University of Pittsburgh

Design and Manufacturability of a High Power Density MMC Inverter

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High Power Density MMC- Design and Manufacturability

Overview

- Objective
- Modular Multilevel Converter (MMC) Overview
- Design Concept
- Preliminary Submodule Design
- Power Board Design and Manufacturability
- Conclusion

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Project Overview

- Objective
  - Develop GaN based single phase inverter
  - Minimize volume (100 W/in^3) requirement to enable inclusion in a wide array of applications

- Proposed Solution
  - Modular Multilevel Converter (MMC) using Gallium Nitride (GaN) High Electron Mobility Transistors (HEMTs)

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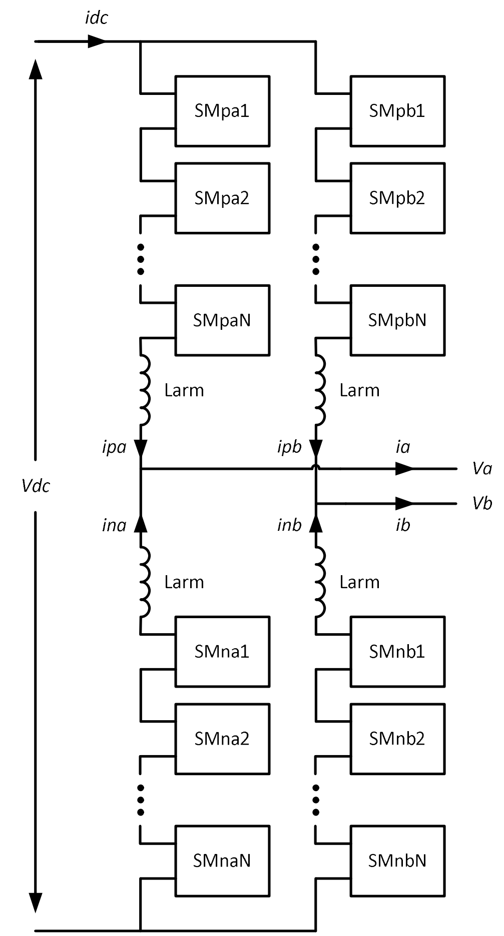
Advantages of MMC Topologies

- The MMC architecture provides a number of benefits resulting from the stacked submodules (SMs):
  - Lower applied device voltage
  - Minimized filtering requirements
  - High resiliency due to modular design

- In MV and HV systems, the MMC structure has been shown to improve on traditional systems:
  - Higher efficiency over wide frequency range
  - Improved voltage control
  - Lower volumetric requirements



Proposed 1ph MMC structure

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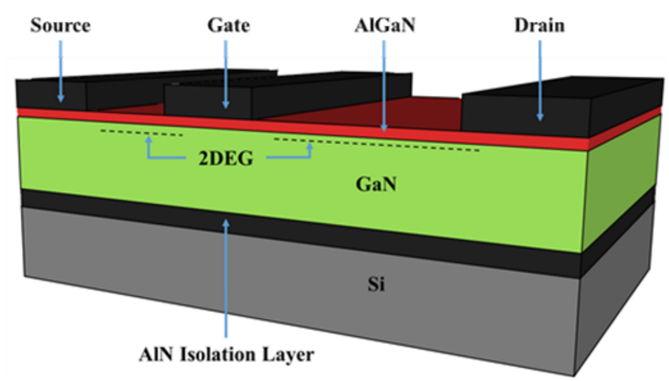
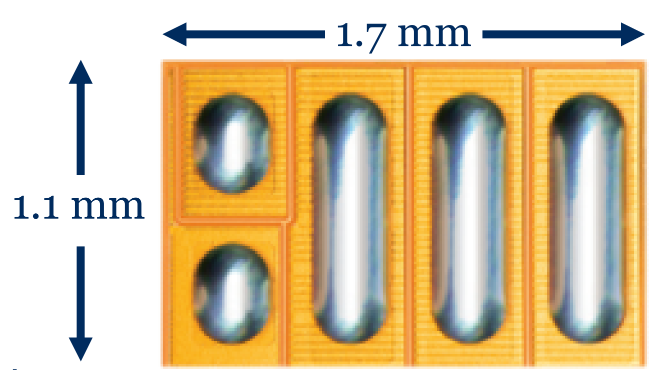
Benefits of GaN Transistors

- Compared to Si MOSFETs and IGBTs, GaN HEMTs, typically exhibit:
  - Lower conduction resistance
  - Lower input and output capacitance
  - Faster turn on and turn off characteristics
  - Smaller footprint
  - Improved performance at high temperatures



GaN HEMT Device Structure

- In this converter, the EPC2014C is used:
  - 40V, 10A device in 1.87 mm² package
  - R_G = 12 mΩ, C_{iss} = 220 pF, C_{oss} = 150 pF



