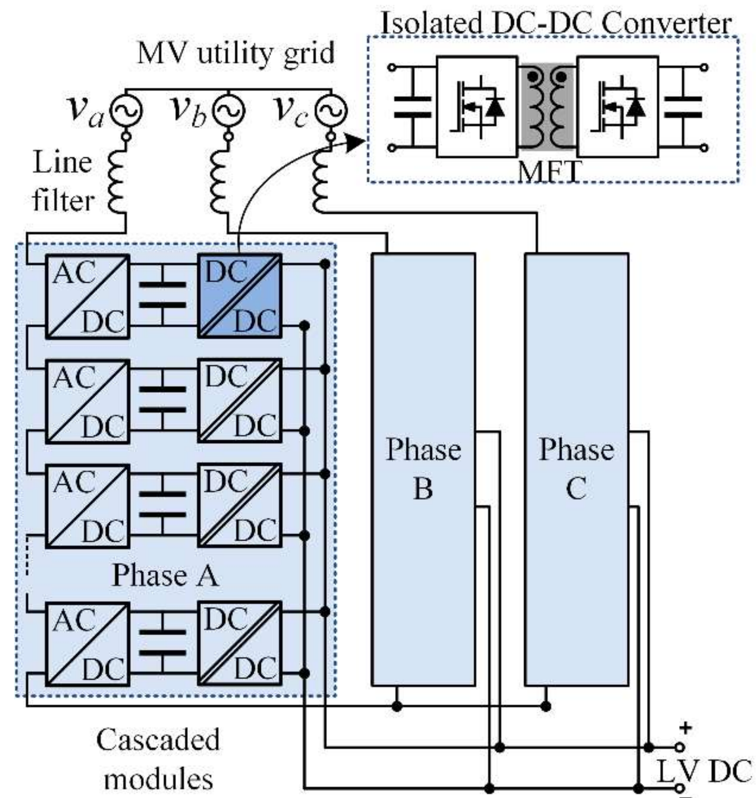
EV Charging Station: Grid Connection through LF Transformer



EV Charging Station: Grid Connection through MV SST



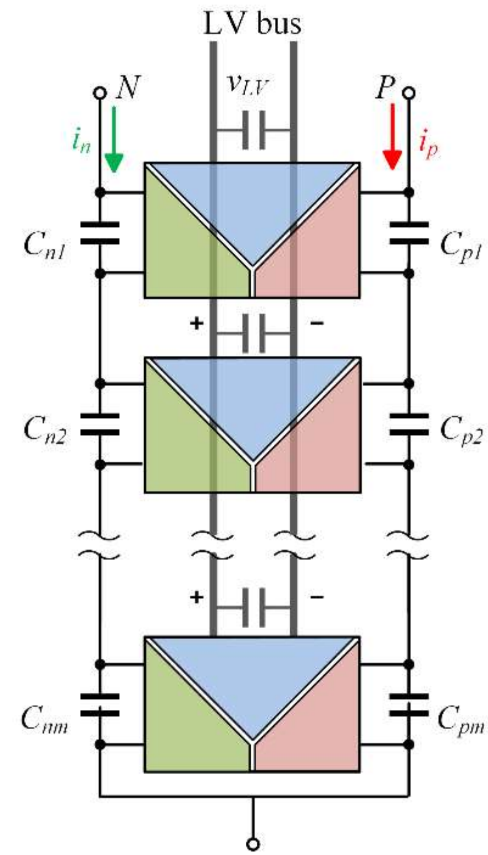
Block Diagram of a Conventional AC to DC SST



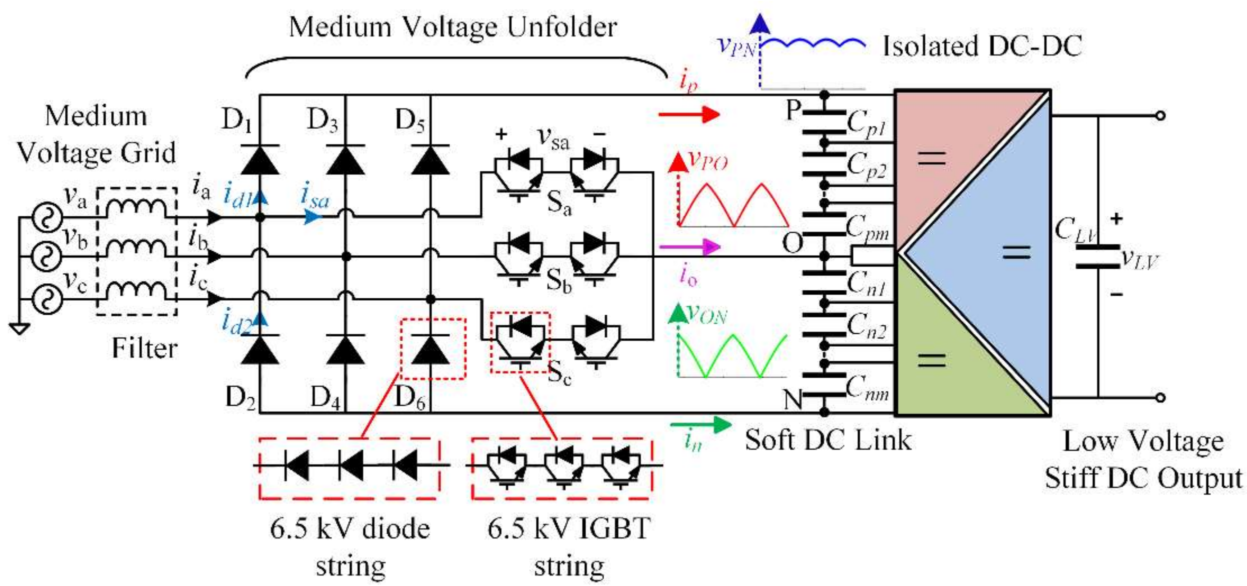
Medium Voltage AC to 800 V DC converter

- 4.16 kV three-phase input, 560 kW, 750 V – 900 V DC output
- Soft DC-link based front-end with 6.5 kV IGBT implementation
- Seven DC-DC series stacked modules each rated at 80 kW
- Each DC-DC module is an isolated three-port converter

Isolated DC-DC Module:



