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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May 10, 2011

Project ID: APE004

2011 U.S. DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting

Overview

Timeline

- Start – FY09
- Finish – FY12
- 65% complete

Budget

- Total project funding
  - DOE share – 100%
- Funding received for FY10
  - $735K
- Funding for FY11
  - $715K

Barriers

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

Inverter targets

- Power density: 13.4 kW/l (2020 target)
- Specific power: 12 kW/kg (2015 target)
- Cost: $5/kW (2015 target)

Partners

- ORNL team members: Lixin Tang, Cliff White, Larry Seiber , Zhenxian Liang, Mike Jenkins
- Powerex, UQM

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 targets of $5/kW and 12 kW/kg and the 2020 volume target of 13.4 kW/l by significantly reducing the bus capacitance
- Eliminate the capacitor related hurdle for high temperature operations

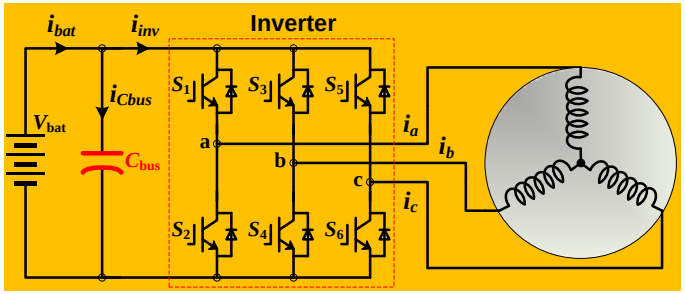
- FY11 Objective: Design and build a 55 kW segmented inverter prototype for packaging with an IPM motor

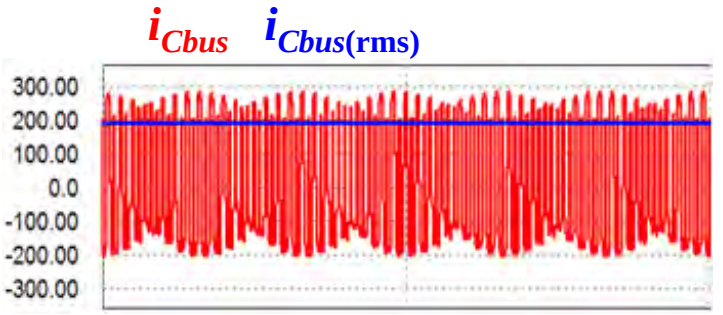
Milestones

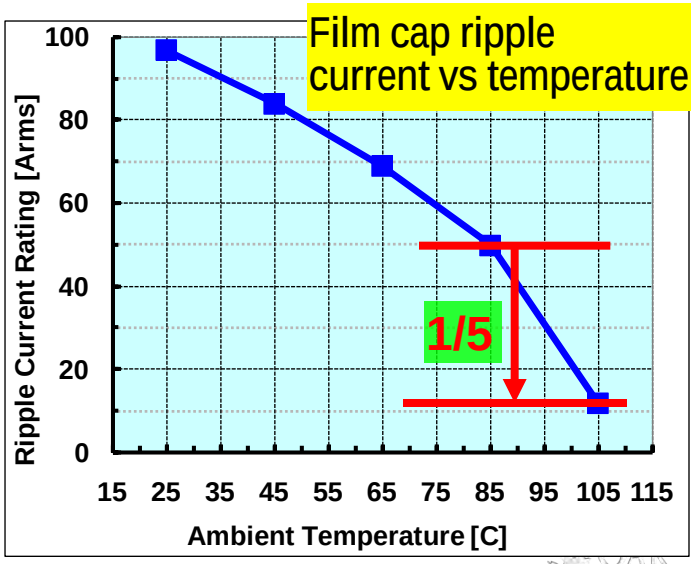
Month/Year	Milestone or Go/No-Go Decision
Sept-2010	Milestone: Experimental demonstration of a 55 kW segmented inverter prototype with a dc bus capacitor of 400 μF (reduced from 1000 μF for a baseline inverter)
Sept-2010	Go/No-Go decision: Determine if developed inverter prototype has potential to meet the cost, volume and weight targets
Sept-2011	Milestone: Complete assembly of a 55 kW segmented inverter prototype for packaging with an IPM motor.
Sept-2011	Go/No-Go decision: Determine whether the integrated inverter/motor packaging design has the potential to meet the cost, volume and weight targets

The Problem and Approach (1)