EPC2014C eGaN HEMT

Source: Efficient Power Conversion EPC2014C datasheet

http://epc-co.com/epc/Portals/0/epc/documents/datasheets/EPC2014C_datasheet.pdf

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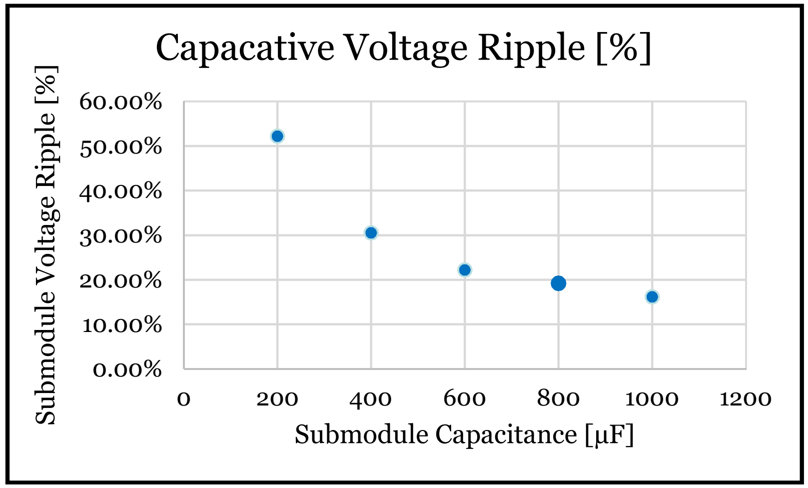
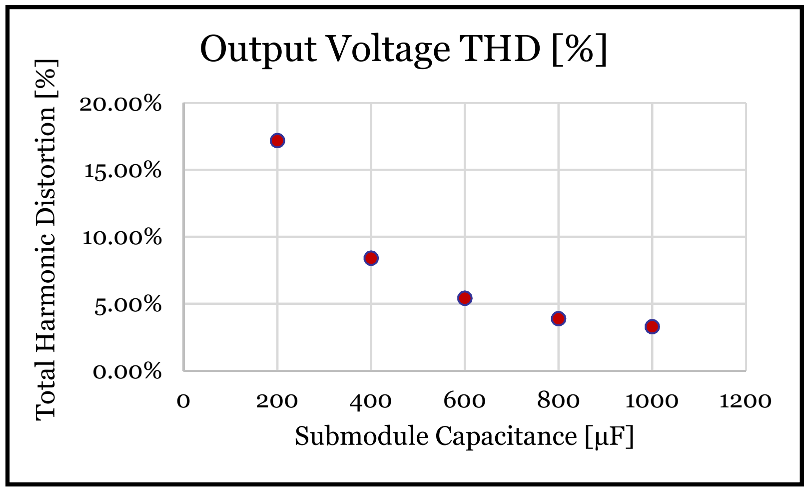
Submodule Design – Capacitor Optimization

- Capacitors selection in MMC systems is dependent on:

$$C_{sm,min} = \frac{P}{2NmV_c\Delta V_c\omega cos\phi}\left(1 - \frac{mcos\phi^2}{2}\right)$$

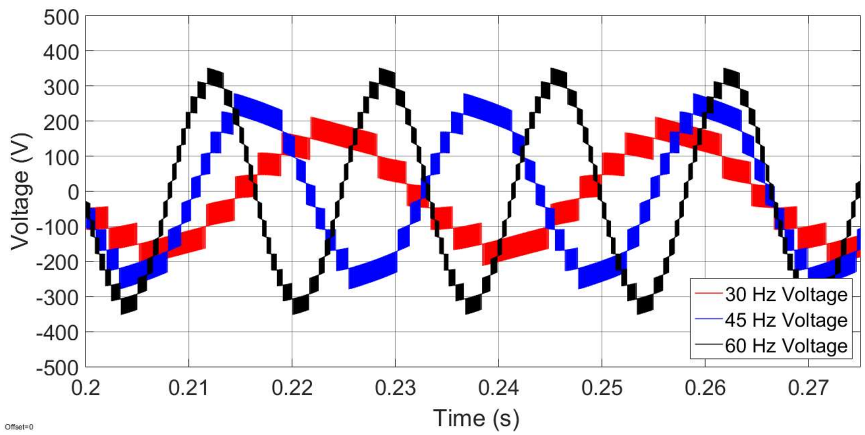
- Important Factors:
  - Increasing SM capacitance reduces submodule ripple
  - Increasing SM capacitance reduced total harmonic distortion on AC output
  - Increasing AC frequency reduces capacitance requirements, but increasing switching frequency does not



