Advanced Soft Switching Inverter for Reducing Switching and Power Losses

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Project ID: ape_06_lai

Outline

- Overview
- Objectives
- Milestones
- Approaches
- Accomplishments
- Future Work
- Summary

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

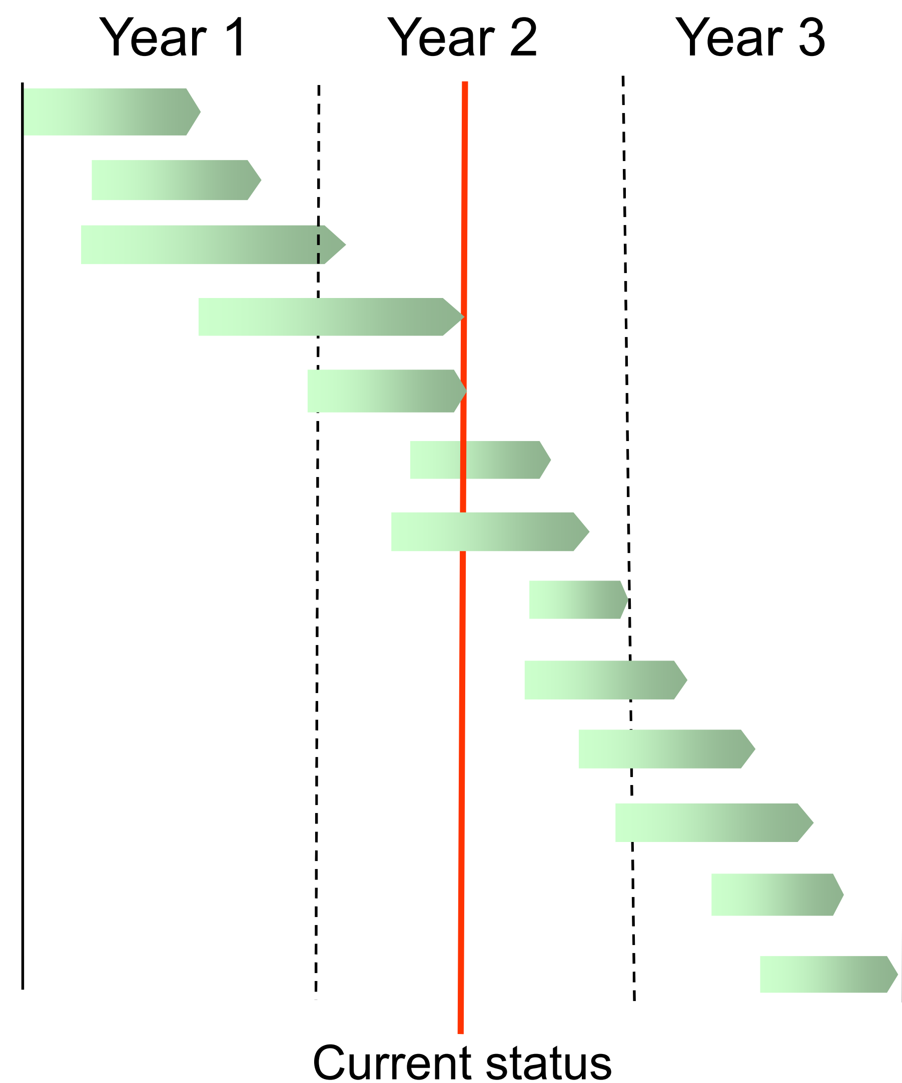
- National Institute of Standards and Technology – Modeling and Simulation
- Powerex – Soft switch module packaging
- Azure Dynamics – Dynamometer and vehicle testing

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

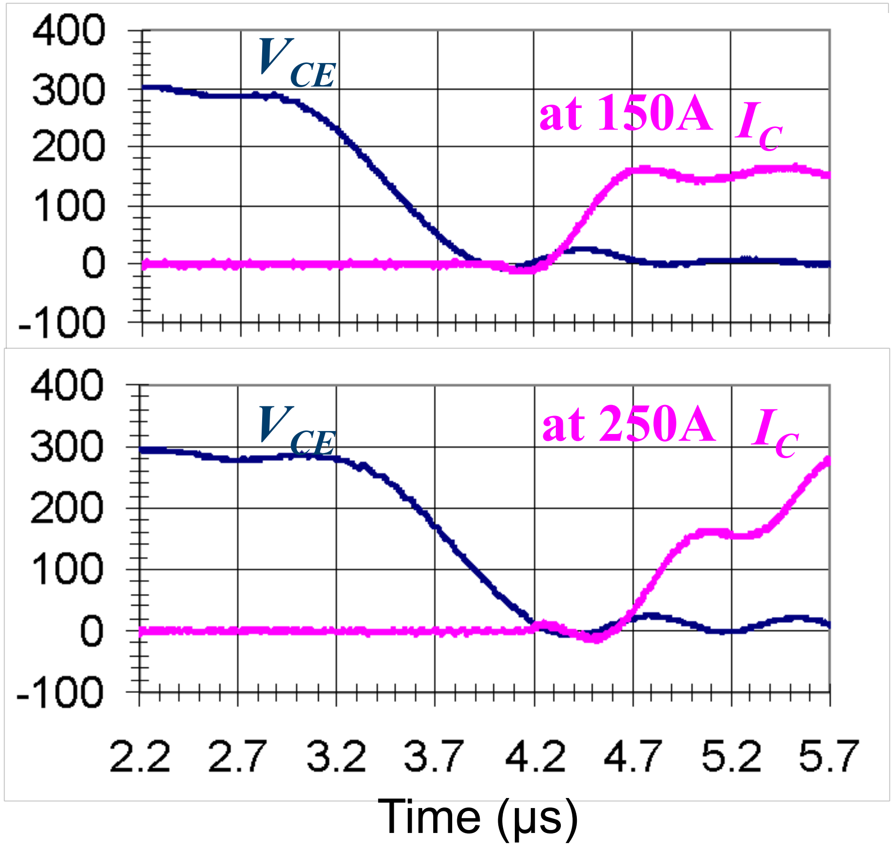
- System level modeling simulation
- Develop variable-timing control
- Develop gen-1 soft-switch module
- Perform failure mode effect analysis
- Characterize gen-1 module
- Test inverter with dyno and calorimeter
- Develop gen-2 soft-switch modules
- Evaluate EMI performance
- Design controller and gate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

