U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

A Segmented Drive Inverter Topology with a Small DC Bus Capacitor

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Project ID: APE004

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Overview

Timeline

- Start – FY09
- Finish – FY12
- 85% complete

Budget

- Total project funding
  - DOE share – 100%
- Funding for FY11
  - $715K
- Funding for FY12
  - $550K

Barriers

- Capacitor cost, volume, and weight
- Capacitor high temperature capabilities

Inverter targets

- Cost: $5/kW (2015 target)
- Power density: 13.4 kW/l (2020 target)
- Specific power: 14.1 kW/kg (2020 target)

Partners

- **ORNL team members:** Lixin Tang, Cliff White, Larry Seiber , Zhenxian Liang, Mike Jenkins
- Capacitor vendors
- IGBT device and module manufacturers

Project Objective

- **Design, develop, build, and test a 55 kW integrated segmented traction drive system that can reduce the dc bus ripple current and thus the capacitance by at least 60%**
- **The goal is to reach the 2015 cost target and the 2020 weight and volume targets**
- **Eliminate the capacitor related hurdle for high temperature operations**

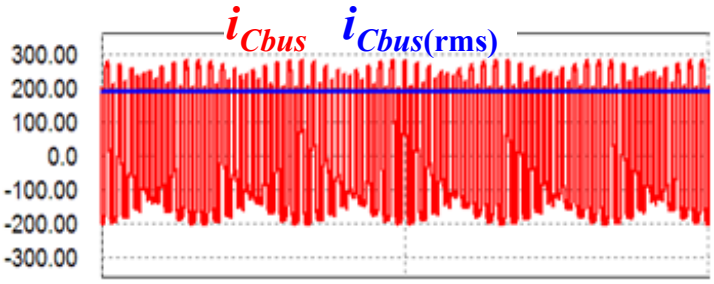
- **FY11 – FY12:** Design, build, and test 55 kW segmented inverter prototypes for integration with a motor

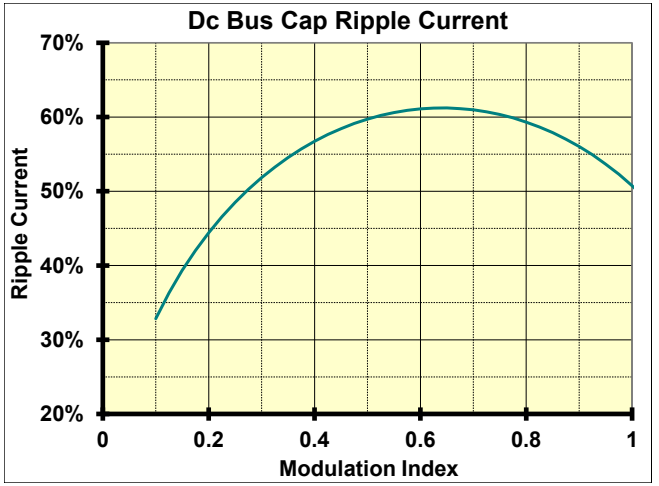
Milestones

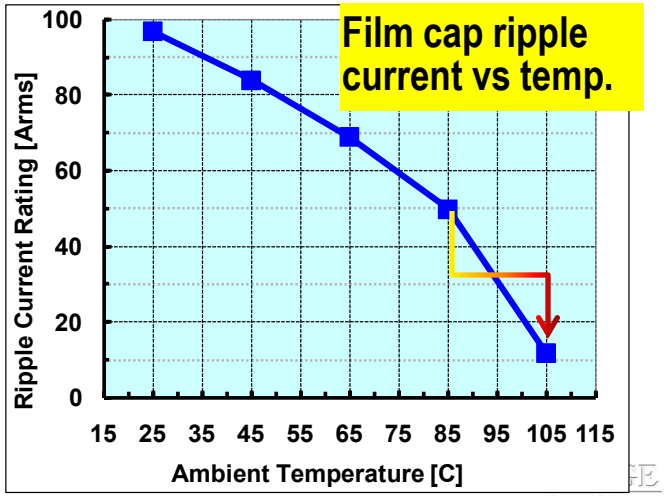
Month/Year	Milestone or Go/No-Go Decision
Sept-2011	Milestone: Complete assembly of 1st prototype of 55 kW segmented inverter for packaging with a motor.
Sept-2011	Go/No-Go decision: Determine via simulation whether the integrated inverter/motor packaging design has the potential to meet the cost, volume and weight targets
Mar-2012	Milestone: Complete tests of 1st prototype of 55 kW segmented inverter packaged for integration with a motor.

