Advanced Soft Switching Inverter for Reducing Switching and Power Losses

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Project ID: APE011

Outline

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

Overview

Timeline

- Start – Sep 2007
- Finish – Sep 2010
- 75% Complete

Budget

- Total project funding
  - DOE - $1,587,448
  - Contractor - $1,126,358
- Funding received in FY09
  - $454,460
- Funding received in FY10
  - $482,722

Barriers

- Barriers addressed
  - Inverter Cost
  - Inverter Weight and Volume
  - Inverter Thermal Management
- Target
  - Achieve efficiency >99% to allow the use of silicon devices at 105° coolant operating condition

Partners

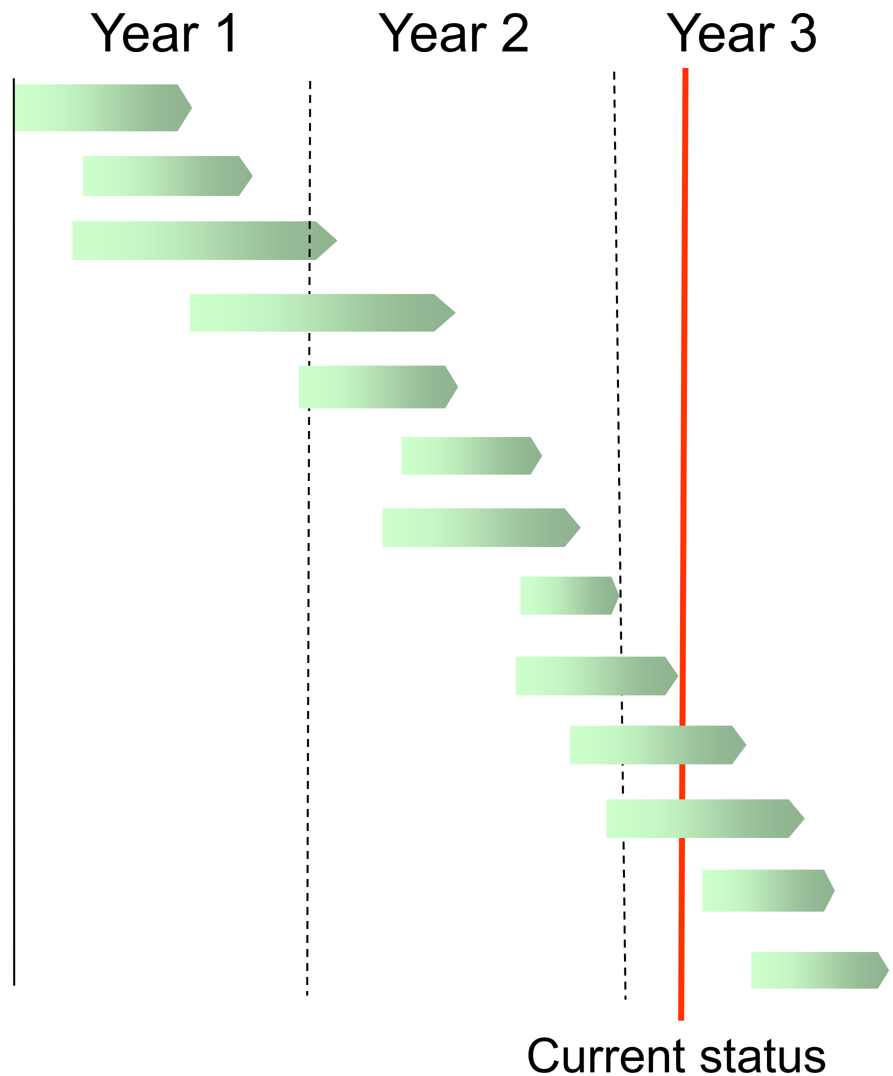
- National Institute of Standards and Technology – Modeling and Simulation
- Powerex – Soft switch module packaging
- Azure Dynamics – Dynamometer and vehicle testing