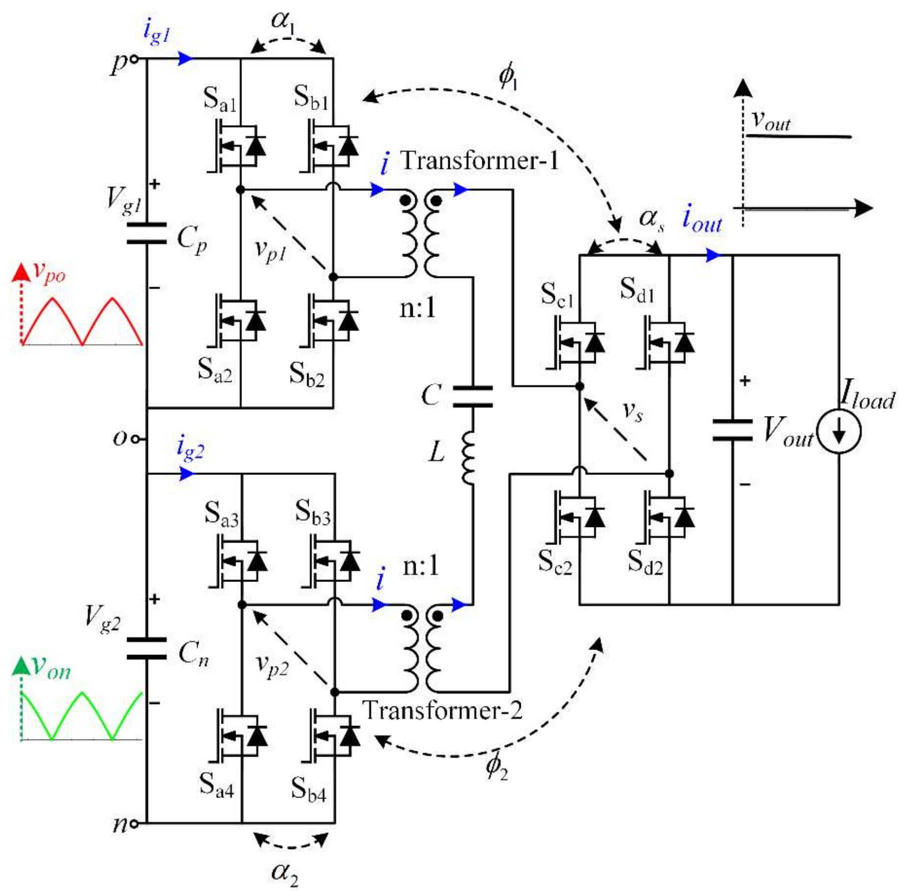
Block Diagram: MV Unfolding



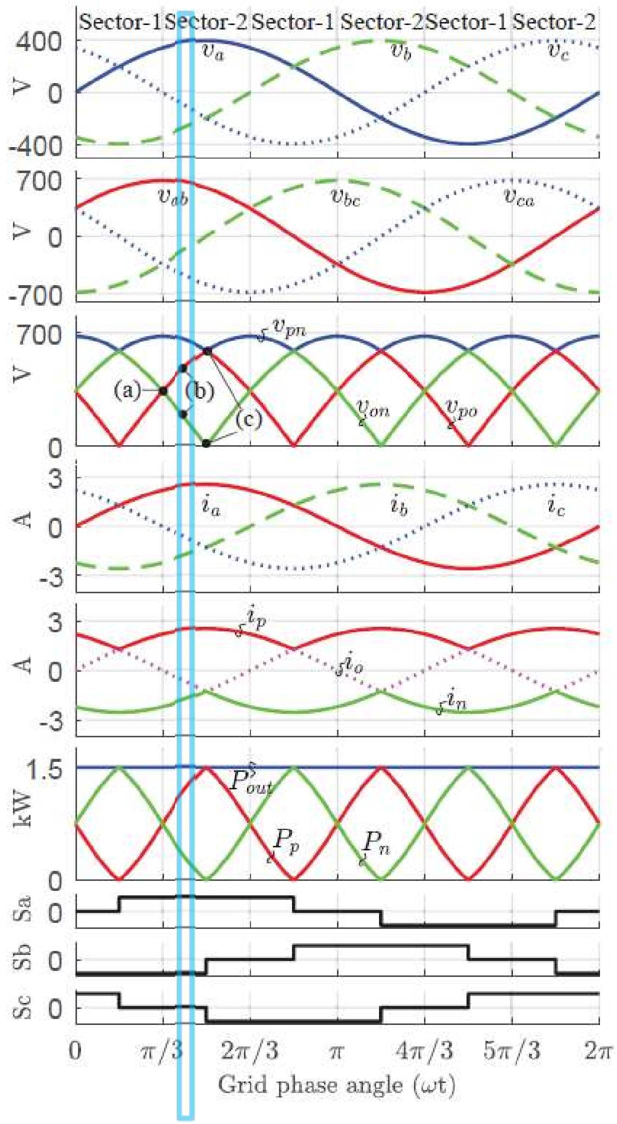
Triple Active Bridge Series Resonant Converter

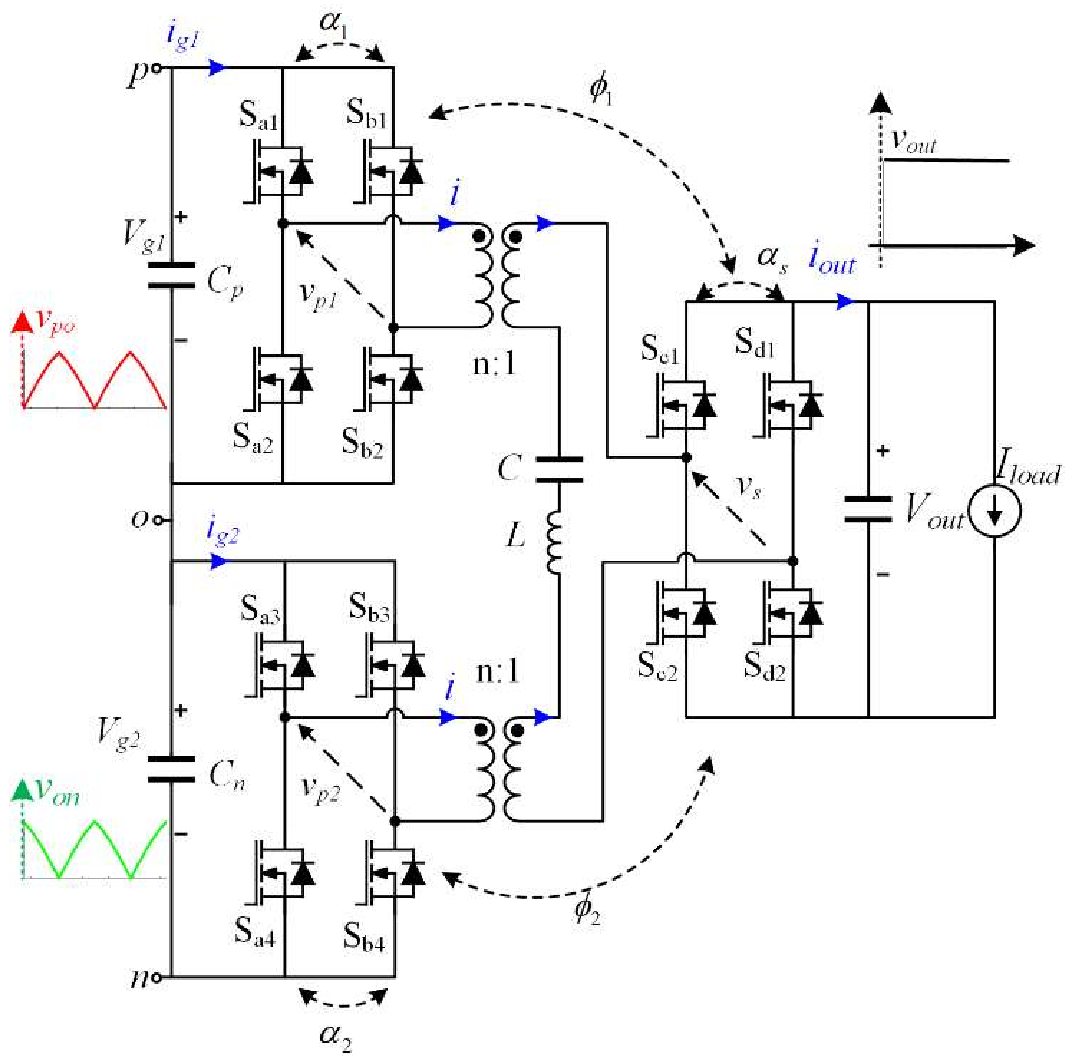
- Two H-bridges on primary, one per port
- Series connected secondary windings
- Low variation in the resultant primary voltage
- One LC tank and secondary bridge required
- Seven Modules are to be implemented in the final design
- Design Steps:
  - Topology validation
  - Control Validation
  - High-power module Validation
  - Series stacking Validation
  - Full system validation

