

Design and Evaluation of Hybrid Switched Capacitor Converters for High Voltage, High Power Density Applications

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Exceptional service in the national interest



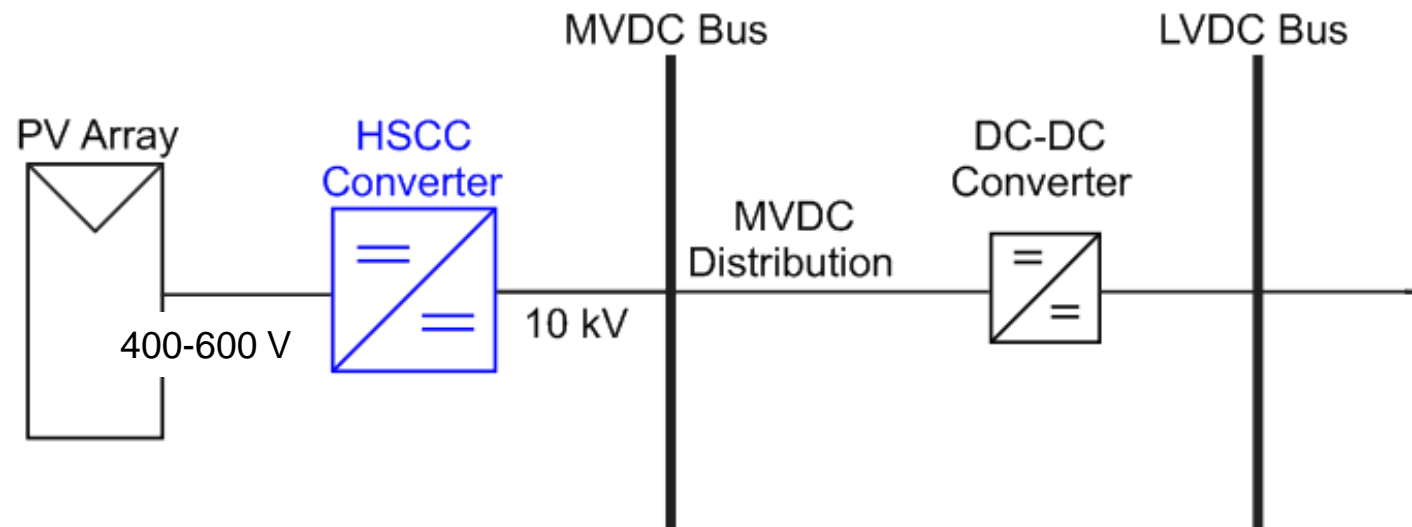
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Agenda

- Motivation and Approach for a Hybrid Switched Capacitor Converter (HSCC) study
- *Hybrid Switched Capacitor Circuit* (HSCC) Operation
- Prototype 1 – Bipolar HSCC Design and Operation
- Improved Converter Control
- Prototype 2 – Optimized Bipolar HSCC Design and Operation
- Hardware Results, Performance Comparison
- Future Work

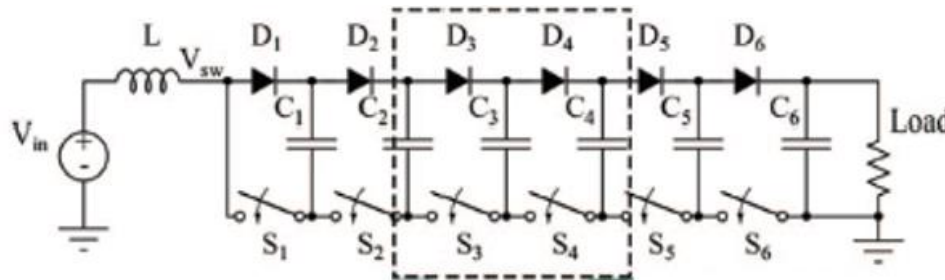
The Proposed Prototype Demonstrates a Converter for Medium Voltage DC Distribution

- Medium Voltage DC is projected to outperform Low Voltage AC and Medium Voltage AC in investment and operation cost [1]
- Direct connection of DC renewables such as PV will reduce conversion losses on generation and consumption side
- A high-gain boost converter capable of **10 kV** output, **>5 kW**, **>95% efficiency** with superior power density was selected as an exemplar

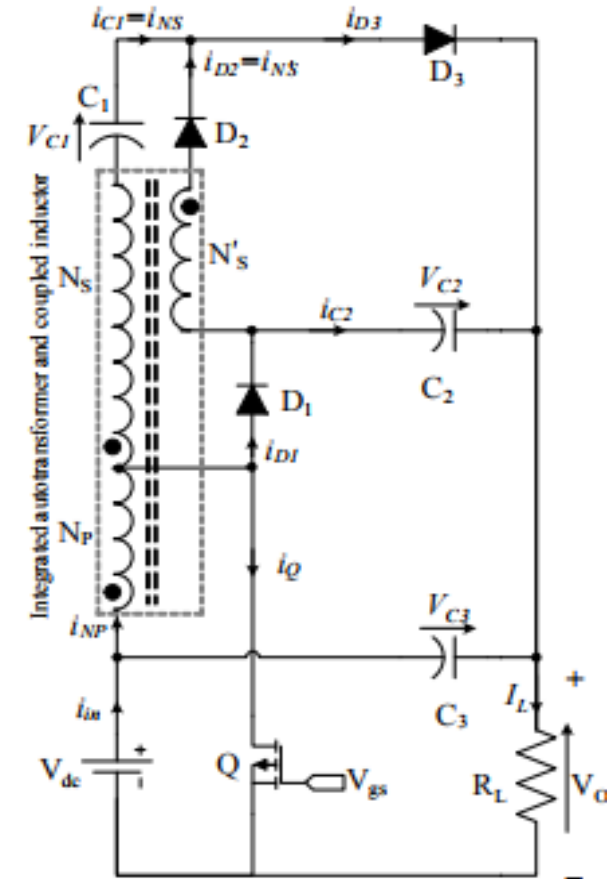


Previous Work has Investigated High Gain Converters

- Various capacitor-diode voltage multiplier circuits have been built demonstrating high gain
- Converters were limited to several hundred volts or low switching frequency
- Some converters approach kV output, but use many controlled switches



7-level voltage multiplier with 6 active switches [1]



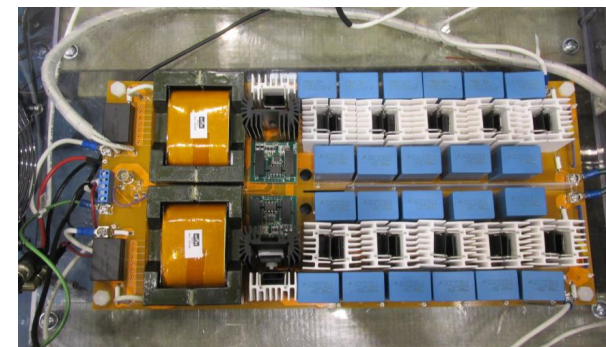
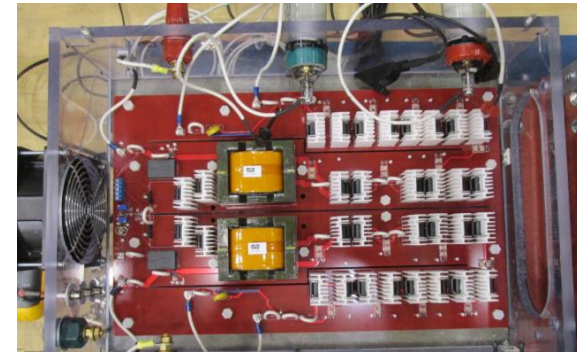
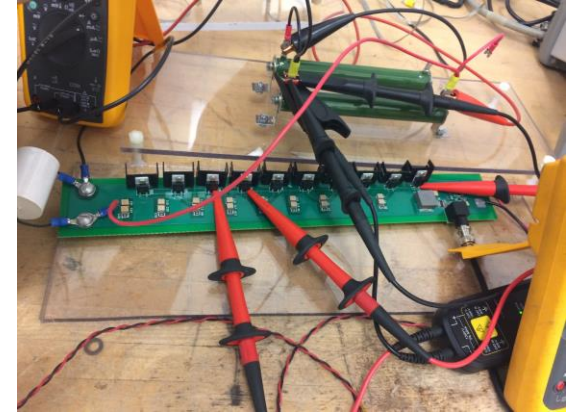
Voltage multiplier with autotransformer [2]

[1] Z. Liao, Y. Lei and R. C. N. Pilawa-Podgurski, "A GaN-based flying-capacitor multilevel boost converter for high step-up conversion," 2016 *IEEE Energy Conversion Congress and Exposition (ECCE)*, Milwaukee, WI, 2016, pp. 1-7

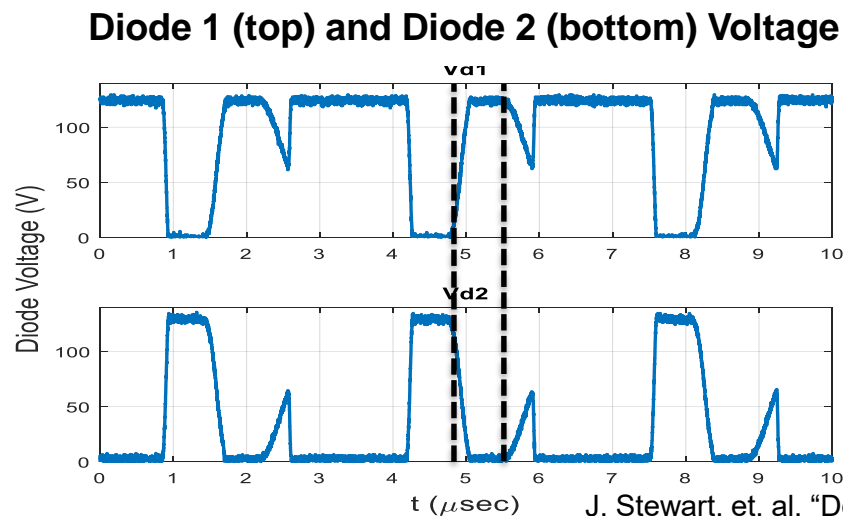
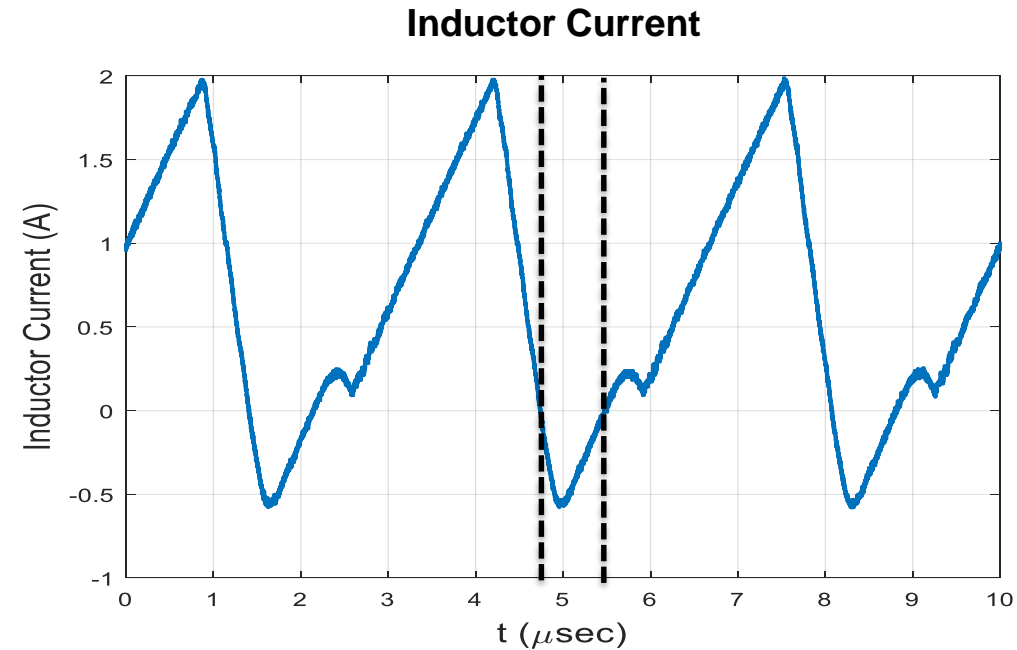
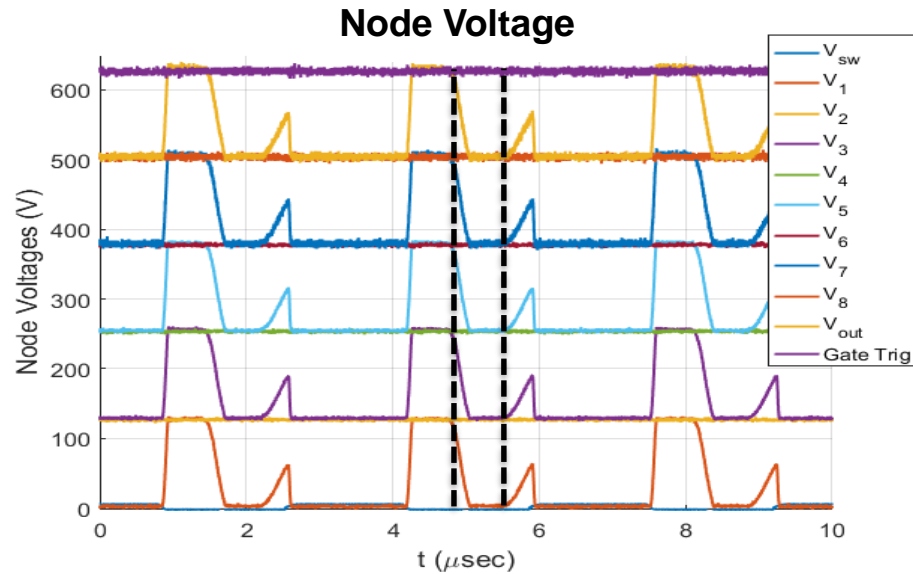
[2] W. Chen, A. Q. Huang, C. Li, G. Wang and W. Gu, "Analysis and Comparison of Medium Voltage High Power DC/DC Converters for Offshore Wind Energy Systems," in *IEEE Transactions on Power Electronics*, vol. 28, no. 4, pp. 2014-2023, April 2013

