Advanced Soft Switching for High Temperature Inverters

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Outline

1. Background – DOE FreedomCAR Program
2. System Level Design Tradeoff
3. HEV Thermal Management System Design Considerations
4. Power Semiconductor Device Characteristics under Different Temperature Conditions
5. Efficiency and Loss Evaluation for Temperature Prediction
6. Summary

Background – DOE FreedomCAR Program Inverter Target

Goal: **Electric Propulsion System with a 15-year life capable of delivering at least 55 kW for 18 seconds and 30 kW continuous at a system cost of $12/kW peak with a 105°C inlet coolant temperature by 2015*.**

APEEM R&D Activities:

- **Electric Traction Drive**
  - Electric Machines - Motors and Generators
  - Power Electronics - Inverter and Boost Converter (if needed)
  - Thermal Control – Key Enabling Technology
- **Vehicle Power Management**

  Bi-Directional Multi-Voltage DC-DC Converter

55-kW System at 105 °C			
	2015 Targets	Camry	R&D Pathways
Cost ($)	660	3740	858
Weight (kg)	45.8	91.7	45.8
Volume (l)	157	33.3	12.5
Efficiency (%)	93	88	91

Source: DOE Vehicle Technology Program – APEEM 2009 Kickoff Meeting

System and Component Level Cost Trade-off with Consideration of Thermal Management System

- Dual cooling loops (70°C plus 105°C)
  - Need dual thermal management systems, penalty on **system level cost**, size and weight
- Single cooling loop with 105°C coolant
  - Need to beef up silicon or use wide bandgap devices, penalty on **component level cost**
  - Need to use high temperature bulk capacitors, penalty on **component level cost**, size and weight
  - Need to design circuit with high temperature rating, penalty on **component level cost**

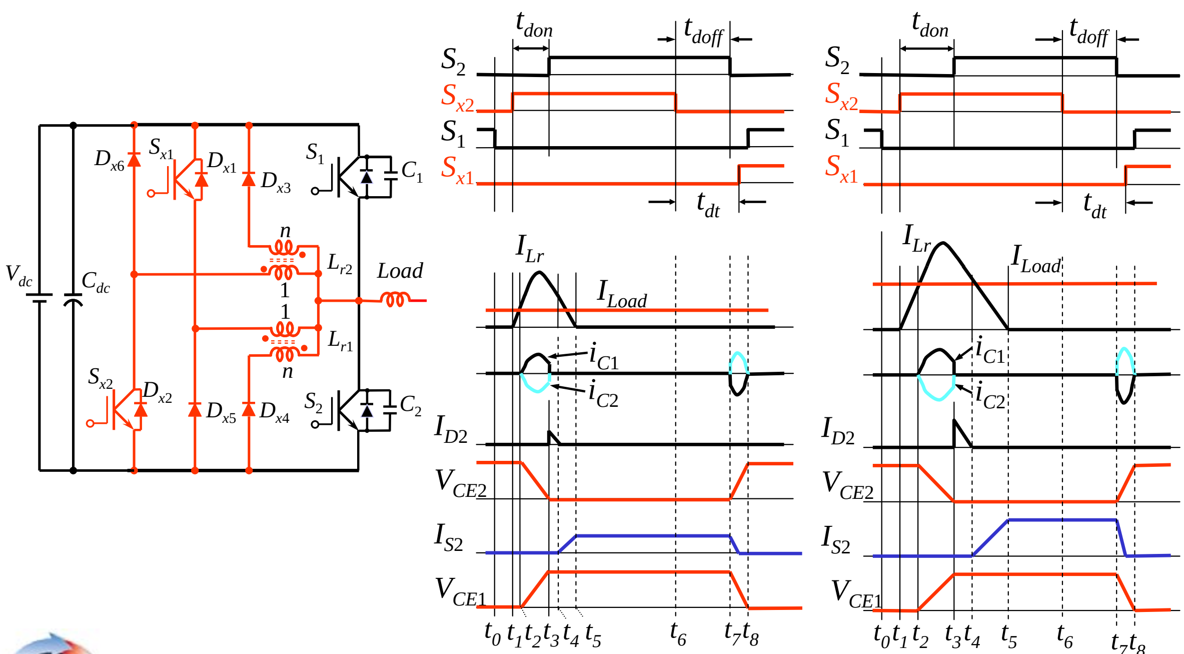
Possible Solutions with Single 105°C Coolant Loop

