U.S. DEPARTMENT OF ENERGY

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

Inverter Using Current Source Topology

Gui-Jia Su

Oak Ridge National Laboratory

June 10, 2010

Project ID: APE002

2010 DOE Hydrogen Program and Vehicle Technologies AMR

Overview

Timeline

- Start – Oct. 2009
- Finish – Sept. 2013
- 20% complete

Budget

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

Barriers

- The VSI has undesirable characteristics and requires a DC bus capacitor that is a significant barrier 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 technologies program targets
  - 2015 targets: $5/kW, 12 kW/kg, 12 kW/l

Partners

- Michigan State University – ZCSI
- Powerex – Custom IGBT modules
- Fuji – Reverse blocking IGBTs

Objectives

- Develop new 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

- Objective for FY10
  - Perform a simulation study on selected ZCSI topologies
  - Perform a feasibility assessment of using the ORNL CSI topology for HEV configurations with more than one motor

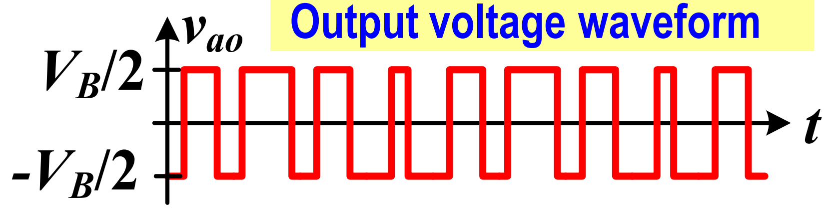
Milestones

Month/Year	Milestone or Go/No-Go Decision
Sept-2010	Milestone: Complete the simulation study on selected new ZCSI topologies. Go/No-Go Decision: A go/no-go decision will be made based on whether the simulation results verify that the following goals can be met: 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%.

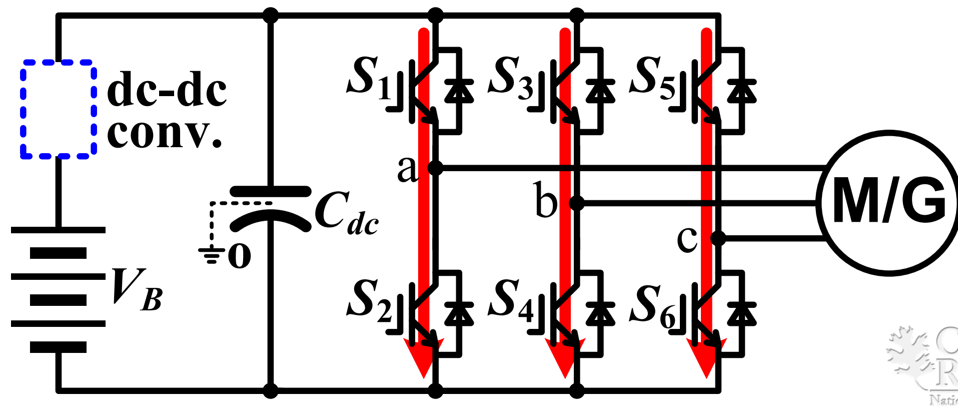
Approach

- **Characteristics of the Voltage Source Inverter (VSI) presents many drawbacks**
  - Undesired output voltage waveform generates
    - High EMI noises
    - High stress on motor insulation
    - High-frequency losses
    - Bearing-leakage currents
  - Requires a bulky & expensive bus capacitor; performance deteriorate significantly at high temperature; increasing switching frequency has little impact on ripple current requirement (cannot utilize the fast switching capability of wide-band gap devices)
  - Possible shoot-through causes long-term reliability concerns
  - Source voltage limits output voltage; a separate dc-dc converter is needed for voltage boosting