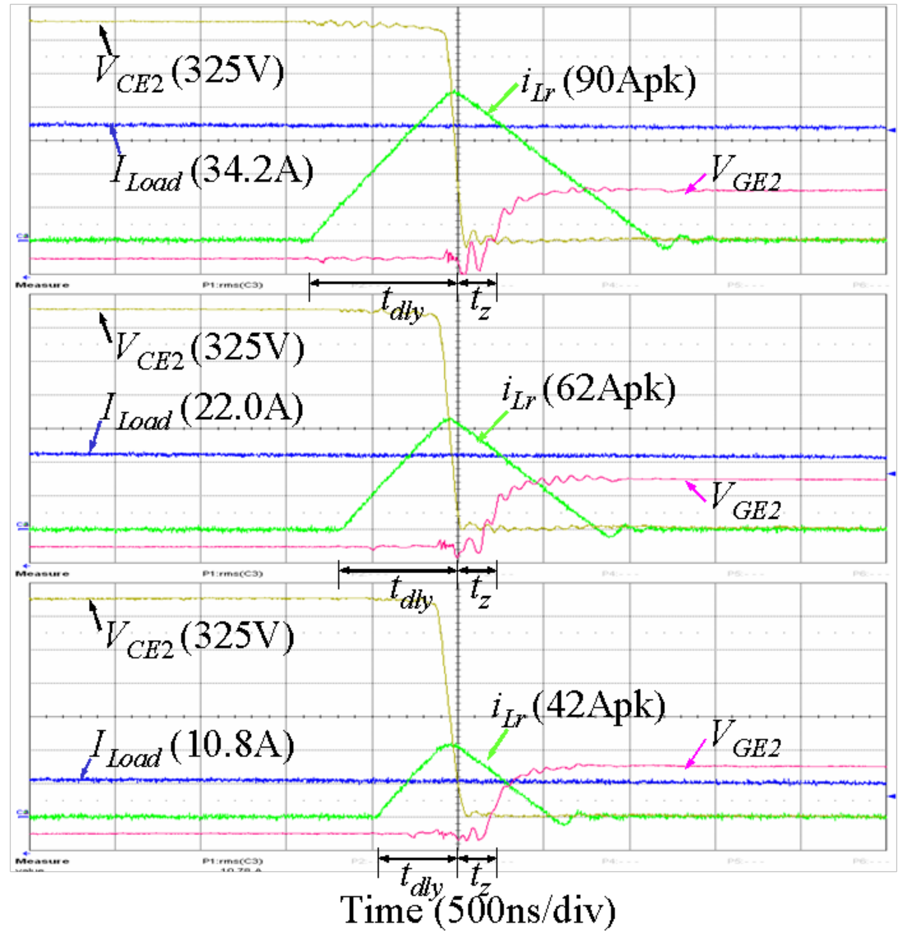


Approach

- 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

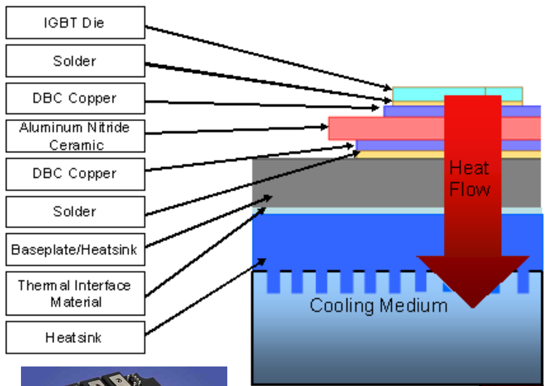


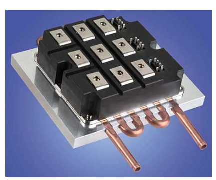


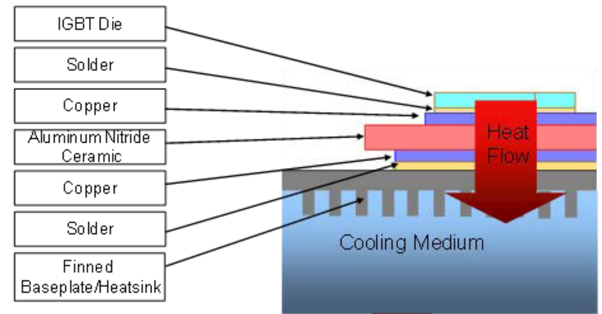
- **During turn-on, current I_C rises after voltage V_{CE} drops to zero**
- **During turn-off, V_{CE} slowly rises after I_C drops to zero**
- **Variable timing achieves soft-switching at all current conditions**
- **Bonus – slow dv/dt that will result in low EMI emission**

