Advanced Soft Switching Inverter for Reducing Switching and Power Losses

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Overview

Timeline

• Start – Sep 2007
• Finish – Sep 2010
• 50% Complete

Budget

• Total project funding
  – DOE - $1,587,448
  – NIST - $93,910
  – Contractor - $1,126,358
• Funding received in FY08
  – $650,266
• Funding received in FY09
  – $454,460

Barriers

• Barriers addressed
  – Inverter Cost
  – Inverter Weight and Volume
  – Inverter Thermal control
• Target
  – Achieve efficiency >98% to allow the use of silicon devices at 105° coolant operating condition

Partners

• National Institute of Standards and Technology – Modeling and Simulation
• Powerex – Soft switch module packaging
• Azure Dynamics – Dynamometer and vehicle testing
Objectives

- **Overall Objective:** To develop advanced soft switching inverter for traction motor drives to support the following DOE targets
  - 105°C coolant temperature – by designing the junction temperature <125°C
  - 94% traction drive system efficiency – by designing the inverter efficiency >98%

- **Year 2 Objectives**
  - Demonstrate the first generation variable-timing soft-switching inverter operation
  - Develop the second generation soft-switching module for cost and integration considerations
Milestones

System level modeling simulation
Develop variable-timing control
Develop gen-1 soft-switch module
Perform failure mode effect analysis
Characterize gen-1 module
Test inverter with dyno and calorimeter
Develop gen-2 soft-switch modules
Evaluate EMI performance
Design controller and gate drive circuits
Integrate inverter for in-vehicle testing
Develop gen-3 soft-switch modules
Perform in-vehicle testing
Volume production cost analysis
Approach

- Develop a **variable timing controlled soft-switching inverter** for loss reduction.
- Develop **low thermal impedance module with integrated heat sink** for high temperature operation.
- Develop a **highly integrated soft-switch module** for low cost inverter packaging.
- **Modeling and simulation** for design optimization.
- Test the soft-switching inverter with existing EV platform and dynamometer for **EMI and efficiency performance** verification.
Accomplishment – Variable Timing Soft Switching over a Wide Load Current Range

- During turn-on, current $I_C$ rises after voltage $V_{CE}$ drops to zero
- During turn-off, $V_{CE}$ slowly rises after $I_C$ drops to zero
- Variable timing achieves soft-switching at all current conditions
- Bonus – slow dv/dt that will result in low EMI emission
Accomplishment – Improve Thermal Efficiency with Integrated Chilled Plate

Standard module w/ external liquid-cooled chill plate

Integrated liquid-cooled chill plate module

Reduction of thermal resistance by eliminating layers in heat flow path with liquid cooled chill plate integrated in module
Accomplishment – 3-D Thermal Simulation Results for Temperature Prediction

Each die loaded with power dissipation results from circuit simulations

Top of AlSiC Baseplate with AlN Substrate & Die

Bottom of AlSiC Baseplate with Molded Pin Fins

Output IGBT $\Delta T = 15^\circ C$ above bottom of Baseplate

Liquid cooled pin-fin chill plate integrated in module reduces thermal resistance and thus $\Delta T_{(junction-liquid)}$
Accomplishment – Conduction Loss Reduction with a New Hybrid Soft Switch Module

- Parallel IGBT and MOSFET for conduction loss reduction for a wide range of current and temperature condition
- Integrated module with direct cooling to reduce thermal resistance
- Higher temperature, lower voltage drop → ideal for high temperature operation
- Compared with commercial modules: 1.46V versus 1.67V drop @400A (13% reduction)
Accomplishment – Switching Loss Reduction Using LPT IGBT

- For hard switching, as compared to 25°C operating condition,
  - Device switching loss is increased by 40% at 100°C
  - Device switching loss is reduced by 80% under soft switching
- Losses in soft switching are due to layout parasitics with discrete components – necessary to integrate the soft switch module
Accomplishment – Completed a Scaled Version Soft-Switching Inverter

- Main power device consists of two MOSFETs and one IGBT, auxiliary device and diode are mounted on the same heat sink.
- Gate drive board sits on top of power devices, and interface board sits on top of gate drive board
- Coupled magnetics are made of ferrite core and Litz wire
- Conventional liquid cooled heat sink for the scaled version
Accomplishment – Full-Version Efficiency Verified with Calorimeter Test (>99%)

- Using integrated module with light-weight water manifold for the full-version soft-switching inverter.
- Calorimeter chamber inlet and outlet temperatures stabilized after 6-hour testing. Chamber temperature differential was 1.6 °C under 0.3 GPM flow rate.
- Efficiency exceeded 99% at full speed, 30% load torque condition.
Accomplishment – Measured Peak Efficiency Exceeds 99%

Test condition: $V_{dc} = 325$ V, $f_{sw} = 10$ kHz (PWM), $f_1 = 83.3$ Hz, $T_a = 25^\circ$C

Accuracy of Instrumentation: ±0.2%

- Measured peak efficiency of both scaled- and full-version inverters reached 99%, higher than the estimated because the experiment was conducted at a lower temperature and half the switching frequency.
- Scaled version is more efficient under light loads, but the full version is more efficient under heavy loads because of larger IGBT dies and well-regulated temperature.
Accomplishment – Using FEA to Predict Temperature for Soft-Switching Inverter

Boundary conditions:
Ambient temperature: 45°C
Heat sink temperature: 105°C

• Simulated hot spot junction temperature consistent with theoretical calculation: 120°C or 15°C temperature rise
• Circuit components inside the chassis see temperature between 65°C and 85°C
Accomplishment – Soft-Switching Inverter Testing with Motor Dynamometer

- Scaled version soft-switching inverter has been tested with the 55-kW motor dynamometer set
- Rigorous test with different torque commands and instant speed reversal

speed reversal with negative torque commanded

200ms/div
Future Work

- Complete More Integrated Gen-2 and Gen-3 Modules
- Complete Controller Board and Softwares
- Integrate Entire Soft Switching Inverter
- Perform In-Vehicle Testing with Soft-Switching Inverter
- EMI Testing with Soft-Switching Inverter
- Manufacturability and Cost Analyses

Preparation for In-Vehicle Testing
Summary

- The first generation soft-switch module successfully demonstrates
  - 13% conduction loss reduction
  - 80% switching loss reduction
  - 60% thermal impedance reduction

- Variable timing control is successfully developed for high efficiency over a wide load range
  - Experimental results of a scaled version inverter demonstrates peak efficiency near 99%

- The full-version first-generation soft-switching inverter shows
  - Peak efficiency exceeds 99% with calorimeter test verification
  - 15°C junction temperature rise with finite element analysis projection
  - 105°C coolant operating at full load is possible

- Other technical accomplishments
  - Completed device characterization and finite element analysis
  - Set up high-accuracy dyno and calorimeter tests