Output voltage waveform

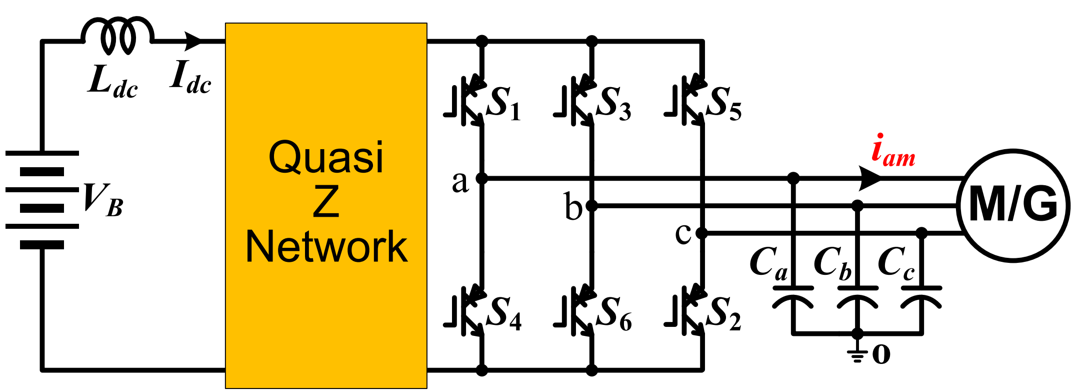


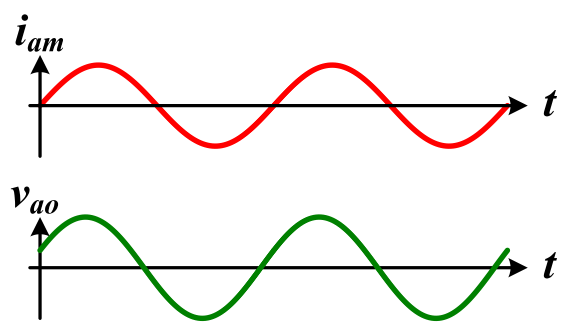
The Voltage Source Inverter (VSI)



Approach (contd.)

- CSI with a quasi-Z network (ZCSI):
  - Use a passive Z-network of inductor, capacitor, and diode in the CSI to enable
    - Single stage voltage buck and boost conversion
    - Battery charging
    - Safe operation in open circuit events
  - Eliminate antiparallel diodes
  - 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 dc-dc boost converter

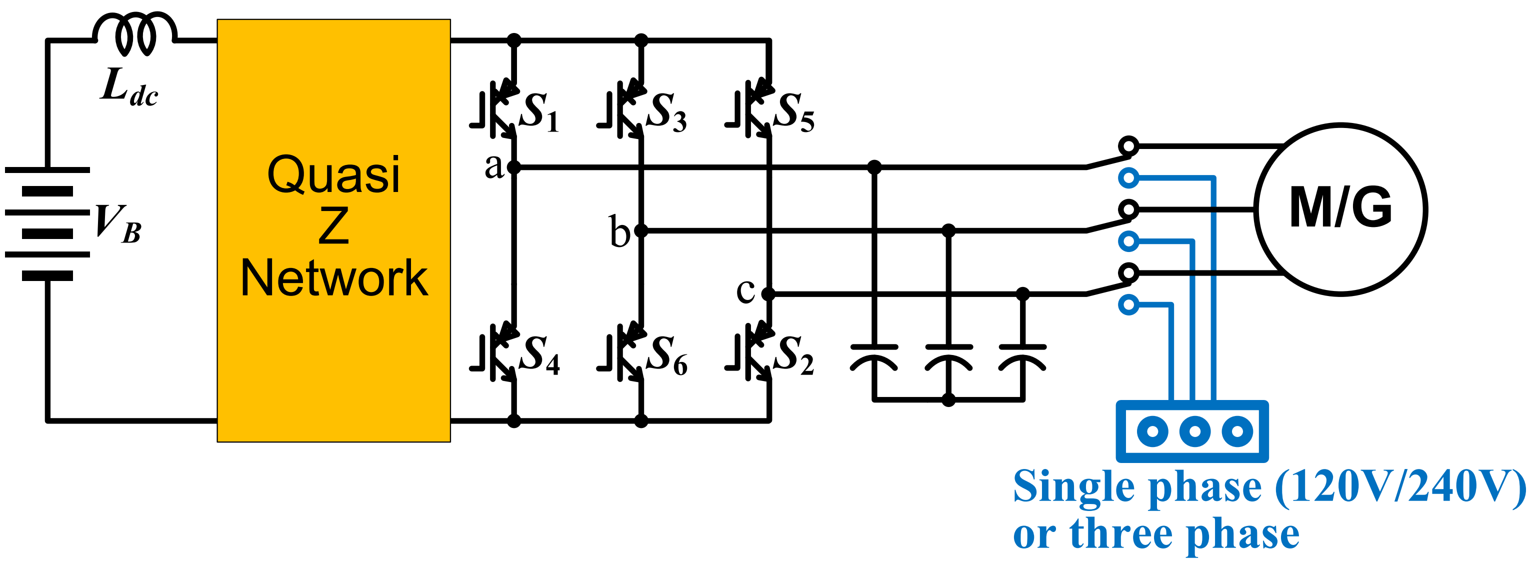




Sinusoidal output voltage & current

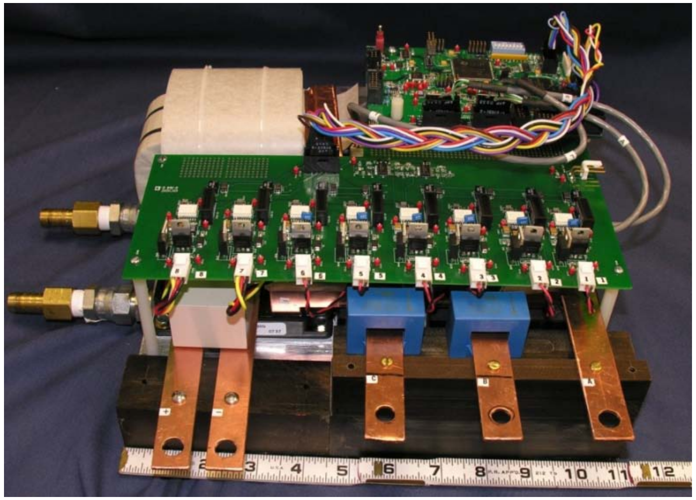
Approach (contd.)