Objectives

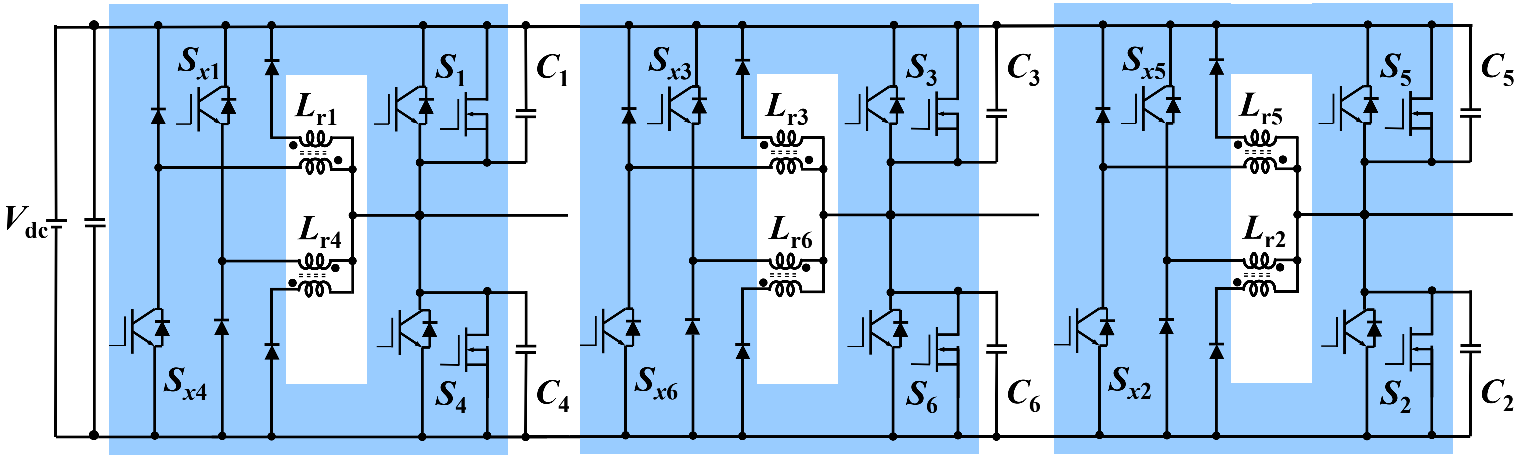
- Overall Objective: To develop advanced soft switching inverter for traction motor drives to support the following DOE targets
  - 105°C coolant temperature – by designing the junction temperature <125°C
  - 94% traction drive system efficiency – by designing the inverter efficiency >98%
- Year 3 Objectives
  - Demonstrate the integrated soft-switching inverter for in-vehicle testing
  - Develop the third 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

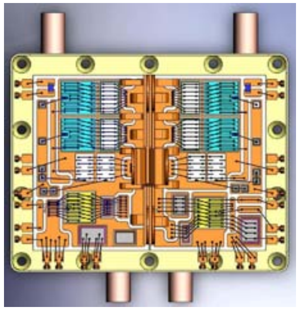


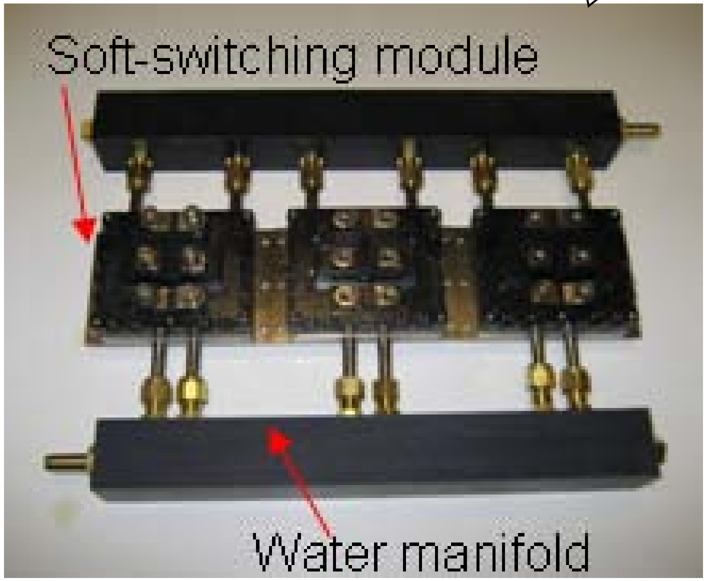
Approach – Separate Auxiliary Switching Circuits to Avoid Magnetizing Current Circulation



