Inverter Using Current Source Topology

Gui-Jia Su

Oak Ridge National Laboratory

May 10, 2011

Project ID: APE002

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

Overview

Timeline

- Start – FY10
- Finish – FY12
- 50% complete

Budget

- Total project funding
  - DOE share – 100%
- Funding for FY10
  - $816K
- Funding for FY11
  - $640K

Barriers

- Cost, weight, volume of the bus capacitor
  - Cost and weight, up to 23% of an inverter
  - Volume, up to 30% of an inverter
- Capacitor high temperature capability
- Undesirable characteristics of the VSI
- High system cost resulted from use of single-function modules

- Inverter targets (2015): $5/kW, 12 kW/kg, 12 kW/l

Partners

- ORNL team members: Lixin Tang, Cliff White, Mike Jenkins, John Hsu
- Michigan State University
- Fuji Electric Semiconductors
- Powerex

Objectives

- Develop novel ZCSI topologies that combine the benefits of ORNL's Current Source Inverter (CSI) efforts and MSU's work on Z Source Inverters (ZSI) to significantly reduce cost and volume through the integration of voltage boost, inverter, regen and PEV charging functions

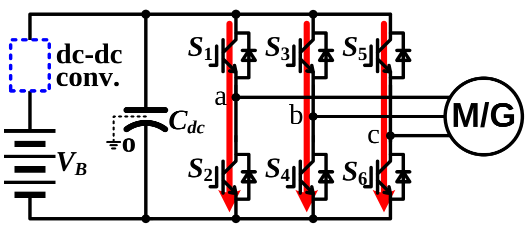
- FY11 Objectives
  - Perform a simulation study on ways to reduce passive component requirements for ZCSIs
    - New voltage boost control methods
    - Impact of increasing switching frequency with wide bandgap switches
  - Assemble and test a 10 kW ZCSI setup using RB-IGBT to validate the simulation study

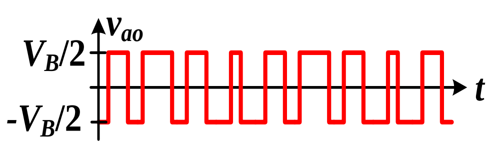
Milestones

Month/Year	Milestone or Go/No-Go Decision
Sept-2010	Milestone: Completion of simulation study on selected new ZCSI topologies. Go/No-Go Decision: Determine from simulation results whether the ZCSIs can meet these goals: 1) a voltage boost capability of 3X, 2) a capability to charge the battery in both buck and boost mode during dynamic breaking, and 3) a reduction of motor voltage harmonic distortion of 90%.
Sept-2011	Milestone: Completion of building and testing a 10 kW ZCSI Go/No-Go Decision: Determine from test results whether the ZCSI can meet these goals: 1) an inherent voltage boost capability of 3X, 2) a capability to charge the battery in both buck and boost mode during dynamic breaking, and 3) a reduction of motor voltage harmonic distortion of 90%.

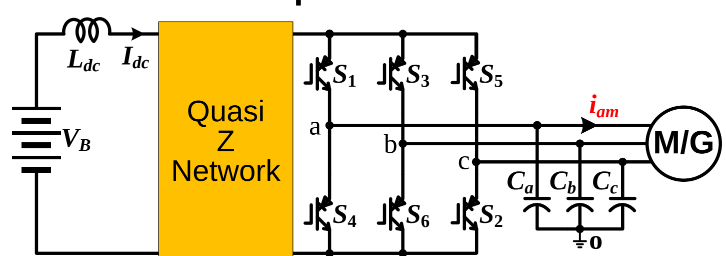
Approach (1)

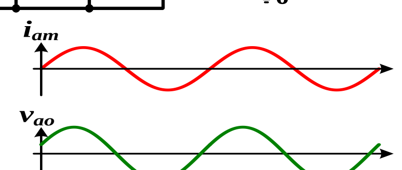
- The VSI
  - Require a bulky & expensive bus capacitor
  - Produce undesired output voltage waveforms that cause
    - High EMI noises
    - High stress on motor insulation
    - High-frequency losses
    - Bearing-leakage currents
  - Present a shoot-through failure mode that is a cause for long-term reliability concerns
  - Output voltage limited by battery voltage; a separate dc-dc converter is needed for voltage boosting





- ZCSI with a quasi-Z network:
  - Use a passive quasi-Z network of inductor, capacitor, and diode in the CSI to enable
    - Single stage buck & boost conversion
    - Battery charging
    - Safe operation in open circuit events
  - Eliminate antiparallel diodes with reverse-blocking IGBTs and GaN switches
  - Reduce total capacitance
  - Produce sinusoidal voltages & currents to the motor
  - Tolerant of phase-leg shoot-through and open circuit
  - Extend constant-power speed range without a separate boost converter