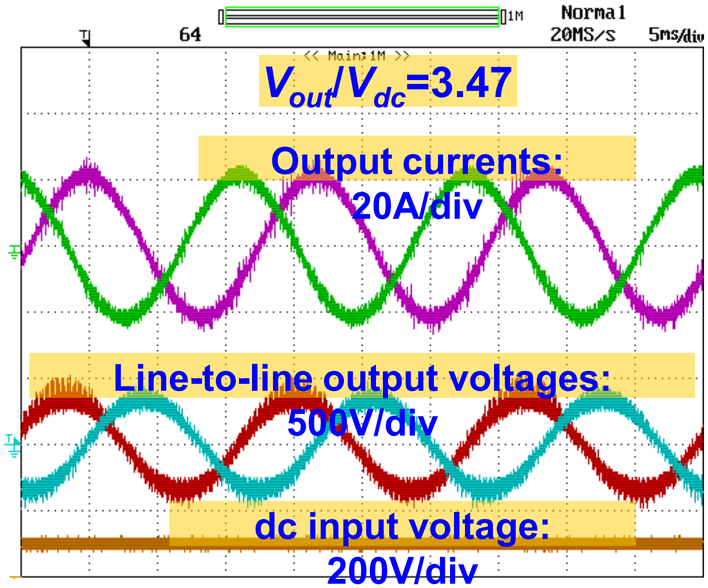
- CSI can be configured to operate as a charger in PEVs
  - Charge battery from a single-phase source of 120V or 240V
  - Charge battery from a three-phase source
  - Charge batteries over a wide range of voltage levels due to CSI's capability to buck and boost the output voltage



Technical Accomplishments/Progress –Previous work

- ORNL has demonstrated a 55 kW CSI prototype in a previous project
  - 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)



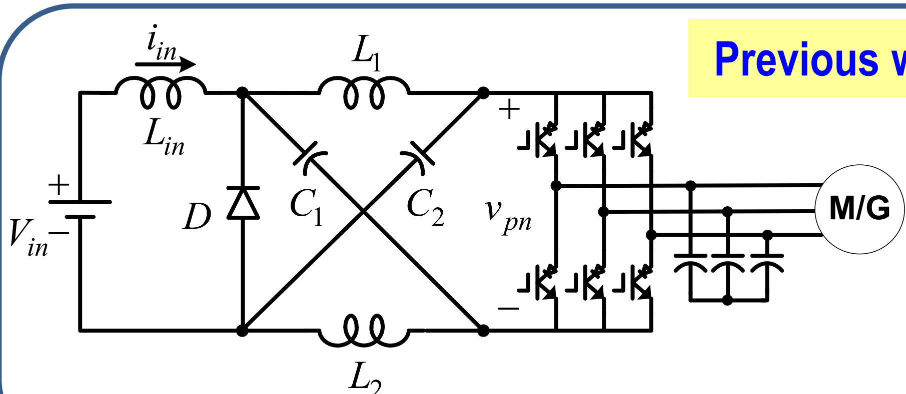


- MSU's early work on a current-fed quasi-Z-source inverter (qZSI) demonstrated buck, boost, and regen operations.

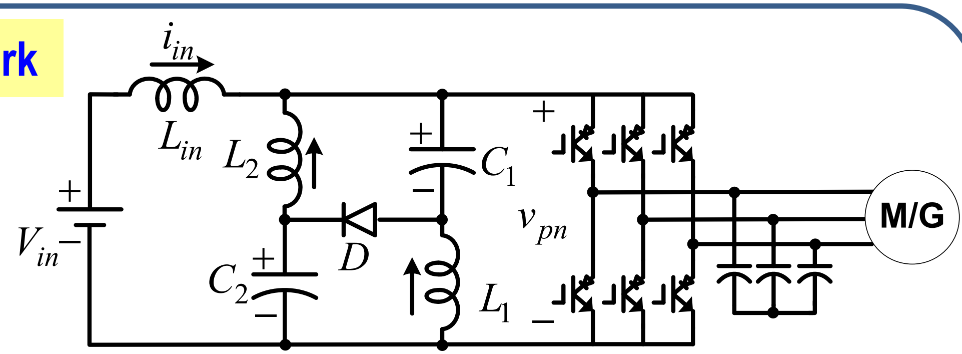
Technical Accomplishments/Progress –FY10

- **Evolution of current-fed ZSIs (ZCSIs) topologies**
  - Four current-fed ZSIs feature buck-boost and regeneration capability with passive impedance network
  - The new current-fed Trans-ZSI and Trans-quasi-ZSI feature wider motoring operation range and reduced component count.