Three Prototypes were Built and Evaluated

- **Prototype 0** is a (unipolar) Hybrid Switched Capacitor Circuit (HSCC) built for low voltage ($< 1\text{kV}$), low power testing and initial model validation
- **Prototype 1** is a Bipolar HSCC designed for 10 kV and high power
- **Prototype 2** is an optimized Bipolar HSCC that achieved 10 kV at higher power and efficiency



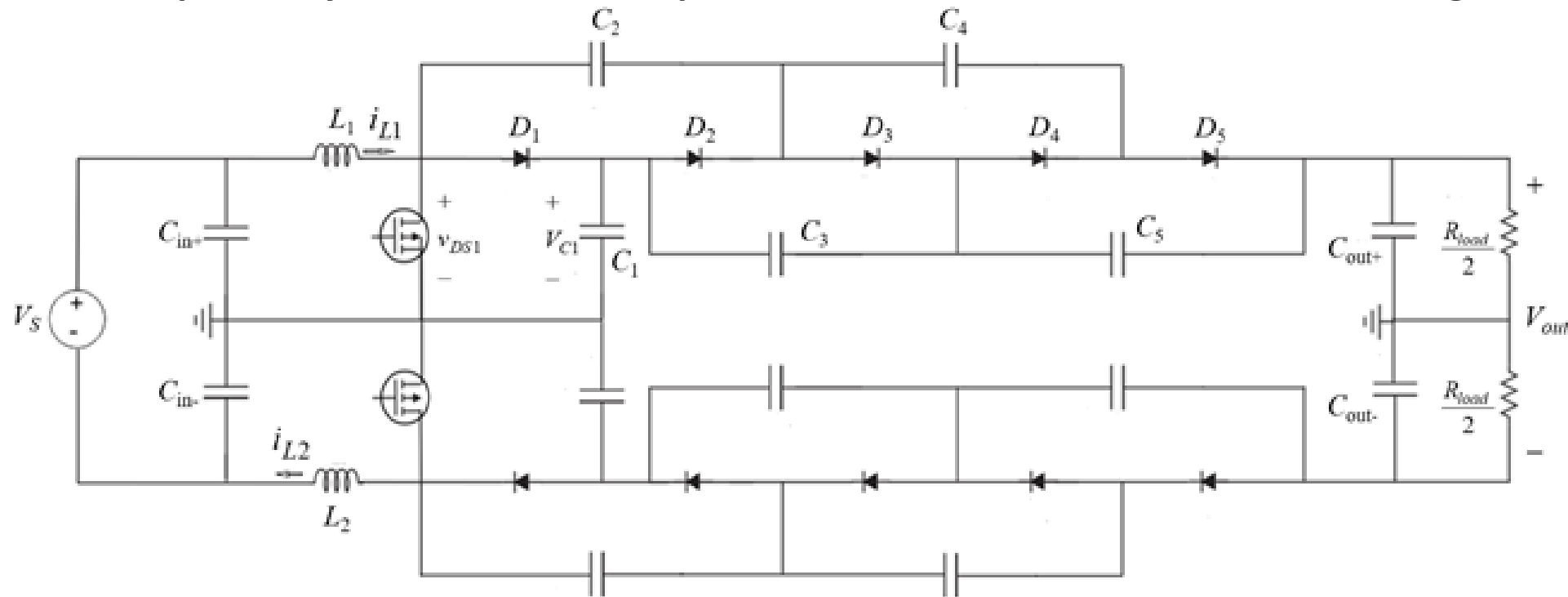
First Prototype Gave Insight into HSCC Operation



- Inductor current goes negative due to direct connection with upper rail capacitors.
- While inductor current is negative, diode biasing is reversed as if switch was turning 'on'.

A Bipolar Configuration Enables Higher Voltage Operation

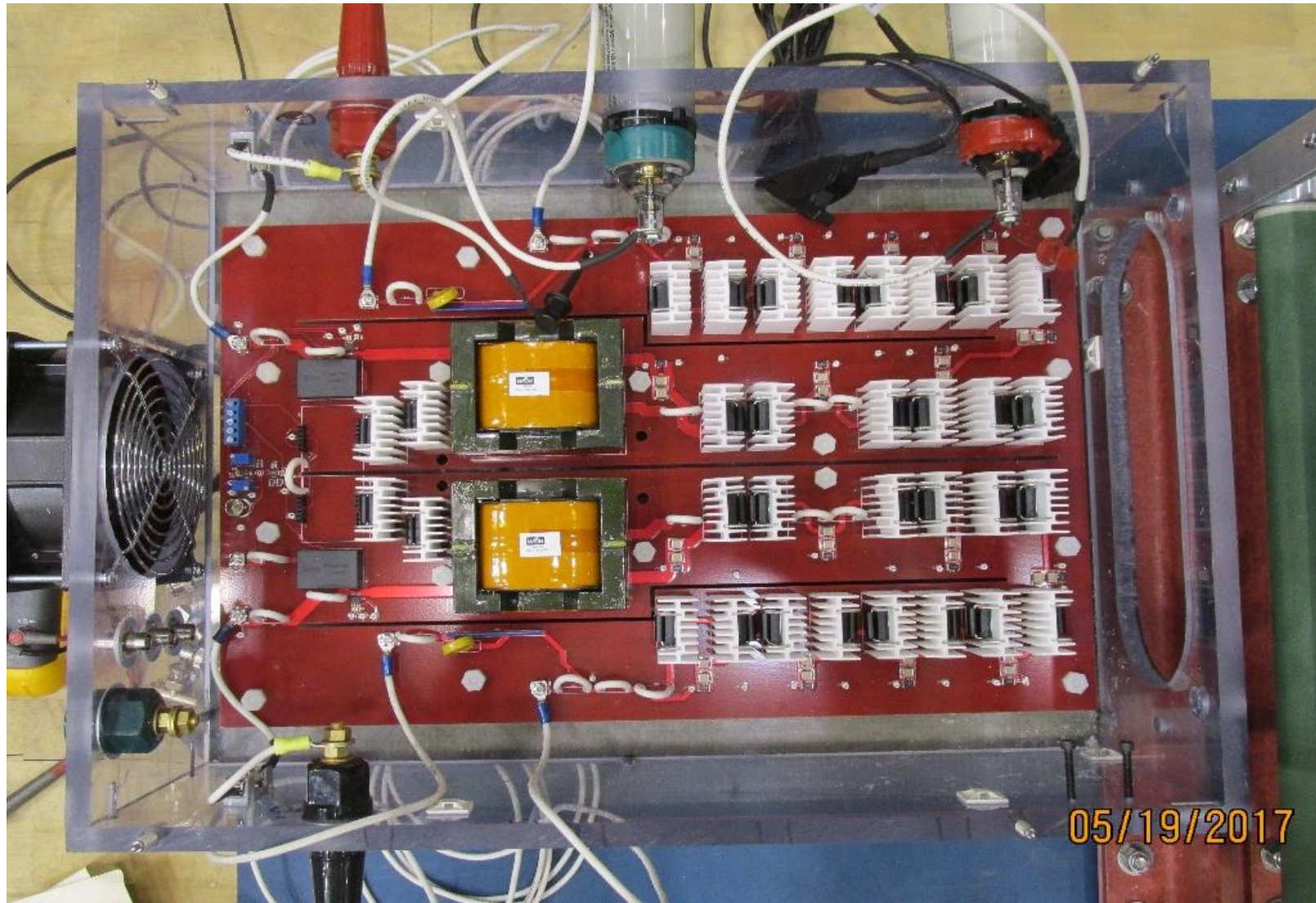
Bipolar Hybrid Switched Capacitor Converter, shown with $N=2$ stages



- Increasing the number of stages has reduced effect on voltage gain after ~ 5
- A bipolar variant with equivalent gain is achievable with one additional switch
- The bipolar configuration reduces component stress by a factor of 2

Prototype 1 – A Bipolar HSCC was Designed for kilowatt-level output

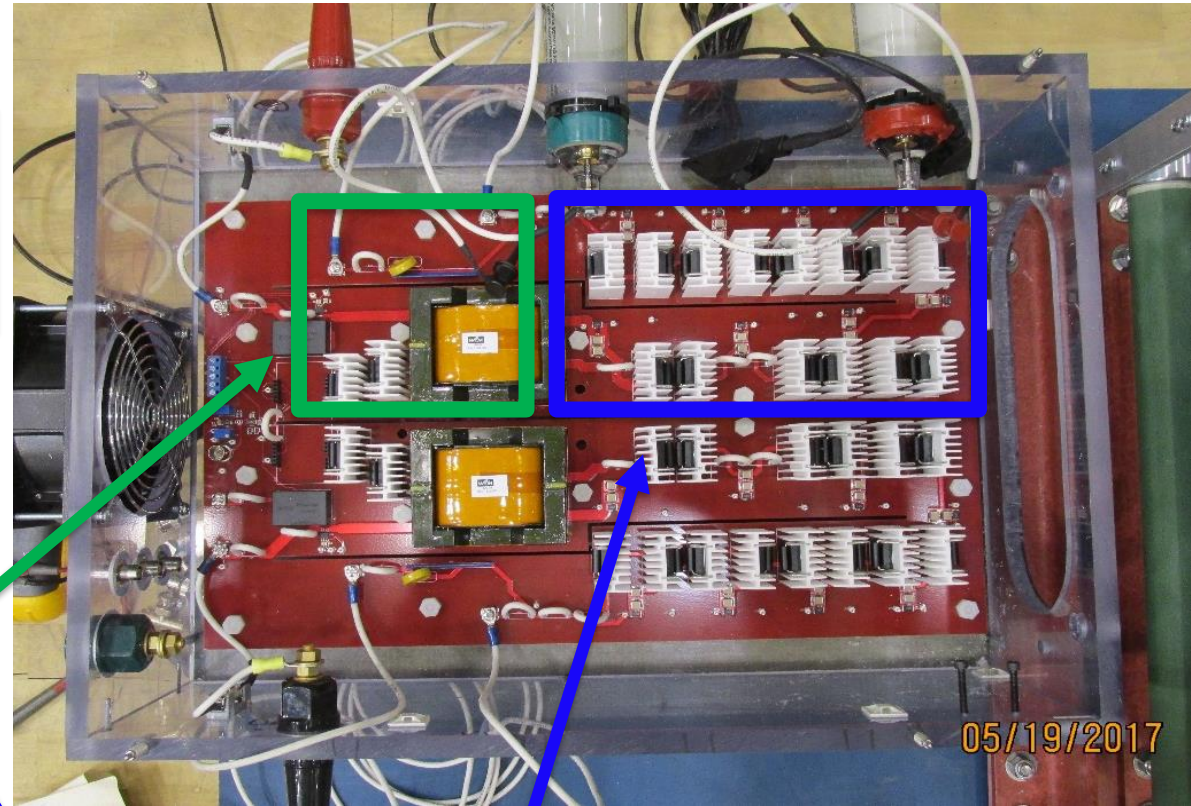
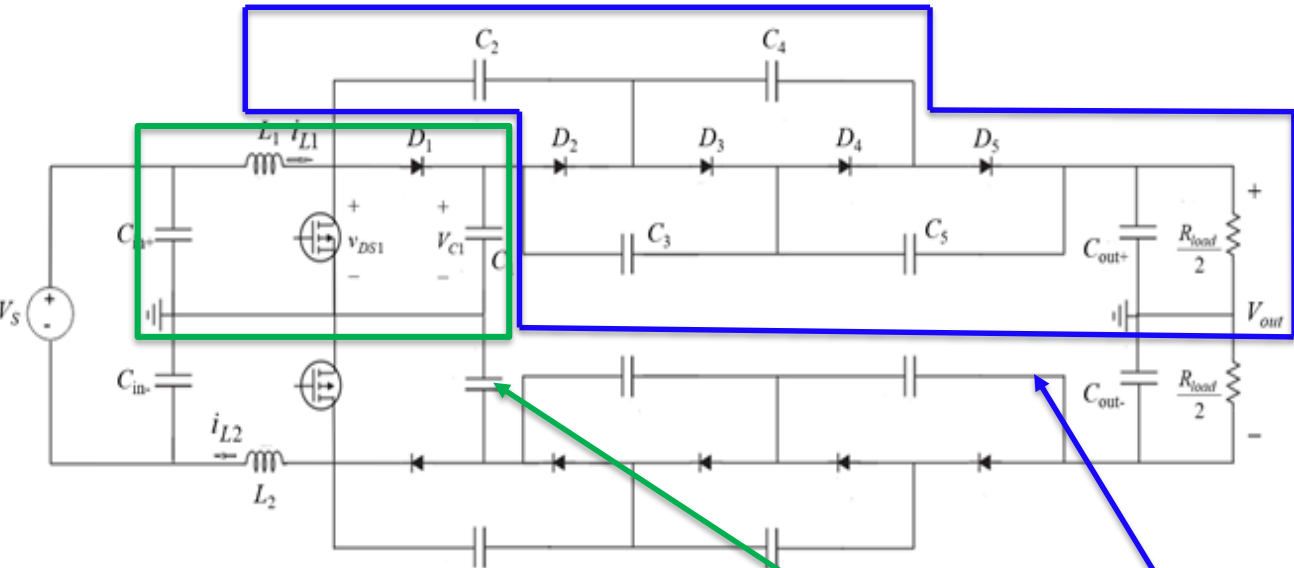
Prototype 1 – Bipolar HSCC