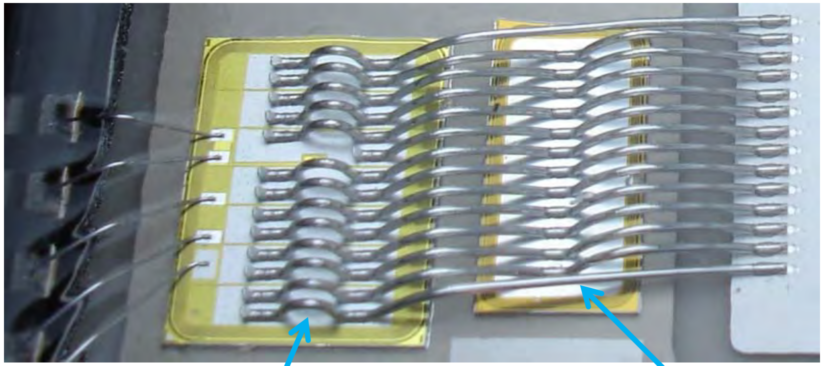




Approach (2)

- Eliminate antiparallel diodes with reverse-blocking IGBTs could shrink the foot print of power modules by 50 – 60 %

Camry IGBT switch

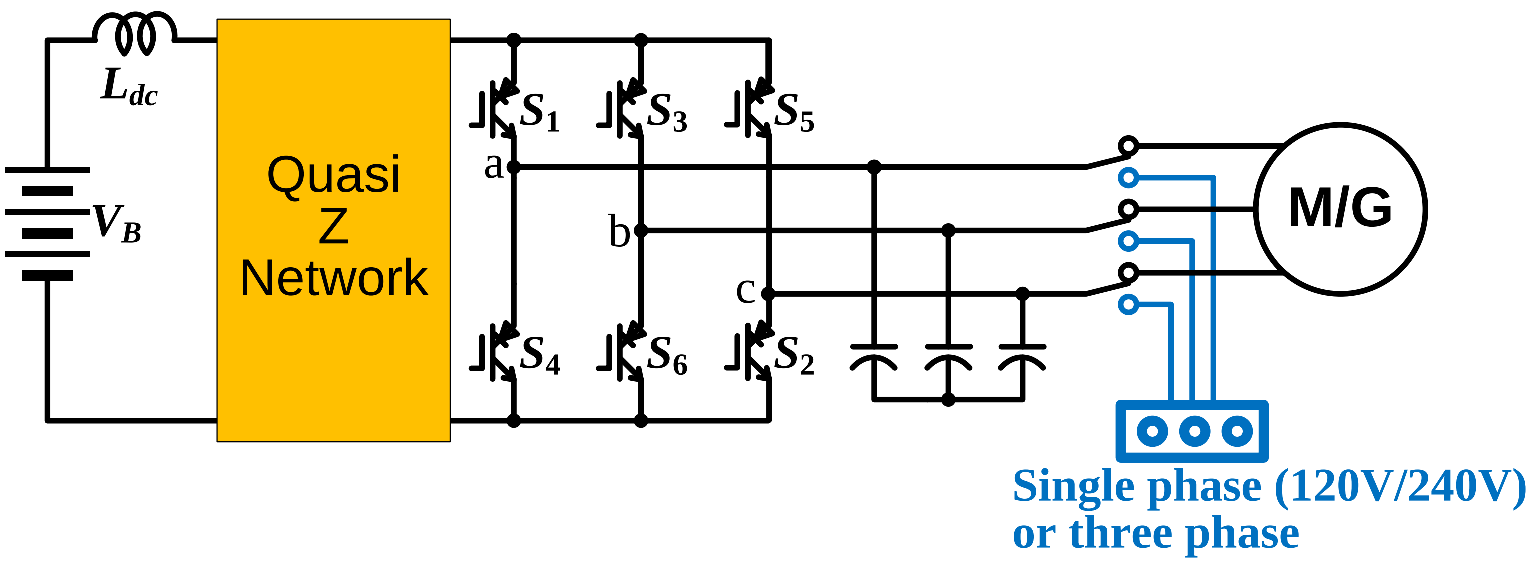


IGBT: **2165 mm^2**

Diode: **1278 mm^2**

Approach (3)