Previous work

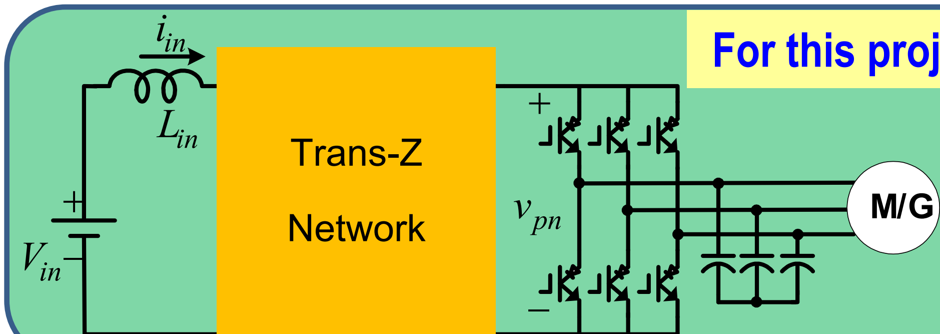


The original current-fed ZSI

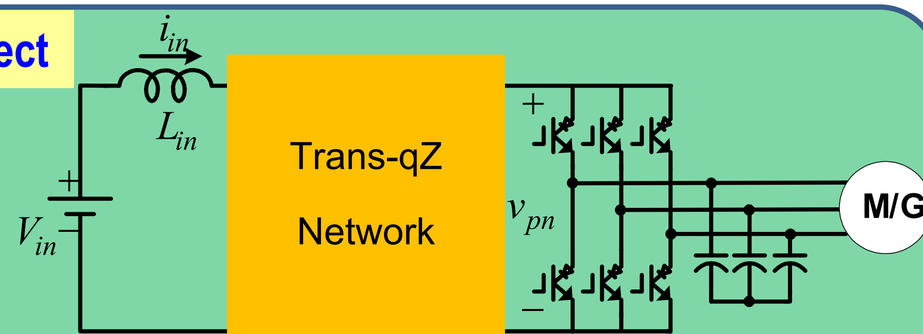


Current-fed qZSI

For this project



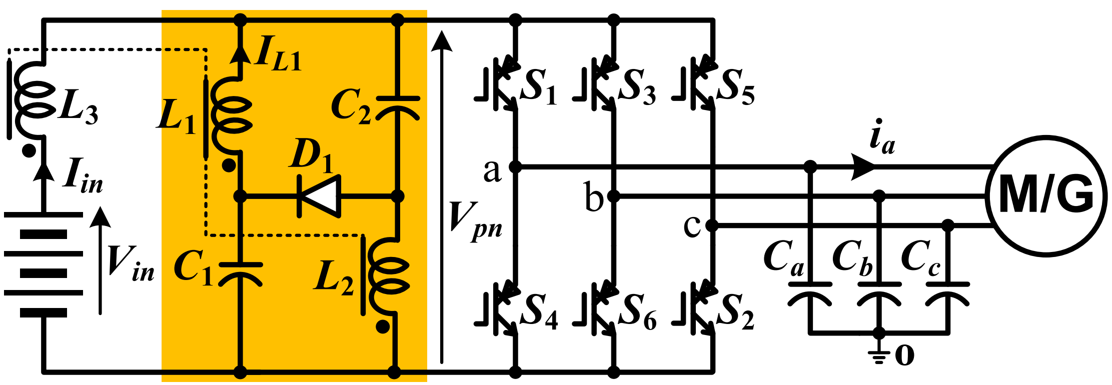
New current-fed Trans-ZSI

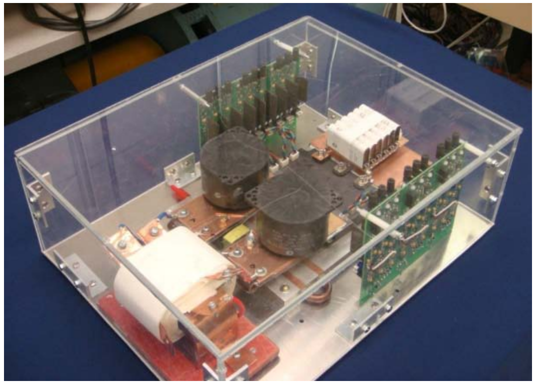


New current-fed Trans-qZSI

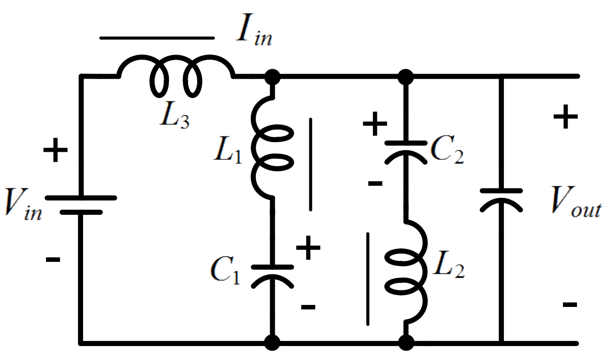
Technical Accomplishments/Progress −Previous work