Prototype 1 – A Bipolar HSCC was Designed for kilowatt-level output

Bipolar HSCC Schematic

Prototype 1 – Bipolar HSCC

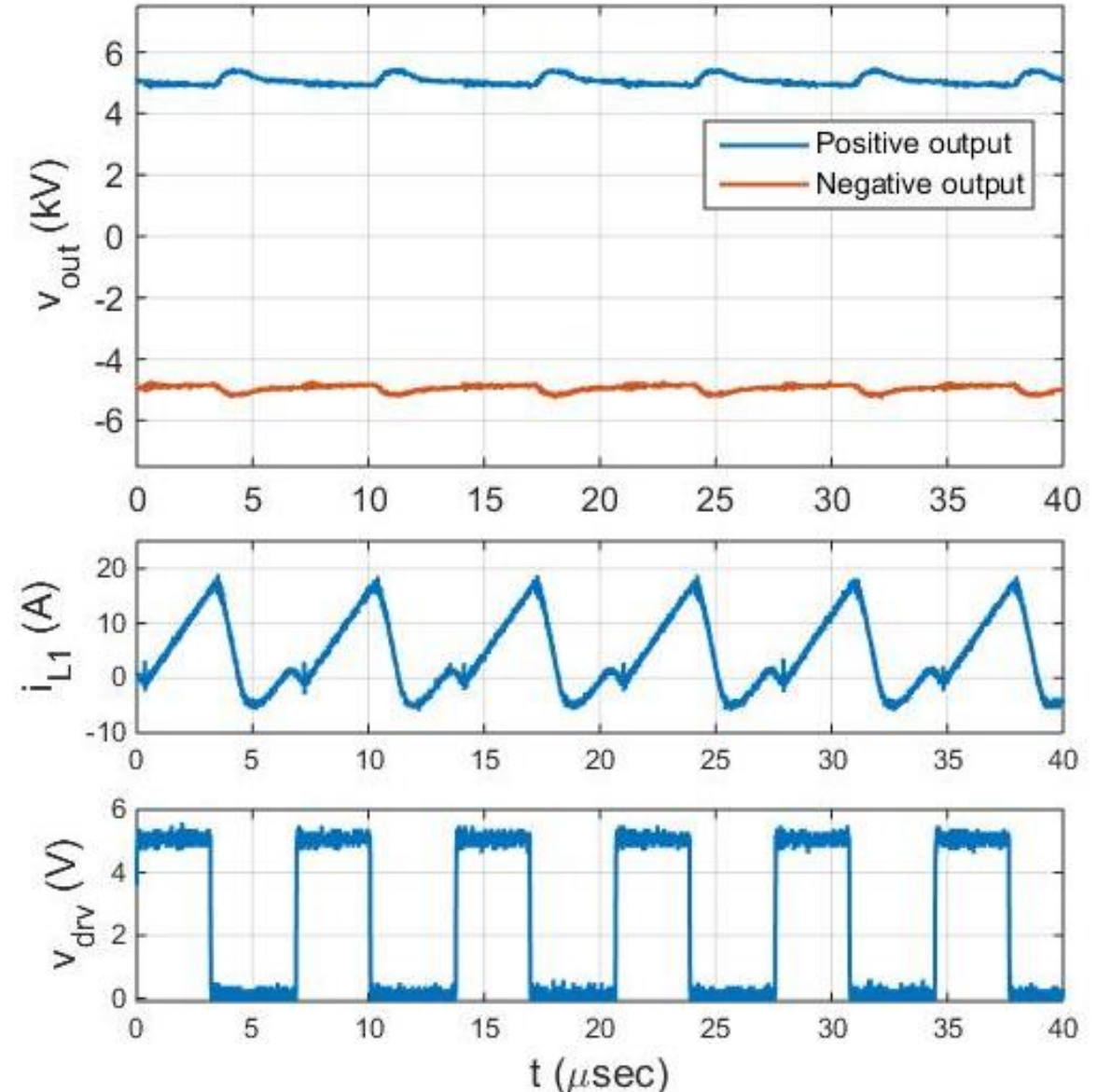


Input Stage

Voltage Multiplier

Prototype 1 – A Bipolar HSCC was Designed for kilowatt-level output

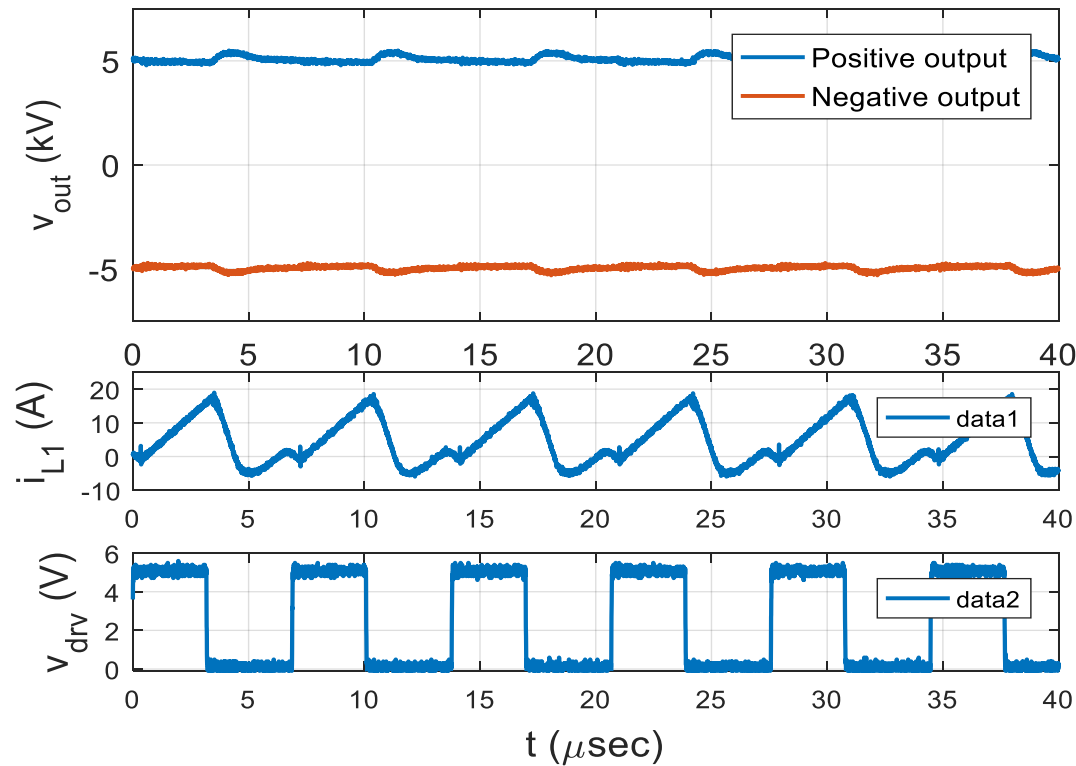
- Converter achieved 10.05 kV output with 600 V input voltage
- A simple constant duty cycle scheme was used with $N=4$ stages
- Positive and negative polarities were well balanced
- Since i_L goes negative, the gain was not so straightforward
- Peak power was 2.57 kW
- Efficiency was 95.3% at peak power



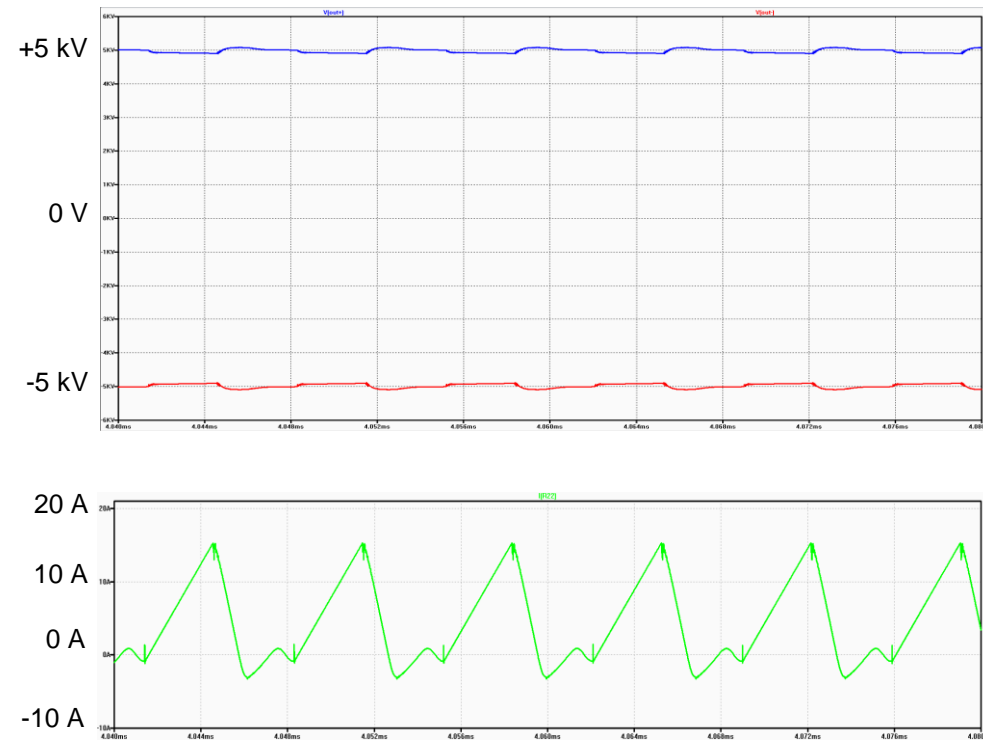
Simulation Models were Calibrated to Prototype 1 Results

- Calibrated simulation models are useful for additional design iterations in simulation