Need to reduce DC Bus Ripple Current

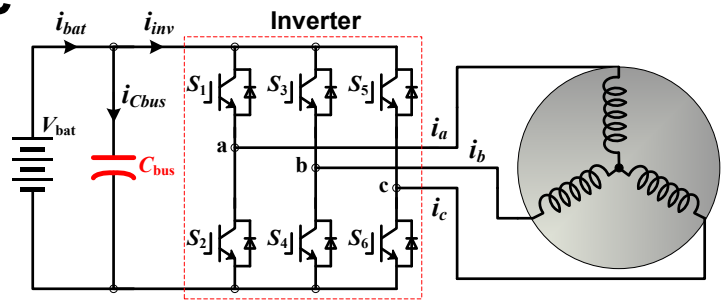
- Because of the large ripple currents in the VSI, the dc bus capacitor is a significant barrier to meeting the inverter cost, volume and weight targets. Currently, it contributes
  - Cost and weight, up to 20% of an inverter
  - Volume, up to 30% of an inverter
- Increasing switching frequency has little impact on the magnitude of the ripple current
- Reducing the capacitance may increase battery ripple current
- Film capacitor ripple current and voltage capability decreases rapidly with temperature





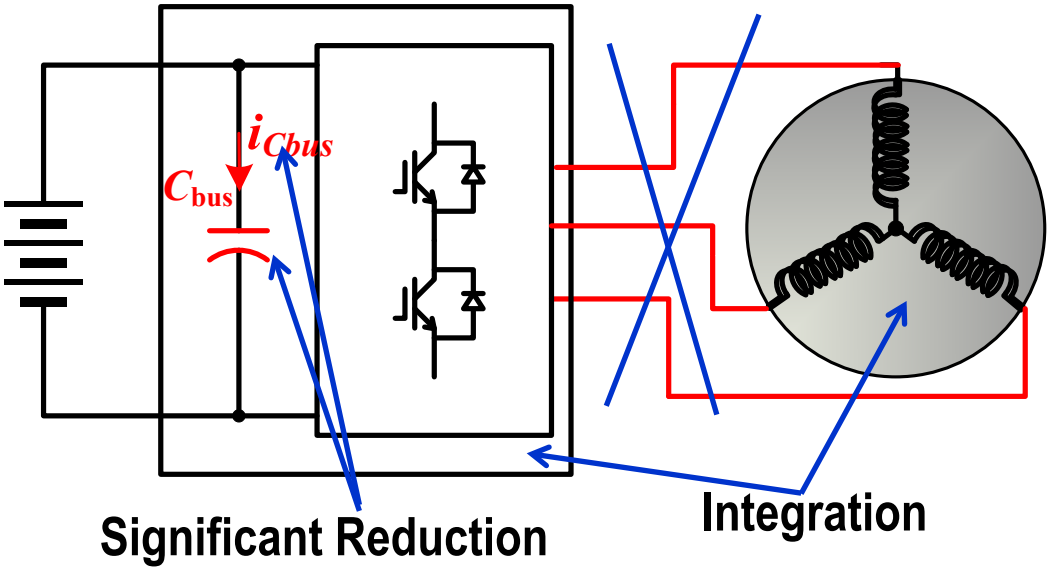


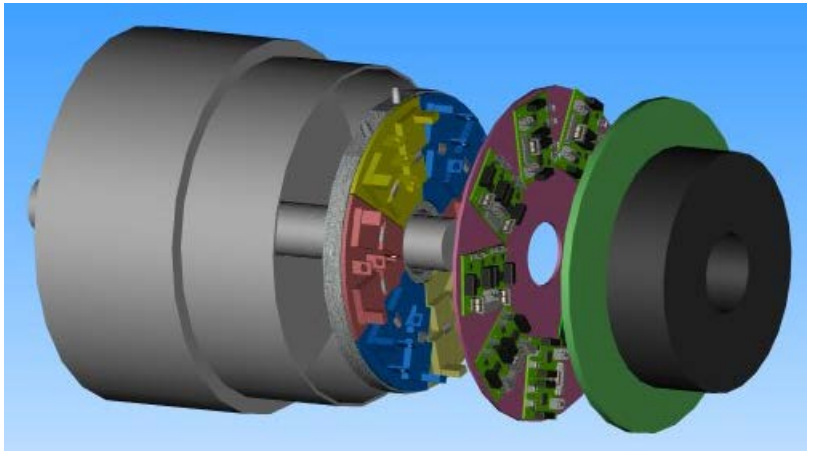
Voltage source inverter (VSI)