Accomplishment – Improve Thermal Efficiency with Integrated Chilled Plate

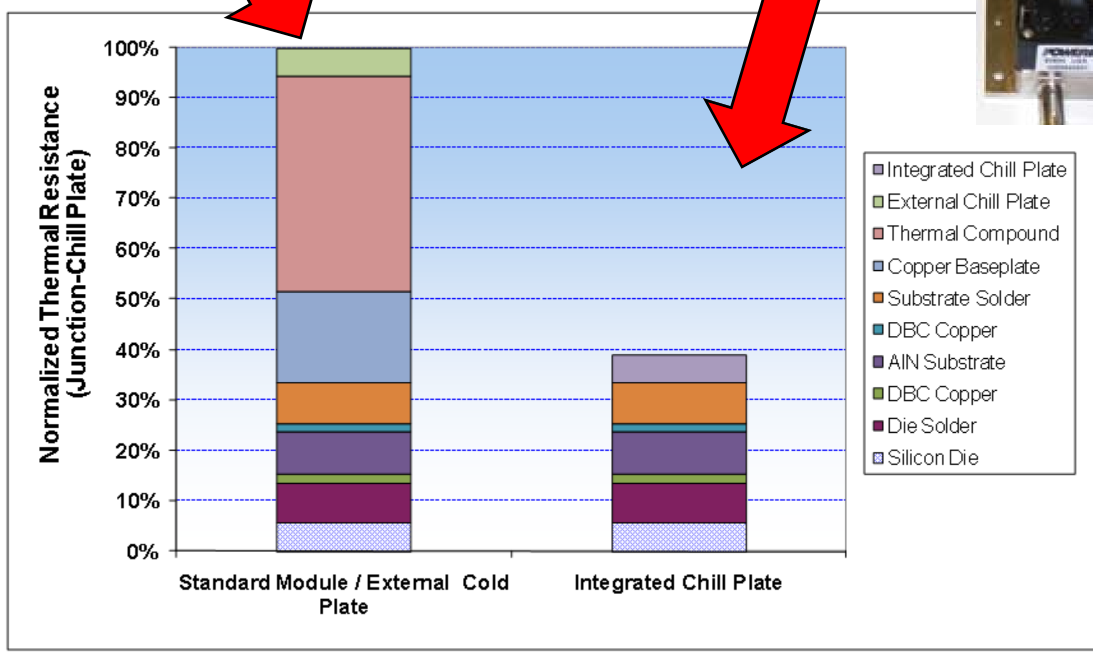
Standard module w/ external liquid-cooled chill plate







Integrated liquid-cooled chill plate module

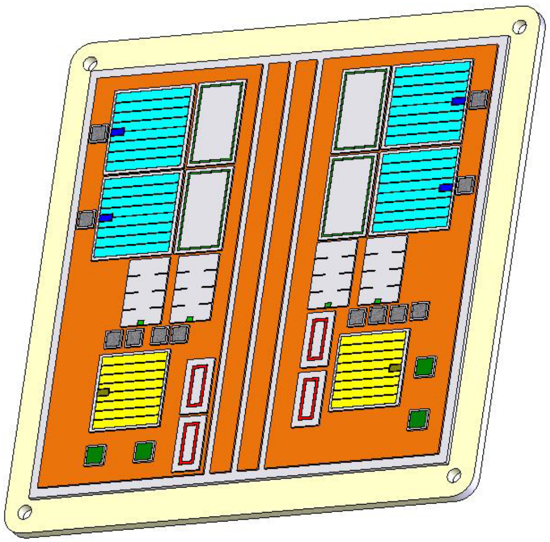


Reduction of thermal resistance by eliminating layers in heat flow path with liquid cooled chill plate integrated in module

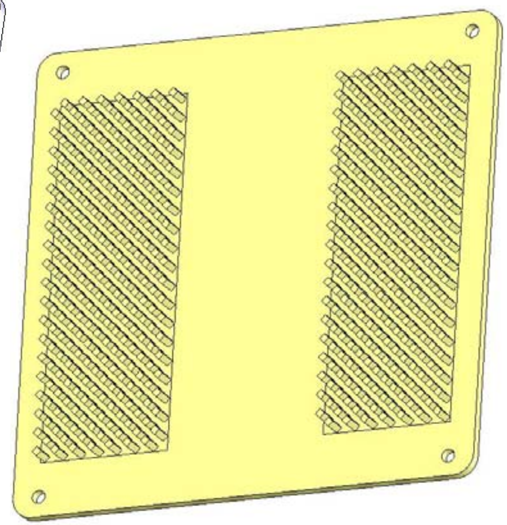
Accomplishment – 3-D Thermal Simulation Results for Temperature Prediction

Each die loaded with power dissipation results from circuit simulations

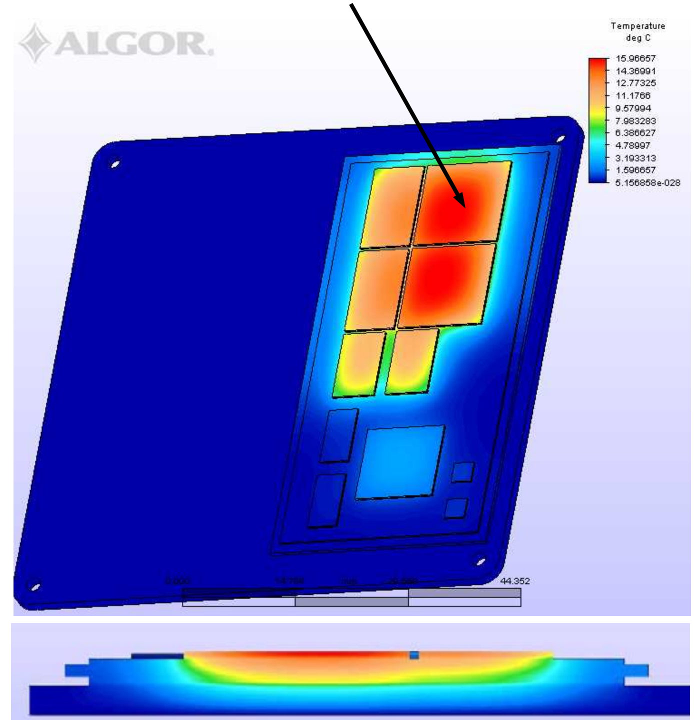
Output IGBT ΔT = 15°C above bottom of Baseplate