- The VSI requires a large bus capacitor to absorb large ripple currents. Currently, the bus capacitor 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
- *Approach/needs*: significantly reduce cap ripple currents

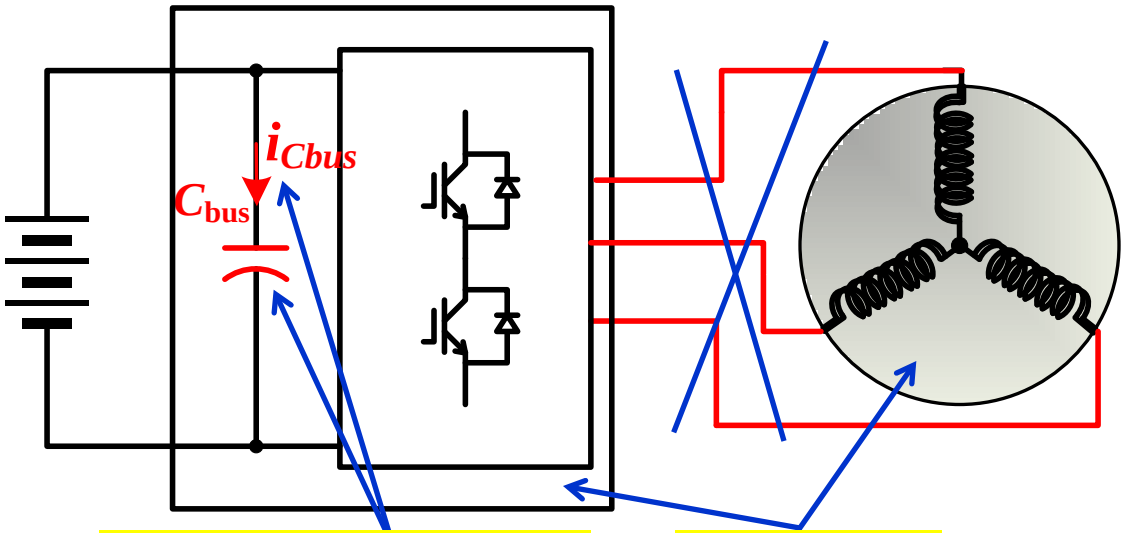






The Problem and Approach (2)