Description of Technology/Approach

- Approach to Capacitor Ripple Current and Drive System Cost Reduction
  - Use a segmented drive system topology that does not need additional switches or passive components but can significantly reduce the dc link ripple current and the amount of capacitance
  - Integrate the segmented inverter and motor into a single package drive system to eliminate cable connections





Conceptual embodiment of an integrated segmented inverter and motor

Impact on Inverter Targets

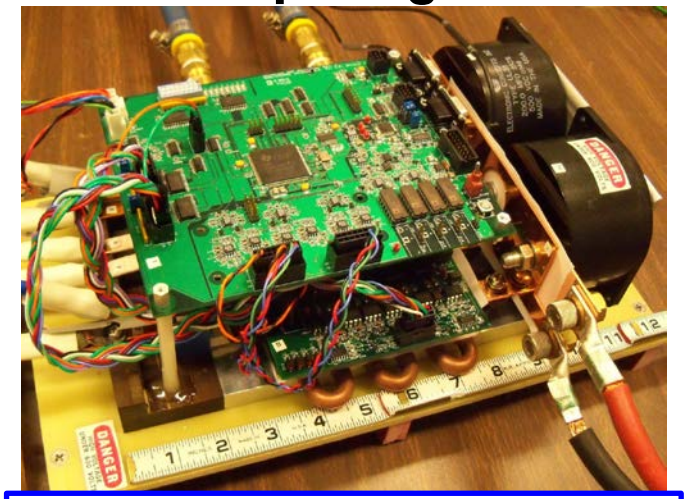
- **Dropping the segmented topology into the state-of-the-art inverter package results in exceeding the 2015 weight target of 12 kW/kg and the 2020 volume target of 13.4 kW/l**
- **Optimization of inverter package will further reduce the weight and volume, and bring the cost within the 2015 target**

	State-of-the-Art Inverter[a]			Segmented Inverter[b]		
	Weight (kg)	Volume (L)	Cost ($)	Weight (kg)	Volume (L)	Cost ($)
Bus Cap	3.57	2.6	182	1.43	1.04	73
Others	3.99	3.36	728	4.0	3.37	735
Subtotal	7.56	5.96	910	5.43	4.41	808
Metrics	**kW/kg**	**kW/L**	**$/kW**	**kW/kg**	**kW/L**	**$/kW**
	9.3	11.7	13	**12.9**	**15.9**	**11.5**
DOE targets	**12**	**12**	5	14.1	**13.4**	3.3
	2015			2020		

*Assumptions: (a) capacitor cost is 20%;
(b) a reduction of 60% in capacitor requirement.

Brief Summary of Accomplishments

- Selected the best PWM scheme by simulation study
- Designed, built, and tested a 55 kW proof-of-concept segmented inverter prototype
  - with a 60 % reduction of dc bus capacitor
  - with a resistive load bank and an induction motor
  - with both carrier and space vector based PWM schemes
- Test results show significant reductions of
  - 55~75% in capacitor ripple current
  - 70~90% in battery ripple current
  - 60~80% in motor ripple current

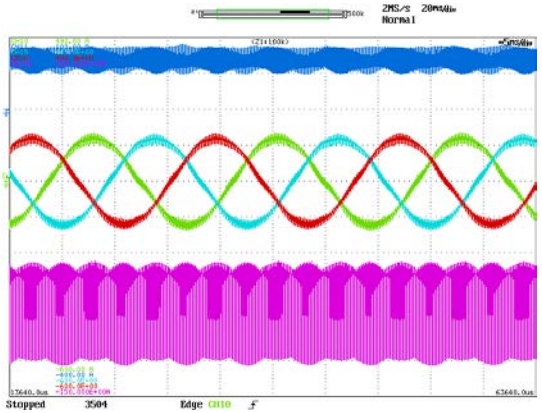


A POC prototype of 55 kW segmented inverter
Capacitance: 1000μF → 400μF
Cap. volume: 1.39L → 0.56L

- Completed design and fabrication of 1st prototype of 55 kW segmented inverter packaged for integrating with a motor
- Initial test results indicate thermal and packaging design goals are met.