Top of AlSiC Baseplate with AlN Substrate & Die



Bottom of AlSiC Baseplate with Molded Pin Fins



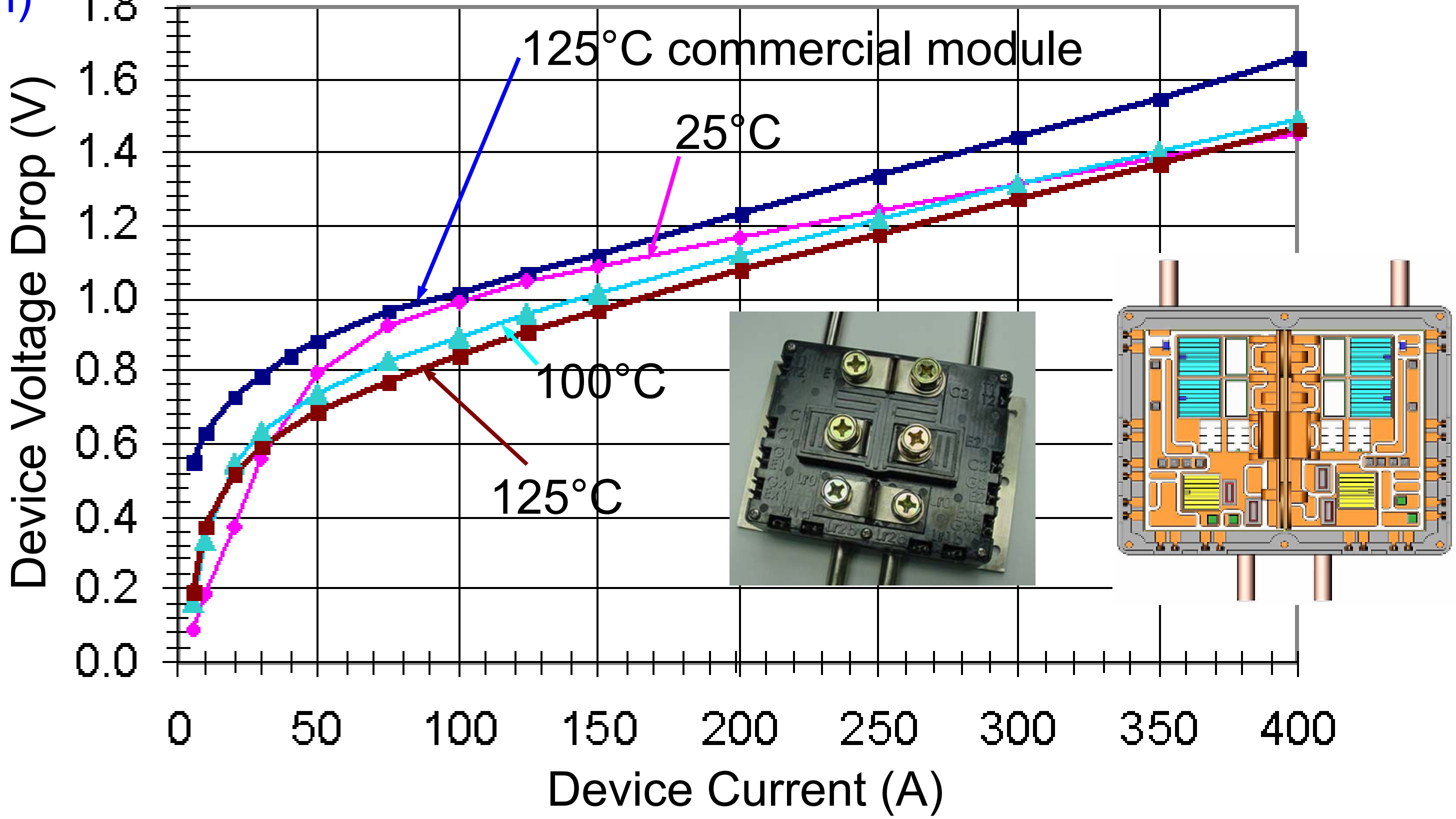
Liquid cooled pin-fin chill plate integrated in module reduces thermal resistance and thus $\Delta T_{(junction-liquid)}$