- 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

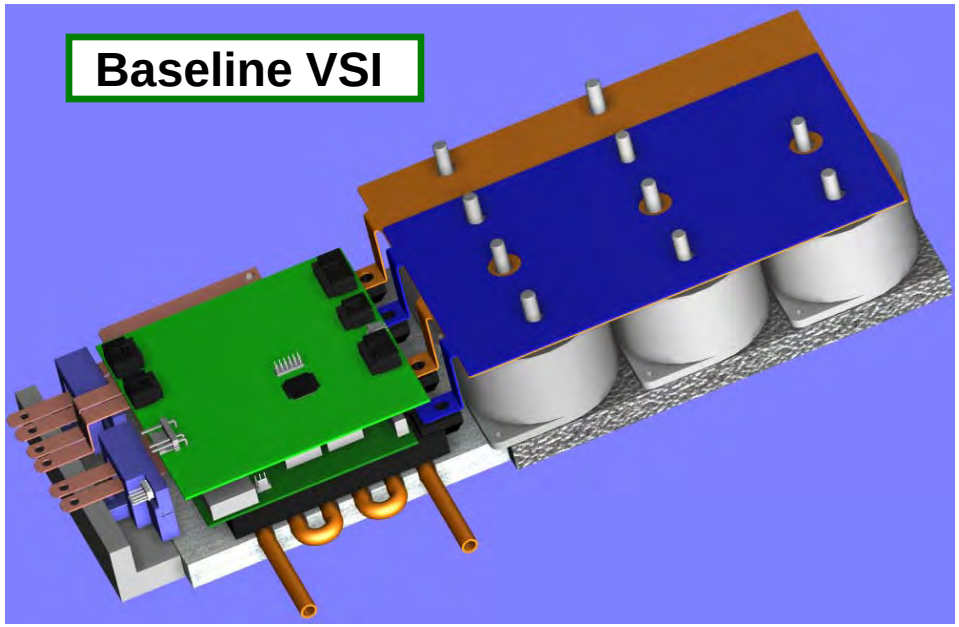


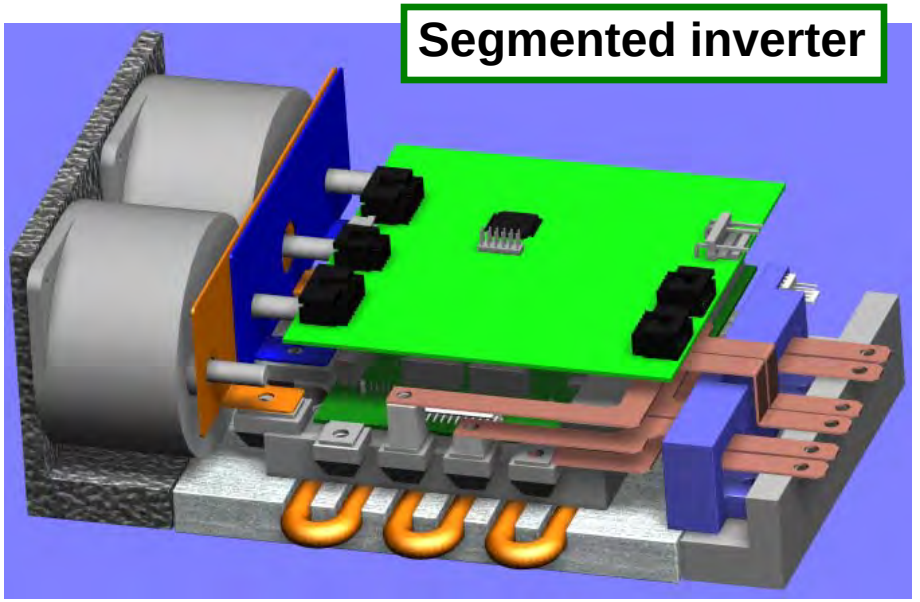
FY11 Approach Highlights

- Work with a PM motor manufacturer to select, procure and modify a motor for packaging together with a segmented inverter
- Design a 55 kW segmented inverter for integrating with the motor
  - Leveraging ORNL's new packaging capability, design custom IGBT modules and an inverter package suitable for integrating with the motor
  - Design gate driver and DSP control boards that fit well into the inverter package
  - Conduct mechanical stress modeling to make sure that inverter package can withstand anticipated vibrations
- Fabricate and package a 55 kW integrated segmented inverter/motor prototype

FY10 Technical Accomplishments

- **Hardware design for 55 kW prototypes**
  - **Two capacitors for segmented inverter, each rated at 500V/200μF**
  - **Five capacitors for baseline inverter, each rated at 500V/200μF**