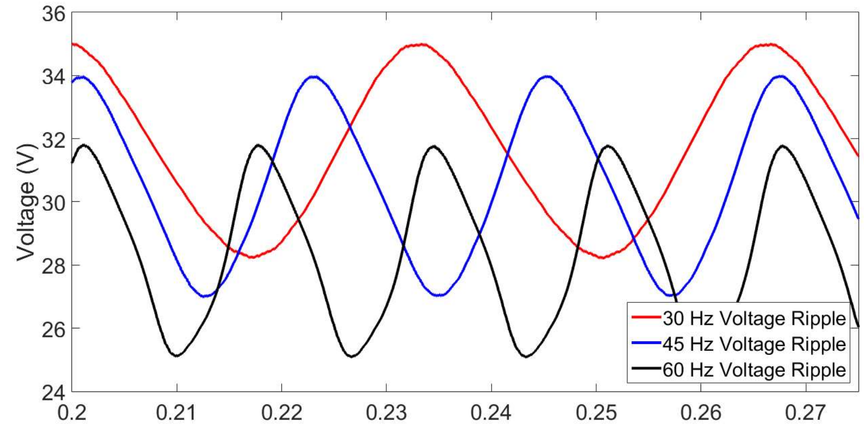


High Density MMC-based 1θ Variable Speed Drive

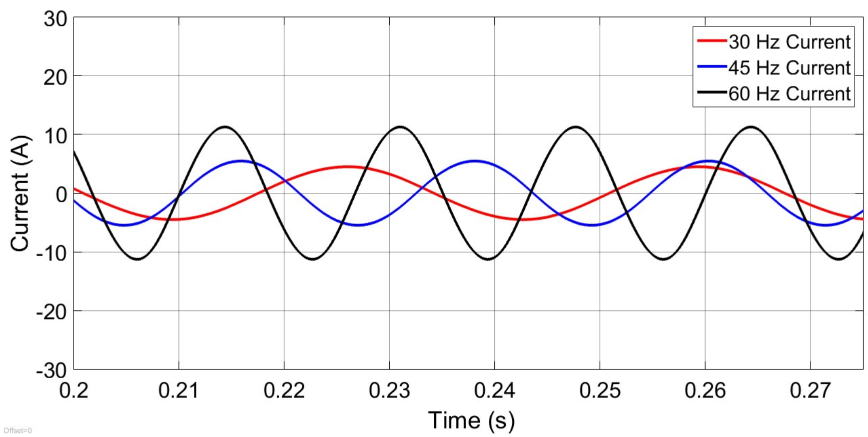
Simulation Results – Waveforms



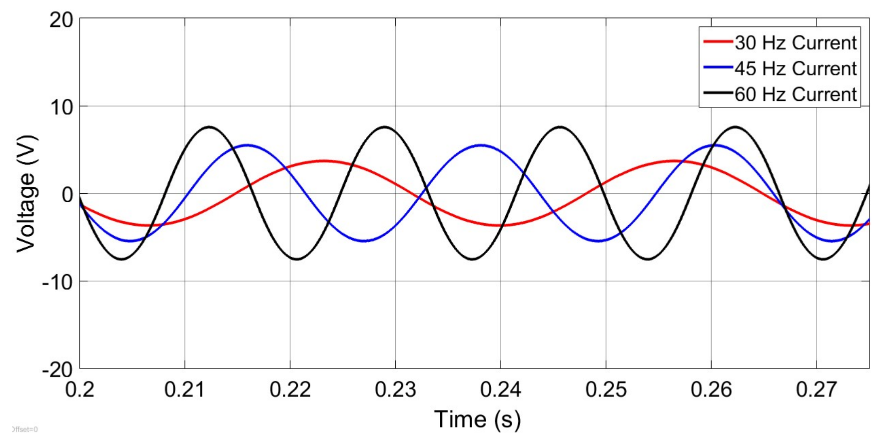
Output voltage from MMC



Capacitor voltage ripple



Output current from MMC



Motor load current

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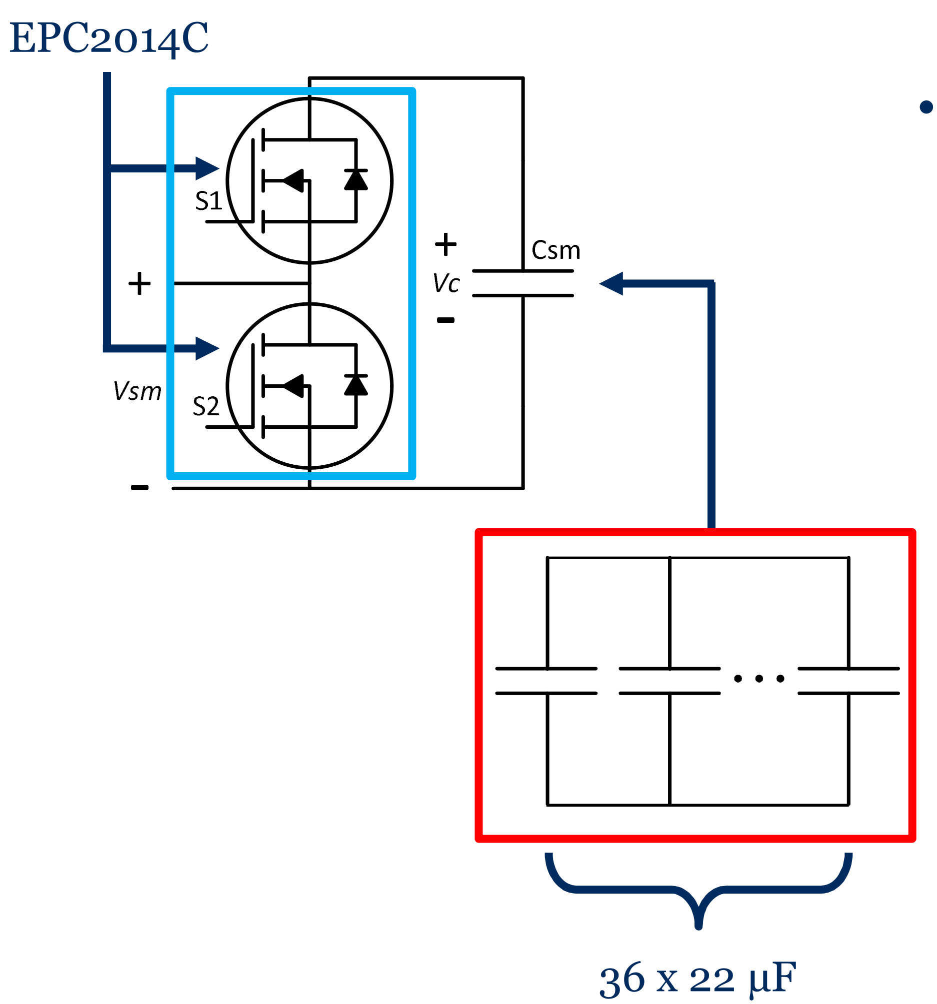
Submodule Design – Component Layout



- In the MMC, submodules (SMs) half-bridges are comprised of:
  - Two GaN HEMTs
  - Parallel array of 22 µF ceramic capacitors to form large bulk capacitance
    - 36 x 22 µF = 792 µF
  - Auxiliary components: eGaN driver, buffer capacitors, digital isolation