Hardware Results

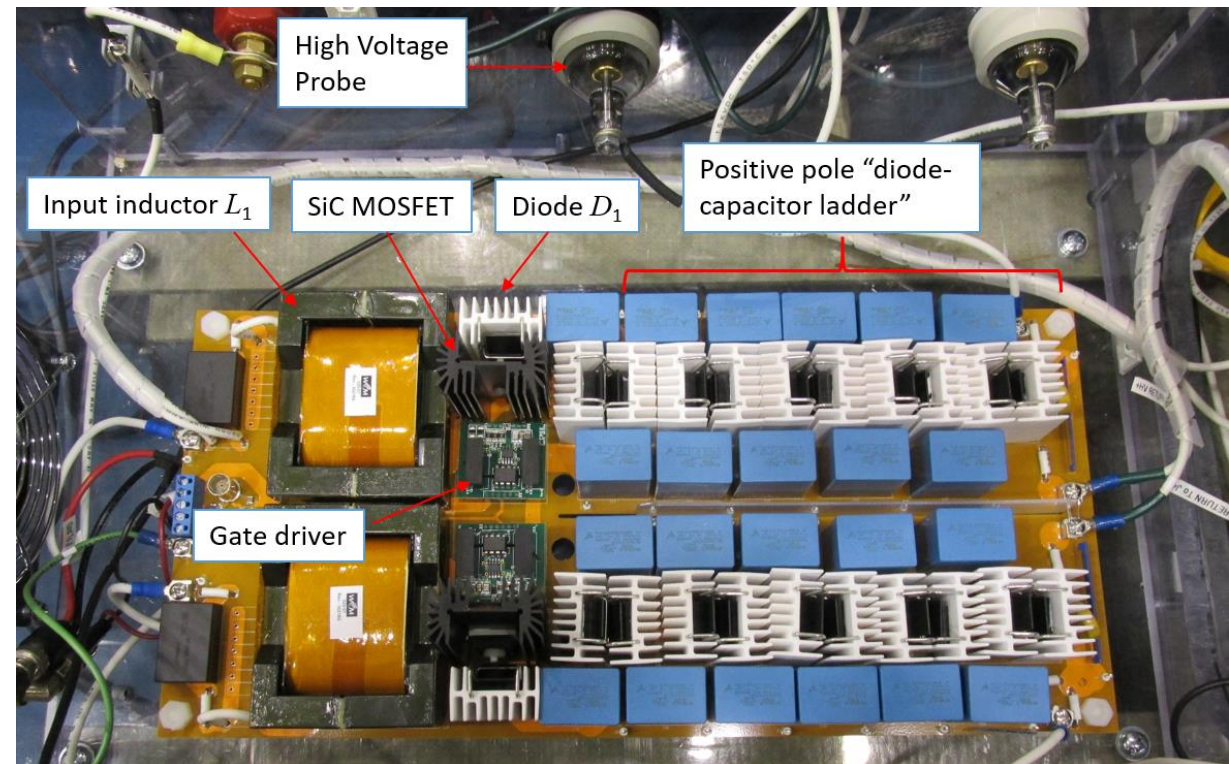
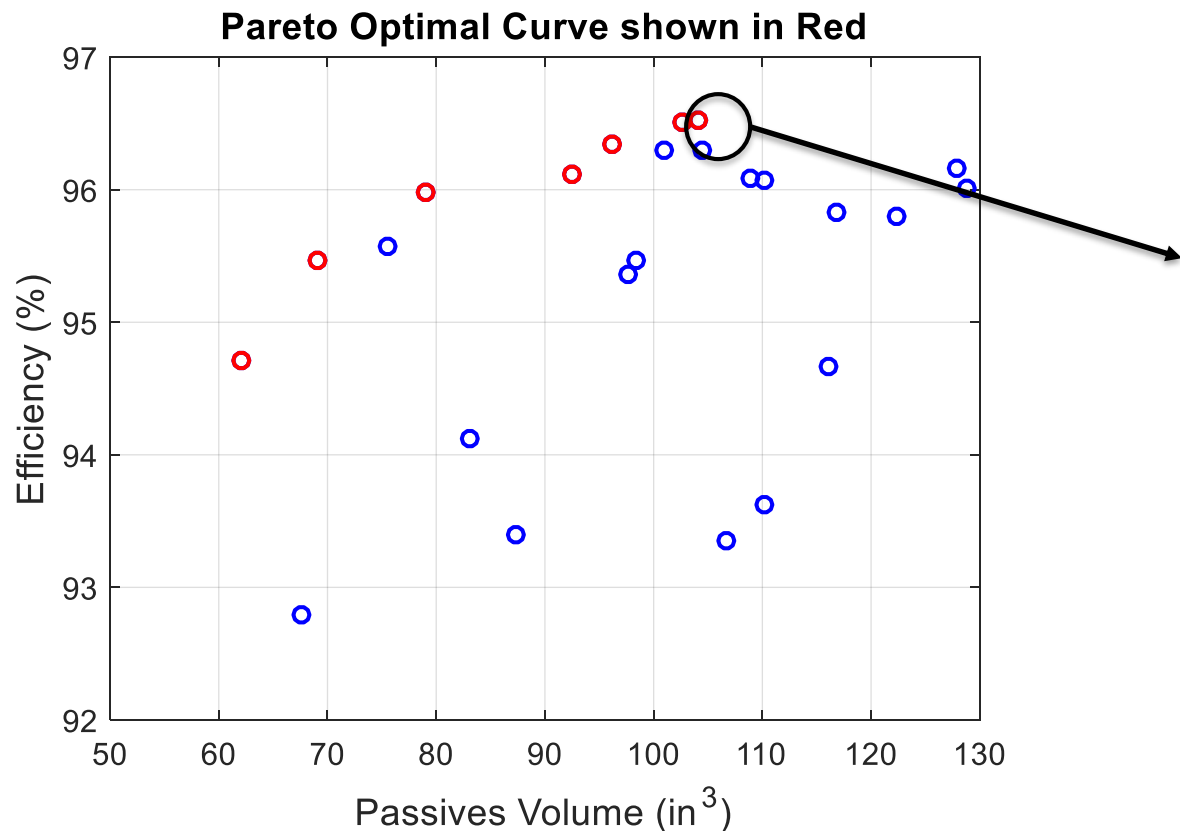


Simulation Results



Prototype 2 was built and Tested

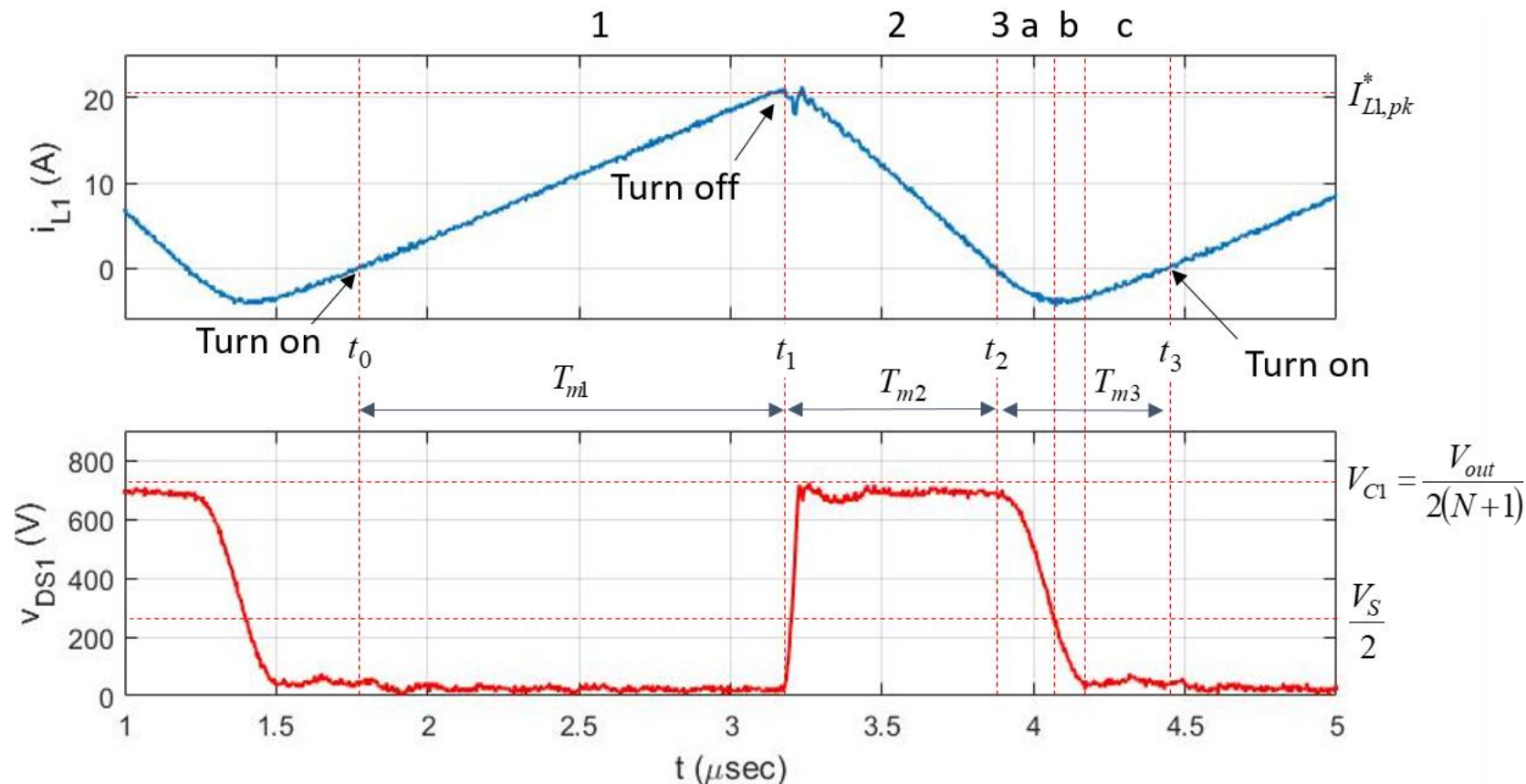
- Based on simulation results, the component parameters were selected for Prototype 2
- Prototype 2 was also operated using a new control



A Method to Regulate Input Power while Reducing Switching Loss was Developed

- MOSFET switches *on* as the inductor current is rising through the $i_L=0$ crossing
- MOSFET switches *off* when a reference peak current is reached
- Inductor current falls, drops below zero and then rises again

Control is similar to Quasi-Square Wave (QSW)

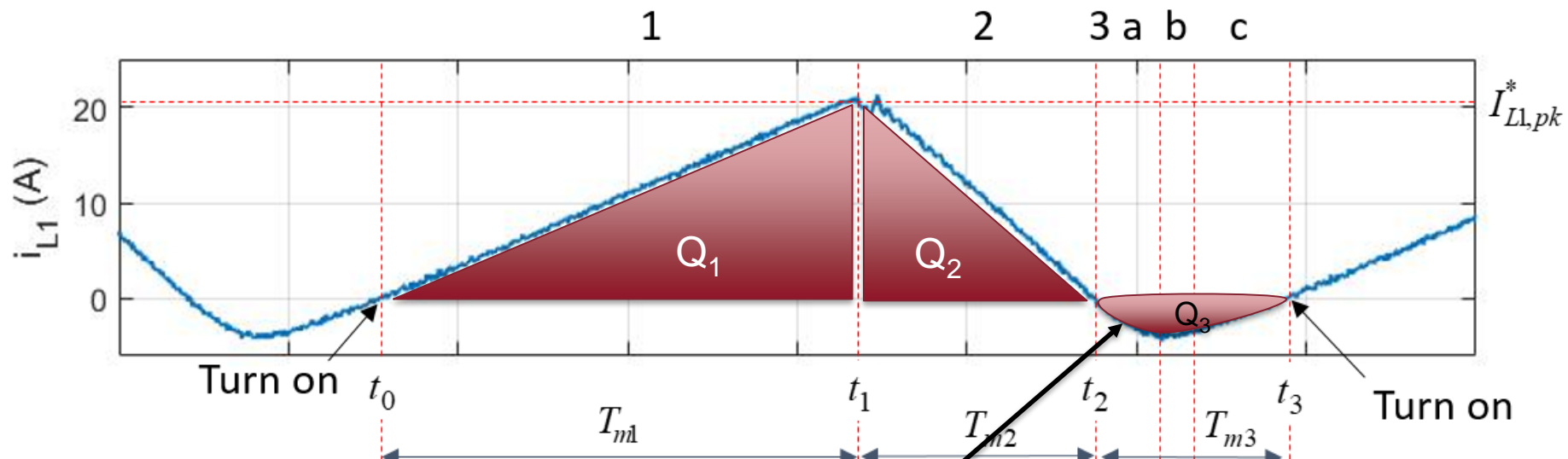


A Method to Regulate Input Power while Reducing Switching Loss was Developed

- The input power is computed by summing the charge delivered to the circuit over the three modes

$$P_{in} = V_S I_{L1} = V_S \frac{(Q_1 + Q_2 + Q_3)}{T_{sw}}$$

- The charge transferred during Mode 3 is a little more complicated, and is negative