Liquid-cooled soft-switching modules

Circuit diagram of a three-phase soft-switching module based inverter





Approach

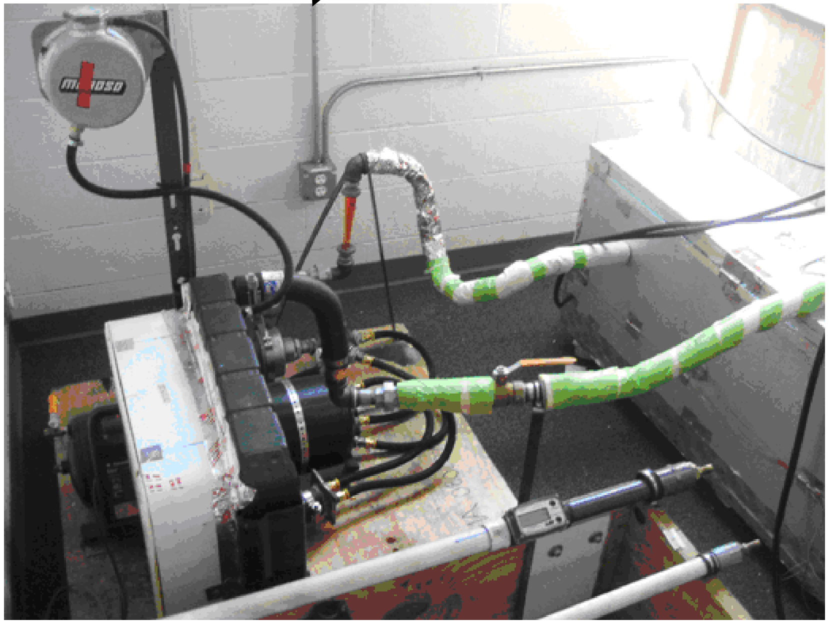
- Develop a **variable timing controlled coupled-magnetic based soft-switching inverter** for loss reduction.
- Develop a **hybrid switch** based soft-switching circuit to reduce the conduction voltage drop at light load.
- Develop **low thermal impedance module with integrated heat sink** for high temperature 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.