- **Loss reduction by reducing switching frequency** will result in high motor current ripple and associated loss thus reducing the entire drive efficiency.
- **Loss reduction by increasing device switching speed** will result in high dv/dt, di/dt and associated EMI and common mode current issues.
- **Emerging SiC and wide band-gap devices** for high temperature operation is not cost effective today.
- **Junction temperature reduction by reducing thermal impedance** – it helps but not enough.
- **Advanced soft switching with silicon devices to achieve significant loss reduction** – a cost-effective way.

Proposed Approach

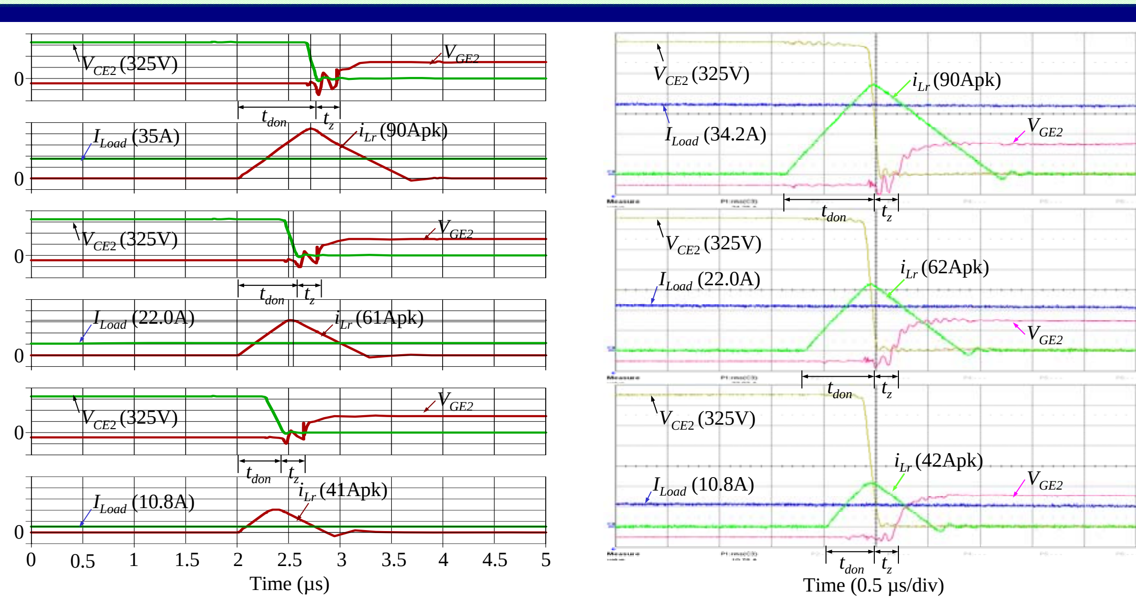
- Develop a **variable timing controlled soft-switching inverter** for loss reduction.
- A **hybrid soft switch module** for conduction loss reduction.
- Develop **low thermal impedance module with integrated heat sink** for high temperature operation.
- Develop a **highly integrated soft-switch module** 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.

