U.S. DEPARTMENT OF ENERGY

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

Current Source Inverters for HEVs and FCVs

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Project ID: ape_02_su

2009 DOE Hydrogen Program and Vehicle Technologies AMR

Overview

Timeline

- Start – Oct. 2006
- Finish – Sept. 2010
- 60% complete

Budget

- Total project funding
  - DOE share – 100%
- Funding received in FY08
  - $772K
- Funding received for FY09
  - $808K
- Funding requested for FY10
  - $632K

Barriers

- The DC bus capacitor presents significant barriers to meeting the targets of cost, volume and weight for inverters. Currently, it contributes
  - Cost and weight, up to 23% of an inverter
  - Volume, up to 30% of an inverter
- Ability of film capacitors to operate at higher temperatures deteriorates rapidly, leading to significant increases in cost, weight and volume
- Vehicle technology program targets
  - 2015 targets: $5/kW, 12kW/kg, 12kW/l, 105°C coolant

Partners

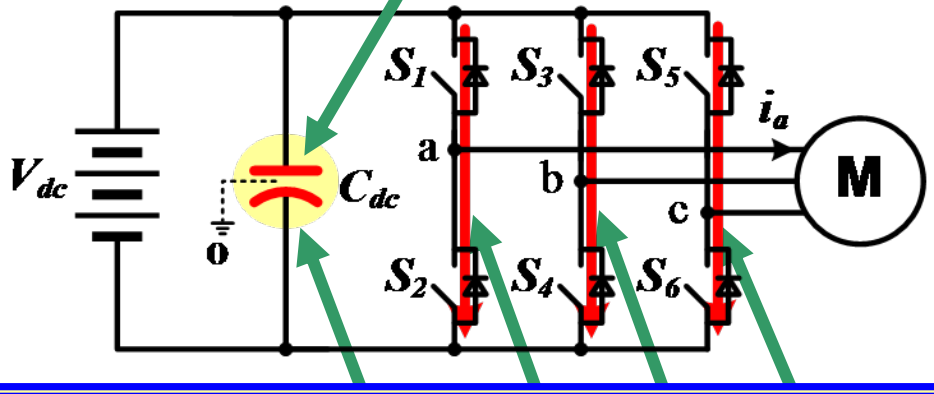
- Powerex – Custom IGBT modules
- Fuji – Reverse blocking IGBTs

Barriers

- **Voltage source inverter (VSI) characteristics present significant challenges to meet the DOE targets, especially at high coolant temperatures.**

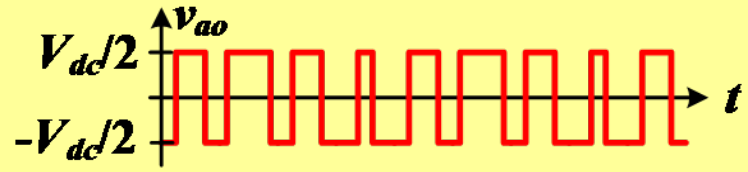
- **Costly and bulky, about 23% of inverter volume and cost**
- **A major hurdle for high-temperature operations**

Voltage Source Inverter (VSI)



- **Possible shoot-through causes long-term reliability concern**
- **Source voltage limits output voltage**