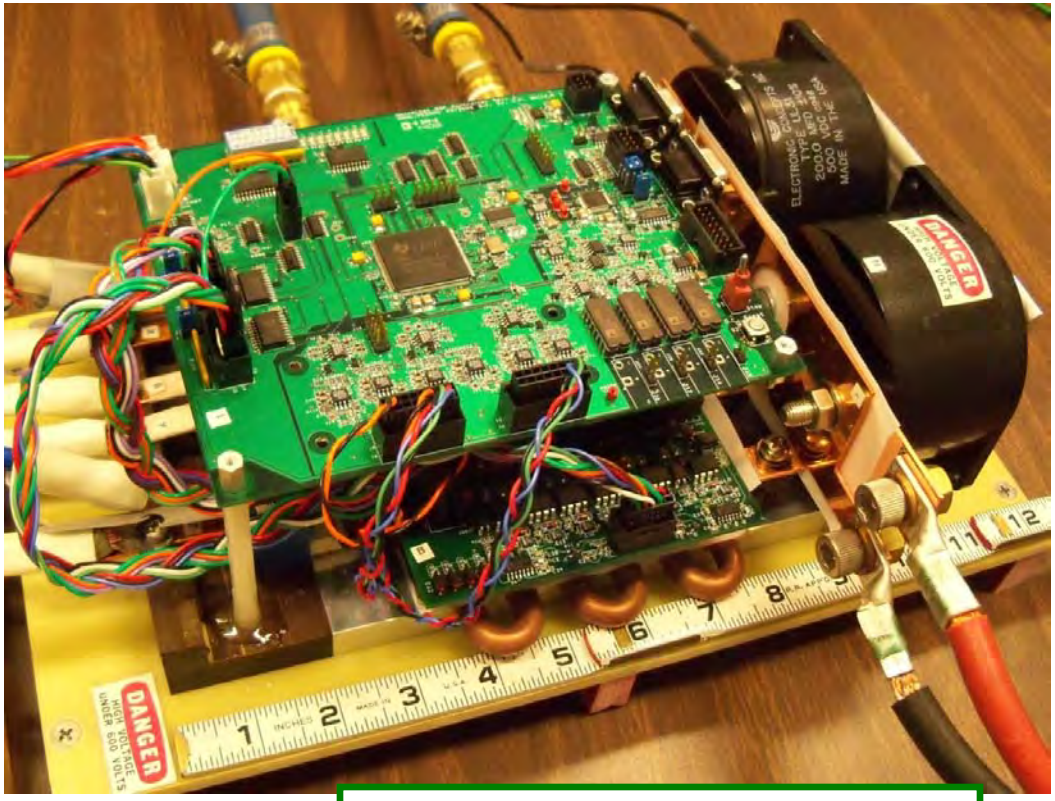




	Baseline	Segmented
Heat sink footprint	6”x7”+ 6.6”x9.6”	6”x7”+ 6.6”x2.2”
Cap. volume	1.39L	0.56L ➡ a 60 % reduction

FY10 Technical Accomplishments

- A 55 kW Segmented Inverter Prototype
  - Powerex IGBT modules
  - Water cooled with a cold plate of 7”x6”
  - TI’s 32bit fixed-pint DSP chip, TMS320F2812