Timing Diagram with a Variable t_{don} Defined as Variable Timing Control



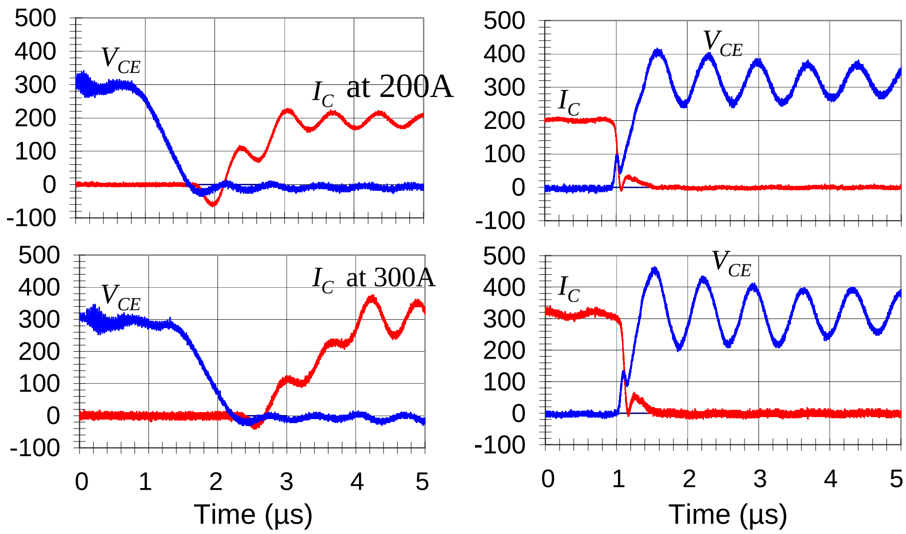
(a) light-load **(b) heavy-load**

Variable Timing Controlled Soft-Switching Verified with Simulation and Experiment



- **Turn-on delay t_{don} controlled by zero-voltage crossing detection. Larger current, longer delay.**
- **Gating time after reaching zero voltage t_z is fixed**

Variable Timing Soft Switching over a Wide Load Current Range



(a) Turn-on (b) Turn-off

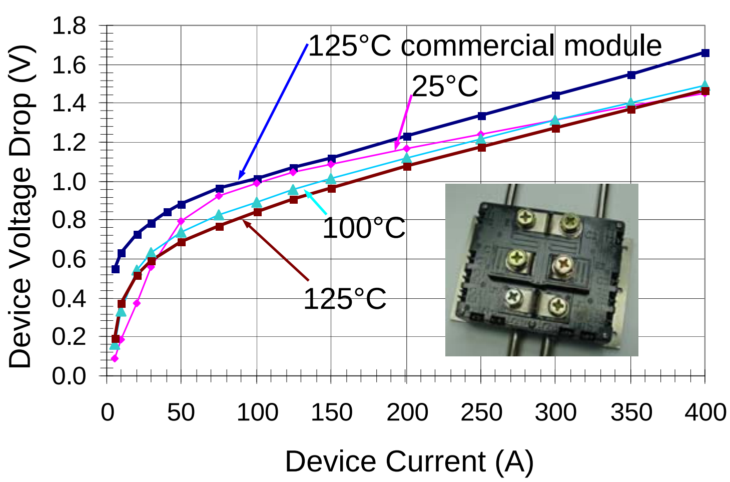
- **During turn-on, current I_C rises after voltage V_{CE} drops to zero**
- **During turn-off, V_{CE} slowly rises after I_C drops to zero**
- **Variable timing achieves soft-switching at all current conditions**
- **Bonus – slow dv/dt that will result in low EMI emission**

Conduction Loss Reduction with a New Hybrid Soft Switch Module

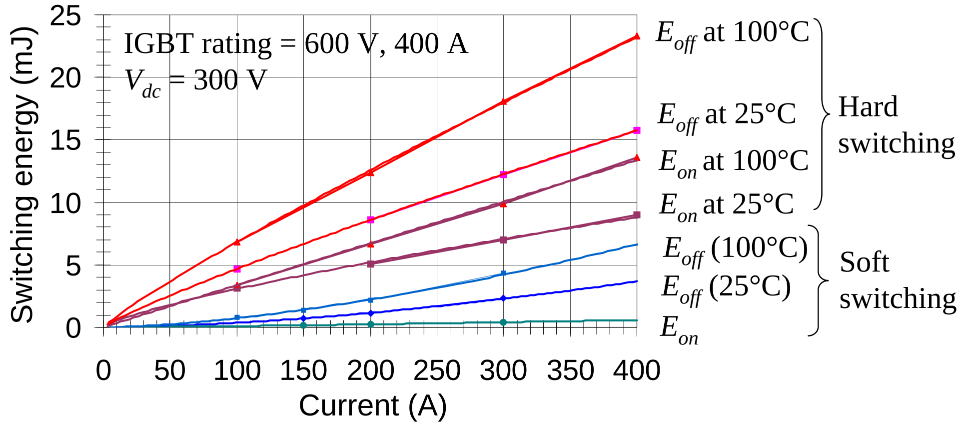
- Hybrid switch reduces conduction loss reduction over a wide range of current and temperature condition
- Integrated module with direct cooling to reduce thermal resistance