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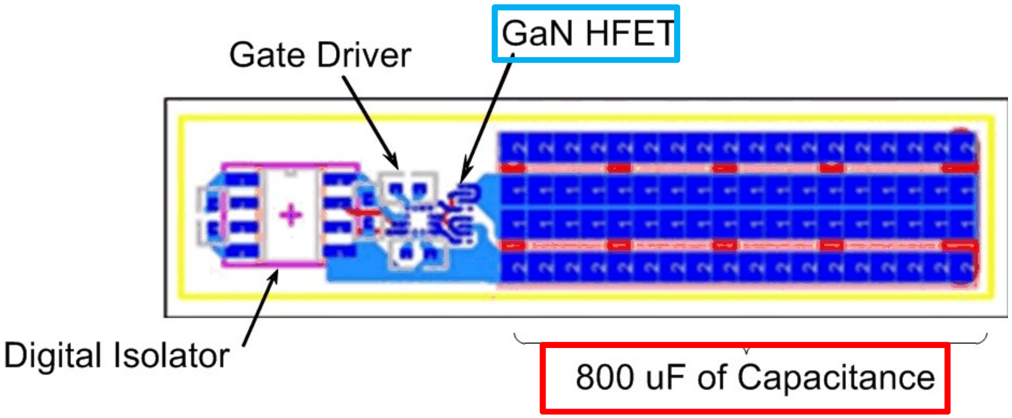
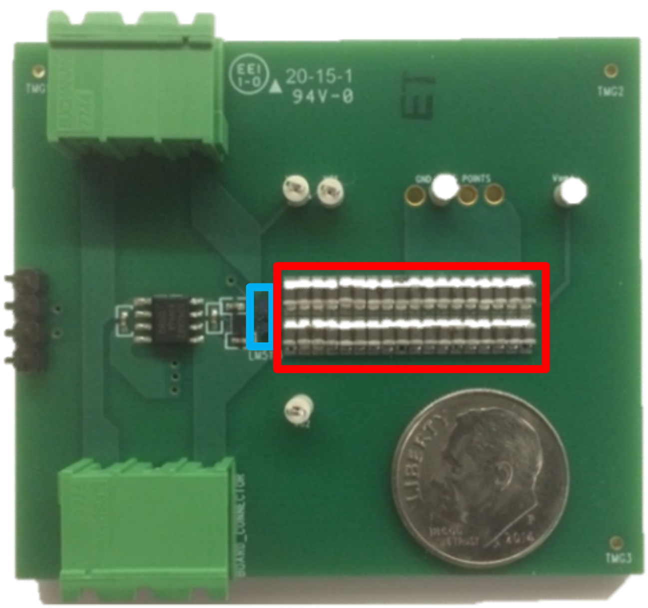
Submodule Design – Hardware Prototype



Single-SM Prototype Board



Turn-on (off) characteristics of upper (lower) HEMT

Turn-off (on) characteristics of lower (upper) HEMT

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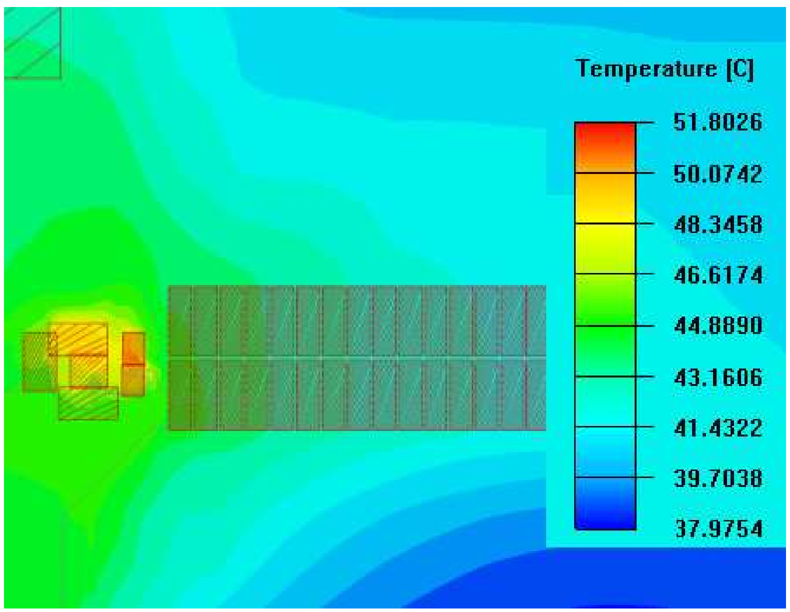
Submodule Design – Thermal Performance

- Thermal modelling of MMC SM:
  - ANSYS Icepak model shows minimal thermal rise on capacitor array
  - Results confirmed using thermal imaging of prototype board under full load



ANSYS Icepak Simulation

Thermal image of prototype
Icepak PCB Design

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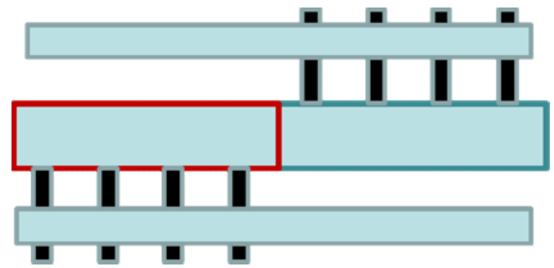
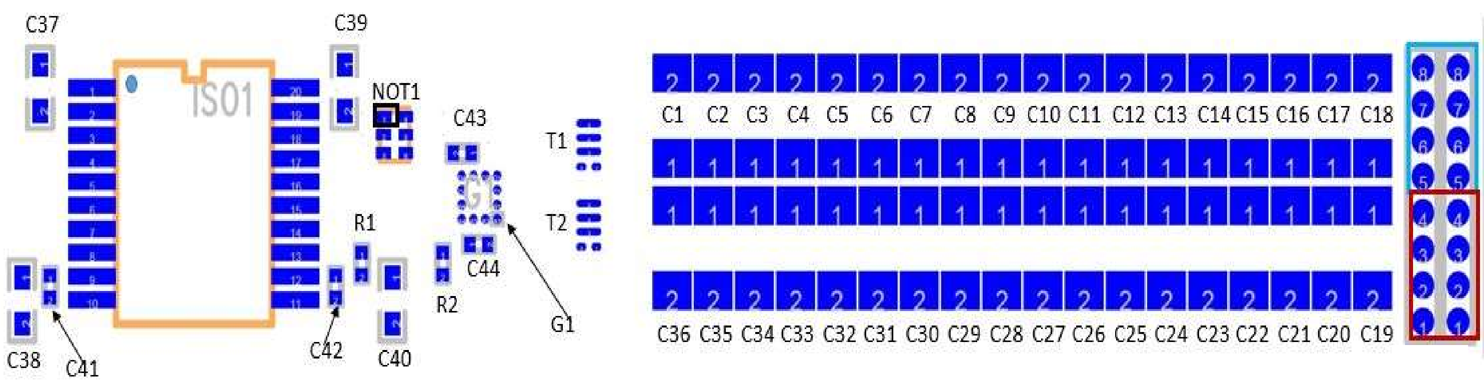
Submodule Design – Capacitor Optimization