Approach – Calorimeter Setup for Precision Efficiency Test

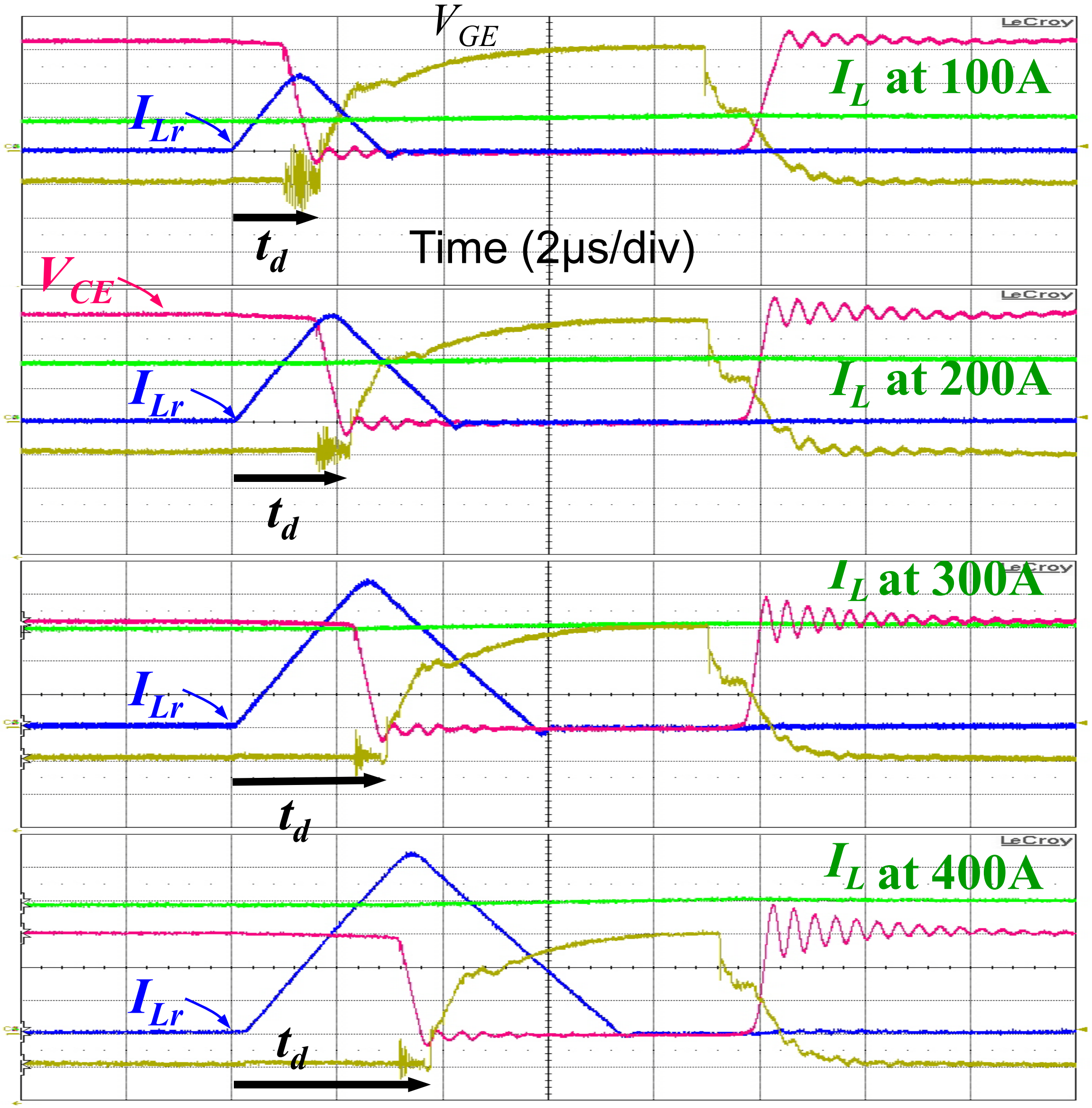
Calorimeter with reference chamber in foreground and inverter chamber in back

$$P_{inv-loss} = P_{heater} \cdot \frac{\Delta T_1}{\Delta T_2} = P_{heater} \cdot \frac{T_{out} - T_{mid}}{T_{mid} - T_{in}}$$

The high temperature heat exchanger and pump hooked into the back of the calorimeter