Proposed DC-DC Topology for ISOP Modules



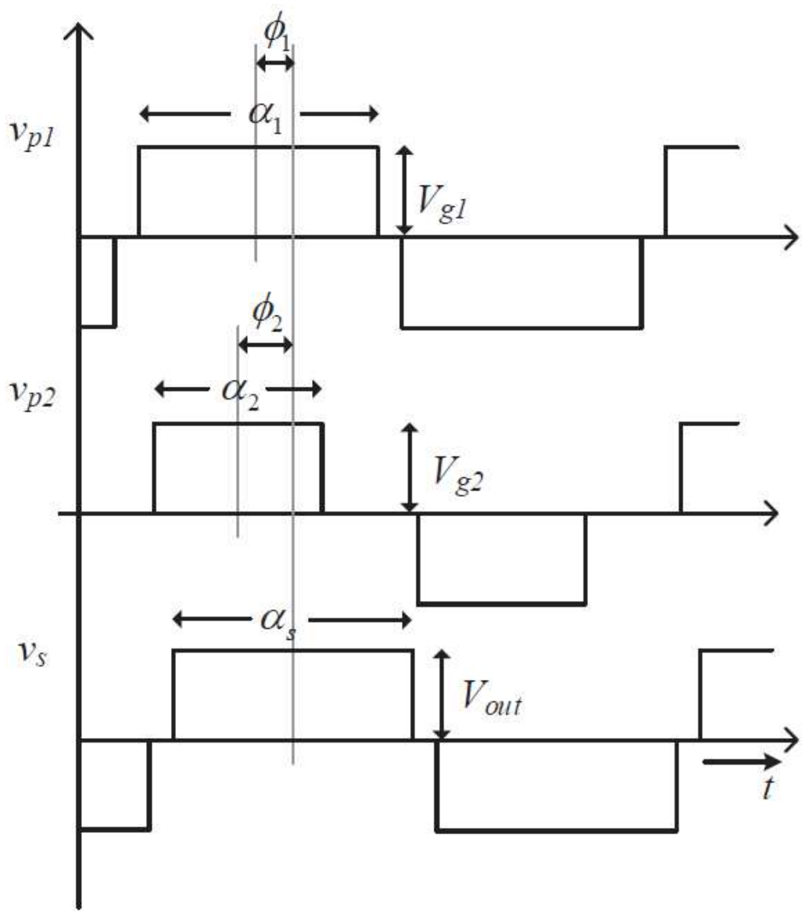
Proposed Topology: Modulation



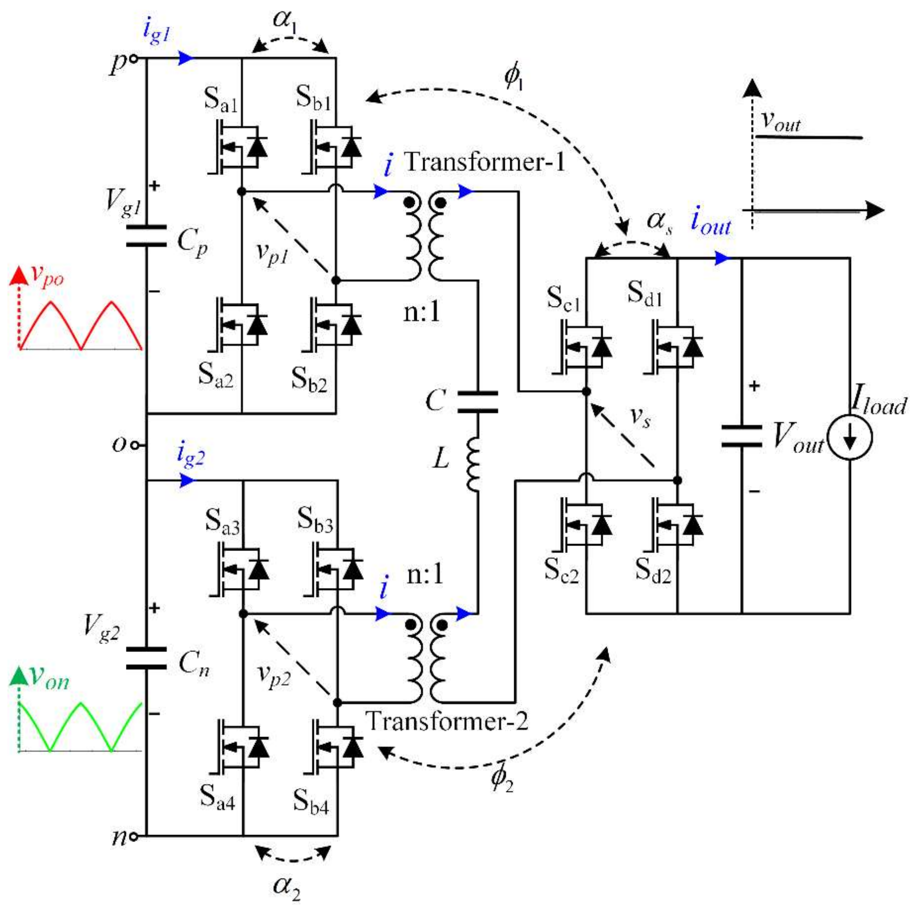


Proposed Topology: Modulation

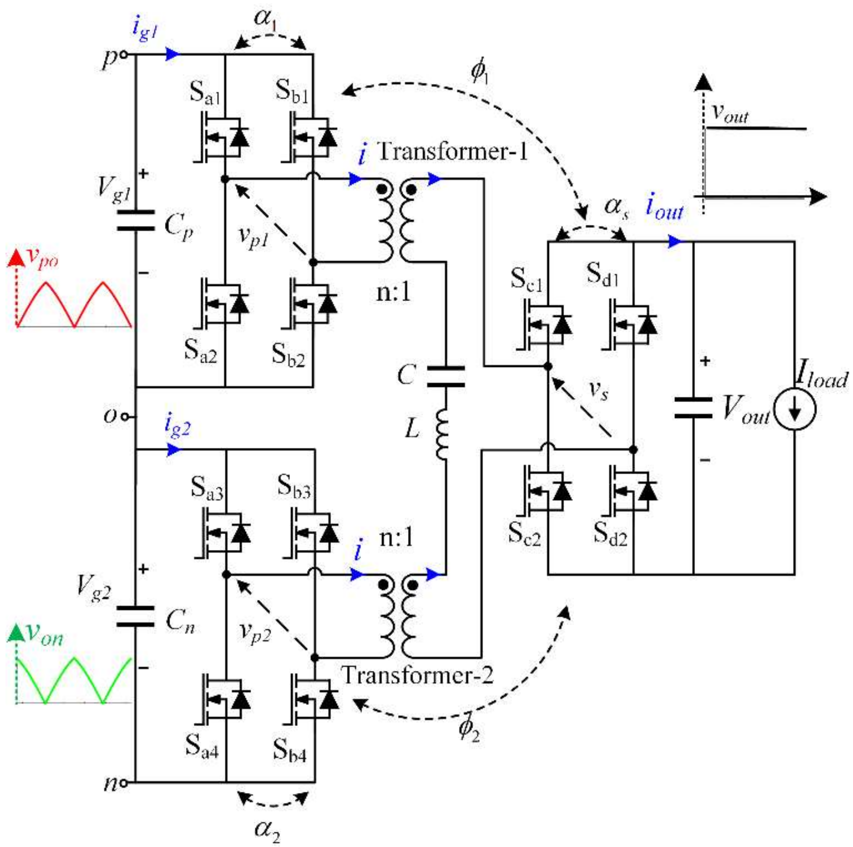
Bridge Voltage Definitions

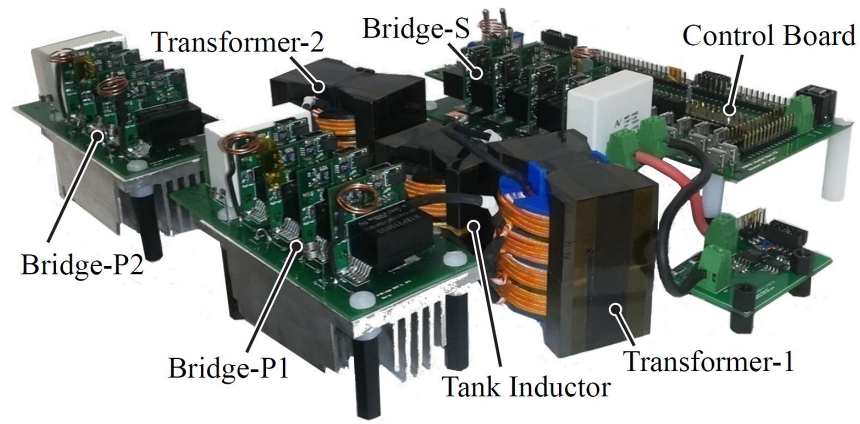


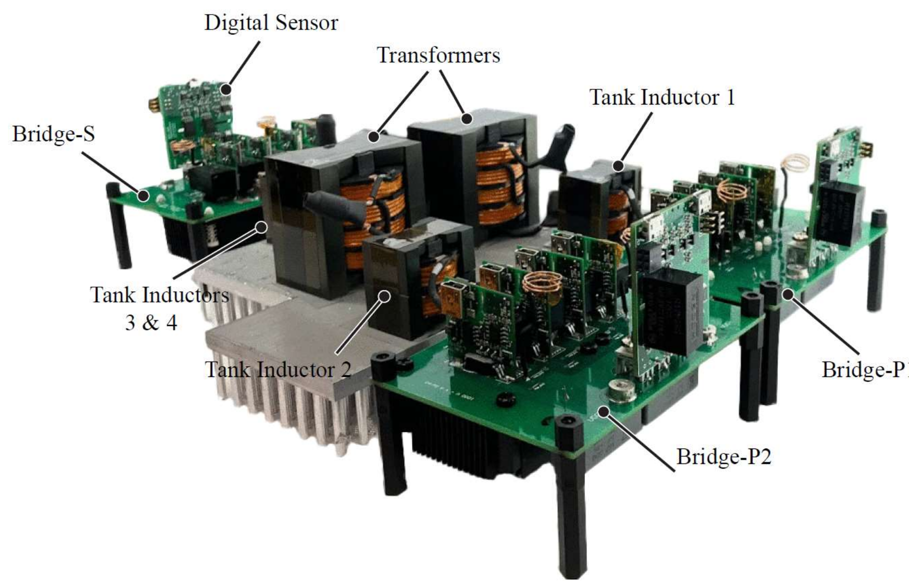
Proposed Converter



Proposed Topology: 2 kW Hardware Prototype







Proposed Topology: Control Approach

Proposed Control Variables:

Output control:

i_{out} is regulated

ϕ_{edge} is control variable

$$\langle I_{\text{out}} \rangle = \frac{8}{\pi^2 X_s}[V_{g1} \sin \phi_{\text{edge}} + V_{g2} \sin(\frac{\alpha_2}{2}) \cos(\phi_{\text{edge}} - \frac{\alpha_2}{2})]$$

$$\langle I_{\text{out}} \rangle = \frac{8}{\pi^2 X_s} v_{p,q}.$$

PFC control:

α_1, α_2 are the control variables.

$d_{p/n}$ is the new intermediate control variable

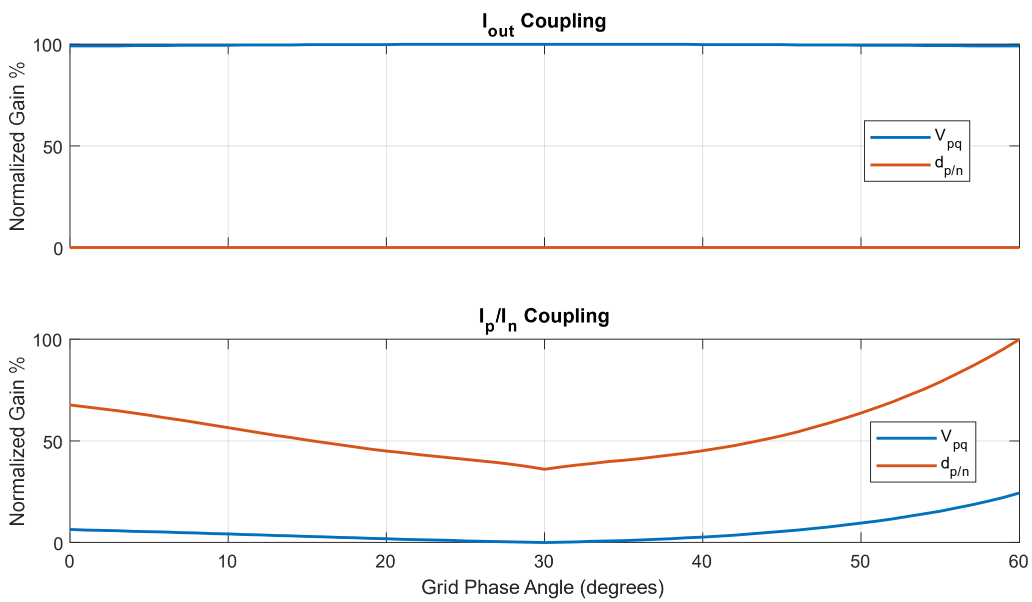
Feed-Forward Calculations:

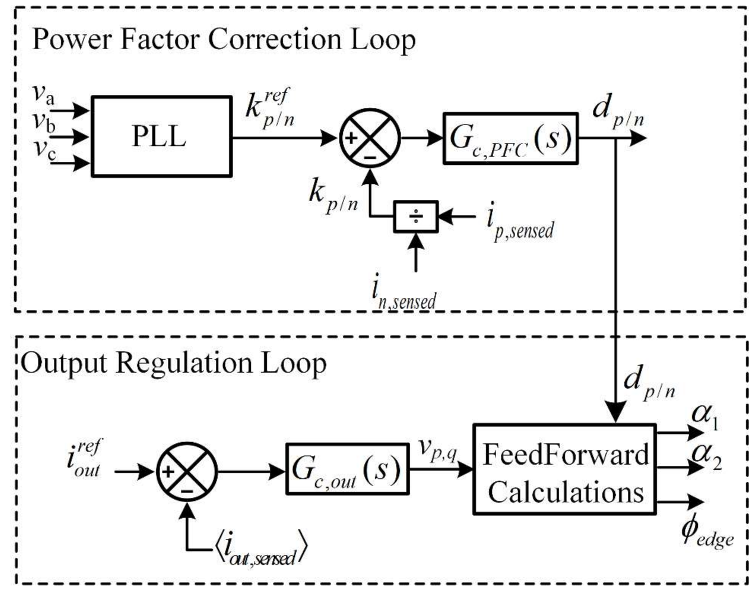
$$\phi_{edge} = \sin^{-1}(\frac{V_{p-q}}{\sqrt{K_1^2 + K_2^2}}) - \sin^{-1}(\frac{K_2}{\sqrt{K_1^2 + K_2^2}}),$$

Parameter	$d_{p/n} < 1$	$d_{p/n} > 1$
α_1	$\pi d_{p/n}$	π
α_2	π	$\pi / d_{p/n}$
K_1	$V_{g1} \frac{1-\cos(\alpha_1)}{2} + V_{g2}$	$V_{g1} + V_{g2} \frac{1-\cos(\alpha_2)}{2}$
K_2	$V_{g1} \sin(\frac{\alpha_1}{2})$	$V_{g2} \sin(\frac{\alpha_2}{2})$

Proposed Topology: Control Approach

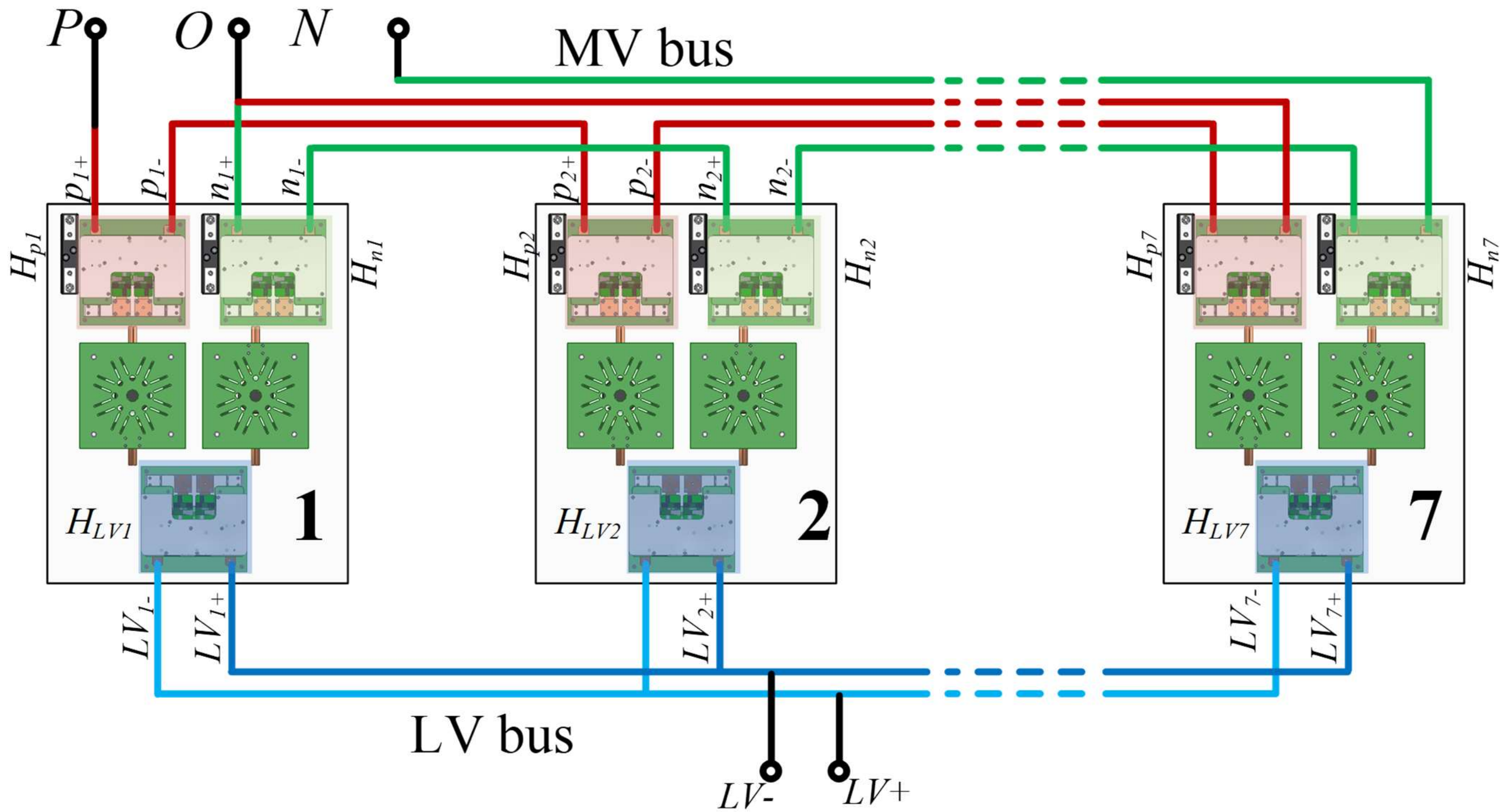
- Small signal analysis validation for decoupled control
- Simulations and hardware validation
- Future work: series stacking control testing