- Challenge: How can more capacitance be realized in the same volume?
- Since there is no need to cool the capacitor array, mezzanine capacitor layers are added to increase capacitance from 0.792 μF to 1.54 mF



Profile of mezzanine capacitor boards



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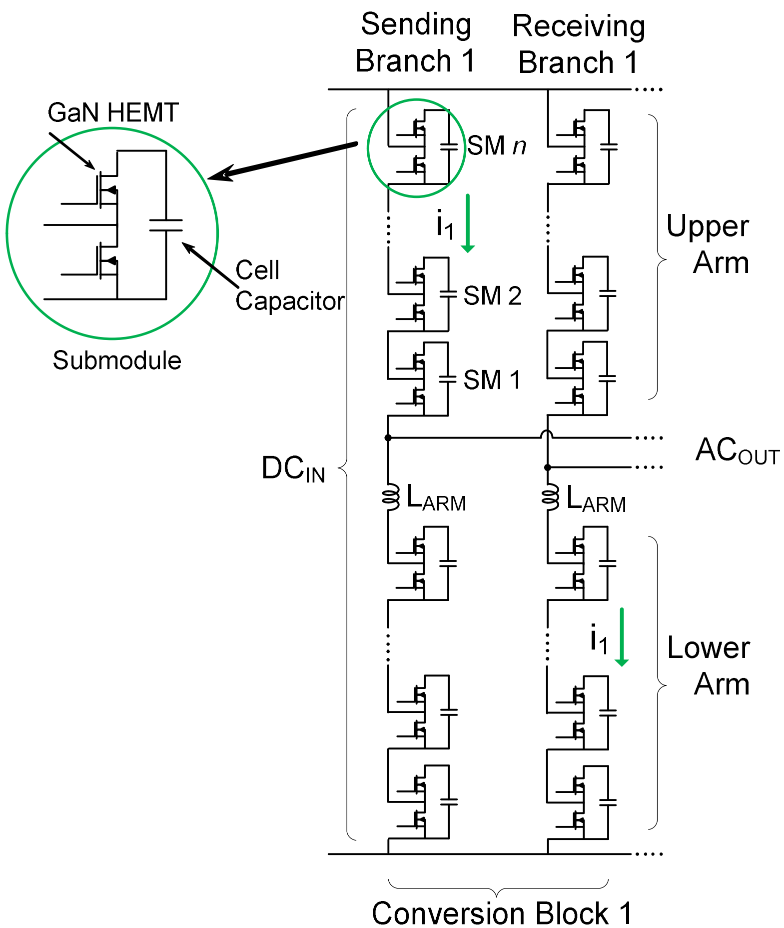
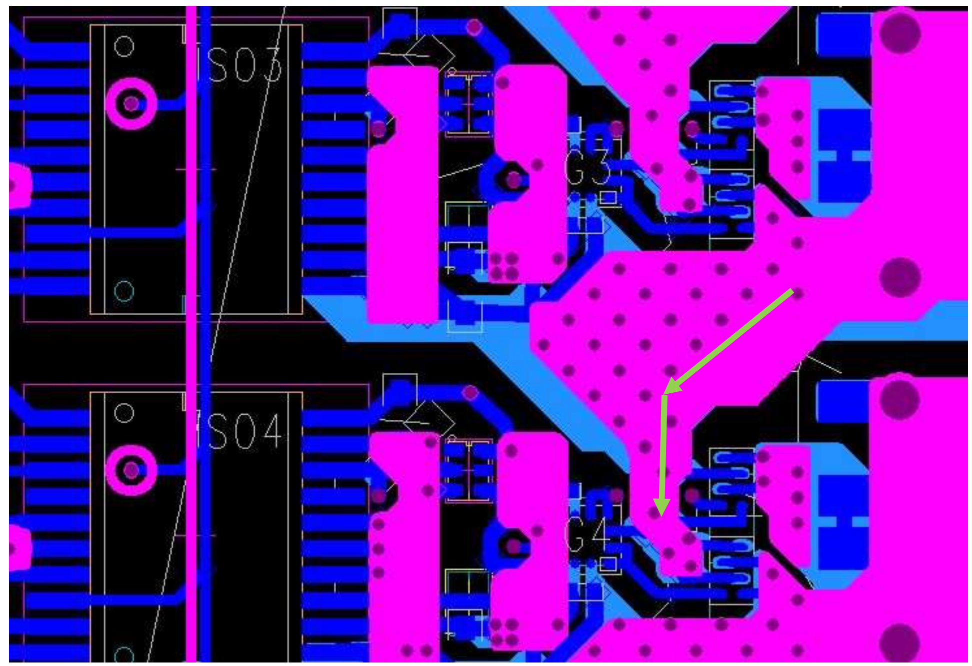
Power Board Design – Manufacturing Challenges