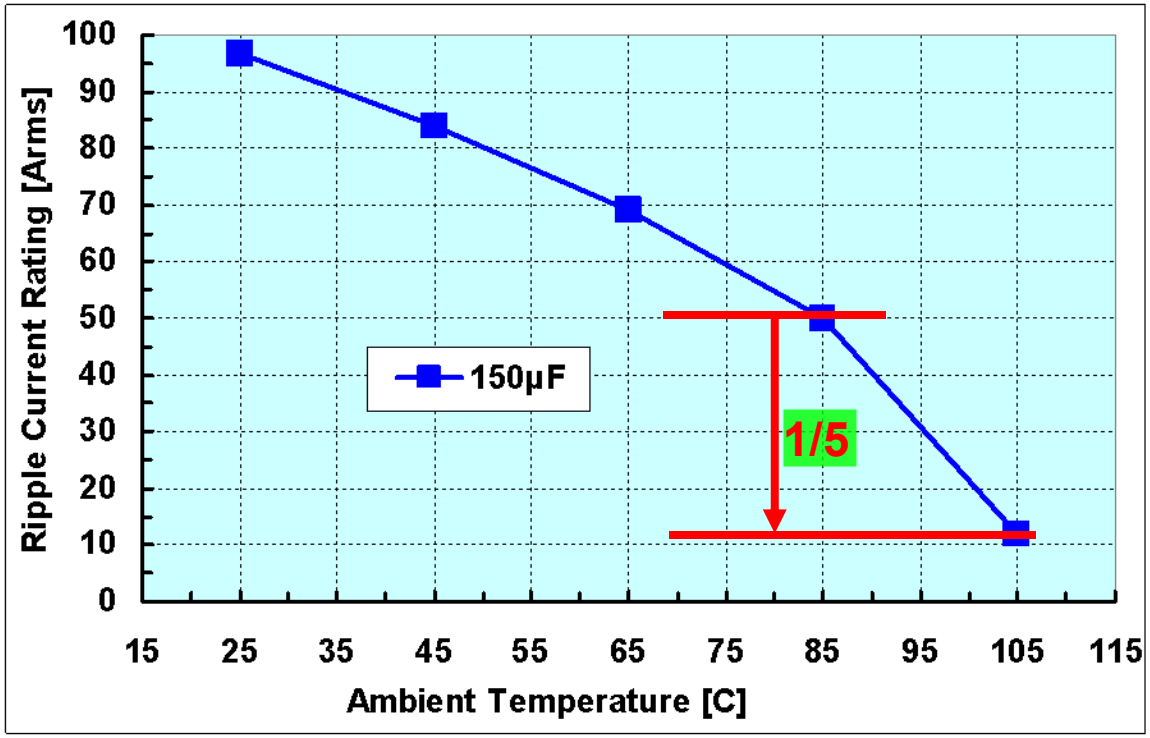
Undesired voltage waveform



- **High EMI noises**
- **High stress on motor insulation**
- **High-frequency losses**
- **Bearing-leakage currents**

Barriers (contd.)

- High Temperature Operation Challenge for the VSI-Capacitor
  - Film capacitor ripple current and voltage capability decreases rapidly with temperature
    - 50% linear voltage derating from 85ºC to 105ºC
  - Non-benign failure modes are concerns for ceramic capacitors



Electronic Concepts
UL31 Series, 600 V
Diameter: 83.3 mm

For example, as temperature rises from 85 to 105°C, weight, volume and cost of capacitors could increase by a factor of 5

Source: http://www.eci-capacitors.com/product_details.asp?productid=29

Objectives

- For FY08
  - Design, assemble, and test a 55 kW current source inverter (CSI) prototype for operating with a 70˚C coolant
  - Demonstrate a prototype that is capable of
    - controlling a PM motor with a voltage boosting factor of 3
    - reducing the capacitance requirement from about 2000 µF to 200 µF
    - producing near sinusoidal output voltages with a 90% reduction of distortion factor compared to a VSI

- For FY09
  - Design and assemble a 55 kW prototype that can operate with a 105˚C coolant
  - Demonstrate feasibility of the technology for
    - Continuing operation at 105˚C coolant temperature
    - Controlling a PM motor in both motoring and regen modes
    - Providing a voltage boosting factor of great than 3