Technical Accomplishments - FY11

Baseline inverter



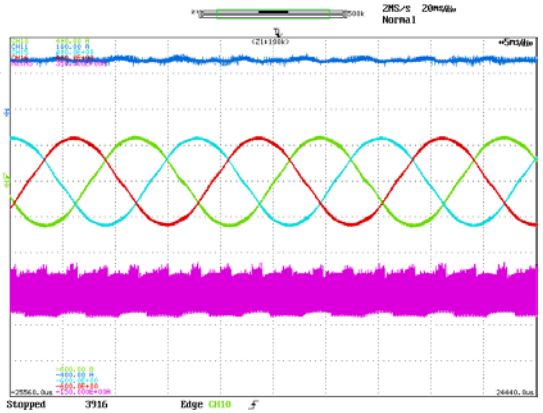
I_{bat}:50A/div

i_a, i_b, i_c: 100A/div

i_{Cbus}: 50A/div

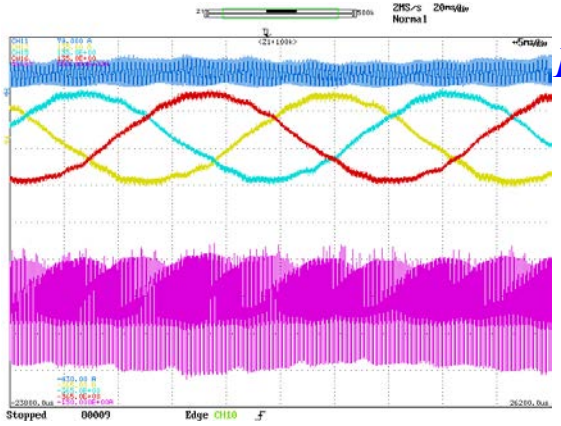
$i_{Cbus(rms)}$:35.7Arms
I_{bat}, p-p ripple:45A

Segmented inverter



$i_{Cbus(rms)}$:13.7Arms
I_{bat}, p-p ripple: 10A

- RL load
  - 78 % reduction in cap. ripple current
  - 62 % reduction in battery ripple current