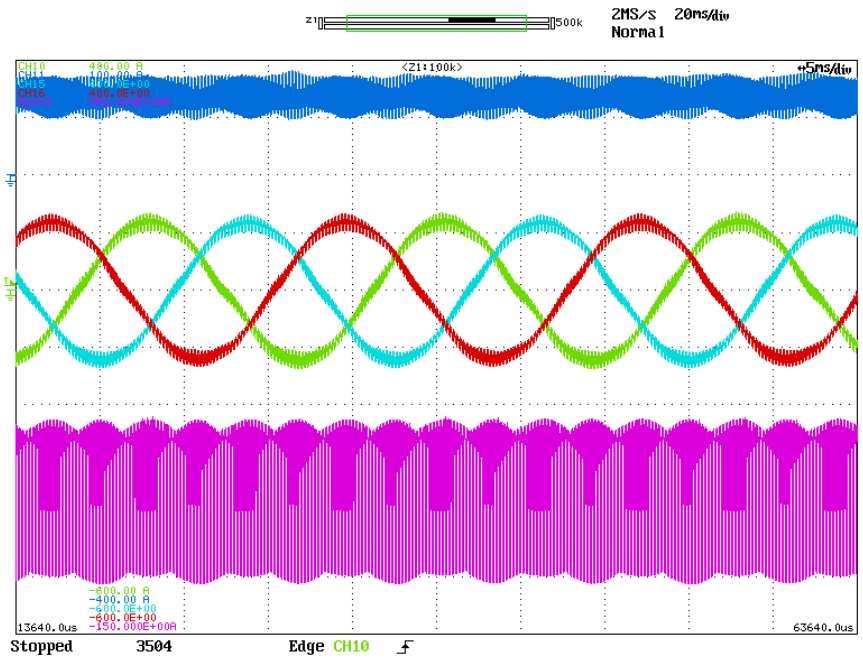


55 kW Segmented inverter

FY10 Technical Accomplishments

- **Test Results with a RL Load – Typical waveforms**

Baseline inverter

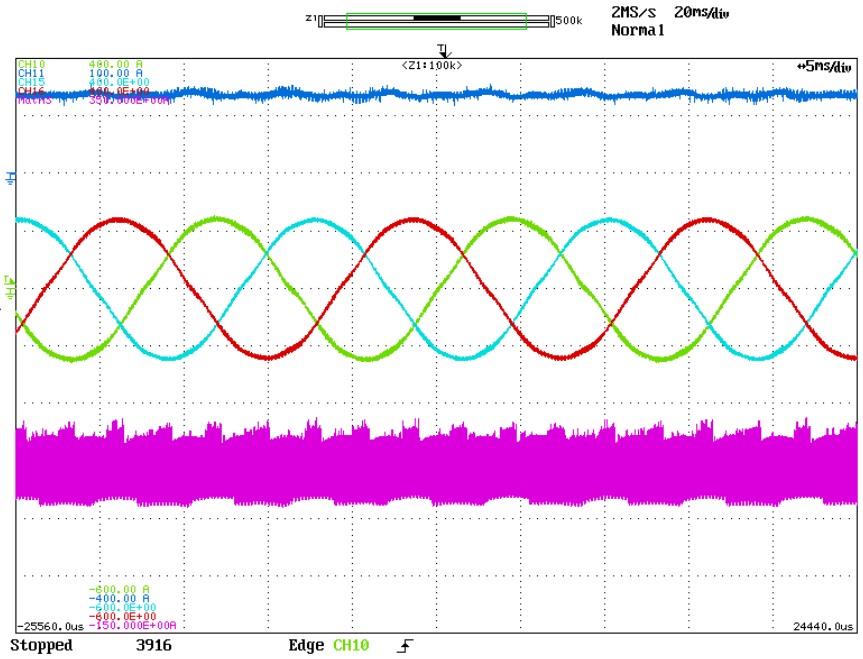


I_{bat}: 50A/div

i_a, i_b, i_c: 100A/div

i_{Cbus}: 50A/div

Segmented inverter

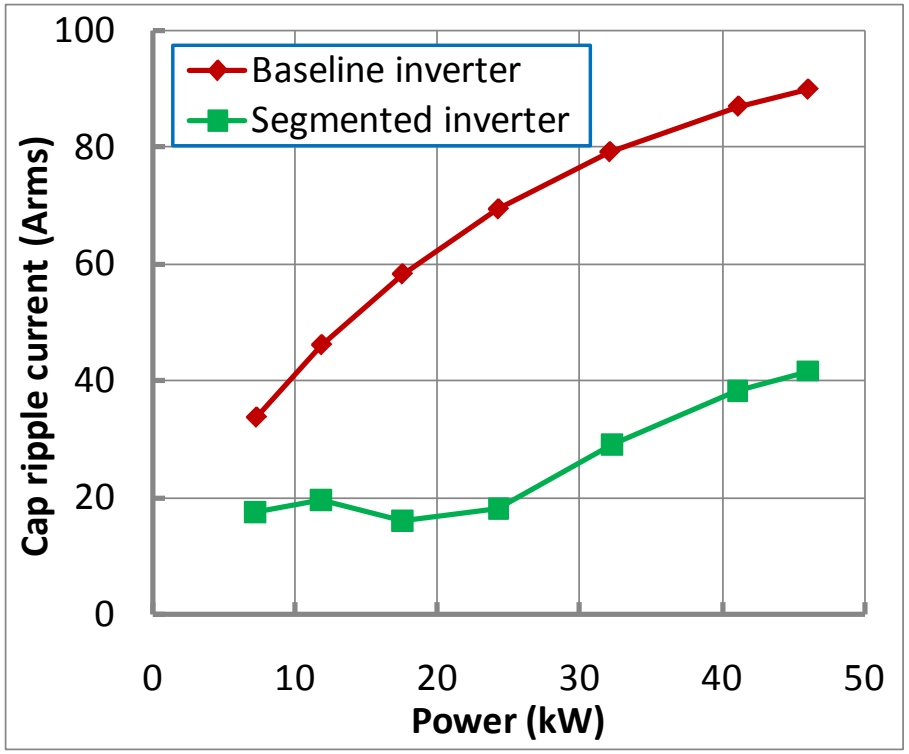


$i_{Cbus(rms)}$:35.7Arms → 62 % reduction → $i_{Cbus(rms)}$:13.7Arms

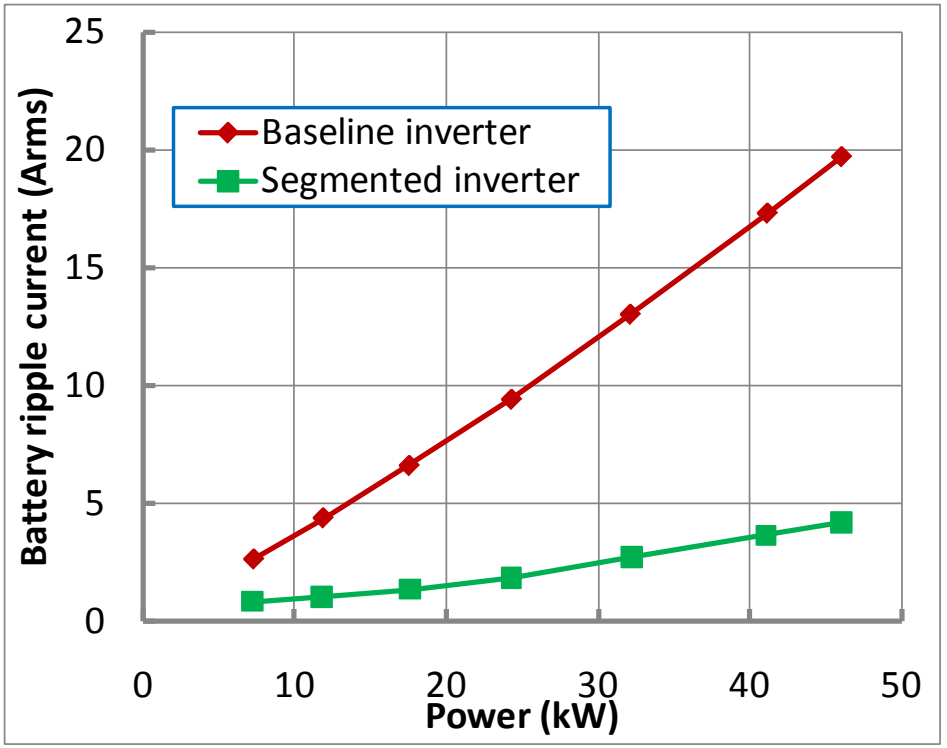
I_{bat}, p-p ripple: 45A → 78 % reduction → I_{bat}, p-p ripple: 10A