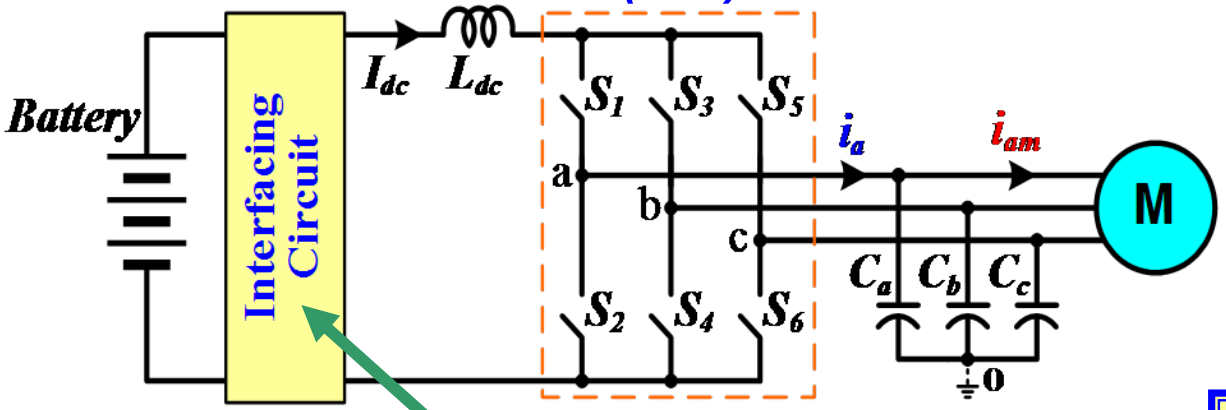
Milestones

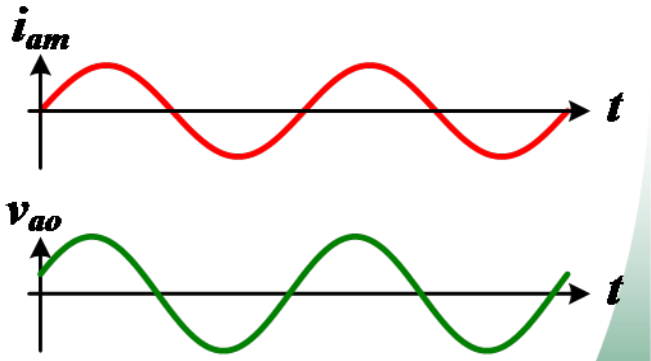
Month/Year	Milestone or Go/No-Go Decision
Dec-07	Milestone: Complete the design for a 55-kW prototype CSI with an inherent boost capability of 3X, a reduction of motor voltage harmonic distortion of 90%, and a reduction in capacitor requirements from 2,000 uF to 200 uF.
Jun-08	Milestone: Complete development of the control algorithm and DSP code for the 55-kW CSI prototype.
Sept-08	Milestone (Joule): Complete fabrication and demonstrate, in the laboratory, the CSI with an boost capability of 3X, a reduction of motor voltage harmonic distortion of 90%, and a reduction in capacitor requirements from 2,000 uF to 200 uF. Go/No-Go Decision: A go/no-go decision will be made based on whether these goals are met.
Jul-09	Go/No-Go Decision: Complete hardware design of a 55 kW CSI prototype for operating at 105ºC coolant temperature. Depending on the outcome of the hardware design, a decision will be made on which area in terms of weight, volume and cost to be focused on in FY10.
Sept-09	Milestone: Complete prototype fabrication.

Approach

- Use of the current source inverter (CSI) with a novel interfacing circuit
  - The bulky dc bus capacitor is replaced by a small inductor and 3 small ac capacitors
  - Antiparallel diodes are eliminated from the switches
  - Phase-leg shoot-through is not only tolerated, but used to boost output voltage; leading to extended constant-power speed ranges

Current Source Inverter (CSI)





- *Enable the CSI to control the motor at low speeds and regen to charge the battery*

- Sinusoidal voltages & currents to the motor

Technical Accomplishments/Progress

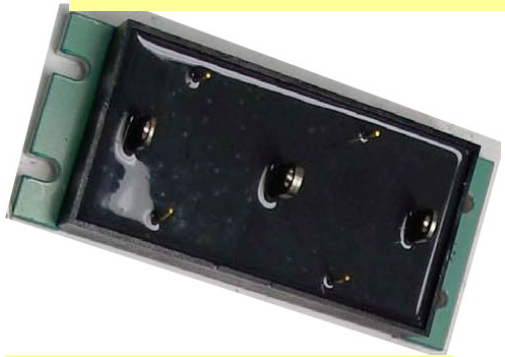
- FY08 - Demonstrated a 55 kW CSI prototype with a 70ºC coolant
  - Total capacitance: < 200 µF (2000 µF for VSI)
  - Output voltage range: 0 ~ 3.47X (0 ~ 0.99X for VSI)
  - Output voltage THD: 6.7% ~ 12.2% (70 ~ 200% for VSI)
  - 6.1kW/kg, 12.8kW/L (Camry: 4.3kW/kg, 7.1kW/L)