Accomplishment – Conduction Loss Reduction with a New Hybrid Soft Switch Module

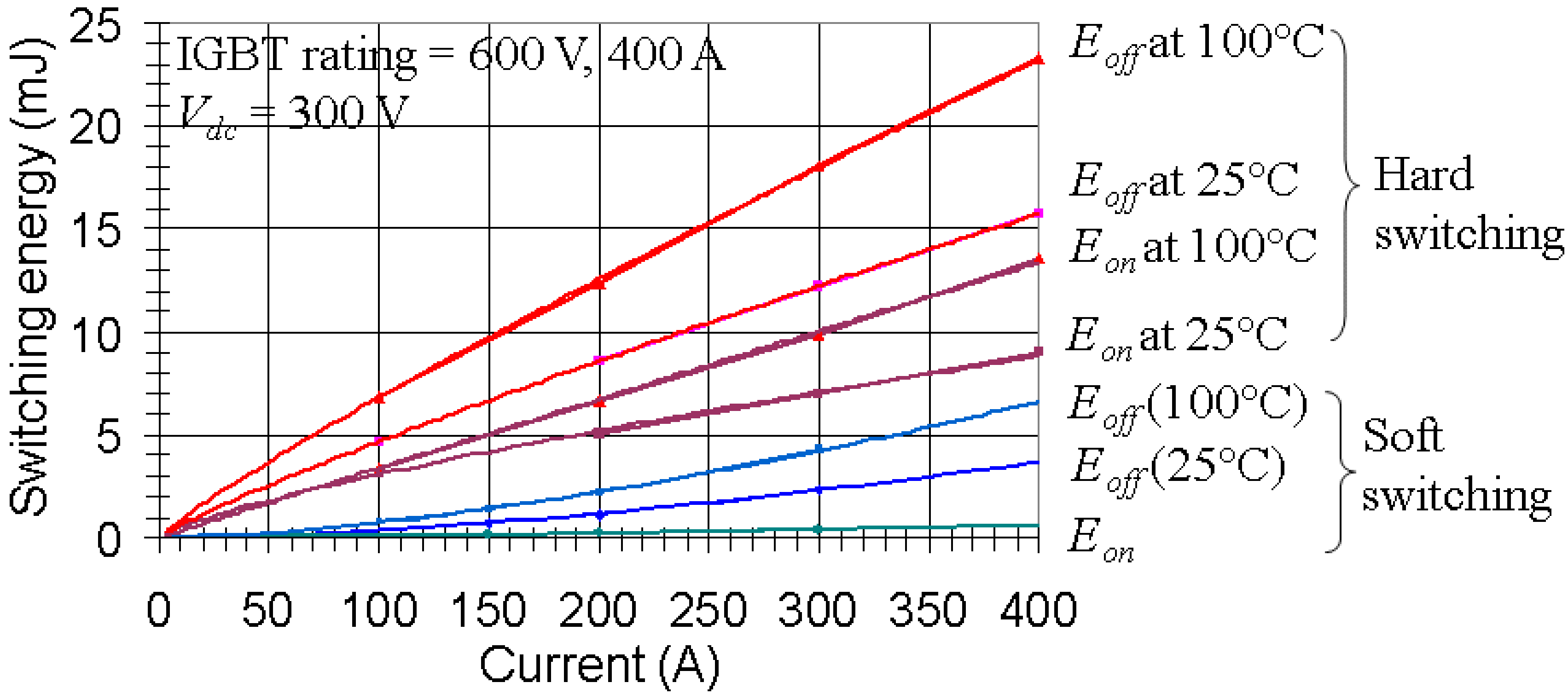
- Parallel IGBT and MOSFET for conduction loss reduction for a wide range of current and temperature condition
- Integrated module with direct cooling to reduce thermal resistance

✓ Higher temperature, lower voltage drop → ideal for high temperature operation

✓ Compared with commercial modules: 1.46V versus 1.67V drop @400A (13% reduction)