Block Diagram of Control Loops

Proposed Topology: High Power Implementation

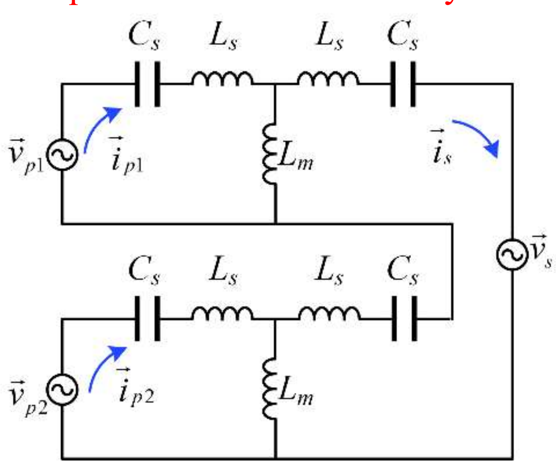


80 kW DC-DC Module Design

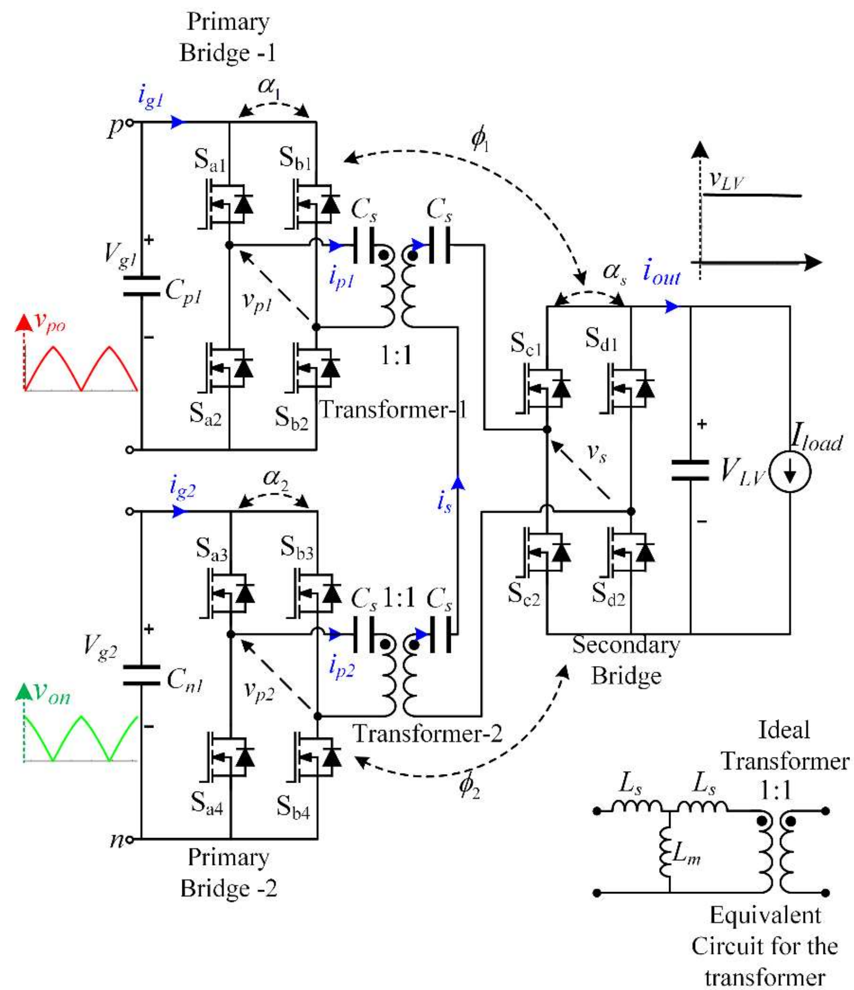
TAB CLLLC 80 kW Design Circuit Parameters

Circuit parameter	Value
Series inductance per winding, L_s	10.4 µH
Series capacitance per winding, C_s	1.5 µF
Magnetizing inductance per transformer, L_m	105.7 µH
Switching frequency, f_s	50 kHz