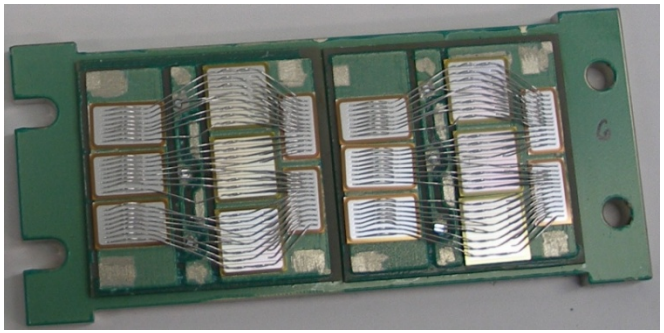
- FY09 task - Design and fabrication of a 55 kW CSI prototype for operating with a 105ºC coolant
  - Completed inverter loss modeling for selected IGBTs and diodes at the 105ºC coolant temperature.
  - Selected and procured components for a dsp control board for operating in a 105˚C cooling environment.

Technical Accomplishments

- **Prototype design for operating with a 70ºC coolant**
  - **Current source inverter requires switches capable of blocking voltage in both forward and reverse directions**
    - **Series connection of IGBTs and diodes**
    - **Reverse blocking IGBT (under development; engineering samples at 1200V/100A and 600V/200A from Fuji)**
    - **Normally-on GaN switches (under development)**

Custom CSI switch leg module made by Powerex 1200V/400A

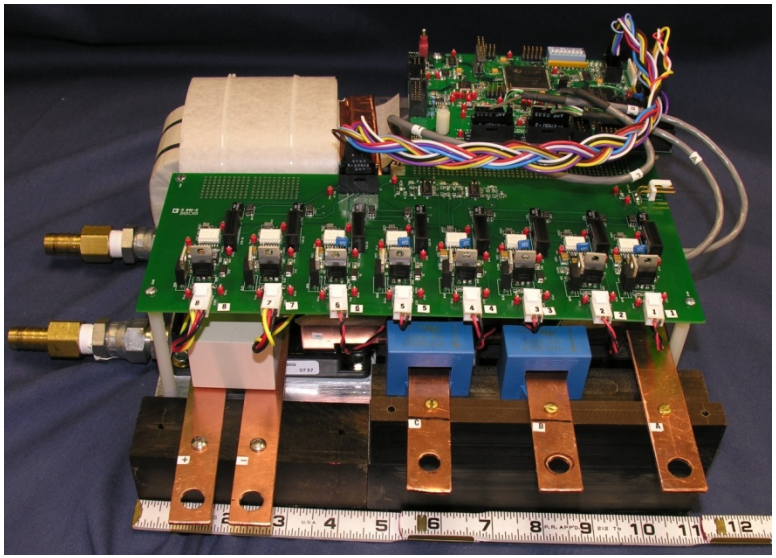


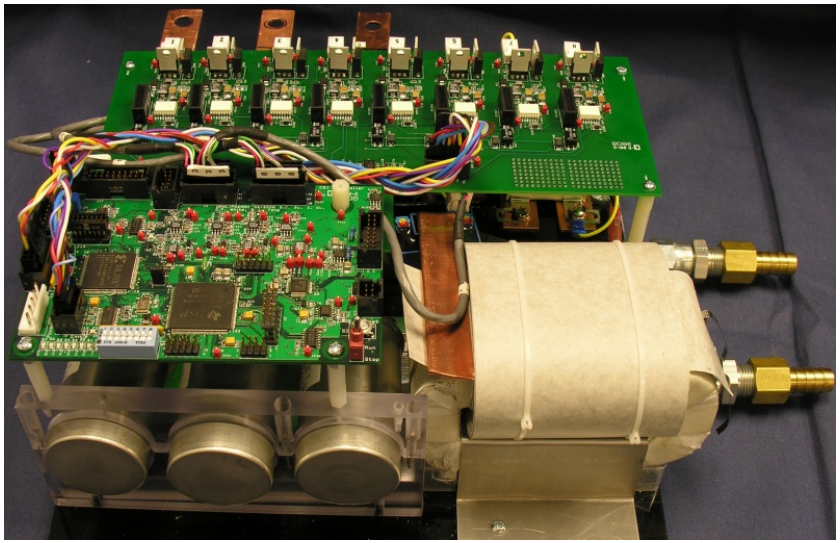


Footprint: 4.5” x 2”