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

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

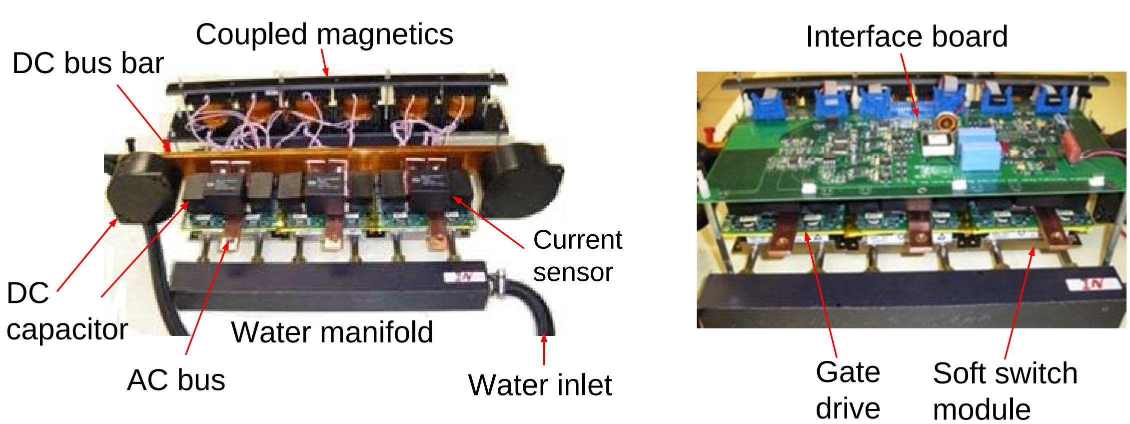


Switching Loss Reduction Using LPT IGBT



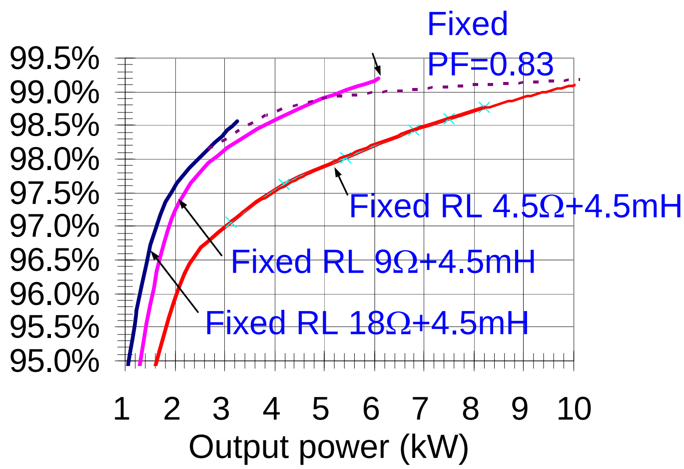
- **For hard switching, as compared to 25°C operating condition,**
  - **Device switching loss is increased by 40% at 100°C**
  - **Device switching loss is reduced by 80% under soft switching**
- **Losses in soft switching are due to layout parasitics with discrete components – necessary to integrate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

Direct Cooled Module Based Soft-Switching Inverter Assembly



- **Direct cooled module – no heat sink is required, but a custom-made water manifold is needed**
- **DC power bus bar and capacitors are placed on top of modules to reduce parasitic inductance**
- **Gate drive board snapped on top of the modules to avoid parasitic ringing**