Equivalent Circuit for Analysis

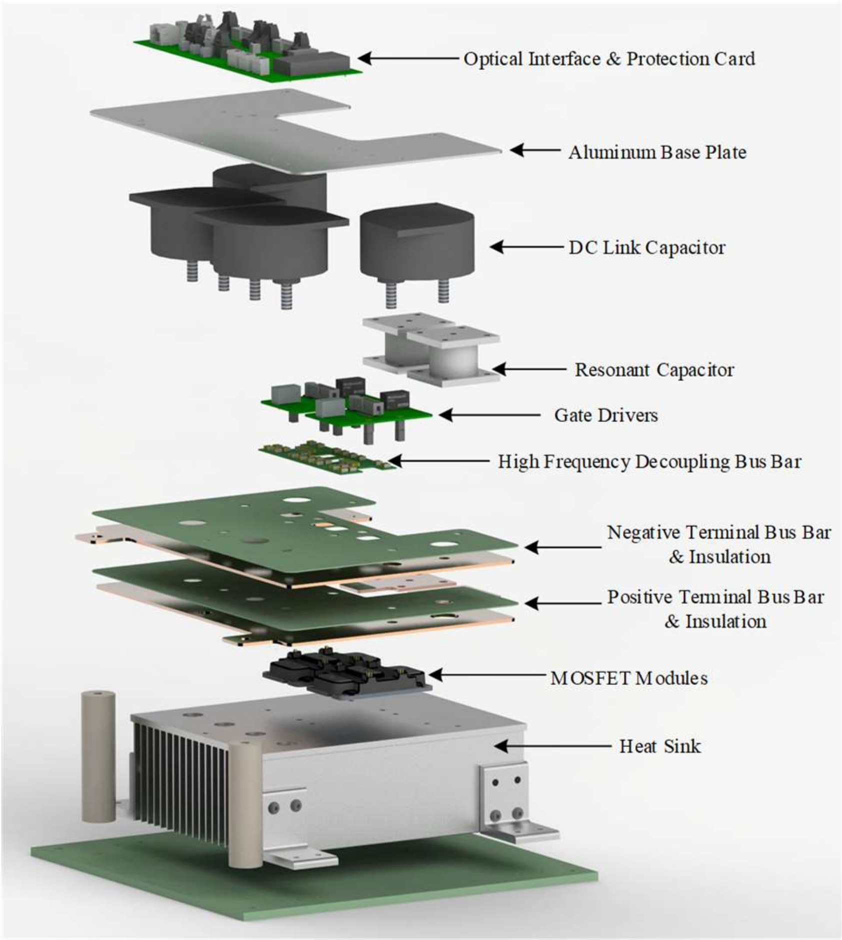


TAB with Low Magnetizing Inductance

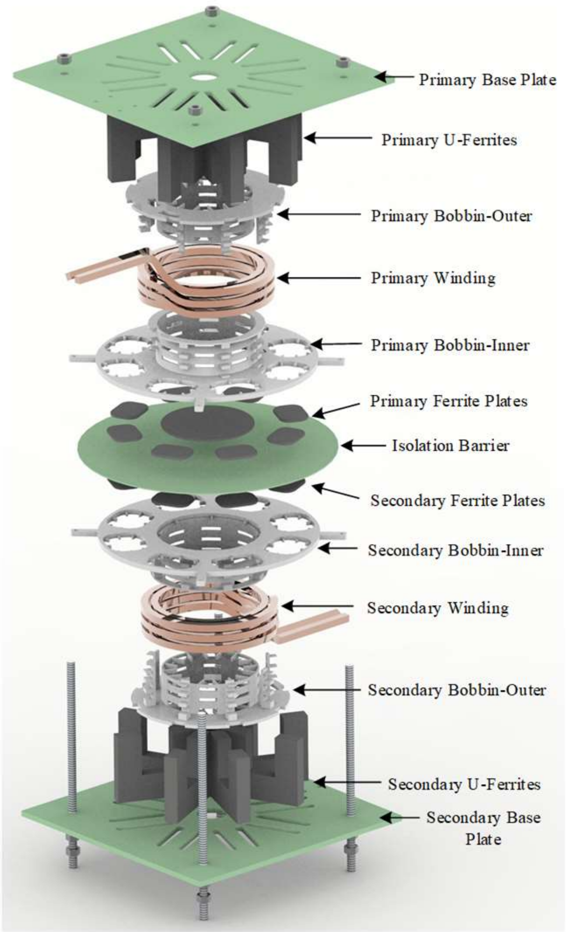


80 kW DC-DC Module Fabrication

80 kW H-Bridge



80 kW, 15 kV Isolated Transformer



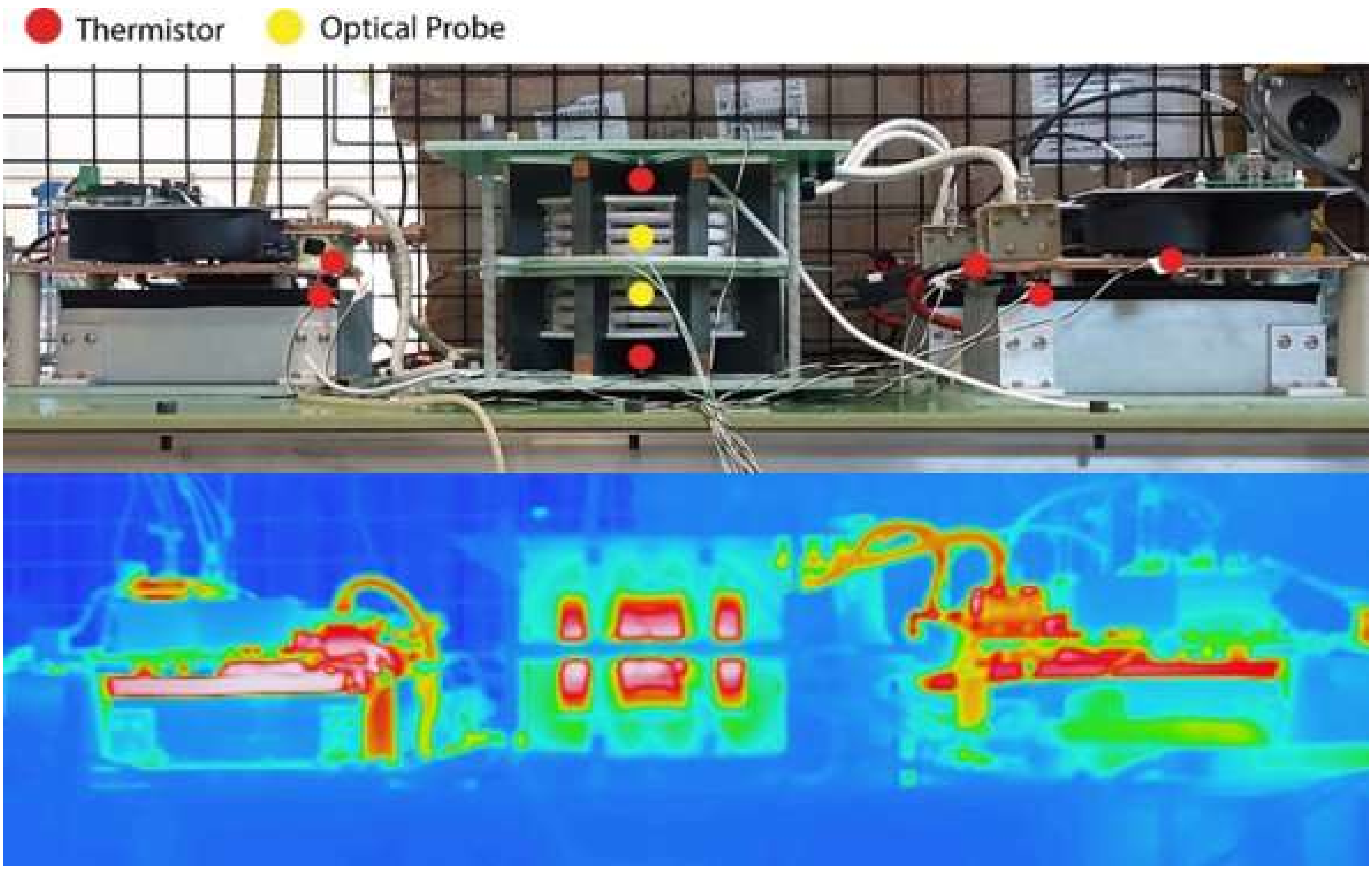
80 kW DC-DC Module Setup

Features

- 15 kV Isolated Transformers
- No External Tank Inductors
- High Power H-Bridge Design
- Optical Isolation for Sensing and Gate-Drive Circuits
- Air Cooling
- 97.5% - 98% efficiency at full load, different AC operating points