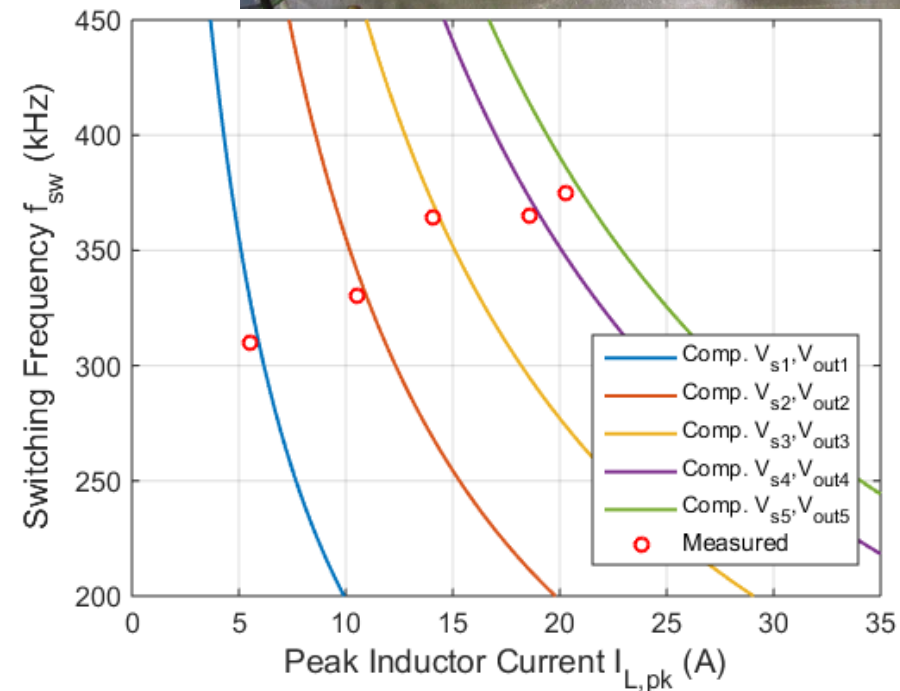
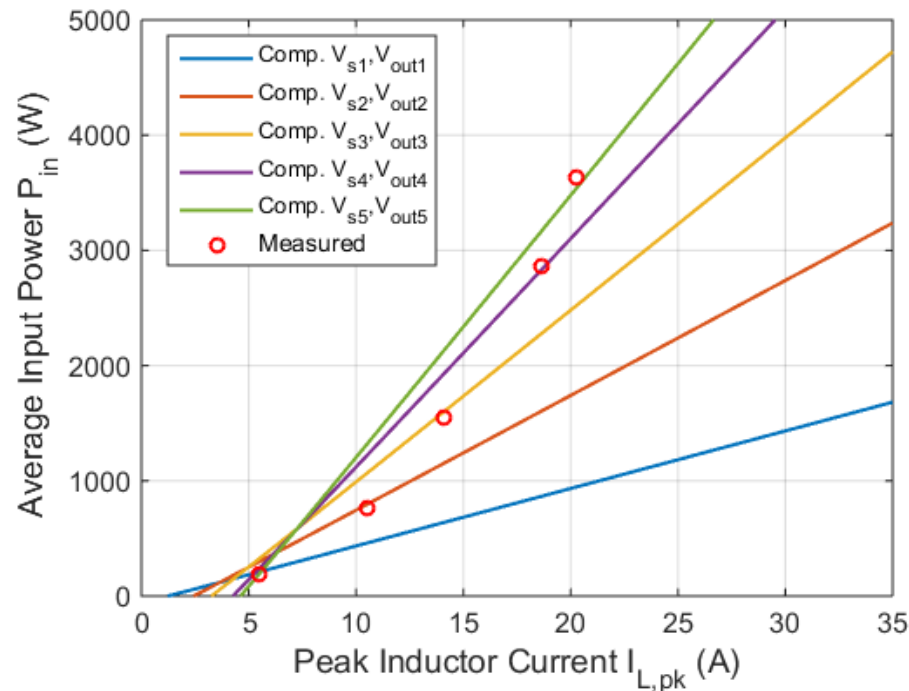
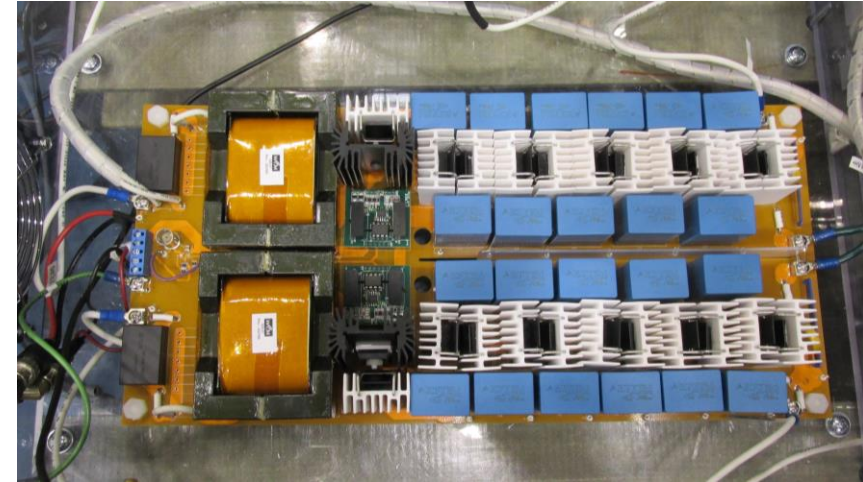
$$Q_3 = \int_{t_2}^{t_2+T_{m3a}+T_{m3b}} i_{L1}(t) dt + \int_{t_3-T_{m3c}}^{t_3} i_{L1}(t) dt = \frac{\tau_{CP}^2}{L} \left(0.6301 \frac{V_{out}}{(N+1)} - 0.4727 \frac{V_{out}^2}{V_S (N+1)^2} \right)$$

The Control Analysis was Validated in Prototype 2

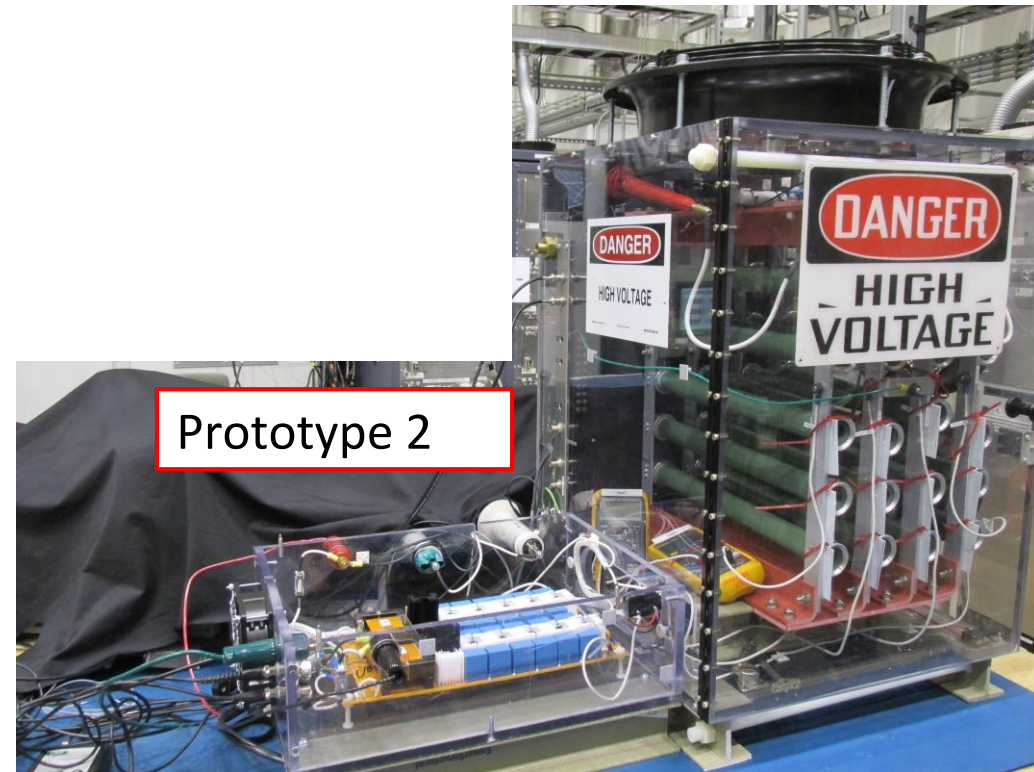
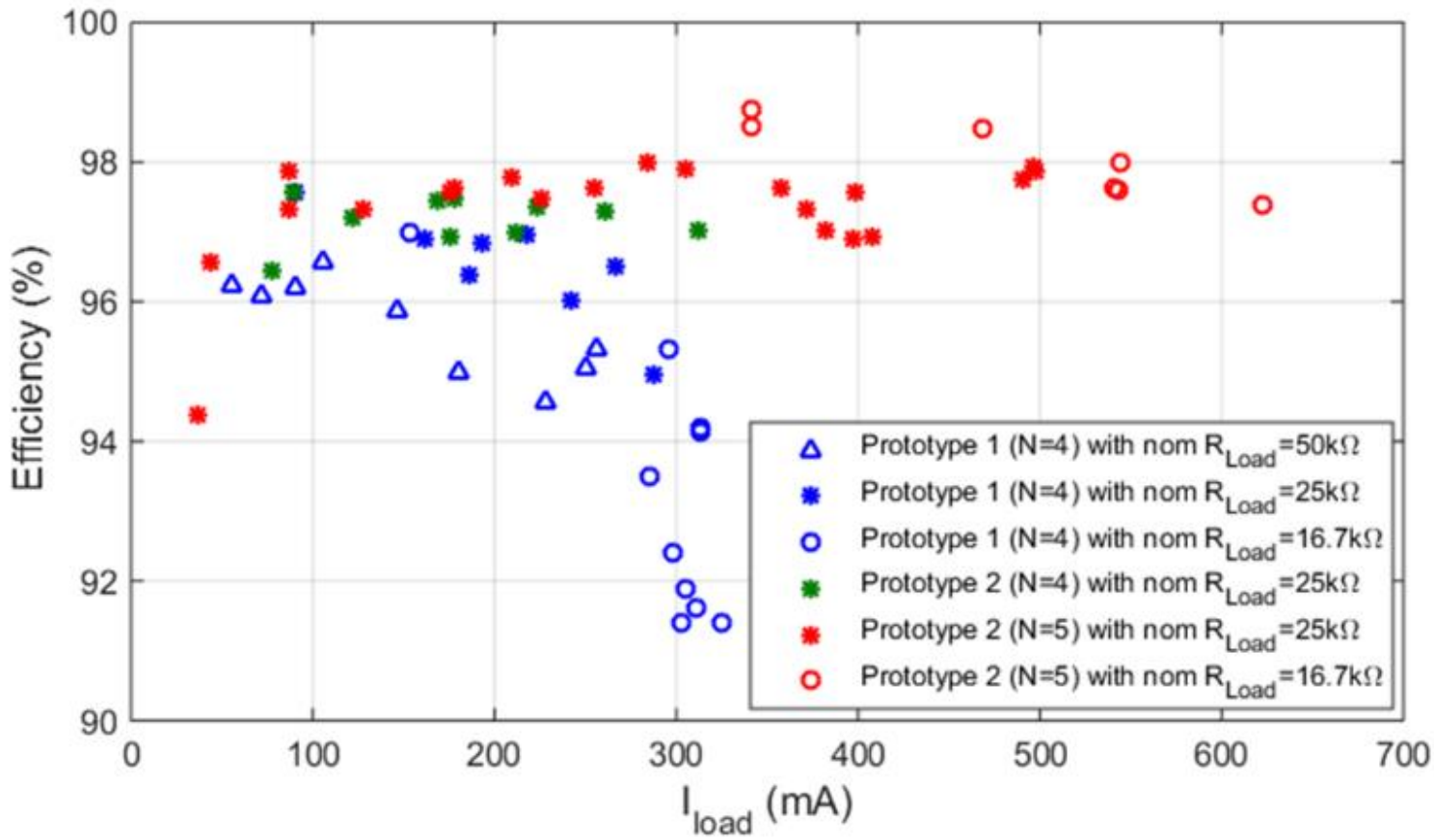
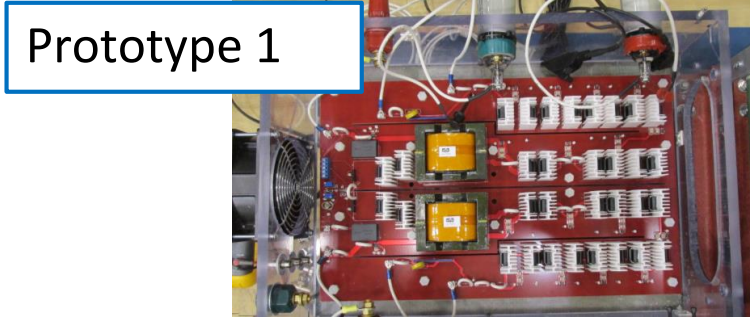
- Analytical prediction was compared to results from Prototype 2 testing

$$P_{in} = V_S I_{L1} = V_S \frac{(Q_1 + Q_2 + Q_3)}{T_{sw}}$$

$$f_{sw} = \frac{1}{\left(\frac{2L}{V_S} + \frac{2L(N+1)}{V_{out} - V_S(N+1)} \right) I_{L,pk} + \frac{1.375\tau_{CP}}{V_S(N+1)} V_{out}}$$

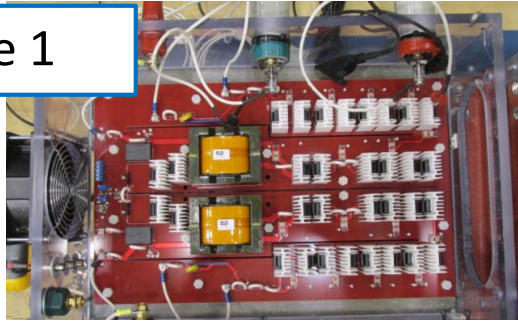


Prototypes 1 and 2 were Compared

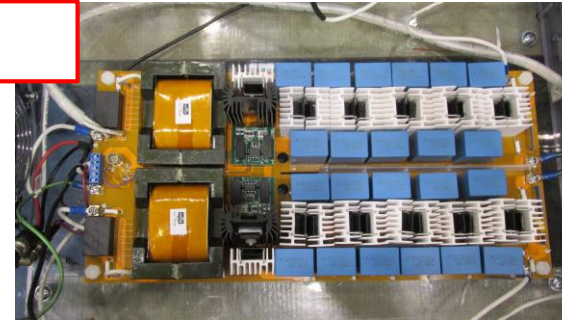


Comparing the Prototypes at *Peak Performance* ...