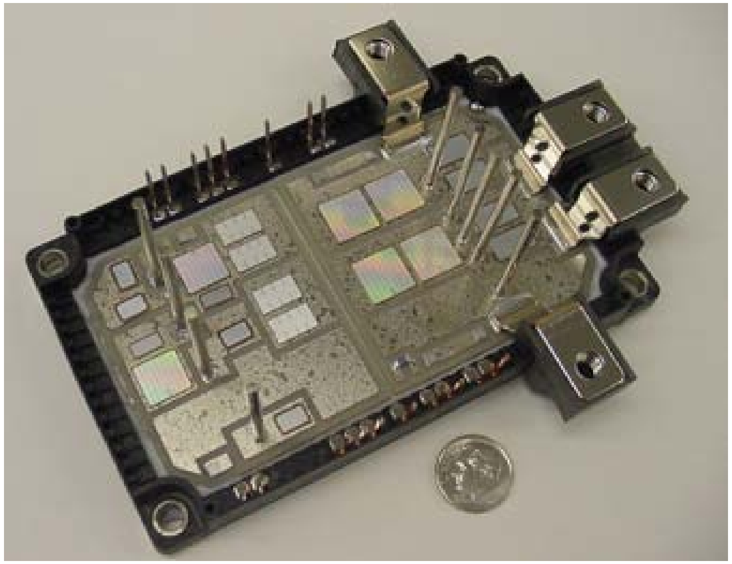


Accomplishment – Variable Timing Soft Switching over a Wide Load Current Range

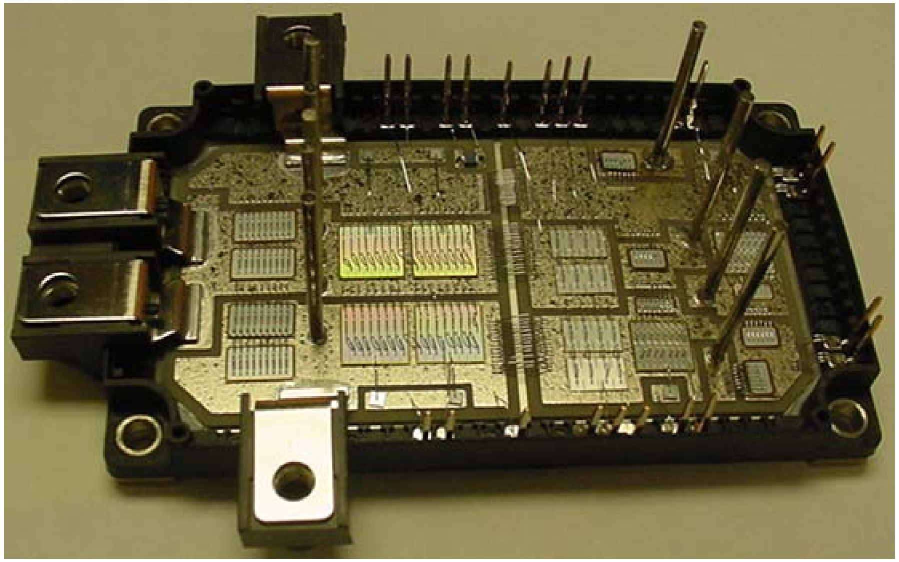


- During turn-on, V_{GE} turns on after V_{CE} drops to zero ➔ zero turn-on loss
- During turn-off, V_{CE} slowly rises after current drops to zero ➔ turn-off loss reduction
- Variable timing delay t_d ➔ achieve soft-switching at all current conditions
- Bonus – slow d*v*/d*t* that will result in low EMI emission
  - Turn-on d*v*/d*t* = 600V/μs
  - At 100A Turn-off d*v*/d*t* = 500V/μs
  - At 200A Turn-off d*v*/d*t* = 1kV/μs

Accomplishment – Gen-2 Soft-Switching Module with Standard Low-Profile Design



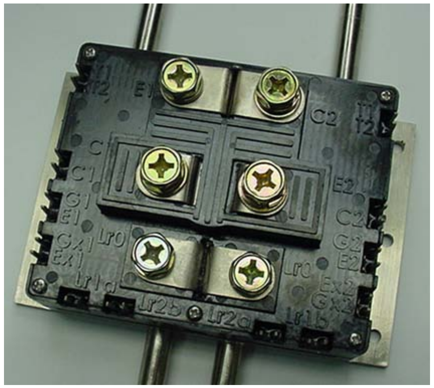
(a) Before wirebond



(b) After wirebond

- Same electrical design as the Gen-1 module
- Low profile with power pins next to the chips – significant parasitic reduction
- Standard baseplate – flexible with air- or liquid-cooled system