- **Current-fed qZSI operating modes**

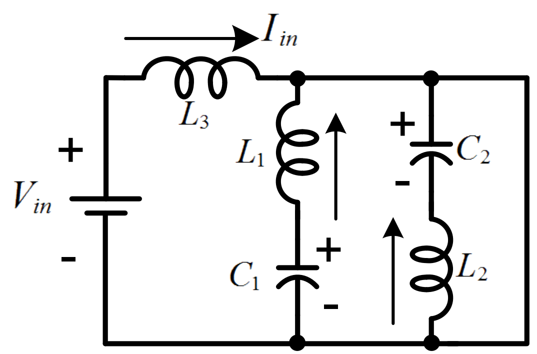




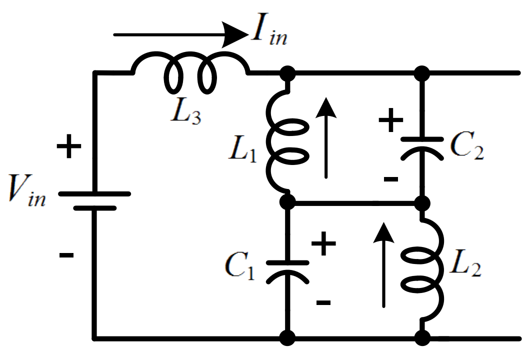
10kW prototype



Mode I: Active states



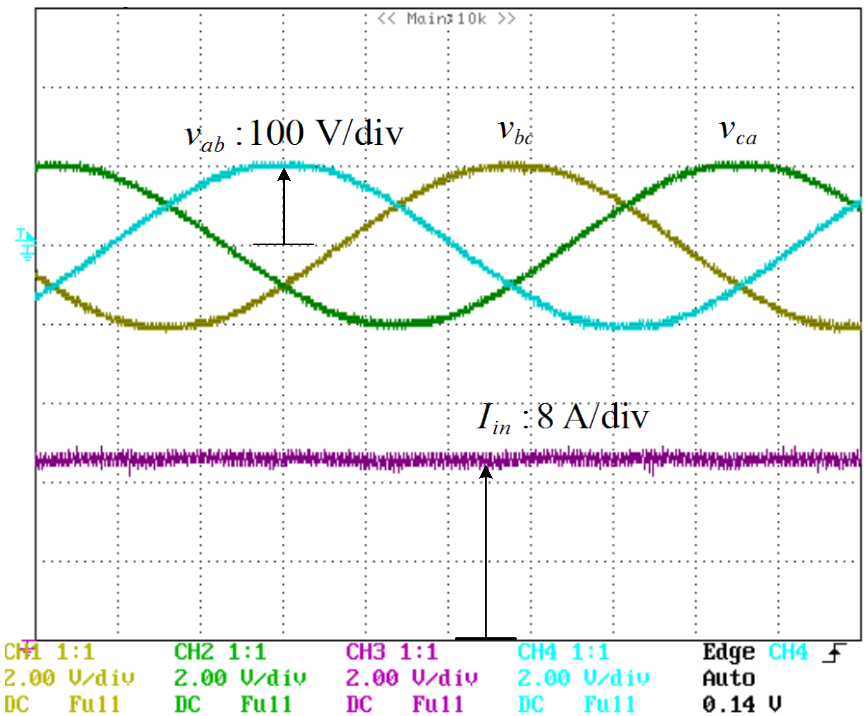
Mode II: Short-zero states