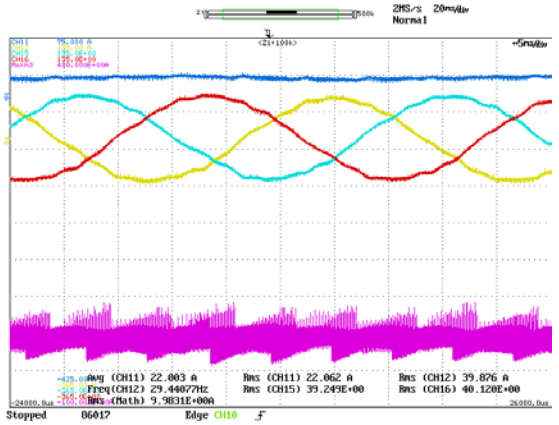


I_{bat}:50A/div

i_a, i_b, i_c: 50A/div

i_{Cbus}: 50A/div

$i_{Cbus(rms)}$: 37.1 Arms
I_{bat}, p-p ripple: 45A

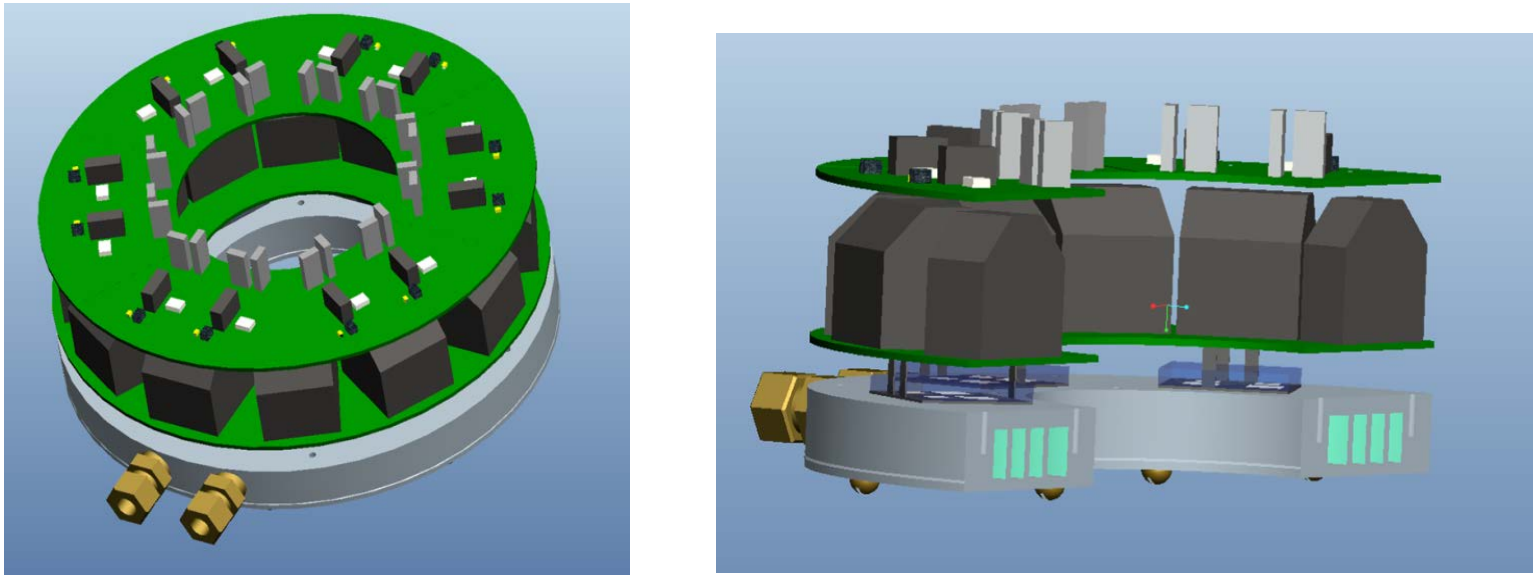


$i_{Cbus(rms)}$:10.0Arms
I_{bat}, p-p ripple: 5A

- Induction motor
  - 73 % reduction in cap. ripple current
  - 89 % reduction in battery ripple current

Technical Accomplishments - FY11

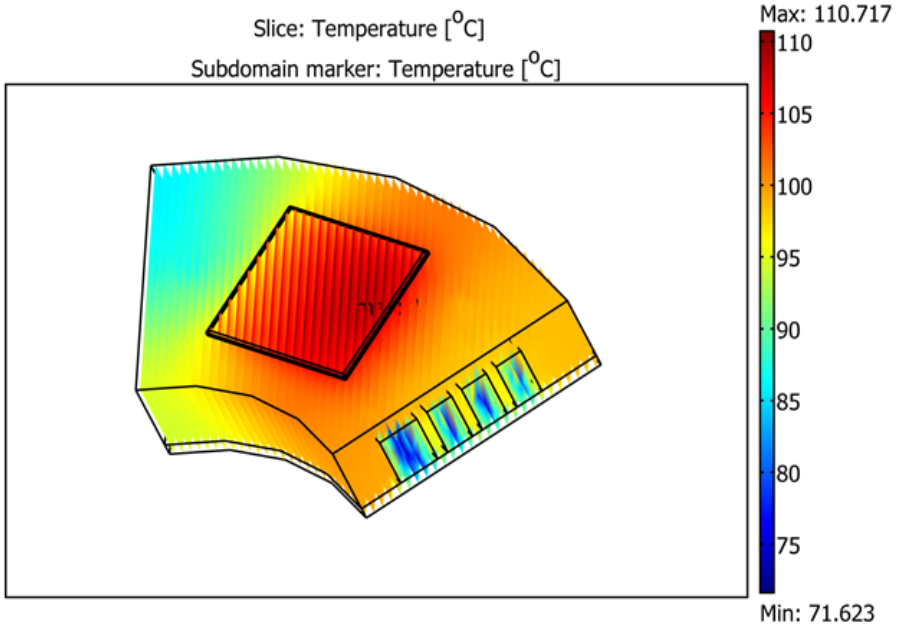
- A segmented inverter design for integration with a motor (1st design)
  - A toroid heat exchange (outer diameter: 9”; inner diameter: 4”)
  - ORNL packaged IGBT modules
  - A heavy copper PCB for interconnecting the power modules and the bus capacitors