FY10 Technical Accomplishments

- **Test Results with an RL Load** – Comparison of capacitor and battery ripple current



Capacitor ripple current vs. dc input power for an R-L load

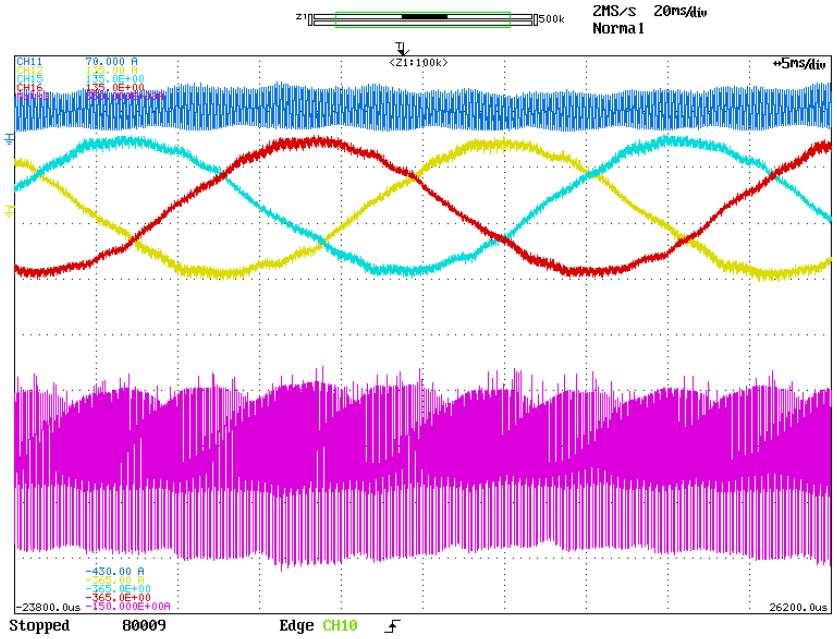


Battery ripple current vs. dc input power for an R-L load

FY11 Technical Accomplishments

- **Test Results with an induction motor – Typical waveforms**
- Motor ratings: 15 HP; 91 Nm; 37.5 Arms