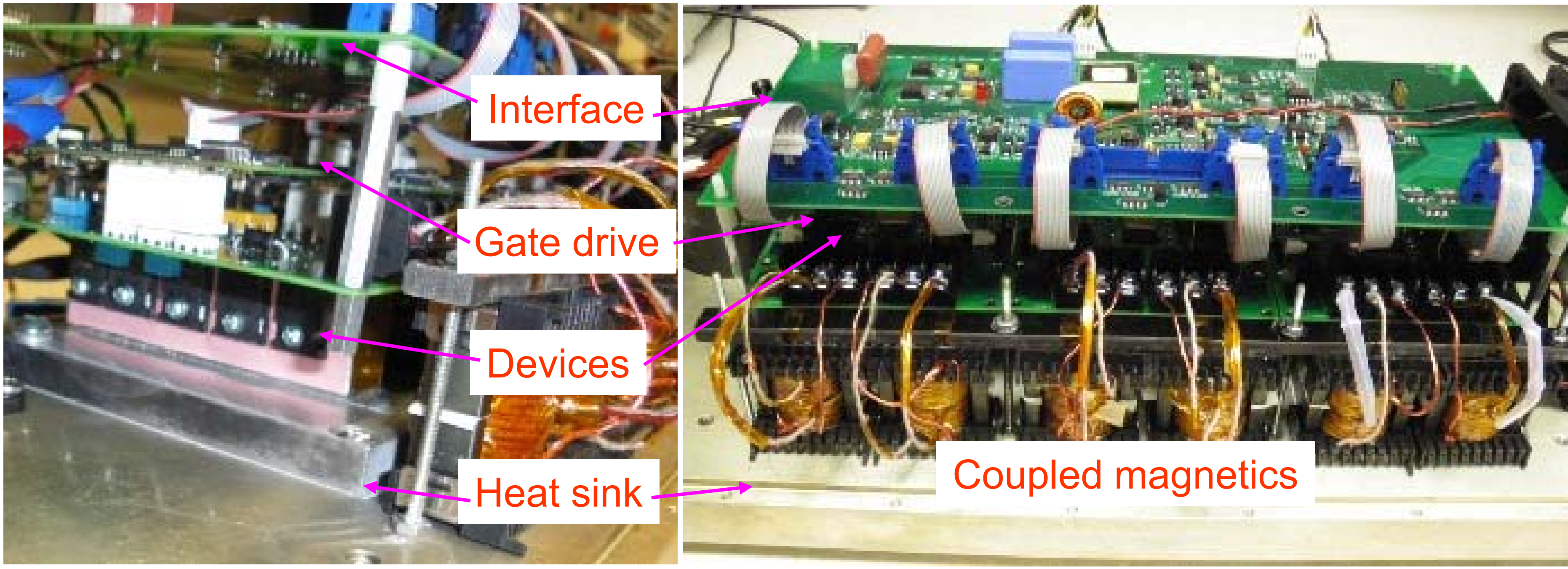


Accomplishment – Switching Loss Reduction Using LPT IGBT



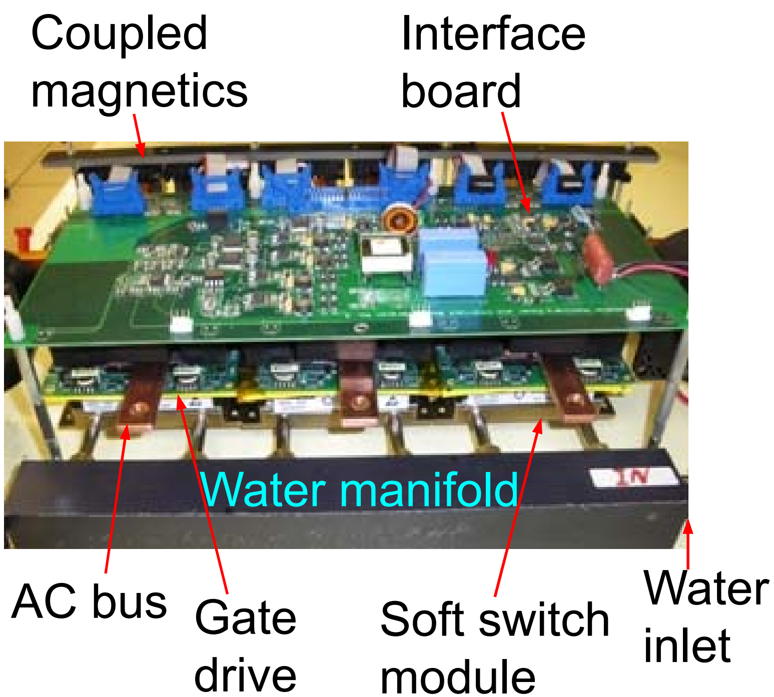
- **For hard switching, as compared to 25°C operating condition,**
  - **Device switching loss is increased by 40% at 100°C**
  - **Device switching loss is reduced by 80% under soft switching**
- **Losses in soft switching are due to layout parasitics with discrete components – necessary to integrate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

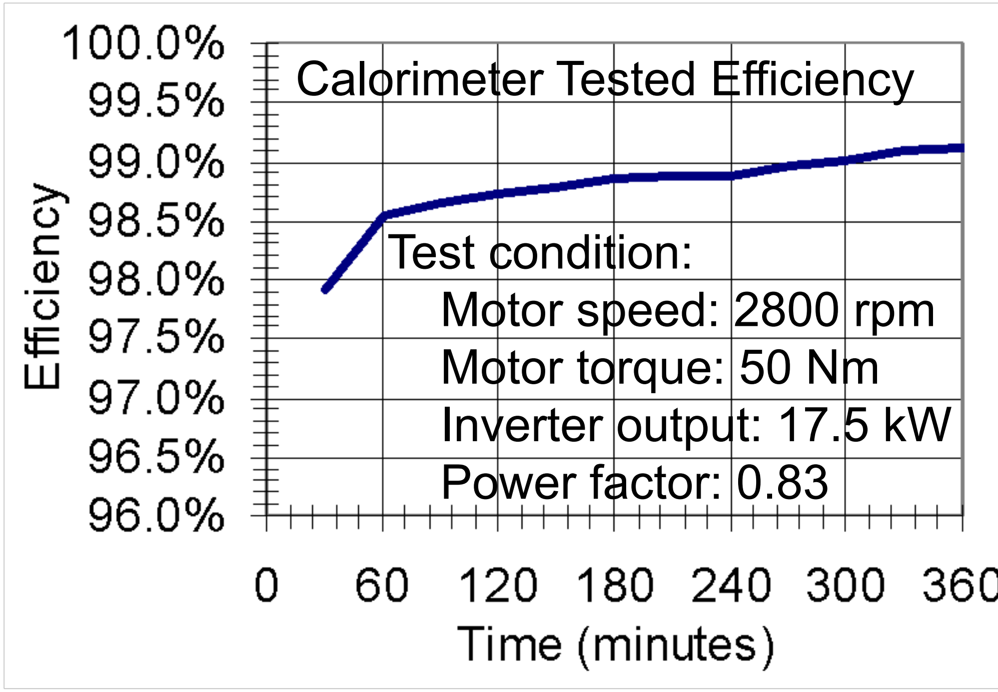
Accomplishment – Completed a Scaled Version Soft-Switching Inverter