Technical Accomplishments

- A 55 kW CSI prototype for operating at 70ºC coolant temperature
  - Total capacitance: < 200 µF (2000 µF for VSI)
  - Opportunity remains for packaging and inductor design optimization

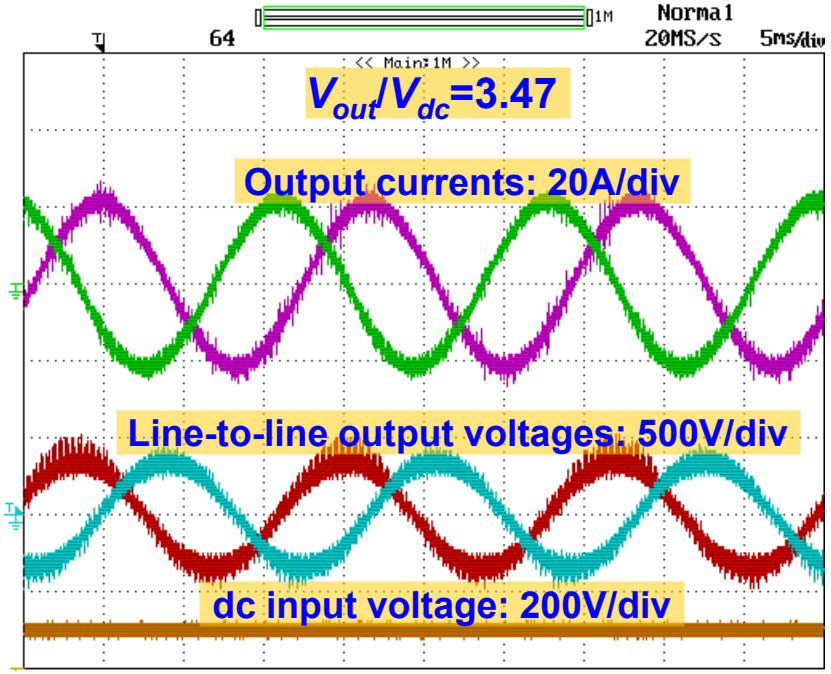


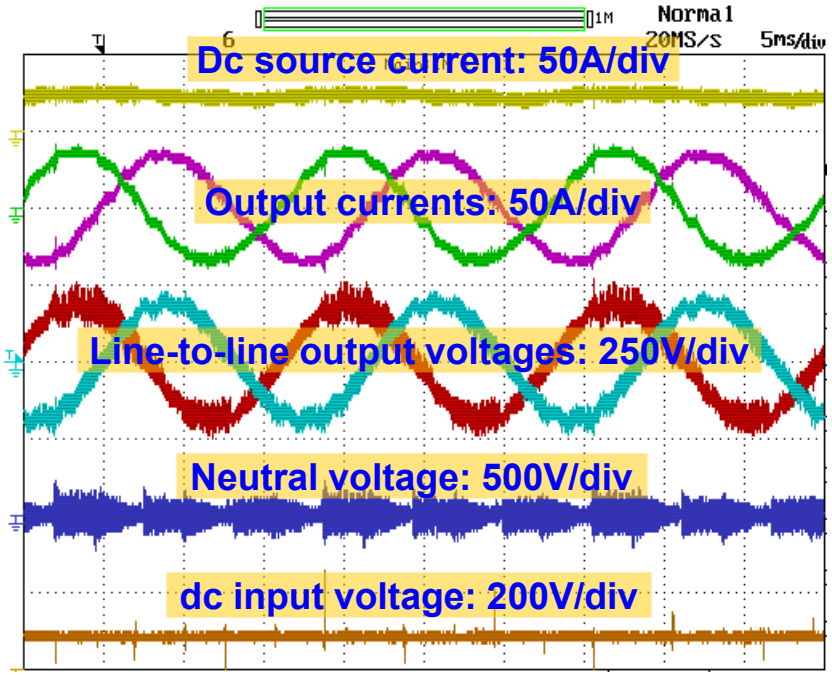


Heat sink footprint: 11” x 7.8”
6.1 kW/kg, 12.8 kW/L (Camry: 4.3 kW/kg, 7.1kW/L)