Baseline inverter

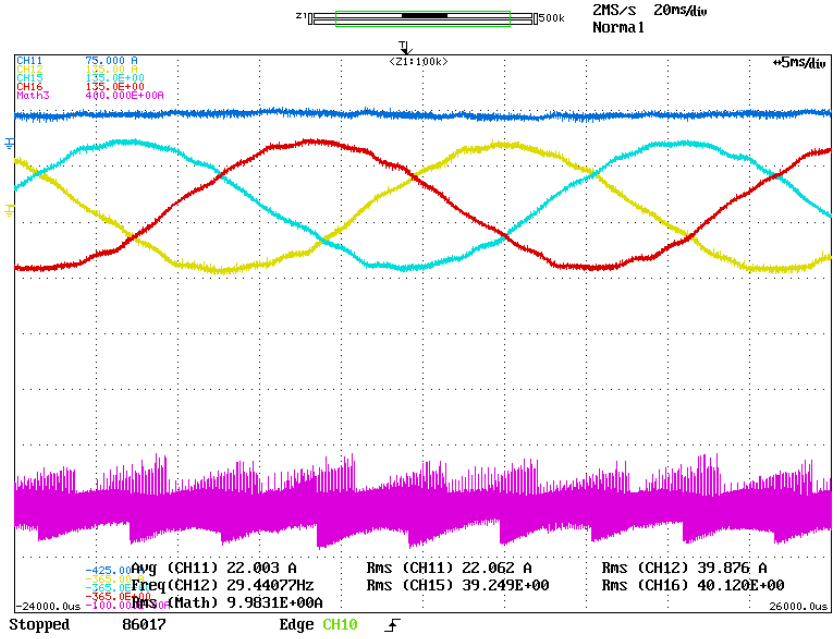


I_{bat}: 50A/div

i_a, i_b, i_c: 50A/div

i_{Cbus}: 50A/div

Segmented inverter

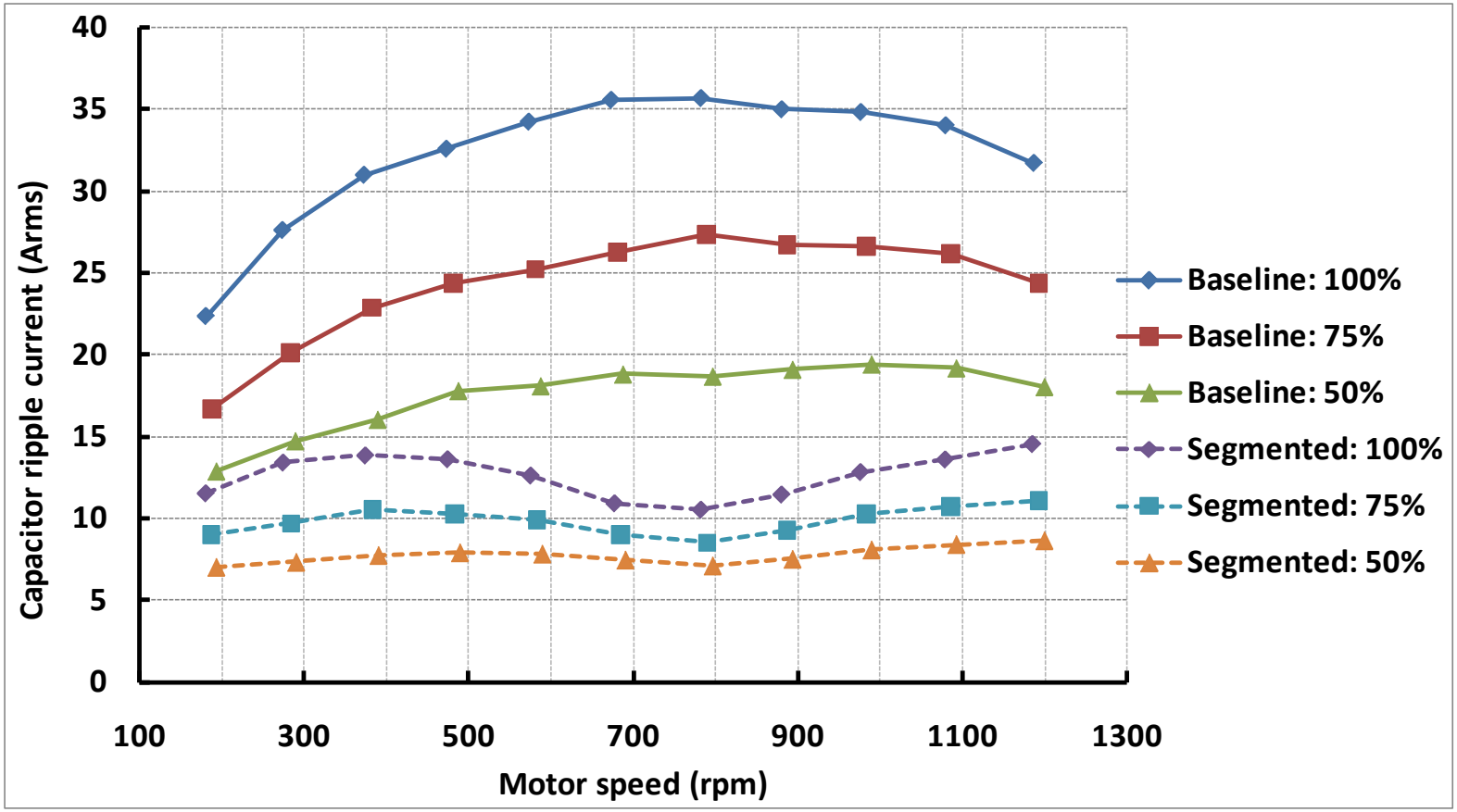


$i_{Cbus(rms)}$: 37.1 Arms → (73 % reduction) → $i_{Cbus(rms)}$:10.0Arms

I_{bat}, p-p ripple: 45A → (89 % reduction) → I_{bat}, p-p ripple: 5A

FY11 Technical Accomplishments

- **Test results — Induction motor**



Comparison of dc bus capacitor ripple current vs. speed at various percentages of rated torque.
(Motor ratings: 15 HP; torque, 91 Nm; current, 37.5 Arms)