Prototype 1



Prototype 2



Design & Operation

- Stage capacitance $\sim 0.2 \mu\text{F}$
- Simple duty-cycle control
- Switching frequency 140 kHz
- Configured for $N=4$

- Stage capacitance $\sim 1.2 \mu\text{F}$
- QSW-like control
- Switching frequency variable 250-375 kHz
- Configured for $N=5$

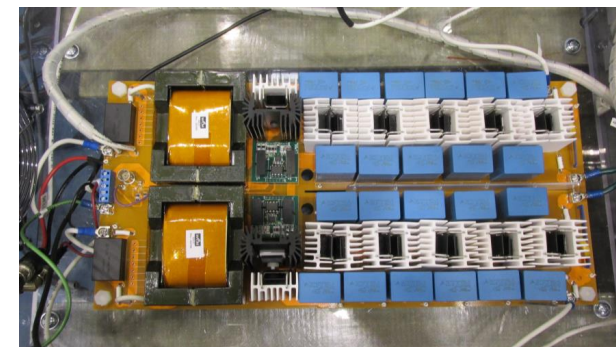
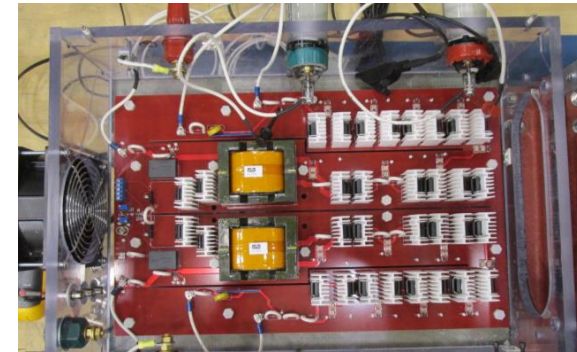
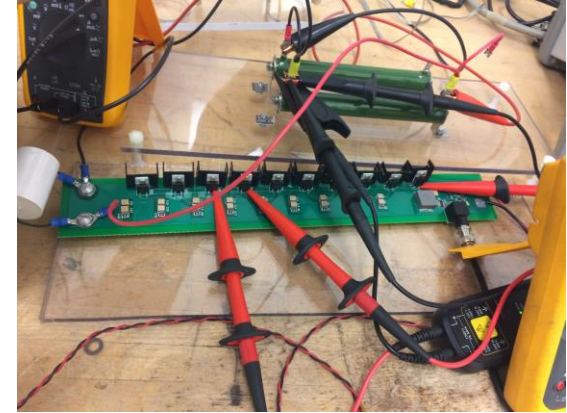
Performance

- Peak voltage demonstrated was 10.05 kV
- Peak demonstrated power was 2.57 kW
- Efficiency at peak power of 95.3%
- Demonstrated power density of $\sim 6 \text{ W/in}^3$
- Peak Gain over 16

- Peak voltage demonstrated was 10.0 kV
- Peak demonstrated power was 5.43 kW
- Efficiency at peak power of 97.4%
- Demonstrated power density of $\sim 23 \text{ W/in}^3$
- Peak Gain over 20

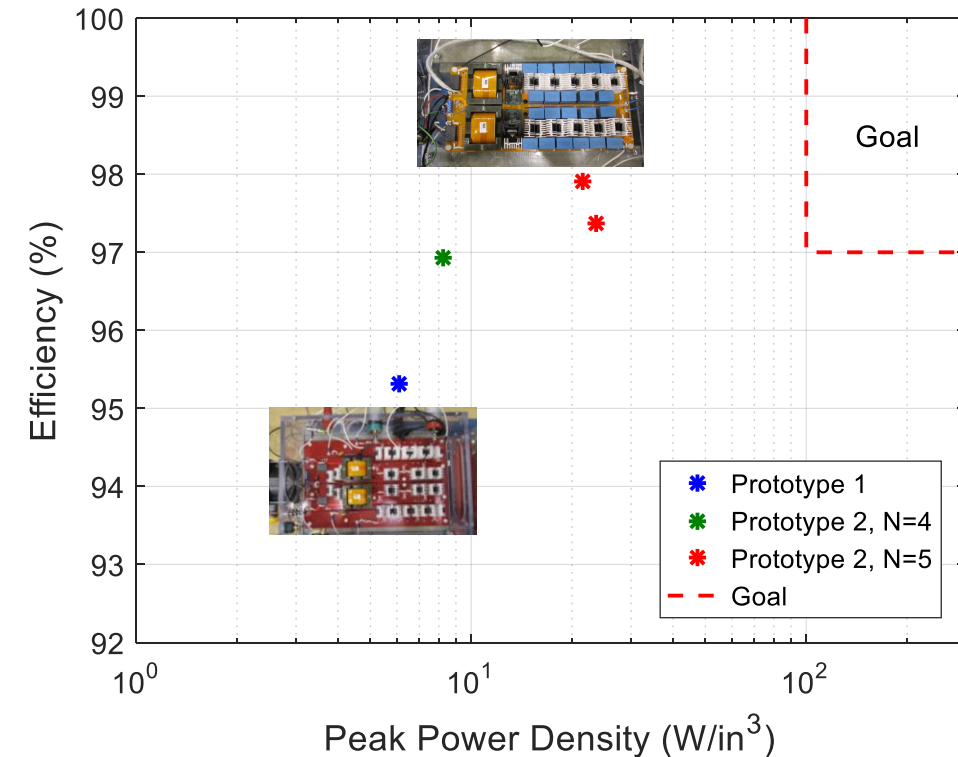
Summary

- This work presents the development of a High Voltage, High gain DC-DC boost converter based on hybrid switched capacitor topology
- Converter prototypes demonstrate high gain, high voltage operation at kW scale, with high efficiency and reasonable power density
- Further, each pole of the converter has just one controlled switch
- This work discusses key control and design aspects impacting efficiency and power handling
- Present and Future work considers the use of SiC switches and GaN diodes to improve efficiency



Summary

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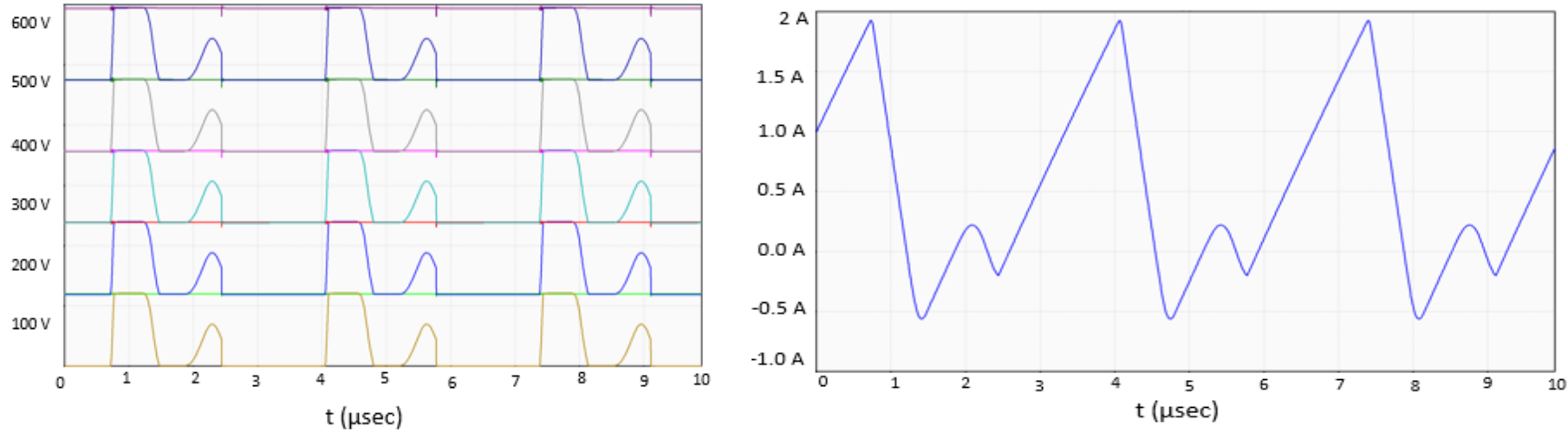
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- Co-Authors
 - James Richards
 - Jarod Delhotal
 - Jason Neely
 - Jack Flicker
 - Robert Brocato
 - Lee Rashkin

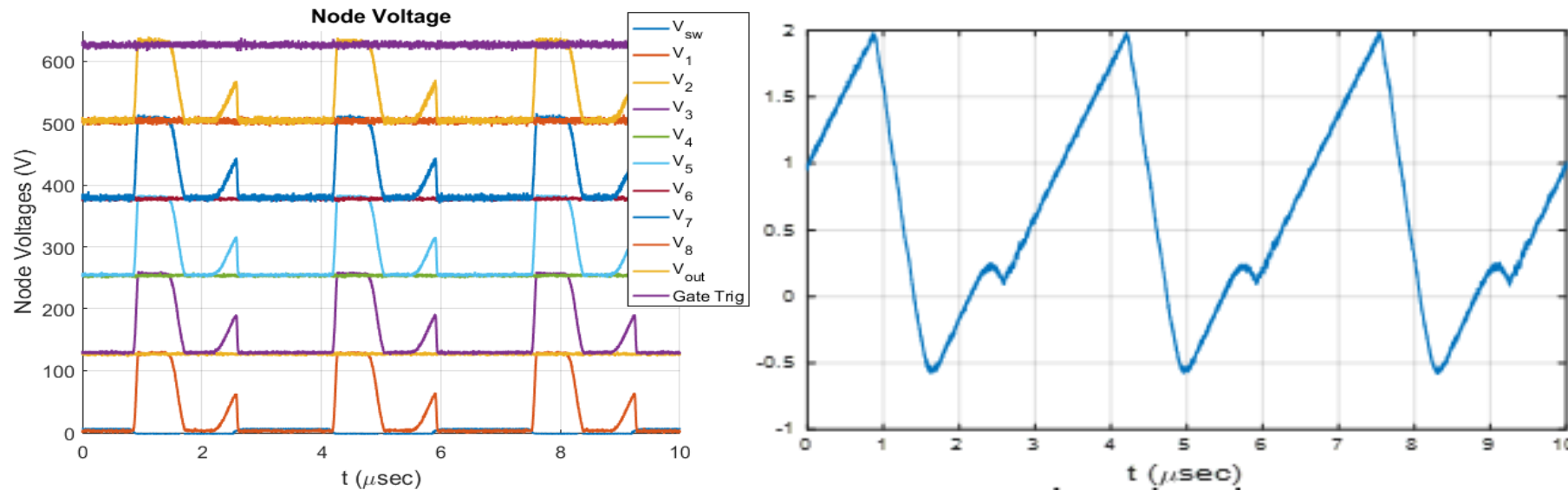
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First Prototype Gave Insight into HSCC Operation

Prototype 0 Simulation Waveforms



Prototype 0 Hardware Waveforms

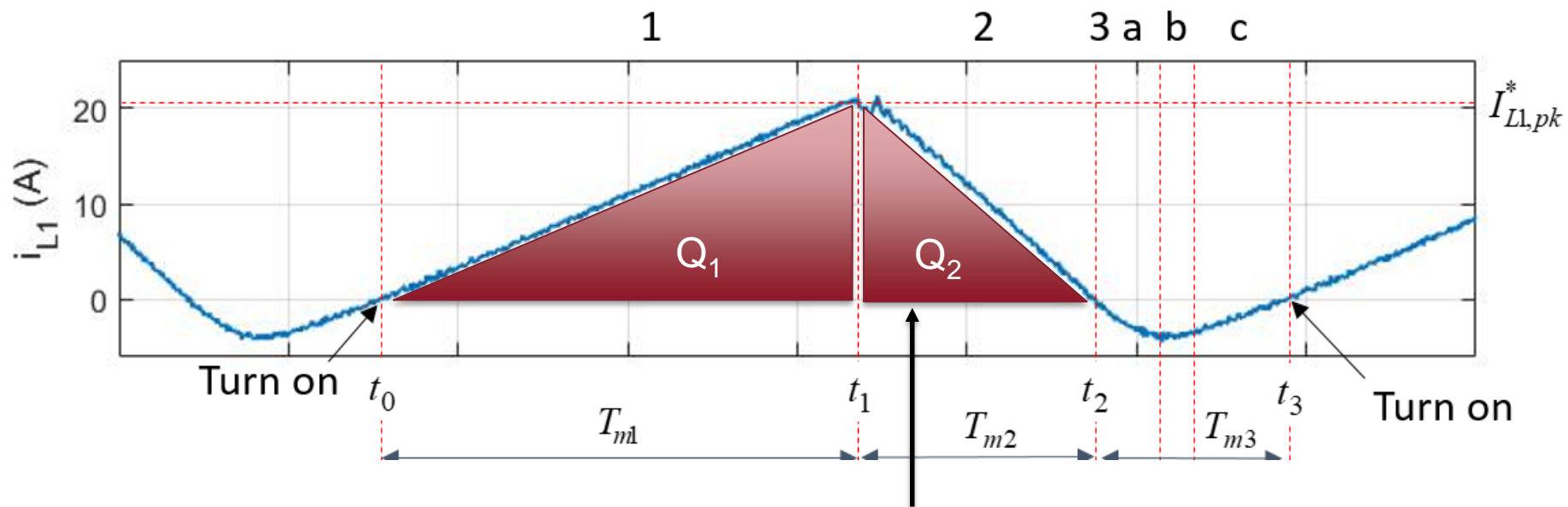


A Method to Regulate Input Power while Reducing Switching Loss was Developed

- The input power is computed by summing the charge delivered to the circuit over the three modes