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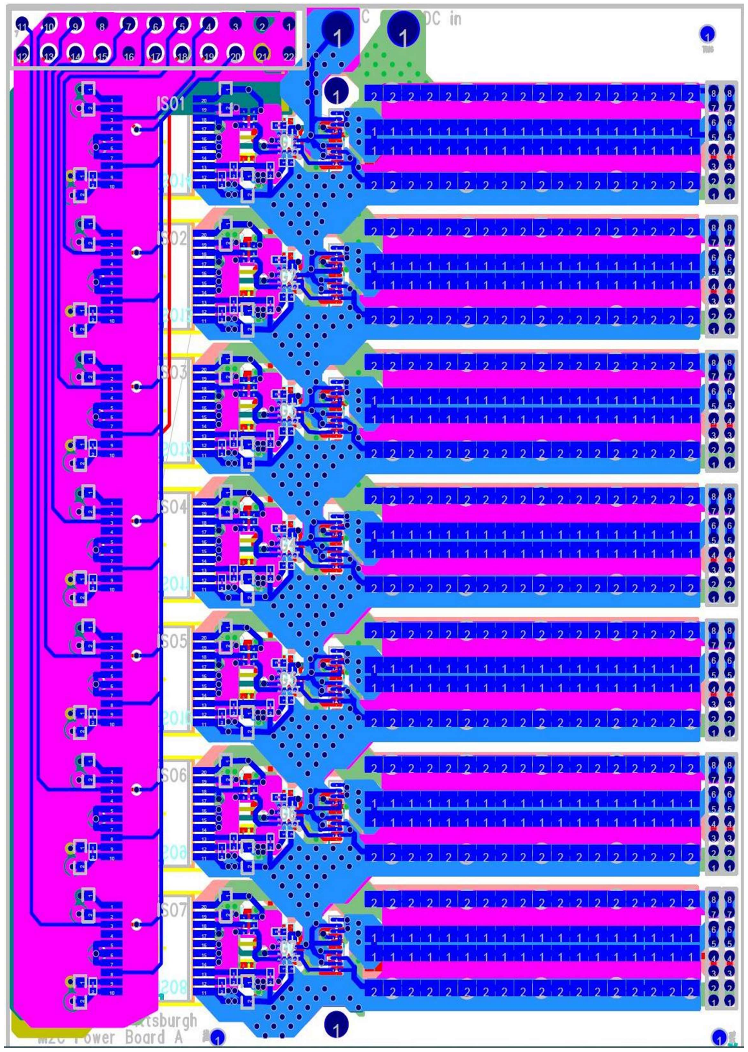
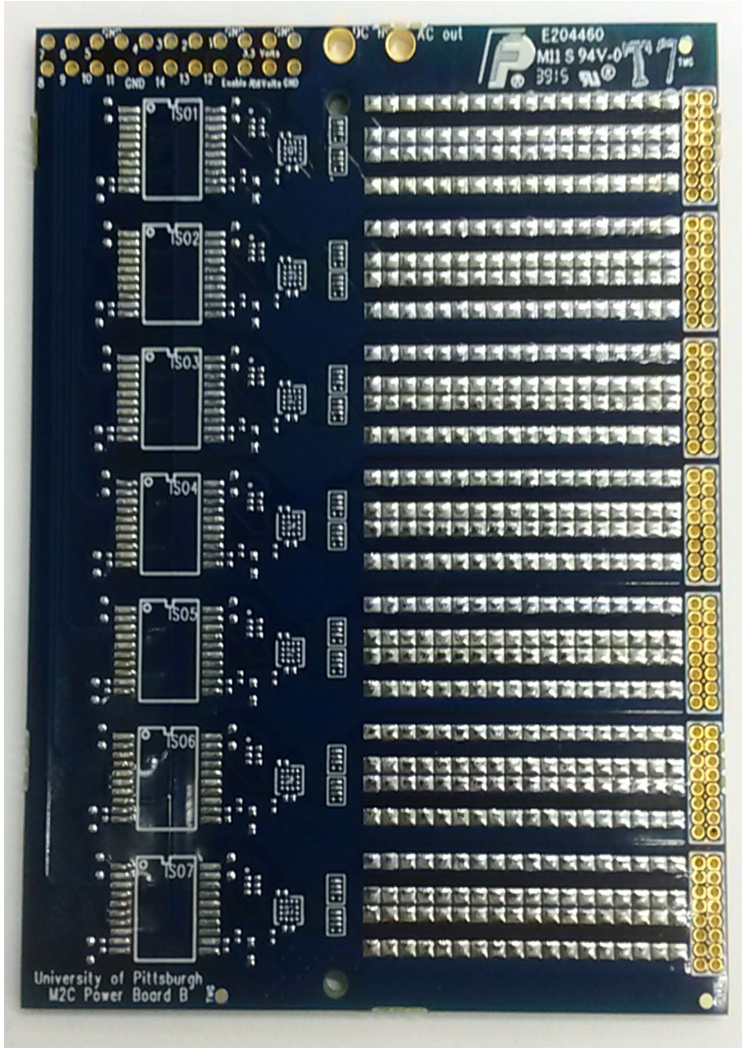
Power Board Design – Manufacturing Challenges