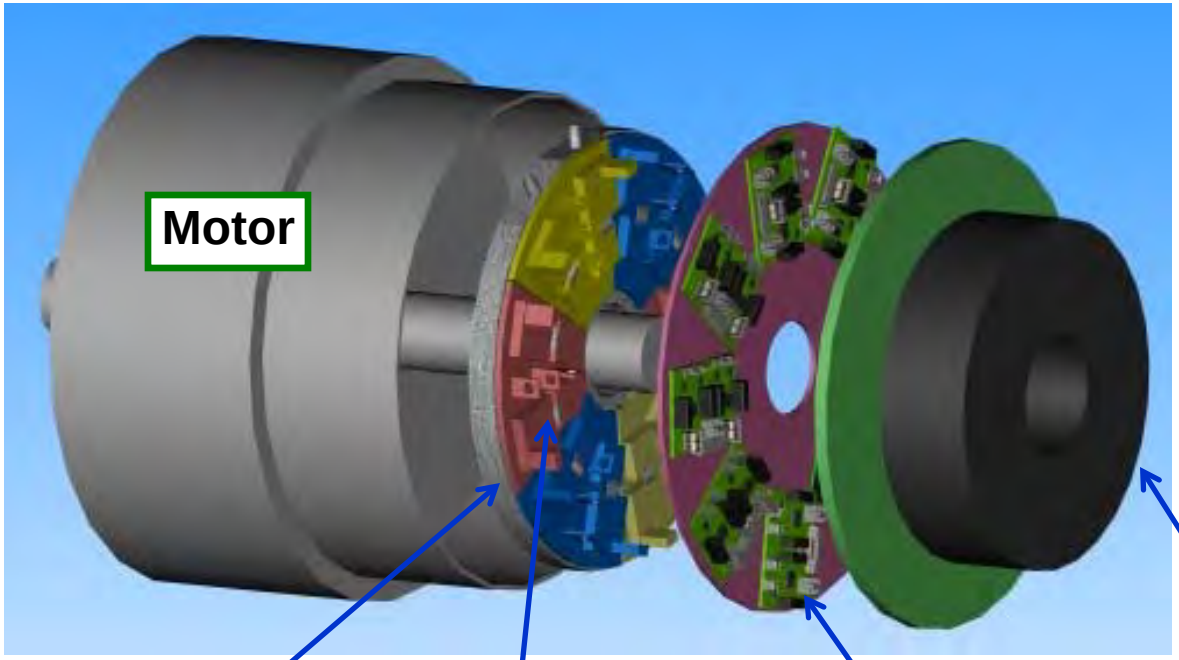
FY11 Technical Accomplishments

- Estimated performance improvements

	Camry 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	4.02	3.37	735
Subtotal	7.56	5.96	910	5.45	4.41	808
Metrics	kW/kg	kW/L	$/kW	kW/kg	kW/L	$/kW
	9.3	11.7	13	**12.8**	**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.						

FY11 Technical Accomplishments

- An integrated segmented inverter design
- Motor candidates
  - UQM IPM motor
  - 2004 Prius motor



Future Work

- Reminder of FY11
  - Complete design of a 55 kW segmented inverter for integrating with the motor
  - Implement the PWM techniques in real-time control DSP code
  - Fabricate and package a 55 kW integrated segmented inverter/motor prototype
- FY12
  - Test, characterize, and refine the 55 kW integrated segmented inverter/motor drive prototype developed in FY11

Collaborations

- Powerex
  - IGBT modules
- UQM
  - PM motor
- Capacitor vendors (Electronic Concepts, SBE)
  - Custom capacitors
- Leveraging ORNL's packaging research efforts and ORNL's expertise on materials science and technology
  - Packaging material
  - Power module packaging

Summary

- The segmented inverter can reduce bus capacitance by 60%, resulting in exceeding the 2015 weight target of 12 kW/kg and the 2020 volume target of 13.4 kW/l
- 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
- 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%
  - Enabler for high temperature operations