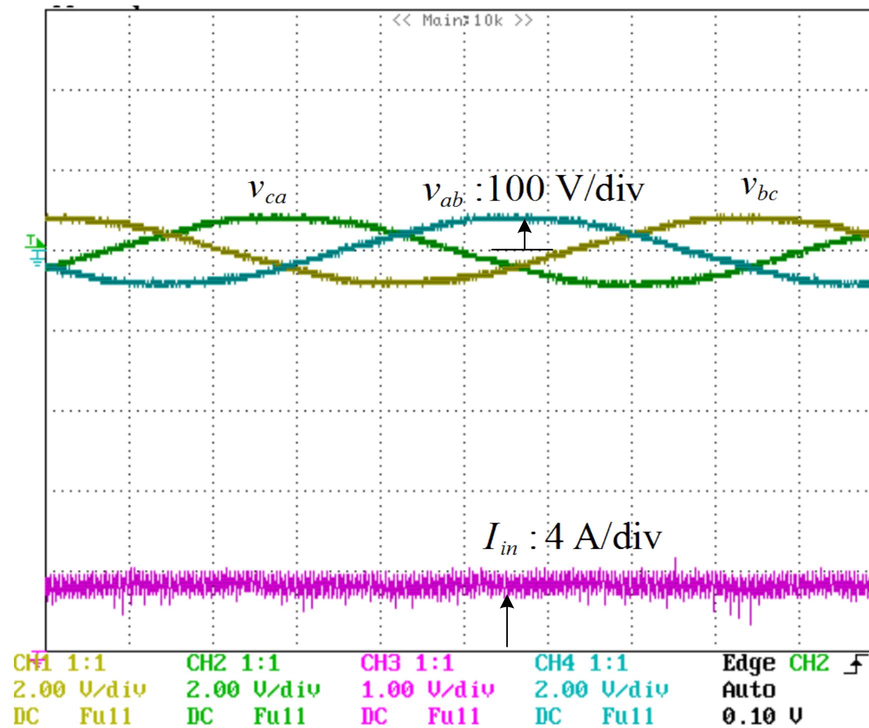
Mode III: Open-zero state

Technical Accomplishments/Progress –Previous work

- Current-fed qZSI test results in motoring operation



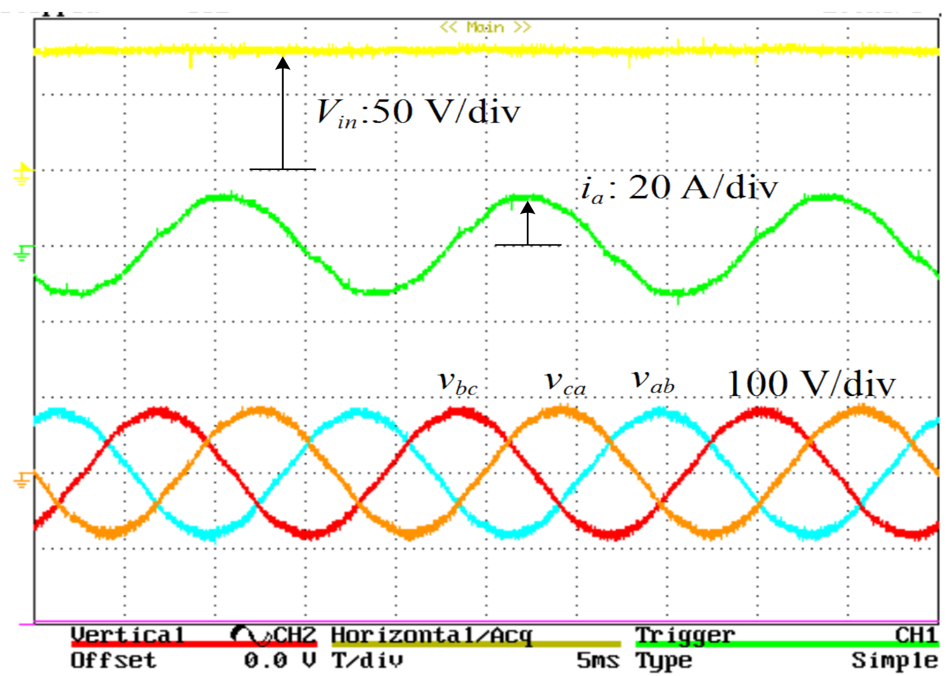
Boost mode

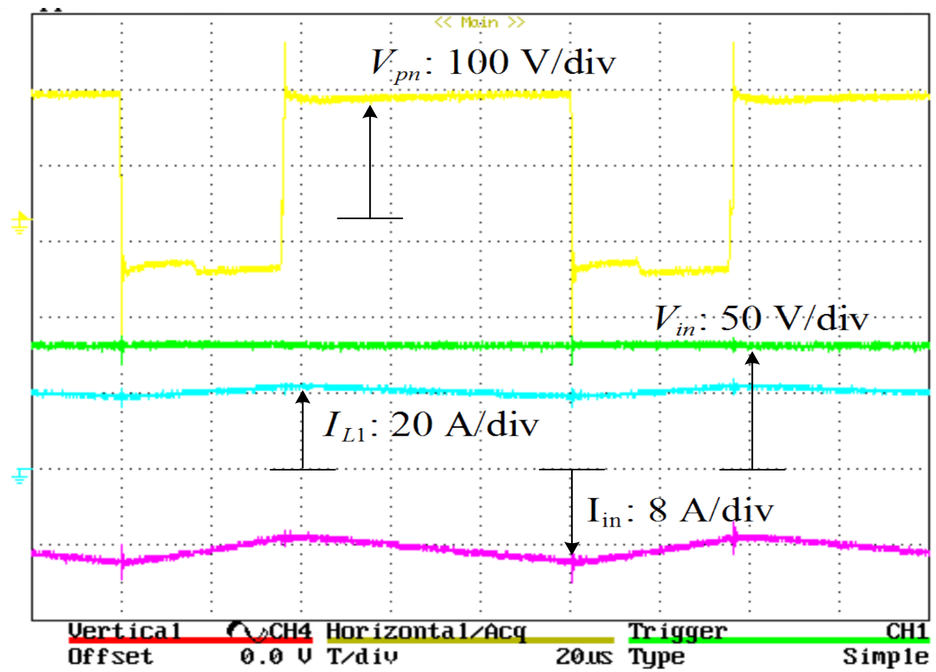