- **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**

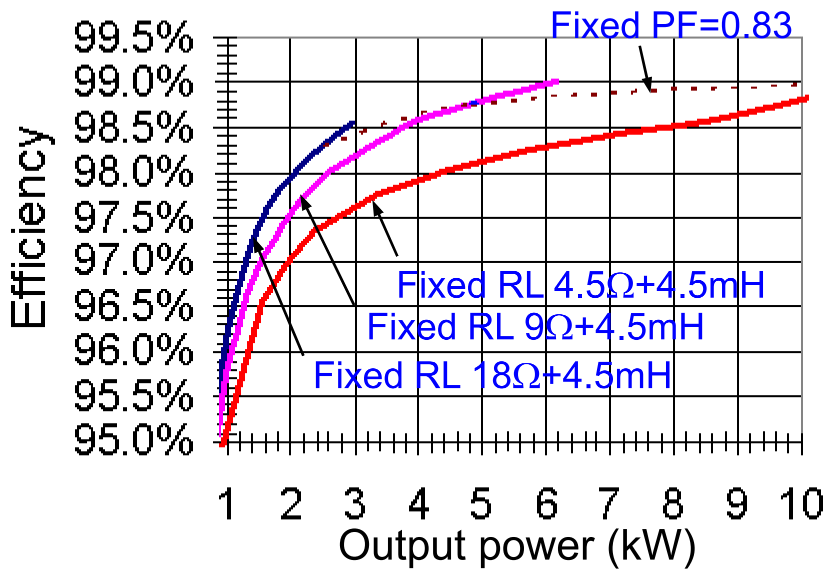
Accomplishment – Full-Version Efficiency Verified with Calorimeter Test (>99%)



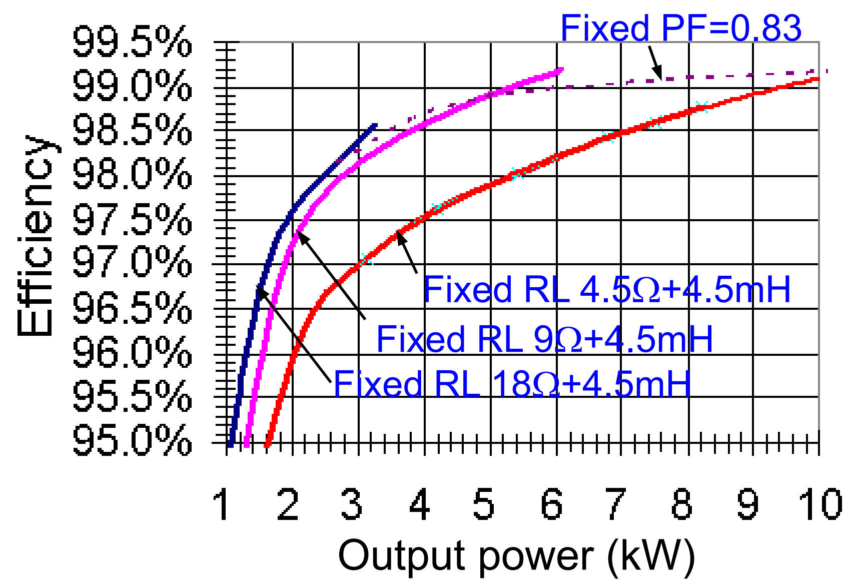


- **Using integrated module with light-weight water manifold for the full-version soft-switching inverter.**
- **Calorimeter chamber inlet and outlet temperatures stabilized after 6-hour testing. Chamber temperature differential was 1.6 °C under 0.3 GPM flow rate.**
- **Efficiency exceeded 99% at full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