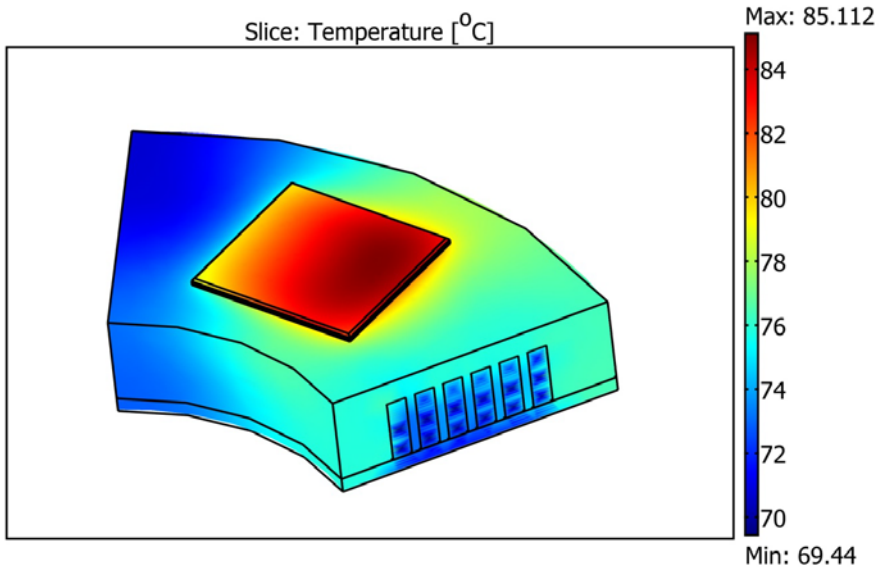


3-D drawings of a segmented inverter design

Technical Accomplishments - FY11

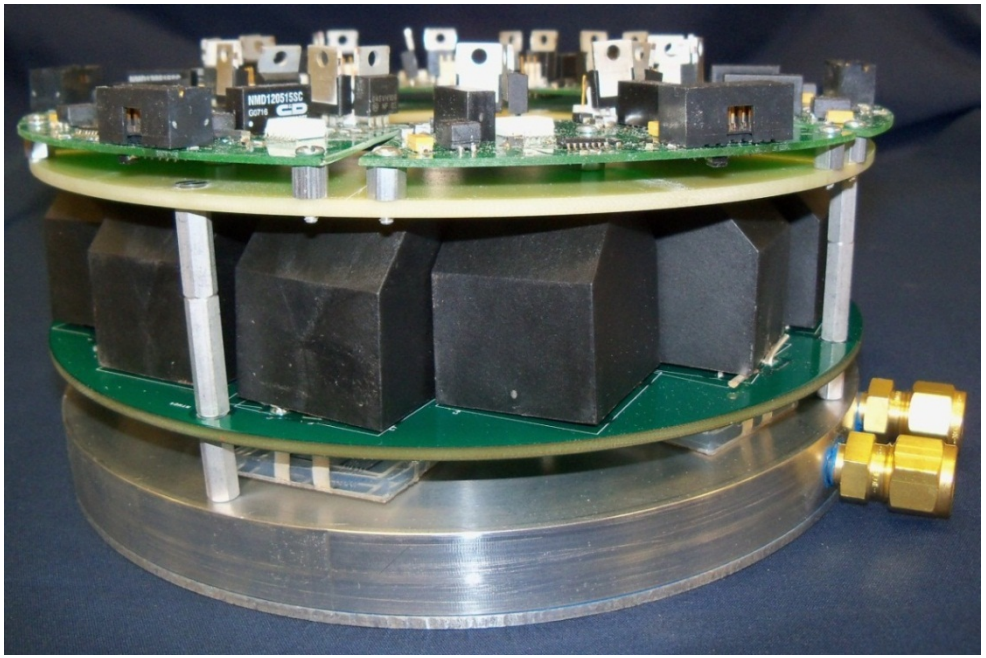
- Finite element analysis results indicated satisfactory thermal performance of the toroid heat exchanger design
  - Max junction temperature of 111°C for the 4 channel design and 85 for the 6 channel design at an inlet coolant (water ethylene glycol) temperature of 70°C
- FEA results also indicate the 6 channel design can keep junction temperatures below 125°C with 105°C coolant temperature