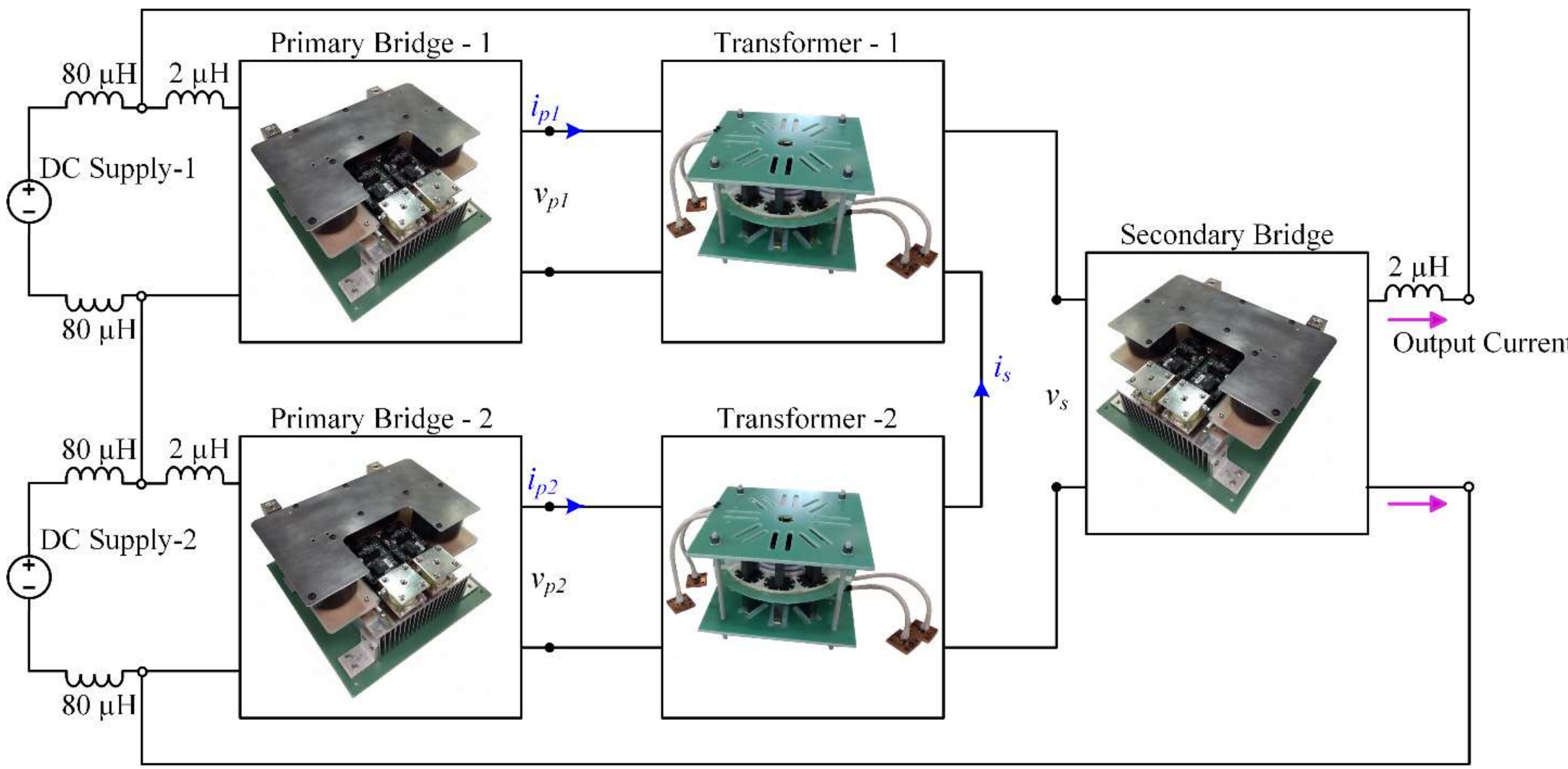
80 kW TAB Converter Experimental Setup

80 kW DC-DC Module Setup

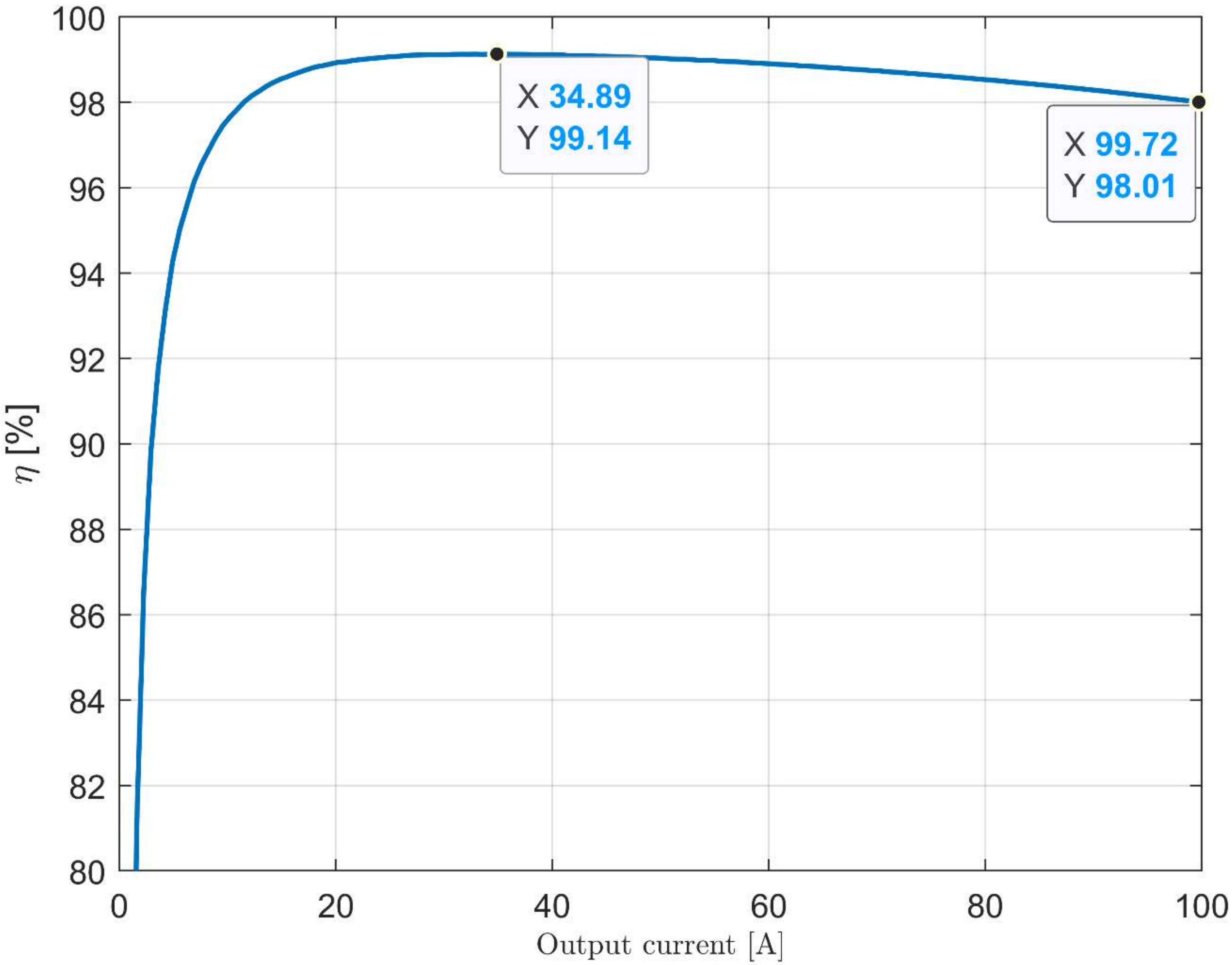


Recirculating Power Test Setup for Efficiency Measurements

80 kW TAB Converter Experimental Setup



Experimental Efficiency Results



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Conclusion and Future Work

- 2 kW prototype designs for topology and control validation
- Control analysis and validation for an unfolding based AC-DC converter
- 80 kW high-power hardware validation
- Future work:
  - Control validation for a series stacked 2 kW modules
  - Hardware validation for a full 560 kW system