- CSI can be configured to operate as a charger in PEVs
  - Charge battery from a single-phase source of 120V or 240V
  - Charge battery from a three-phase source
  - Charge batteries over a wide range of voltage levels due to CSI's capability to buck and boost the output voltage

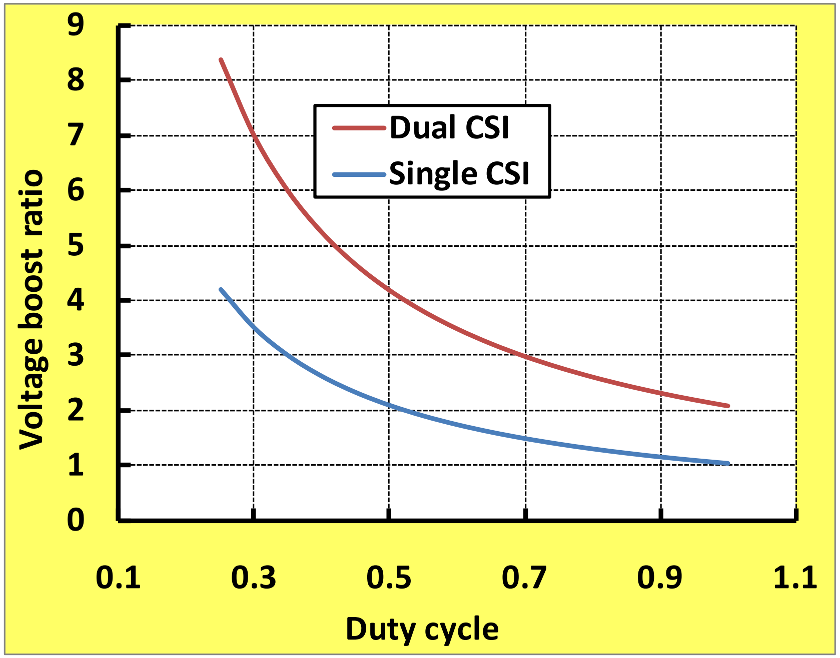


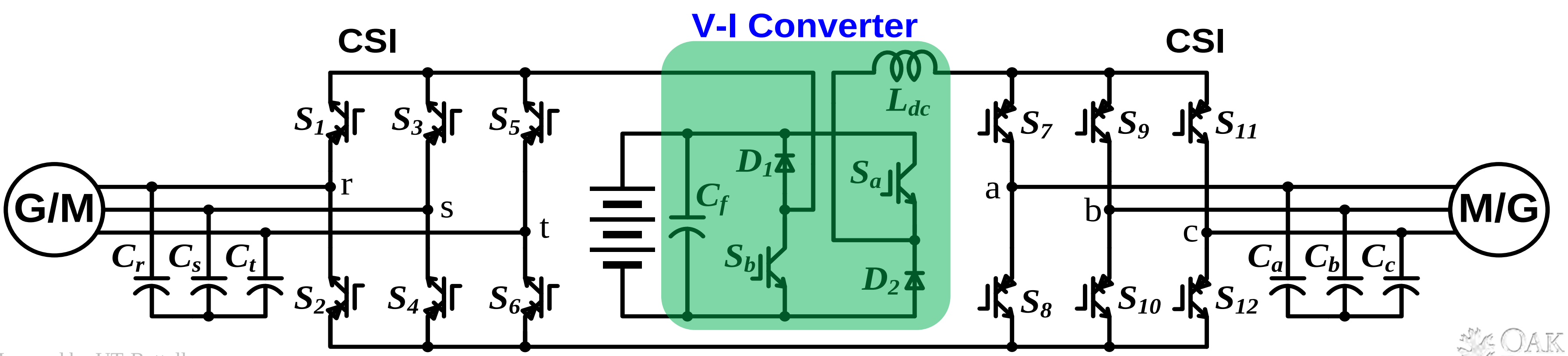
FY10 Technical Accomplishments (1)

- Confirmed by simulation the feasibility of using the ORNL CSI topology in series and power- split series/parallel HEV configurations
- The CSI dual-motor-drive (DMD) PE using RB-IGBTs provides significant performance improvements over the Camry PE
- Developed two new ZCSIs with a reduced component count and a higher voltage boost ratio (3 vs. 2 for the previous ZCSIs)
  - Current-fed Trans-ZSI (CF-trans-ZSI)
  - Current-fed Trans-quasi-ZSI (CF-trans-qZSI)
- Completed a design for a 55 kW ZCSI based on the CF-trans-qZSI
  - Using the first generation RB-IGBT technology
  - Power density: 16.6 kW/L
  - Specific power: 4.89 kW/kg

FY10 Technical Accomplishments (2)