$$P_{in} = V_S I_{L1} = V_S \frac{(Q_1 + Q_2 + Q_3)}{T_{sw}}$$

- The charge transferred during Mode 2 is similarly computed



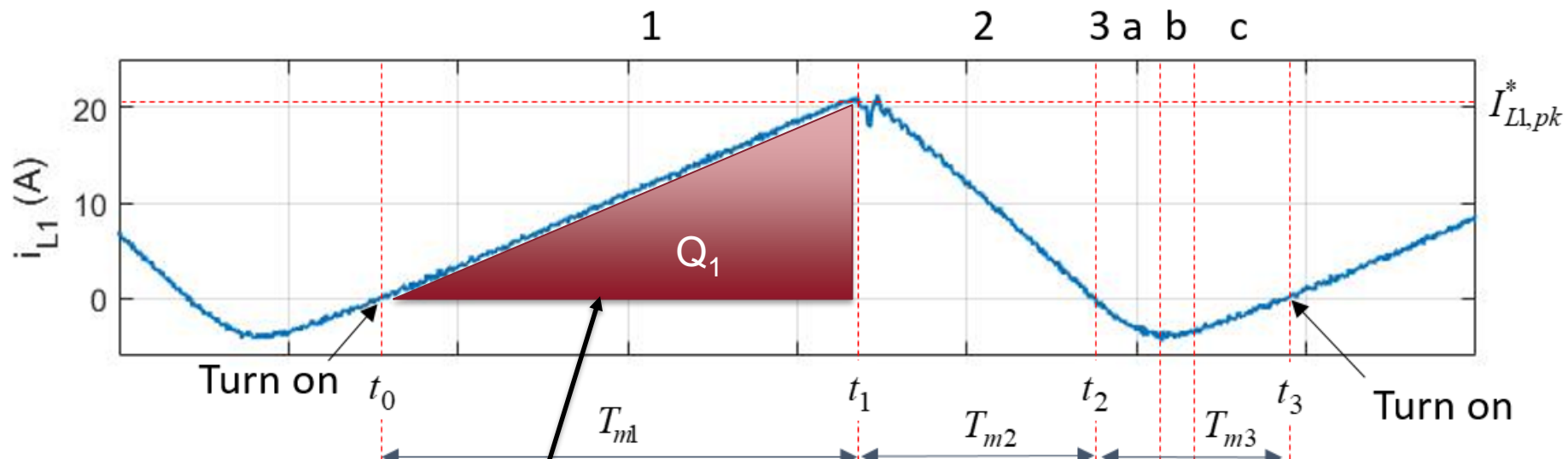
$$Q_2 = \int_{t_1}^{t_2} i_{L1}(t) dt = \frac{I_{L,pk} T_{m2}}{2} = \frac{L(N+1)}{V_{out} - V_S(N+1)} I_{L,pk}^2$$

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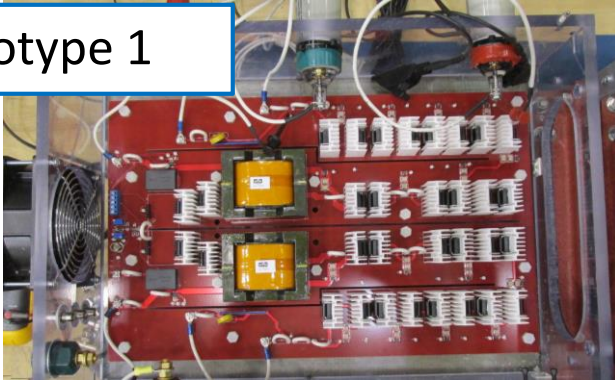
- The charge transferred during Mode 1 is given as the integral of inductor current over the interval



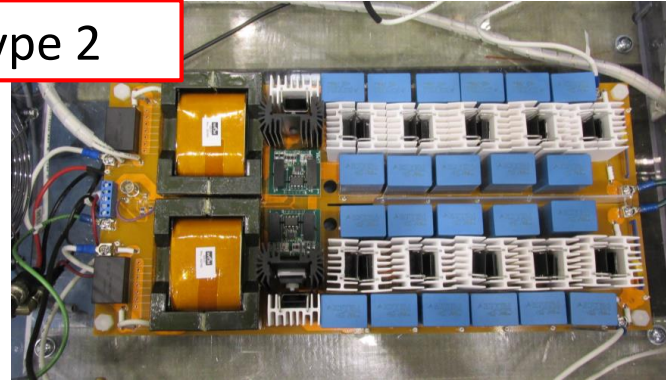
$$Q_1 = \int_{t_0}^{t_1} i_{L1}(t) dt = \frac{I_{L,pk} T_{m1}}{2} = \frac{L}{V_S} I_{L,pk}^2$$

Prototypes 1 and 2 were Compared

Prototype 1



Prototype 2

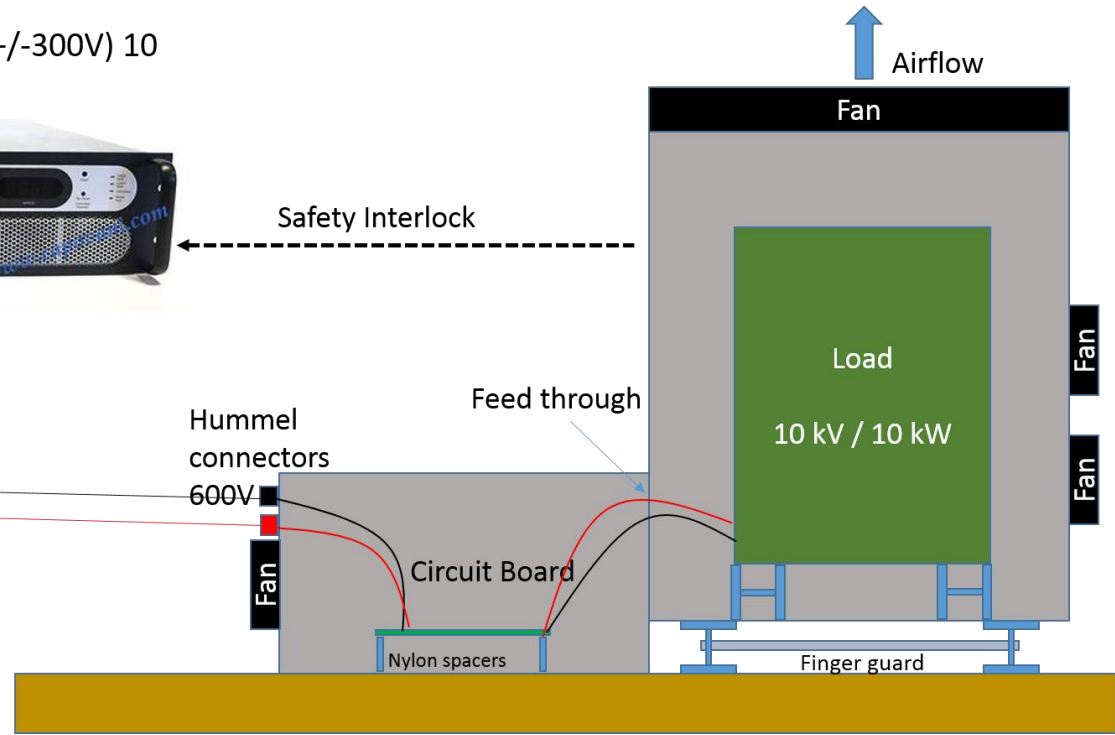


Sorenson 600 V (+/-300V) 10 kW power supply



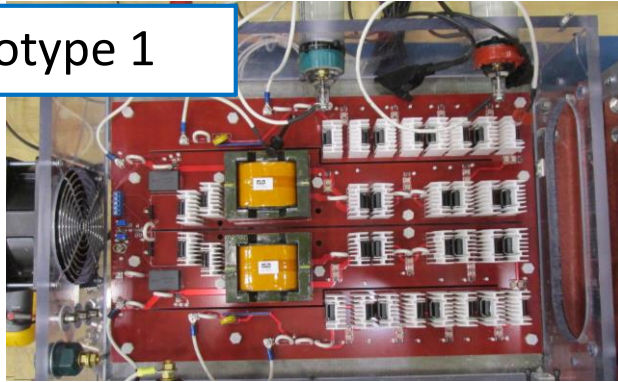
Safety Interlock

Airflow ↑

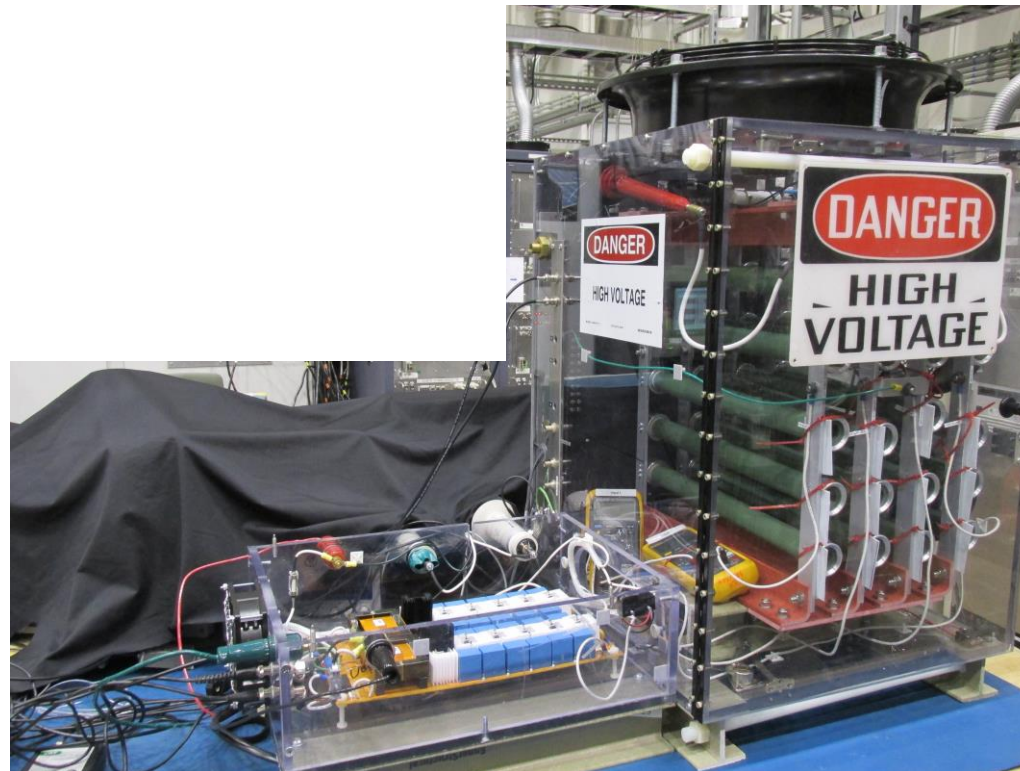
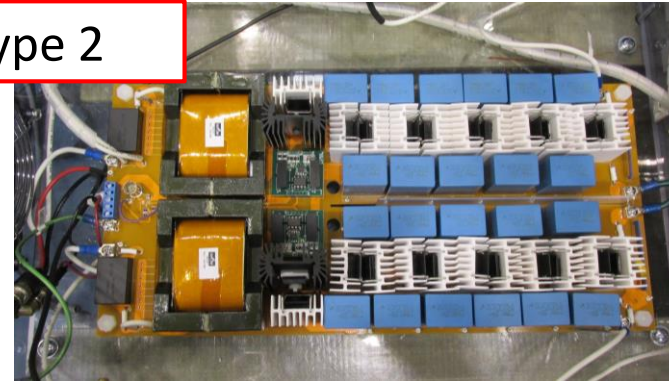