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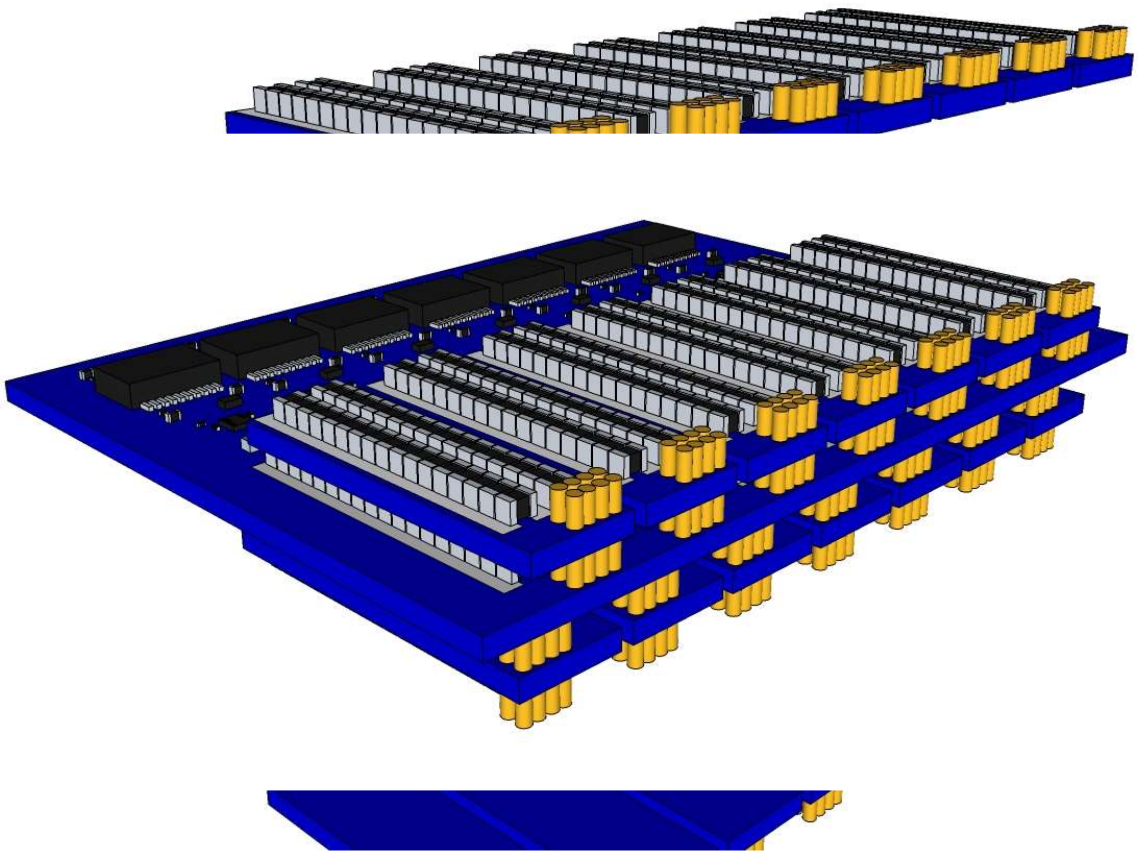
Prototype Realization



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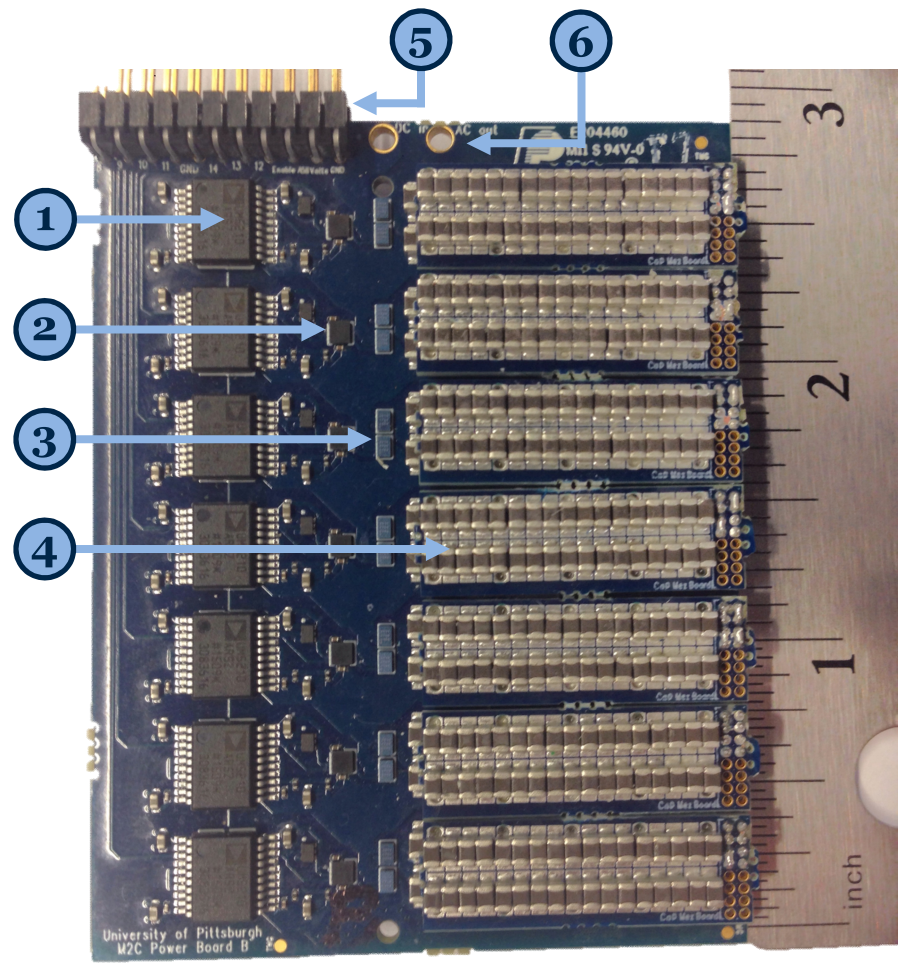
Prototype Realization

Prototypes of the converter arms have been developed, assembled by TMG Electronics.