- ORNL CSI dual-motor-drive (DMD) for HEVs/PHEVs using two motors
  - Share a single dc link inductor and battery interface circuit
  - Enable 3 operation modes: 1) both M/Gs in motoring, 2) both in regen, and) one in motoring and one in regen
  - Can produce even higher output voltages for the motor compared to a single CSI drive





FY10 Technical Accomplishments (3)

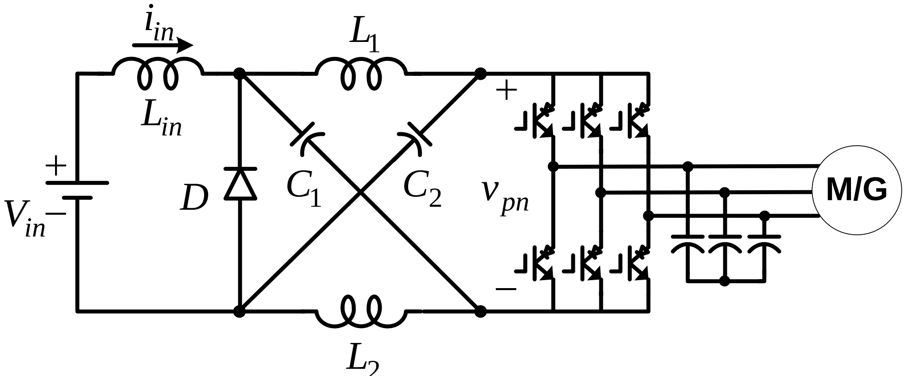
- Predicated performance improvements of the CSI DMD PE over the Camry PE

	Camry PE			CSI DMD PE with regular IGBT[a,b]			CSI DMD PE with RB-IGBT[a,b,c,d]		
	Weight (kg)	Volume (L)	cost ($)	Weight (kg)	Volume (L)	Cost ($)	Weight (kg)	Volume (L)	Cost ($)
Bus Cap	3.57	2.6	$260	0.36	0.26	$26	0.36	0.26	$26
Side housing	1.2	0.98	$1,040	1.20	0.98	$1,040	1.20	0.98	$728
Power module	5	4.3		5.00	4.30		2.75	2.37	
Boost/V-I converter	6.6	3.5	$325	6.60	3.50	$325	6.60	3.50	$325
subtotal	16.37	11.38	$1,625	13.16	9.04	$1,391	10.91	7.11	$1,079
Reduction in kg, L & $				20%	21%	14%	33%	38%	34%
Metrics	4.3	6.2	23.2	5.3	7.7	19.9	6.4	9.9	15.4
	kW/kg	kW/L	$/kW	kW/kg	kW/L	$/kW	kW/kg	kW/L	$/kW
Increase in kW/kg & kW/L				24%	26%		50%	60%	
Reduction in $/kW						14%			34%

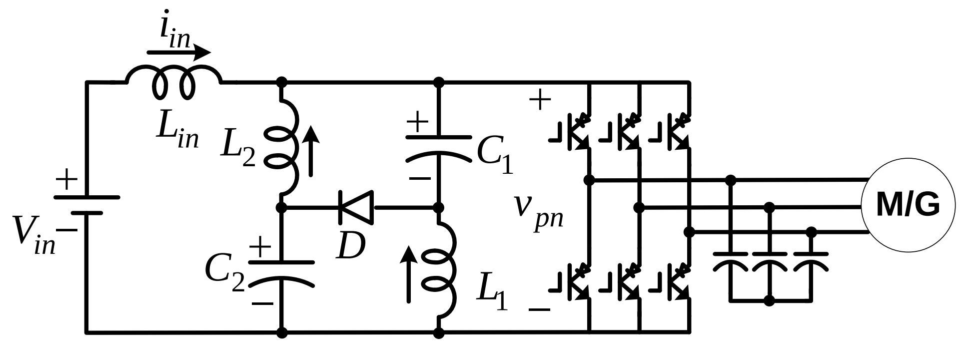
Assumptions: a) 90% reduction of capacitance, b) 20% of inverter cost from capacitor, c) 30% reduction in diode cost of the inverter switch module, d) 45% reduction in diode volume and weight of the inverter switch module, e) no changes between the boost converter in the Camry PE and V-I converter in the CSI.