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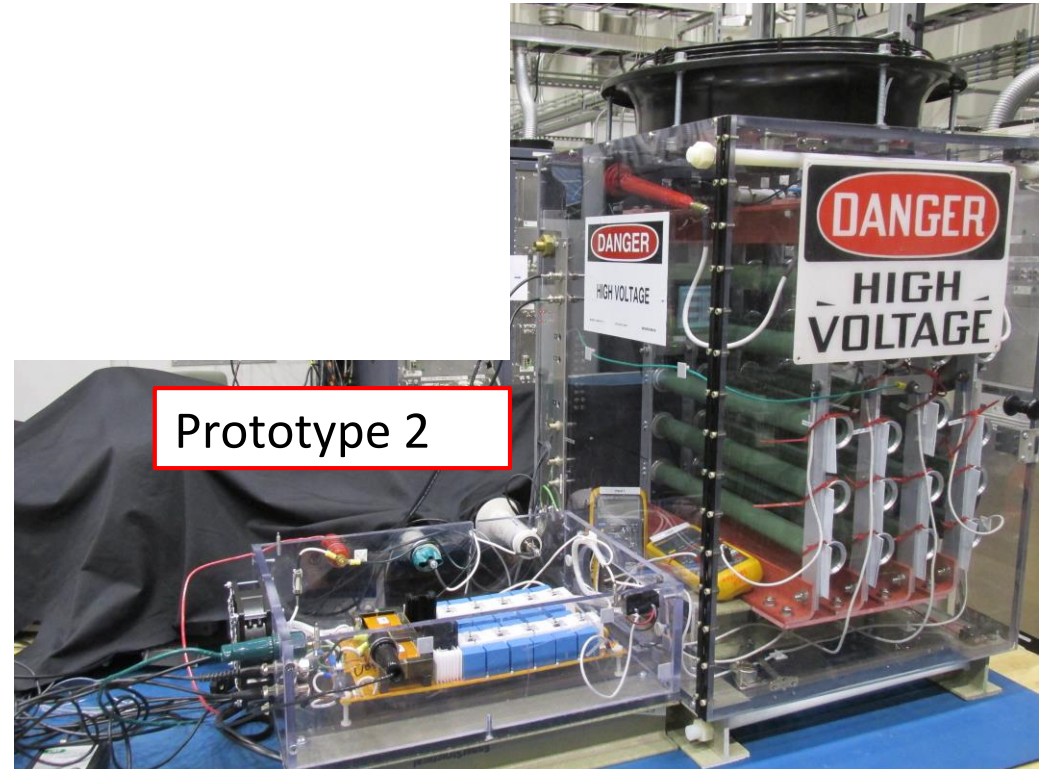
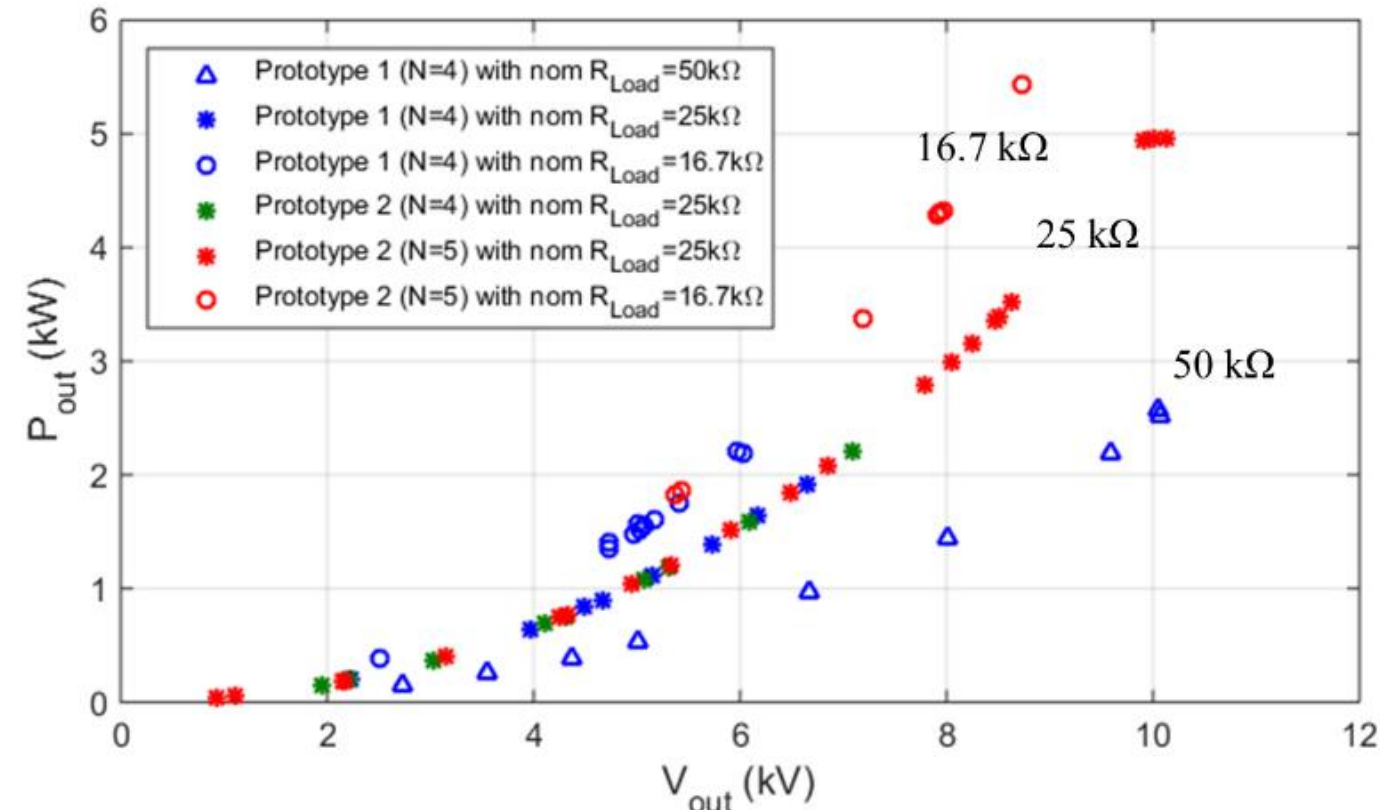
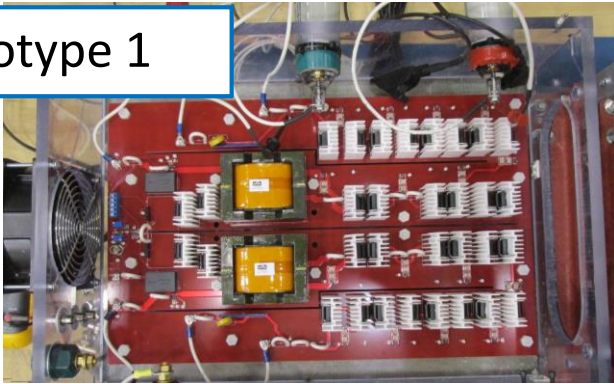


Prototype 2



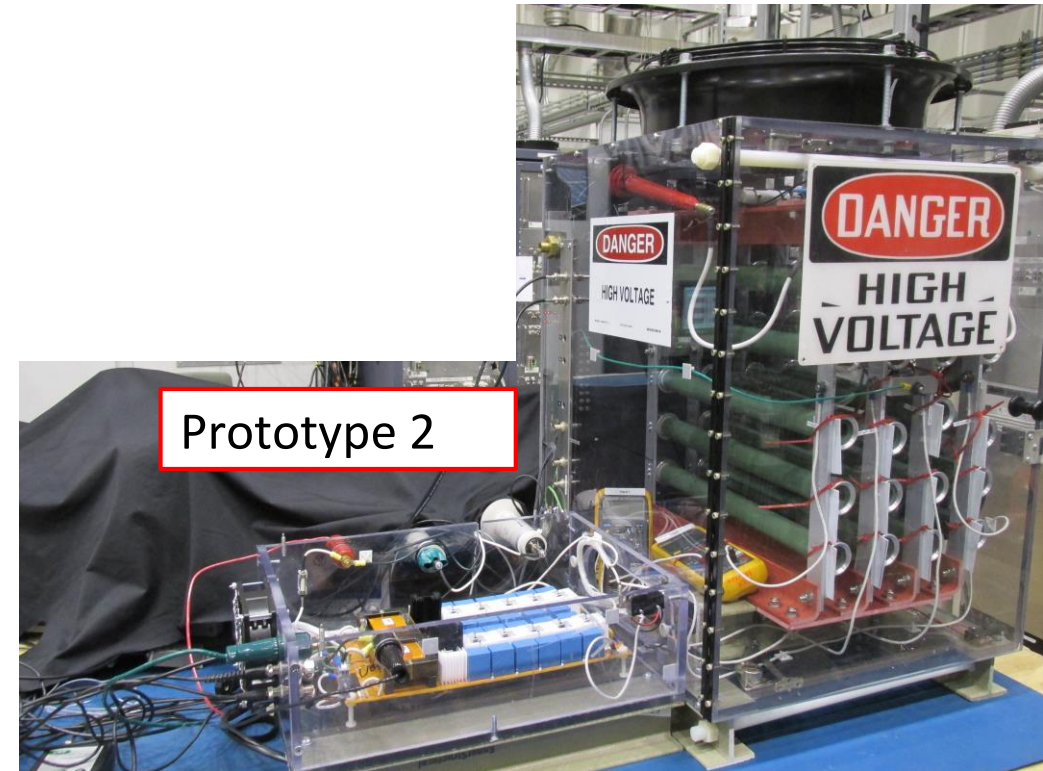
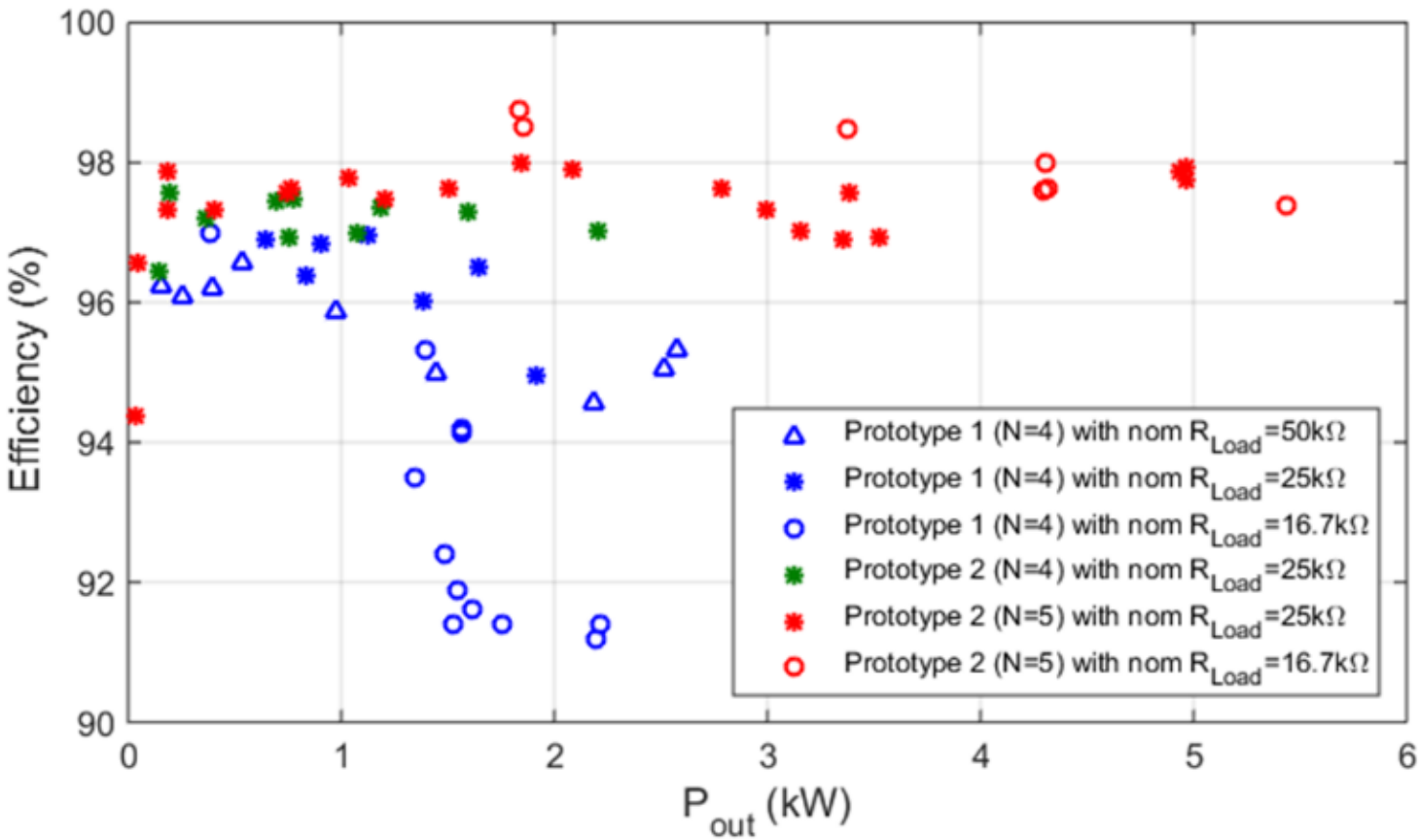
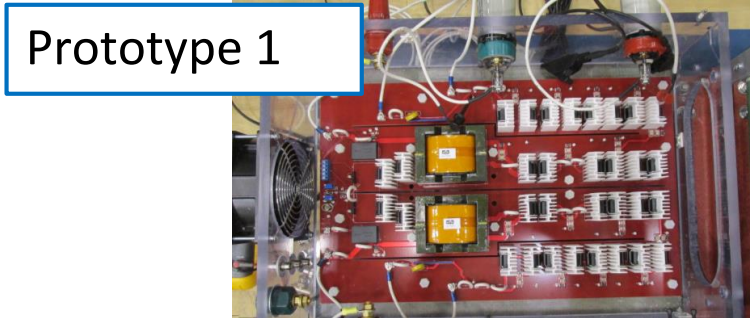
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- Further, each pole of the converter has just one controlled switch
- This work discusses key control and design aspects impacting efficiency and power handling
- Present and Future work considers the use of SiC switches and GaN diodes to improve efficiency
- Novel packaging methods are being pursued for volume reduction