1. Digital isolator – combined signal and power
2. Half-bridge driver for GaN HEMTs
3. EPC2014C GaN HEMTs
4. Capacitor Bank: combination of main board and mezzanine layer
5. Communication Ports
6. Power Ports



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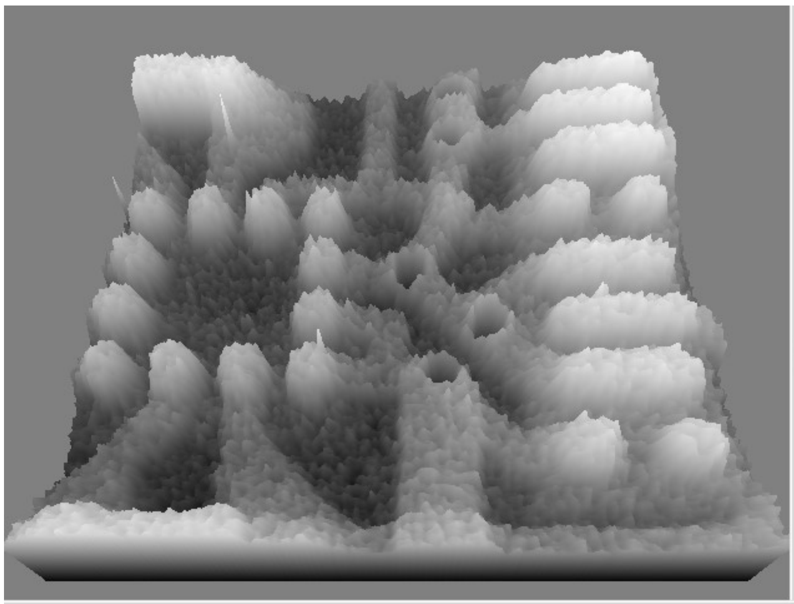
Manufacture Challenges



Challenges included:

-Tolerance of Capacitors

-Tolerance between Transistors

-Copper plating for current handling

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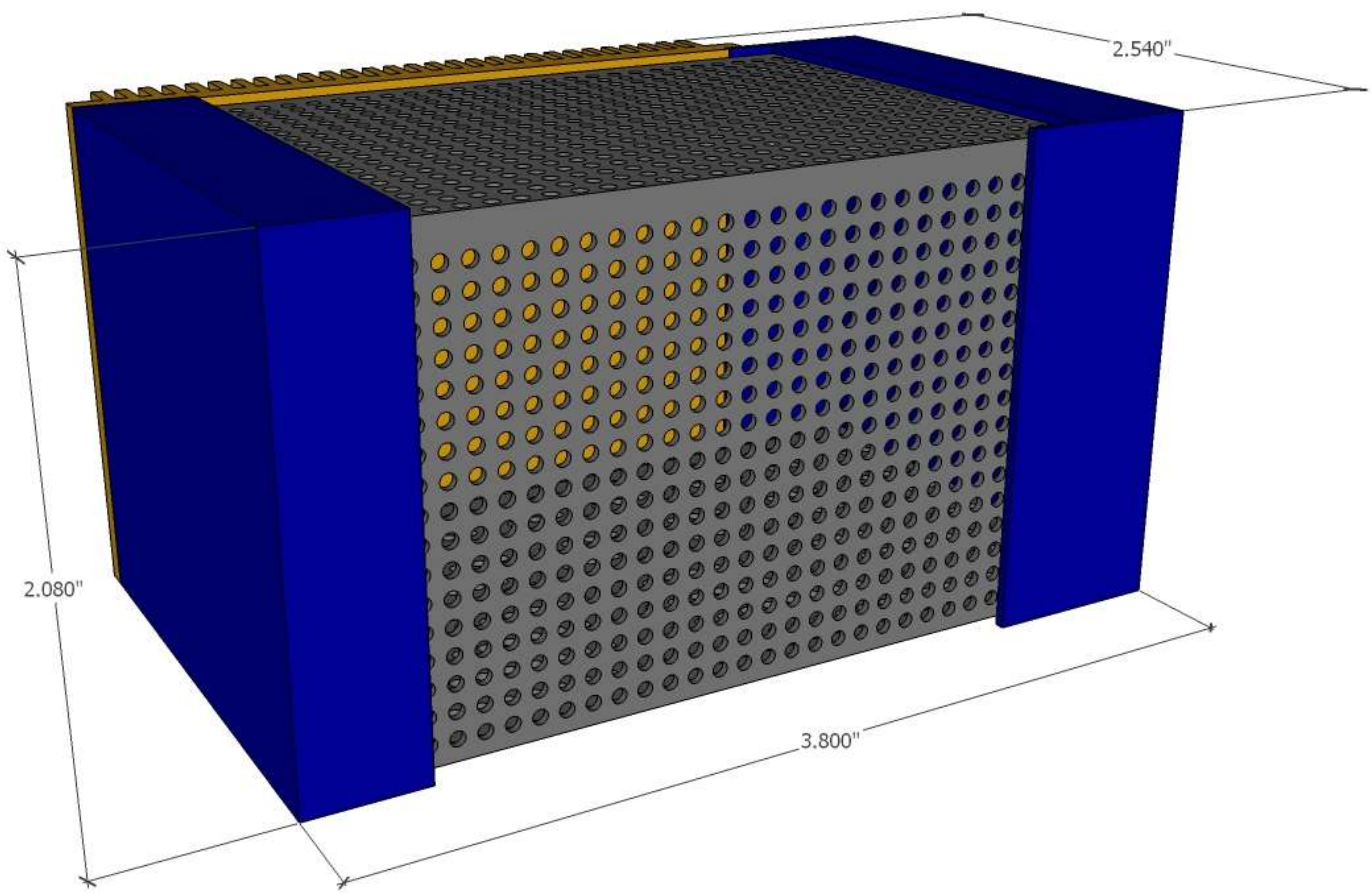
Prototype Realization



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Conclusions and Future Work

- Summary
  - MMC-based topologies present a high-density, high-efficiency solution for multiple applications
  - Anticipated total volume: 20.07 in^3
  - Anticipated power density: 98.65 W/in^3
  - Proposed applications: Low voltage inverters for PV integration, battery charge control, variable speed drives, and other power management and distribution applications

- Planned future work
  - Testing of full MMC under a variety of loading conditions
  - Implementation of adaptive control to reduce impacts of 2^{nd} harmonic circulation
  - Development of DC-DC architectures based on modular GaN topologies

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Thank you for your attention!

Questions?

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