FY10 Technical Accomplishments (4)

- Original current-fed ZSIs topologies

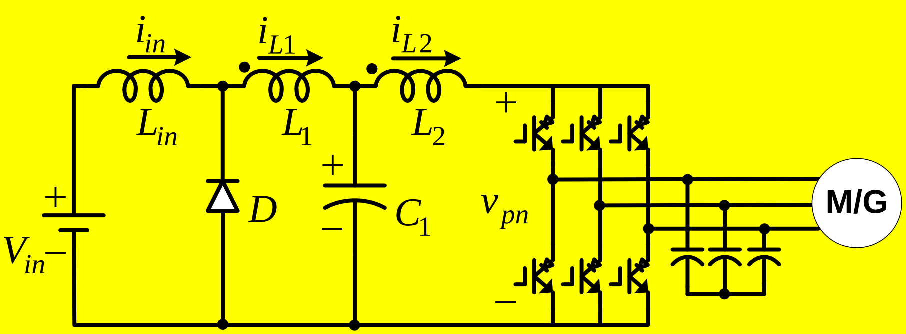


The original current-fed ZSI

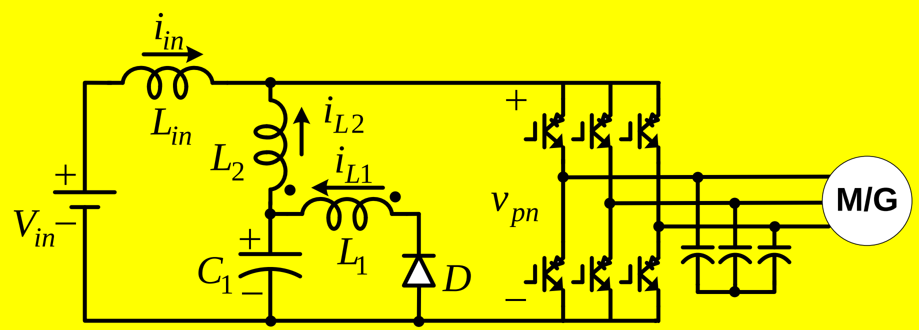


Current-fed qZSI

- New ZCSIs developed under this project
  - The newly developed current-fed Trans-ZSI and Trans-quasi-ZSI feature wider motoring operation range and reduced component count.