Buck mode

Technical Accomplishments/Progress –Previous work

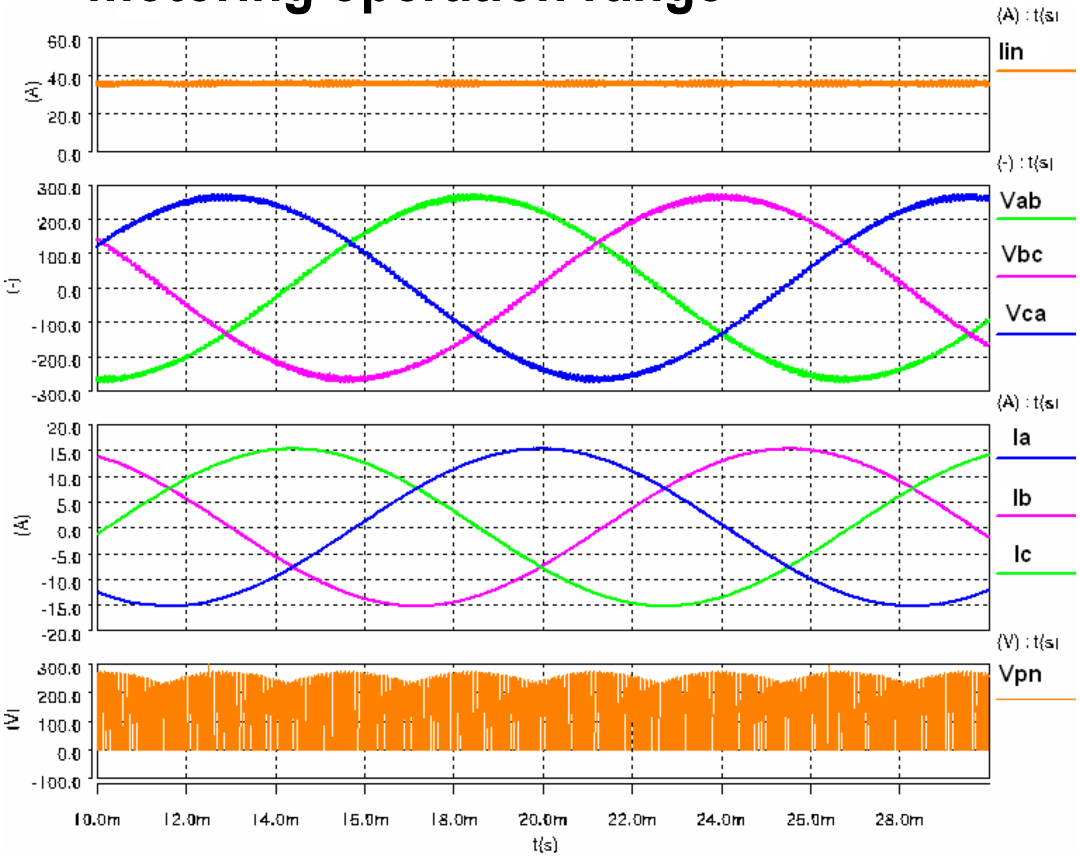
- Current-fed qZSI test results in regen operation





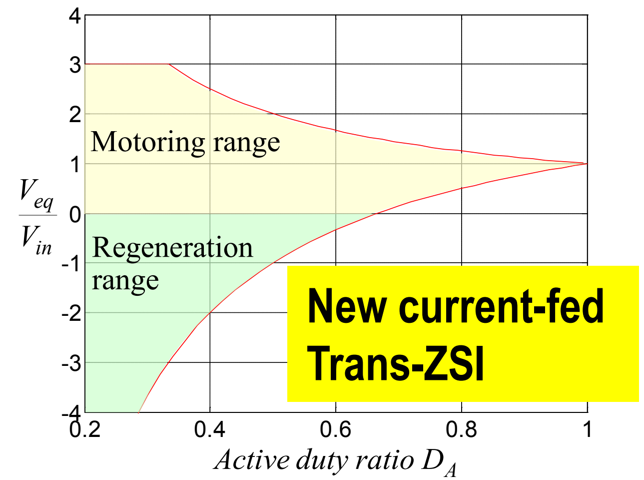
Technical Accomplishments/Progress –FY10