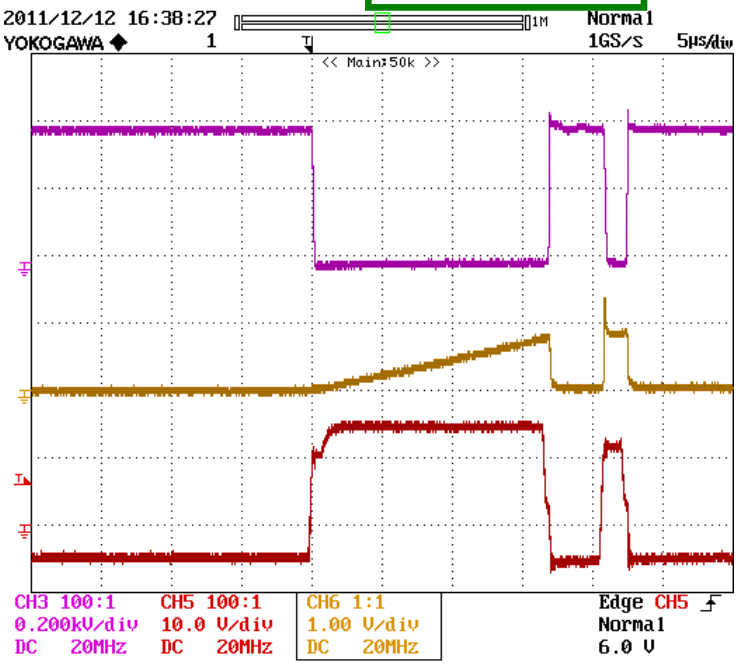
Technical Accomplishments - FY12

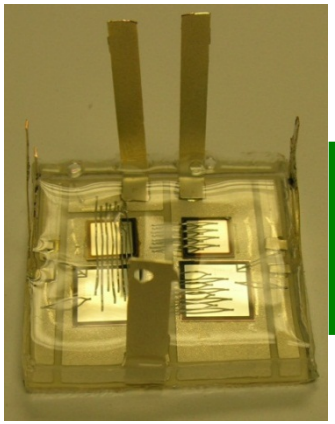
- 1st prototype of 55 kW segmented inverter
  - 17.1 kW/l, 15.6 kW/kg
    (2020 targets: 13.4 kW/l, 14.1 kW/kg)