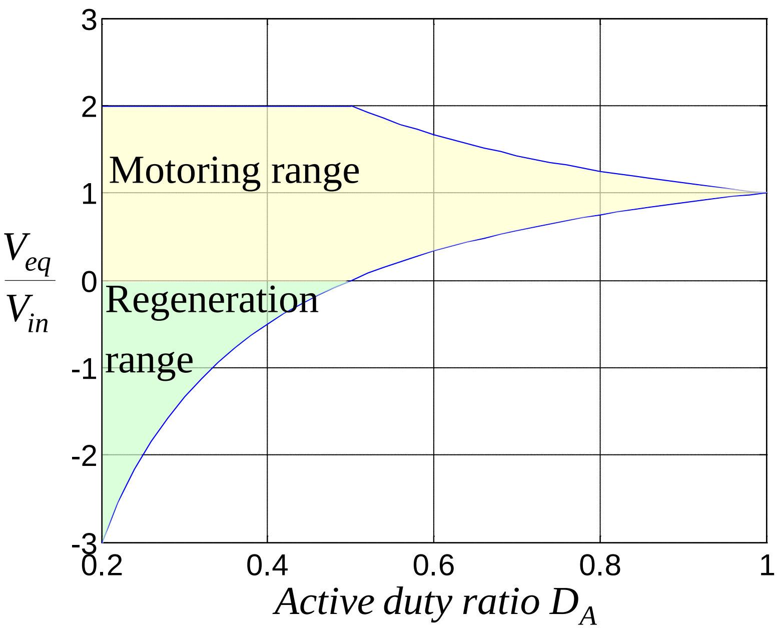
Current-fed Trans-ZSI



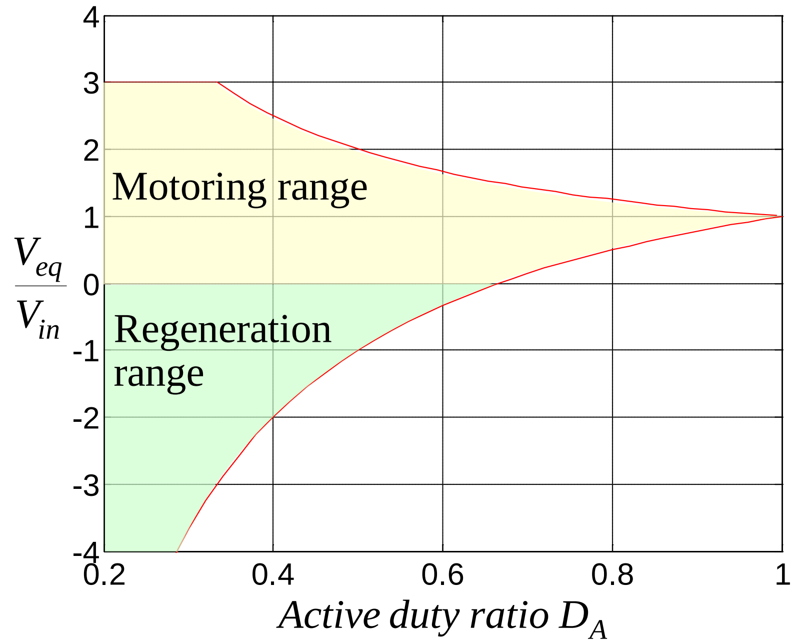
Current-fed Trans-qZSI

FY10 Technical Accomplishments (5)

- Comparison of voltage boost ratio vs. duty ratio D_A (simulation results)



Current-fed qZSI



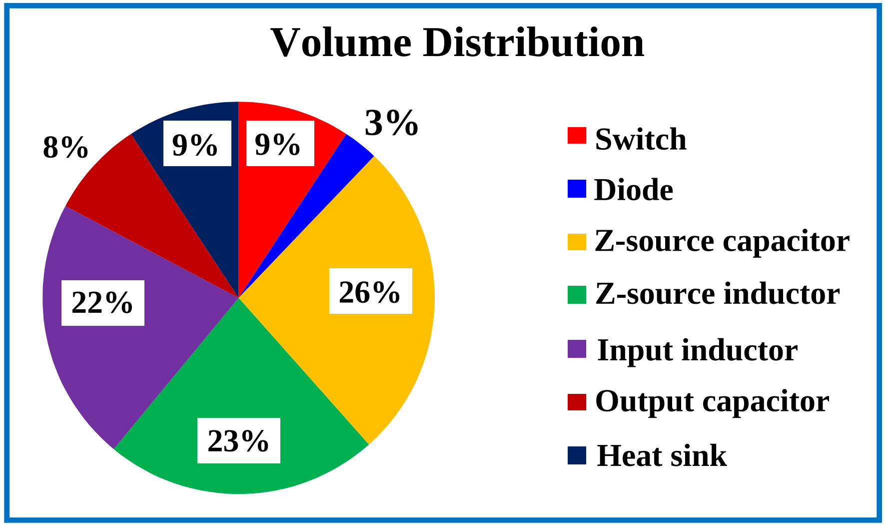
New current-fed Trans-ZSI

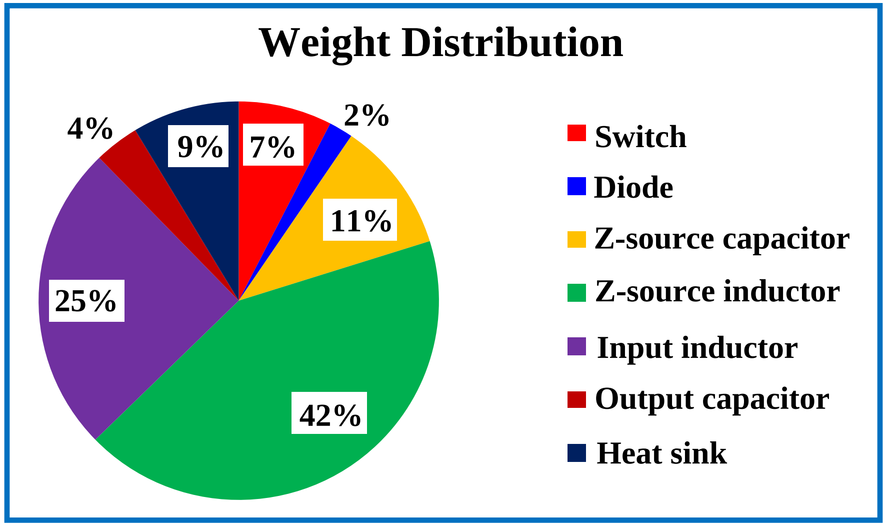
FY10 Technical Accomplishments (7)

- Completed a design for a 55 kW CF-trans-qZSI for the following conditions:
  - Peak power rating: 55 kW
  - Battery voltage, V_{in}: 260 V
  - Output line-to-line voltage: 0~500 V
  - Switching frequency: 10 kHz
  - Coupled inductor turns ratio: 2