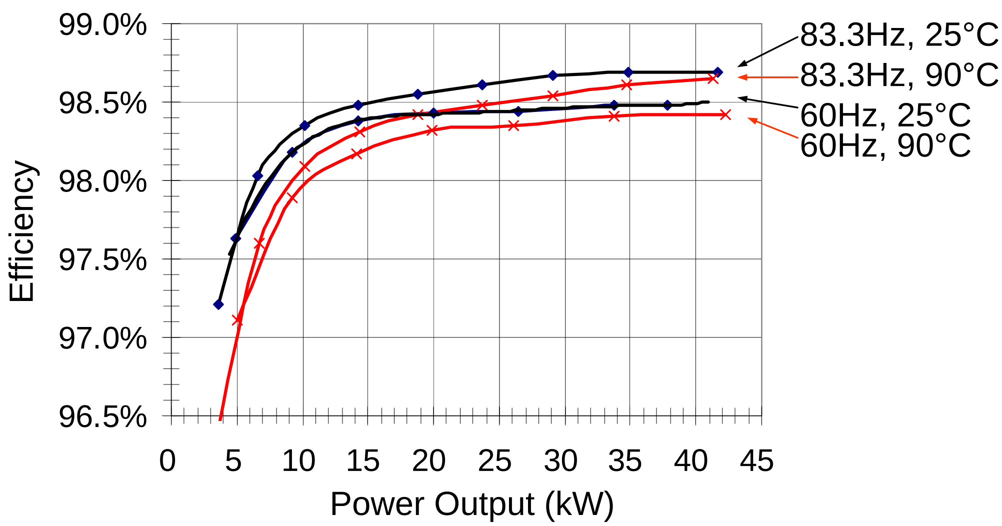
Power Meter Measured Peak Efficiency Exceeds 99% at Low Relatively Low Power Condition



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

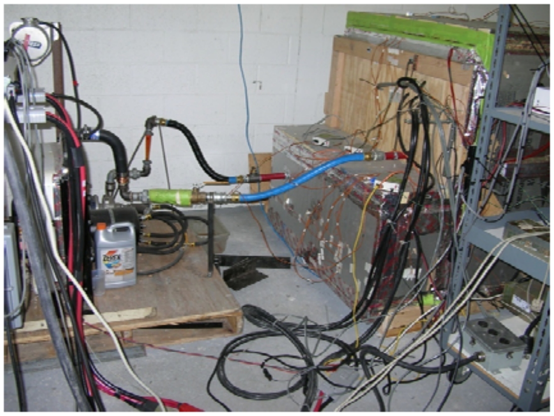
- Using well calibrated power meter, the measured peak efficiency of the inverter exceeded 99% at room temperature condition.

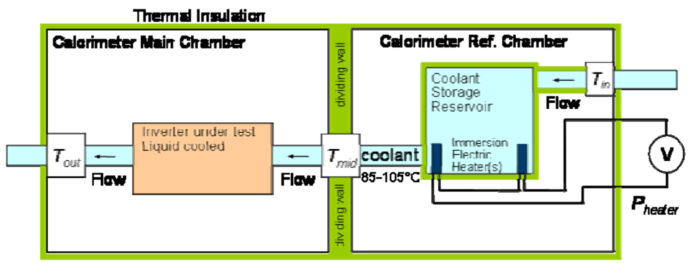
Projected Efficiency Using Loss Measurement with Inductor Load Test



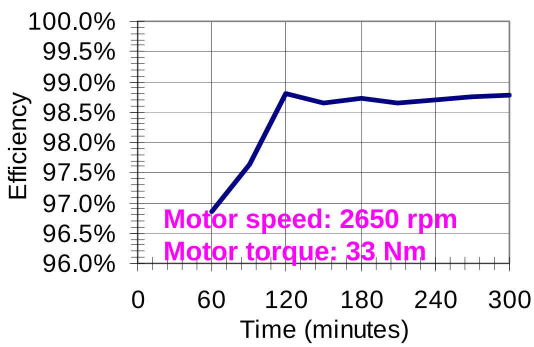
Test condition: DC bus voltage: 325 V dc
Switching frequency: 10 kHz
Load inductance: 2.4 mH per phase
Modulation index: 0.2 to 1.15