Accomplishment – Measured Peak Efficiency Exceeds 99%



(a) Scaled version

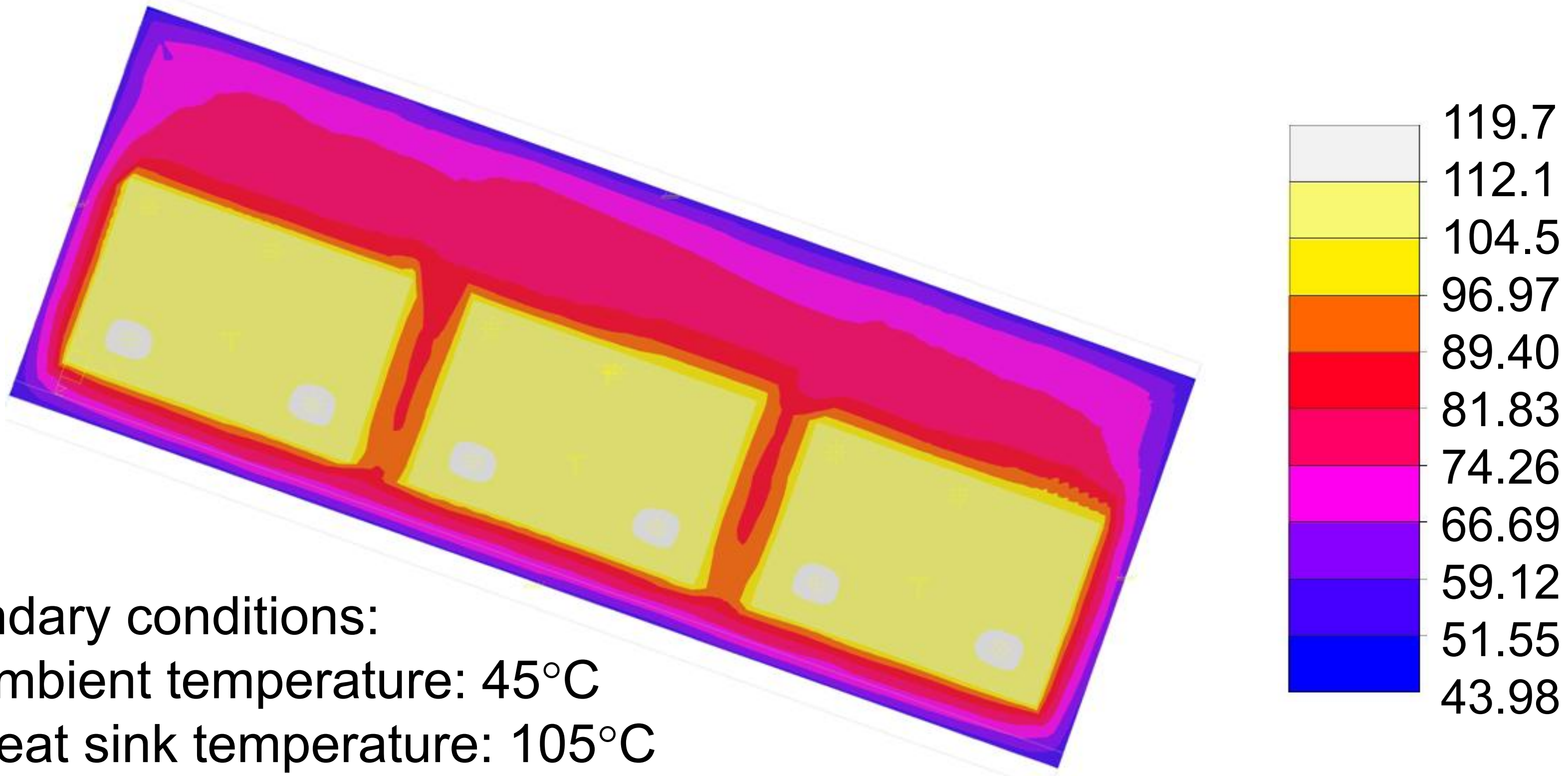


(b) Full version

Test condition: $V_{dc} = 325$ V, $f_{sw} = 10$ kHz (PWM), $f_1 = 83.3$ Hz, $T_a = 25°$C
Accuracy of Instrumentation: $\pm 0.2\%$

- **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

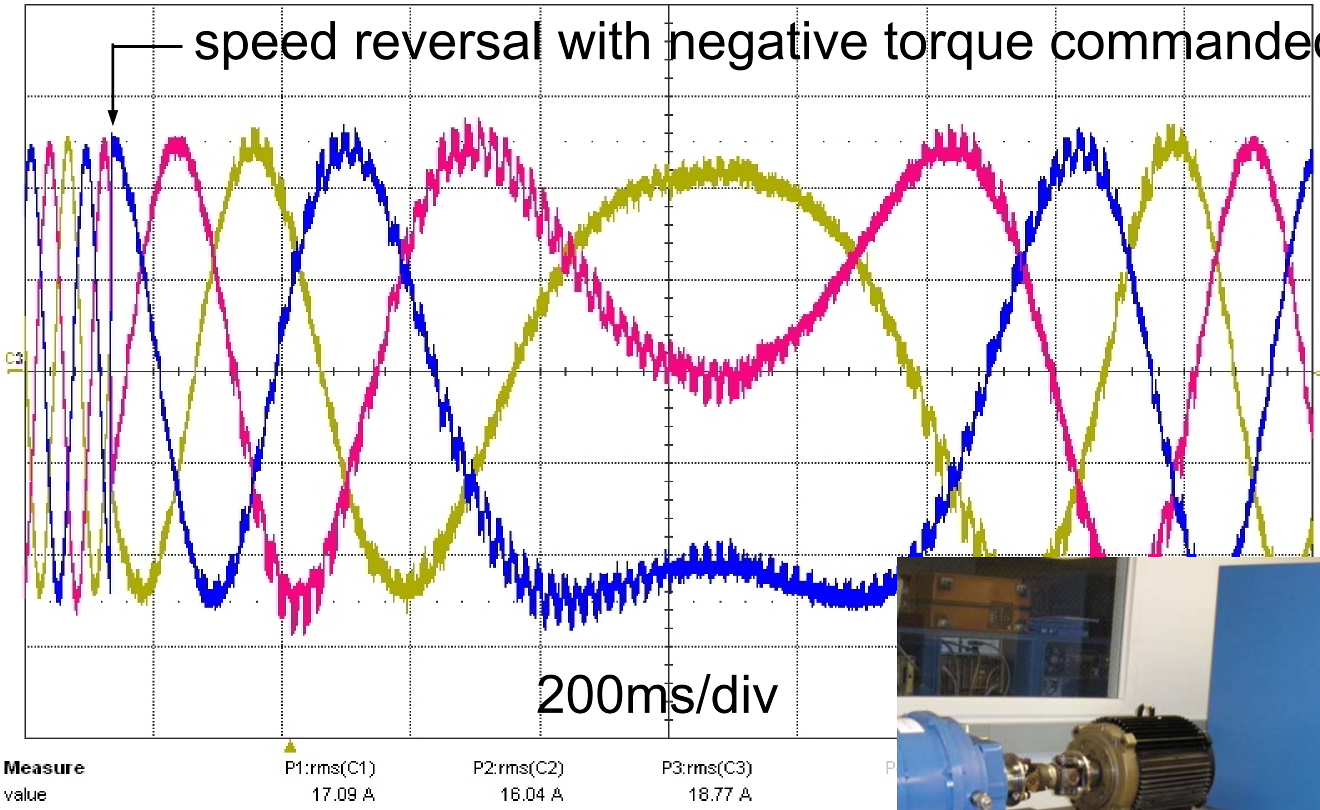


Boundary conditions:
Ambient temperature: 45°C
Heat sink temperature: 105°C

- 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



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