Power density: 16.6 kW/L
Specific power: 4.89 kW/kg

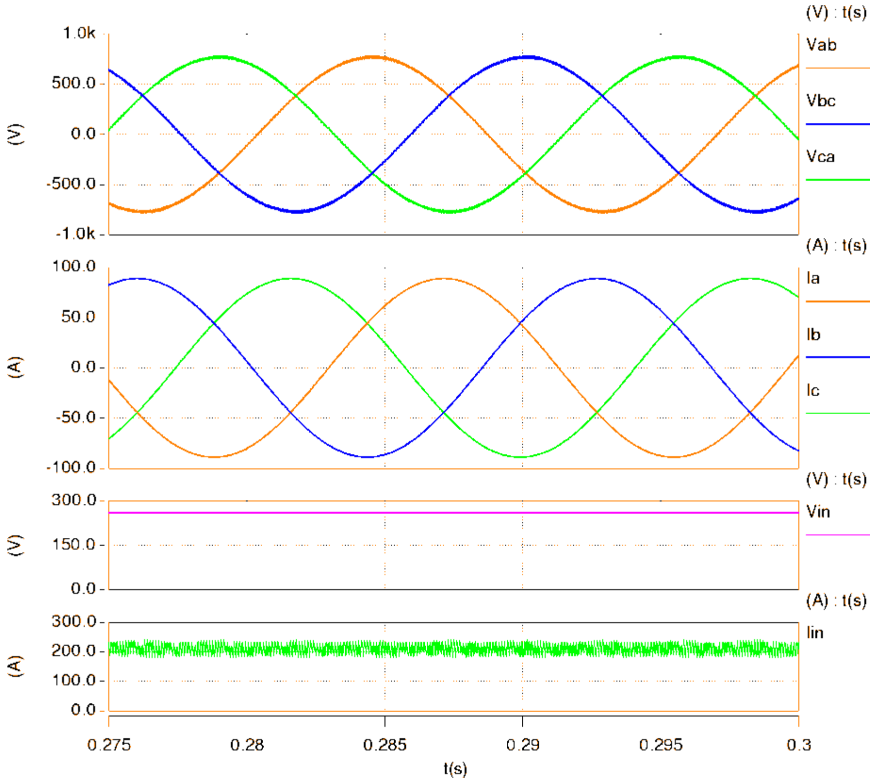
Camry: 7.4 kW/L, 4.6 kW/kg
2015 targets: 12 kW/L, 12 kW/kg



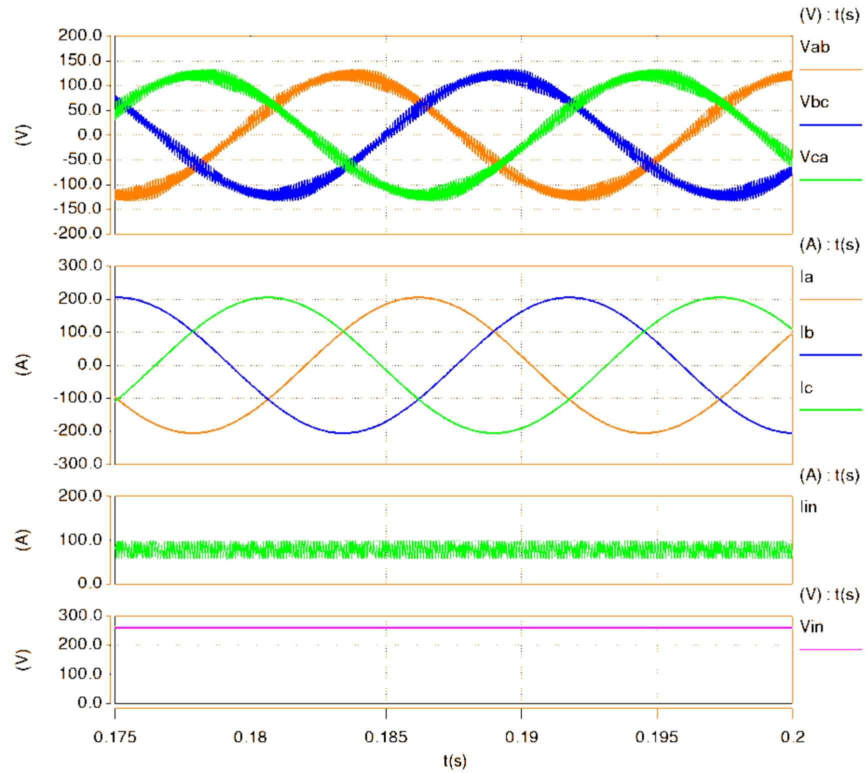


FY11 Technical Accomplishments (6)