Technical Accomplishments

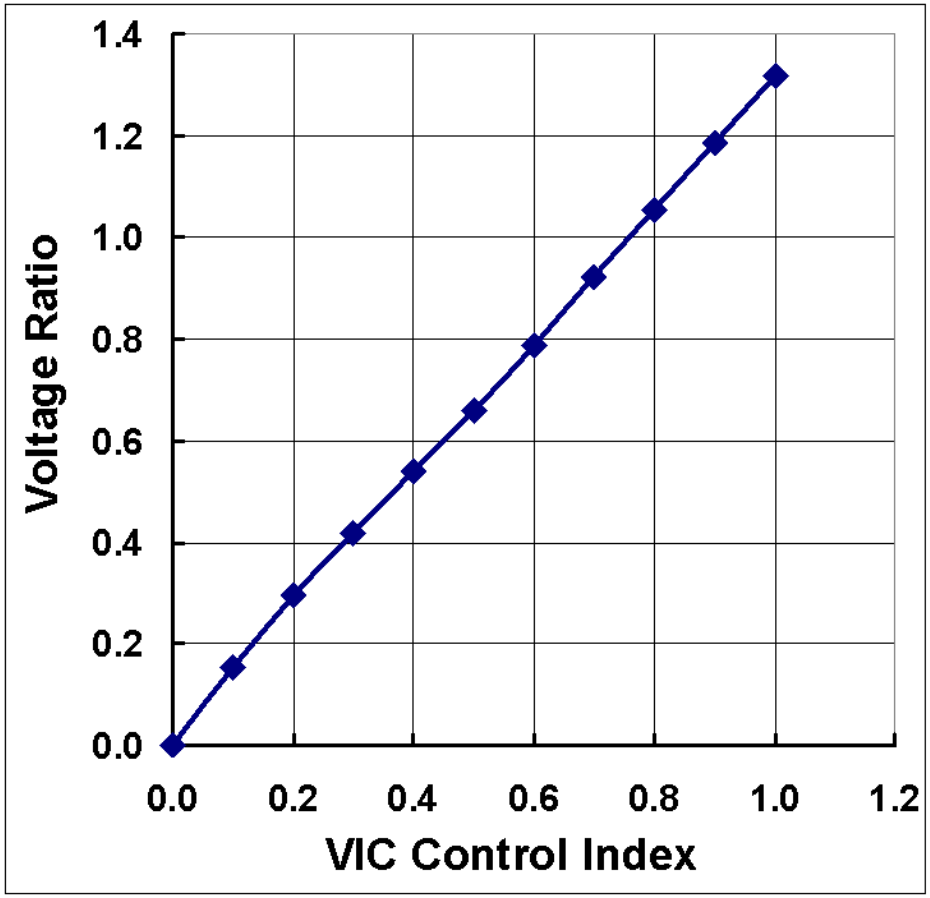
- Test results
  - Output voltage range: 0 ~ 3.47X (0 ~ 0.99X for VSI)
  - Output voltage THD: 6.7% ~ 12.2% (70 ~ 200% for VSI)





Technical Accomplishments

- Test results - Measured output voltage range
  - 0 ~ 3.47X (0 ~ 0.99X for VSI)



Buck operation

Boost operation

Future Work

- **Remainder of FY09**
  - **Complete the hardware design and fabrication of a 55 kW CSI for operating with a 105°C coolant**
  - **Complete the dsp control PCB design and fabrication**

- **FY10**
  - **Test and refine the prototype built in FY09 with a 105°C coolant**
  - **Incorporate the latest technology advancements in capacitor, switch, packaging and thermal control from DOE R&D programs and industry**
  - **Perform feasibility study of the CSI for additional vehicle architectures**

Summary

- The proposed CSI can
  - Operate a motor from a battery from 0 to higher speed with a voltage boost ratio of greater than 3
  - Charge the battery during dynamic breaking
  - Reduce the capacitance by 90%
  - Improve inverter and motor lifetime by providing sinusoidal voltages and currents
  - Reduce the cost and size of batteries in plug-in HEVs
  - Eliminate the hurdles presented by existing capacitor technologies for an inverter to operate at elevated temperature environments

- Prototype test results indicate the CSI is a promising alternative to the VSI by offering many advantages.