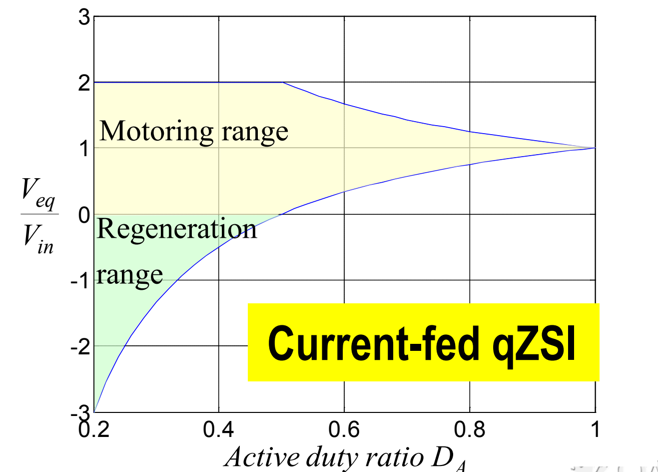
- Simulation results of the new current-fed Trans-ZSI with wider motoring operation range



V_{in}=100 V, transformer turns ratio=2

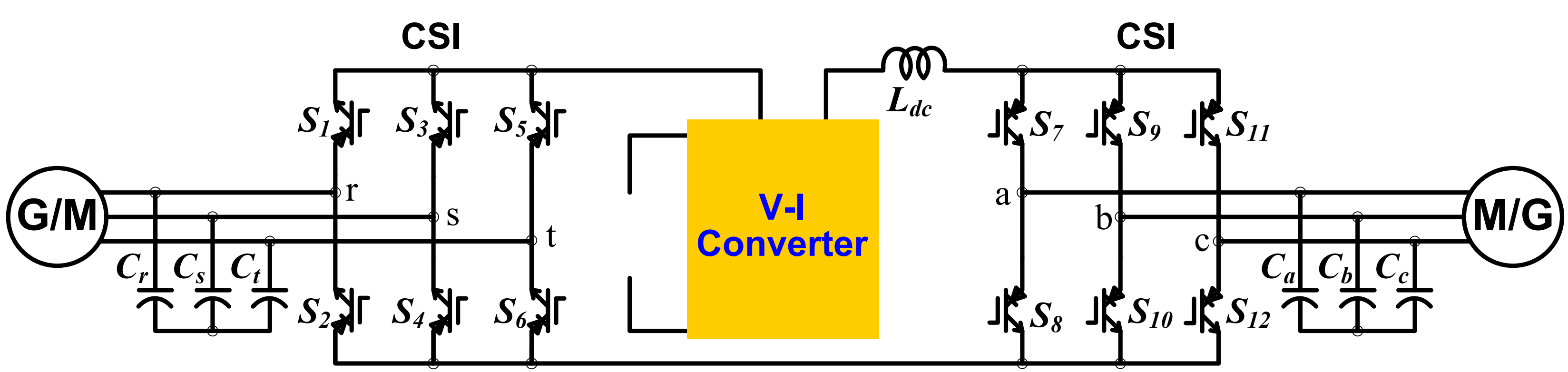
- Comparison of voltage boost ratio vs. duty ratio D_A





Technical Accomplishments/Progress –FY10

- ORNL dual CSI for HEVs/PEVs using two motors
  - Share a single dc link inductor and battery interface circuit (V-I converter)
  - 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
- Simulation results confirmed voltage buck and boost functionality for controlling one motor and one generator.



Collaborations

- Michigan State University (academic) – collaborations on current-fed Z-source inverter (ZCSI) topologies
- Powerex (industry) – collaborations on design and fabrication of custom IGBT modules for prototype development
- Fuji Semiconductor (industry) – collaborations about latest development in reverse blocking IGBTs and its impact on CSIs

Future Work

- Remainder of FY10
  - Complete the simulation study of the two new ZCSI topologies
  - Complete the feasibility assessment of the dual CSI for HEVs/PEVs using two motors
- FY11
  - Design, fabricate, and test two 55 kW prototypes based on the two new ZCSI topologies
- FY12
  - Perform feasibility study of the new ZCSIs for PEV configurations using more than one motor
  - Design and fabricate 55 kW prototypes based on the new ZCSI topologies for PEV configurations using more than one motor
- FY13
  - Test and characterize the 55 kW ZCSI prototypes built in FY12 in traction drive and battery charger modes

Summary

- The ZCSI inverters use passive components to enable the CSI to
  - buck and boost output voltage in a single stage conversion
  - operate in regen mode to charge the battery
  - operate safely in open and short circuit events
  - operate as a universal charger for PHEVs
- Reduce power electronics cost, weight and volume
- Increase constant-power speed range without using a dc-dc boost converter
- Improve inverter reliability and motor lifetime and efficiency
- Provide design flexibility in sizing the battery

- Prototype test results from previous work and simulation study indicate the ZCSI is a promising alternative to the VSI and can fully utilize the fast switching wide-band gap devices to significantly reduce the size, weight and volume of the passive components.