- Simulation results of the CF Trans-qZSI with wider motoring operation range



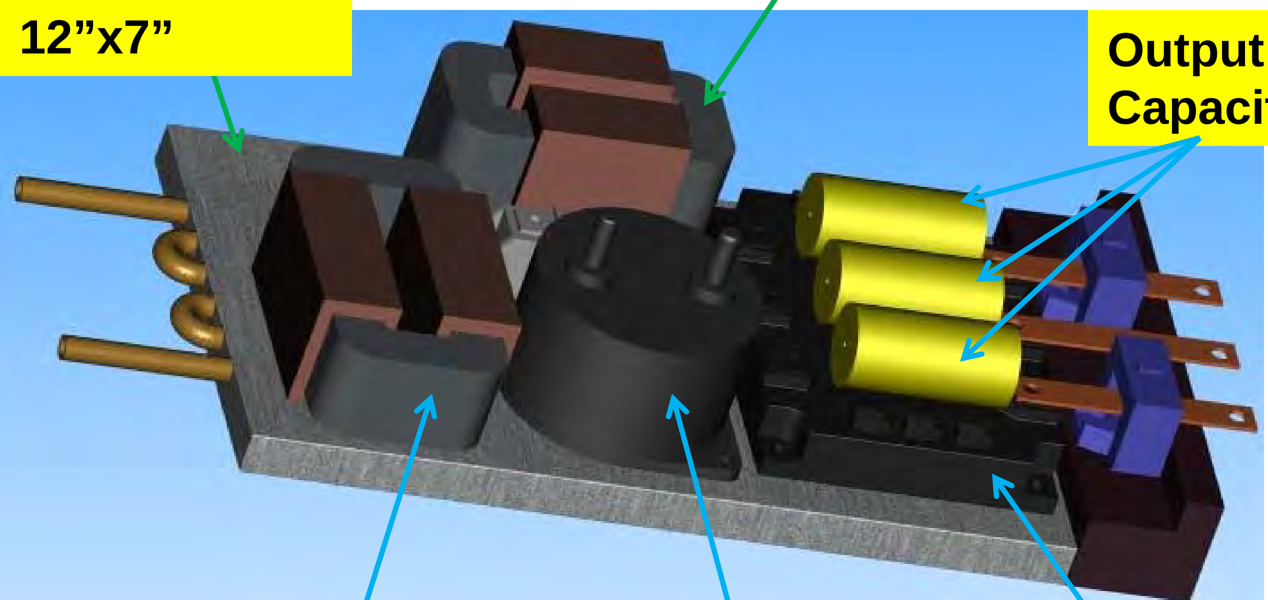
Simulated waveforms in boost mode

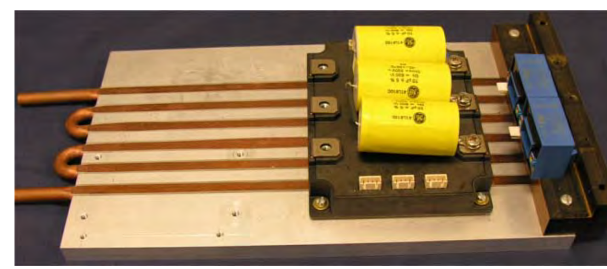


Simulated waveforms in buck mode

FY11 Technical Accomplishments (8)

- Hardware design and fabrication for a 10 kW ZCSI setup
  - Use Fuji RB-IGBTs
  - Optimize design of coupled inductor with amorphous core





Collaborations

- Michigan State University – current-fed Z-source inverter (ZCSI) topologies
- Powerex – design and fabrication of custom IGBT modules for prototype development
- Fuji Electric Semiconductor – reverse blocking (RB) IGBT modules and RB-IGBTs developments
- ORNL, John Hsu - collaborating to eliminate the inductors

Future Work

- Remainder of FY11
  - Finalize hardware design for a 10 kW ZCSI
  - Complete DSP code development that implements the new boost control algorithm
  - Complete fabrication and test of the 10 kW ZCSI

- FY12
  - Design, fabricate, and test a 55 kW ZCSI prototype

Summary

- The ZCSIs offer opportunities to meet the 2015 inverter targets while providing additional capabilities of voltage boost and PEV charging function
- ZCSIs using RB-IGBTs can substantially reduce power module cost, weight and volume by eliminating anti-parallel diodes
- The ZCSIs possess desirable characteristics
  - Sinusoidal voltages and currents to the motor
  - Elimination of failure modes caused by open or short-circuit dc link
  - Elimination of the uncontrolled PM regeneration failure mode
  - Ripple-free battery currents