- Double pulse test results confirmed thermal design goals

Pulse test waveforms

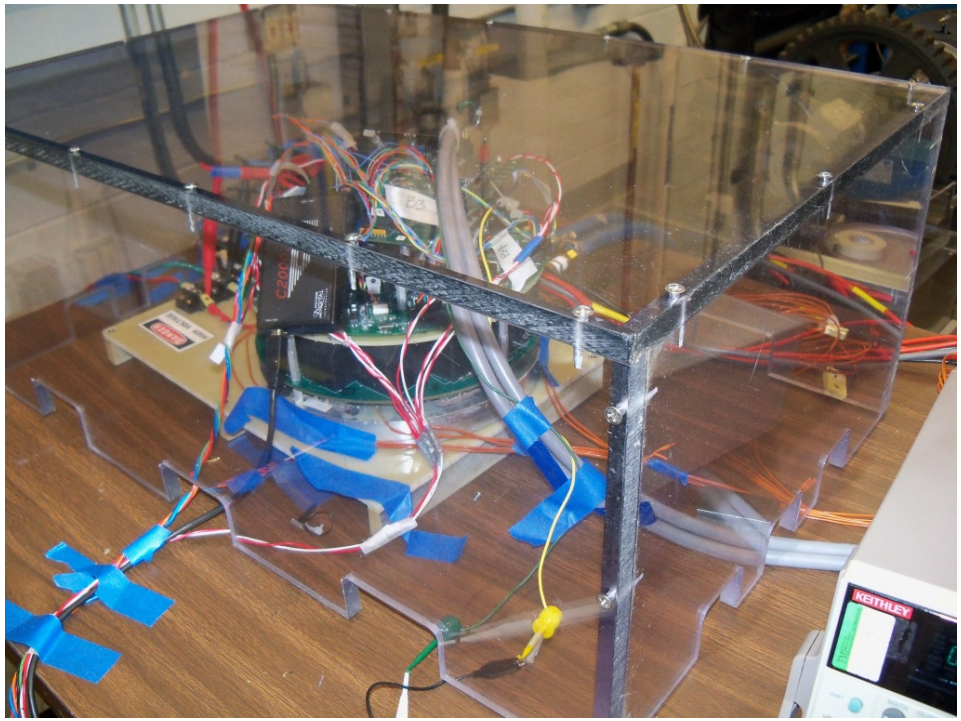




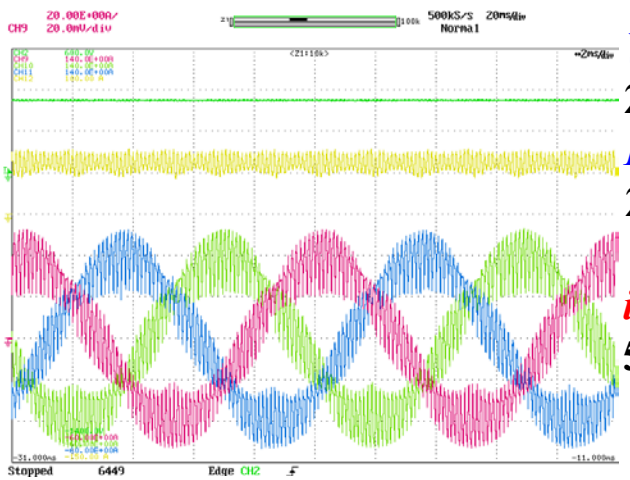
ORNL packaged IGBT module, 1200V/75A

Technical Accomplishments - FY12

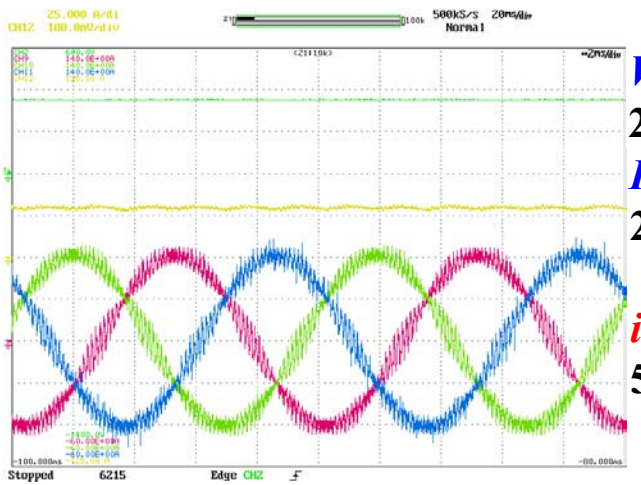
- Tests of the 1st prototype are in progress
- Initial test results with a RL load show satisfactory functionality



Test setup



Non-segmented inverter



Segmented inverter

Collaborations

- Powerex, Infineon, and ABB
  - IGBT modules
  - IGBT and diode dies
- Capacitor vendors (Electronic Concepts, AVX, SBE)
  - Custom capacitors
- Leveraging ORNL's packaging research efforts and ORNL's expertise on materials science and technology
  - Packaging material
  - Power module packaging

Future Work

- Reminder of FY12
  - Complete tests and characterization of the 1st prototype of 55 kW segmented inverter packaged for integrating with a motor
  - Incorporating the test results, refine the design, build and test a second prototype

Summary

- The segmented inverter with a reduction of bus capacitance by 60 % and an optimal package exceeds the 2020 weight and volume targets.
- Test results on a 55 kW prototype demonstrated significant reductions of
  - 55~75% in capacitor ripple current
  - 70~90% in battery ripple current
  - 60~80% in motor ripple current
- Good progress on a prototype design for integration with a motor

- Other Positive Impacts
  - Reduce battery losses and improve battery operating conditions due to substantially reduced battery ripple current
  - Significantly reduce the motor torque ripples (up to 50%), and reduce switching losses by 50%