Efficiency Measurement using Ratiometric Calorimeter

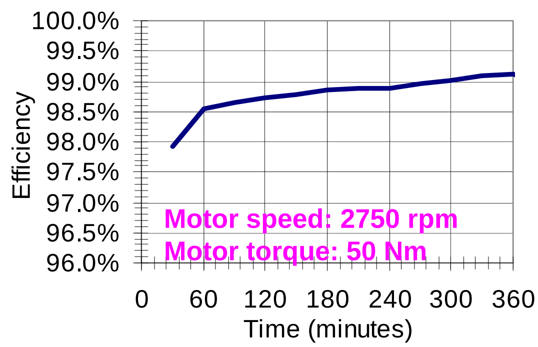




Calorimeter Tested Efficiency Plots over a Long Period of Time



(a) Test results at 12.5 kW

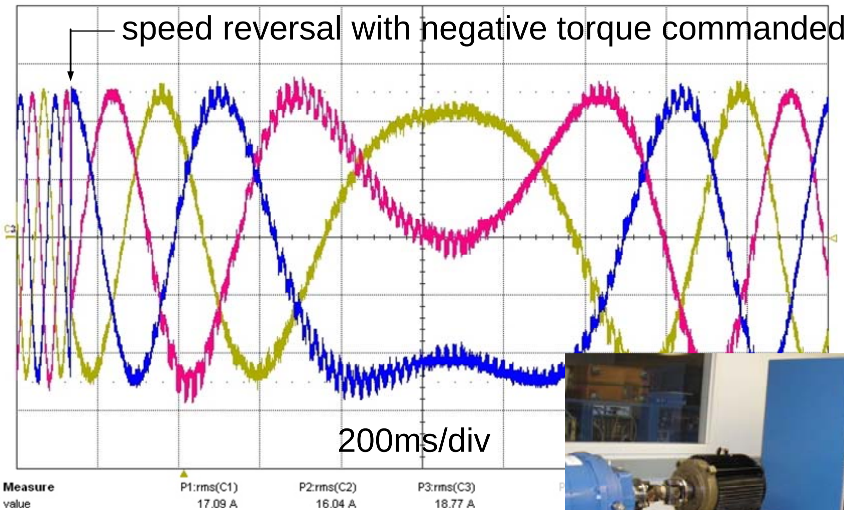


(b) Test results at 18 kW

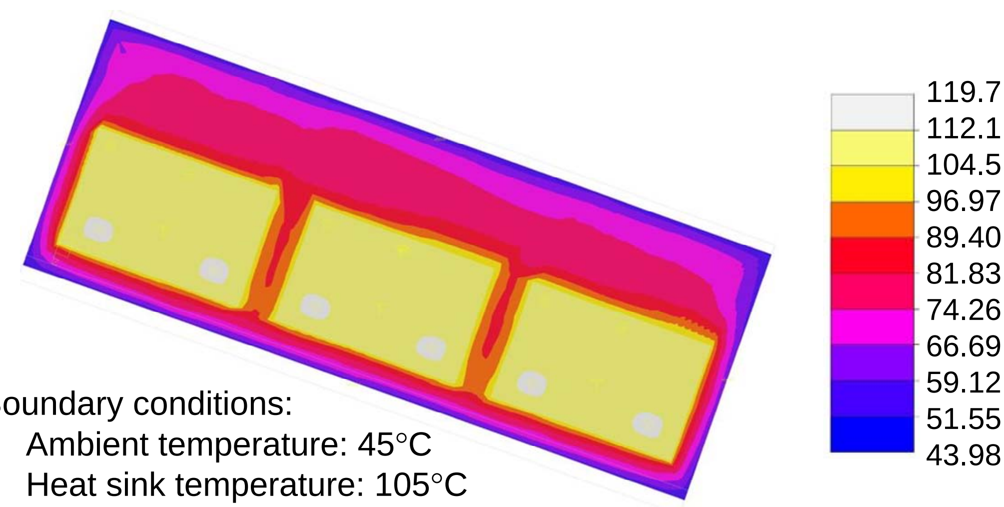
- Using integrated module with light-weight water manifold for the full-version soft-switching inverter.
- Calorimeter chamber inlet and outlet temperatures stabilized after 6-hour testing. Chamber temperature differential was 1.6 °C under 0.3 GPM flow rate.
- Efficiency exceeded 99% at full speed, 33% load torque condition.

Soft-Switching Inverter Testing with Motor Dynamometer

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



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

Summary

- The advanced soft-switch module demonstrates
  - 13% conduction loss reduction
  - 80% switching loss reduction
  - 60% thermal impedance reduction
- The advanced soft-switching inverter with variable timing control demonstrates high efficiency over a wide speed and torque range
  - Soft switched inverter power losses are roughly a factor of 3 less than that of the hard switched inverter
  - Calorimeter test verifies that peak efficiency exceeds 99%
- FEM analysis and projection indicate
  - Less than 15°C junction temperature rise
  - 105°C coolant operating at full load is possible

Questions

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