Accomplishment – Significant Cost Reduction with Gen-2 Module

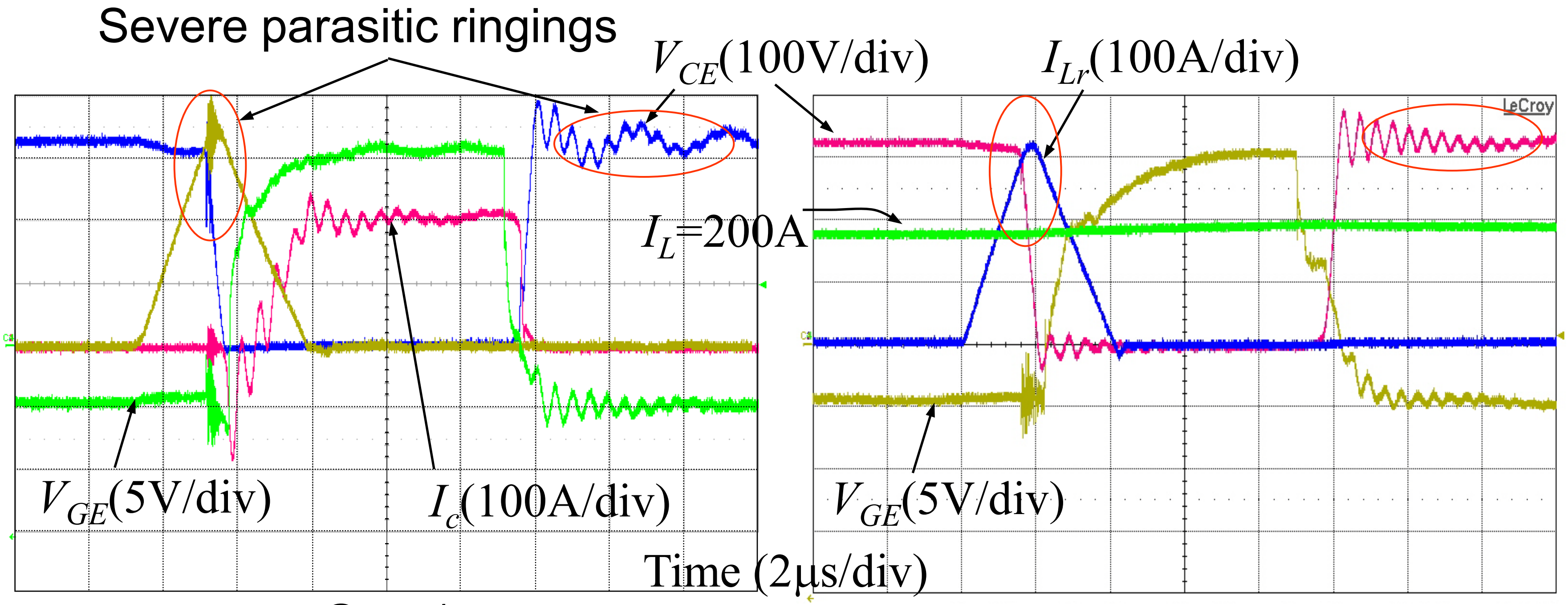


	Gen 1	Gen 2		
	Direct Liquid Cooled	Standard		Direct Liquid Cooled
	Low Volume	Low Volume	High Volume	High Volume
Materials	$545.87	$236.31	$98.25	$114.25
Labor	$360.00	$90.00	$35.00	$35.00
Total	$1,222.92	$440.52	$179.89	$201.49

Gen 2 Cost Advantages

- Less expensive terminals
- Standard flat copper baseplate
- Use high volume parts
- Easier to assemble - automate

Accomplishment – Parasitic Inductance Reduction with Gen-2 Module



Gen-1 Gen-2

- Gen-2 module reduces total loop parasitic inductance from **91nH** to **19nH**.
- During turn-on, Gen-1 resonant current I_{Lr} and device voltage V_{CE} present high frequency parasitic ringing, but not Gen-2.
- During turn-off, Gen-1 device voltage V_{CE} has an overshoot voltage of **75V**, as compared to Gen-2's **50V**. In addition to the test setup induced high frequency ringing, Gen-1 also presents a sub-harmonic oscillation.

Accomplishment – Complete Gen-2 Inverter with Significant Volume Reduction

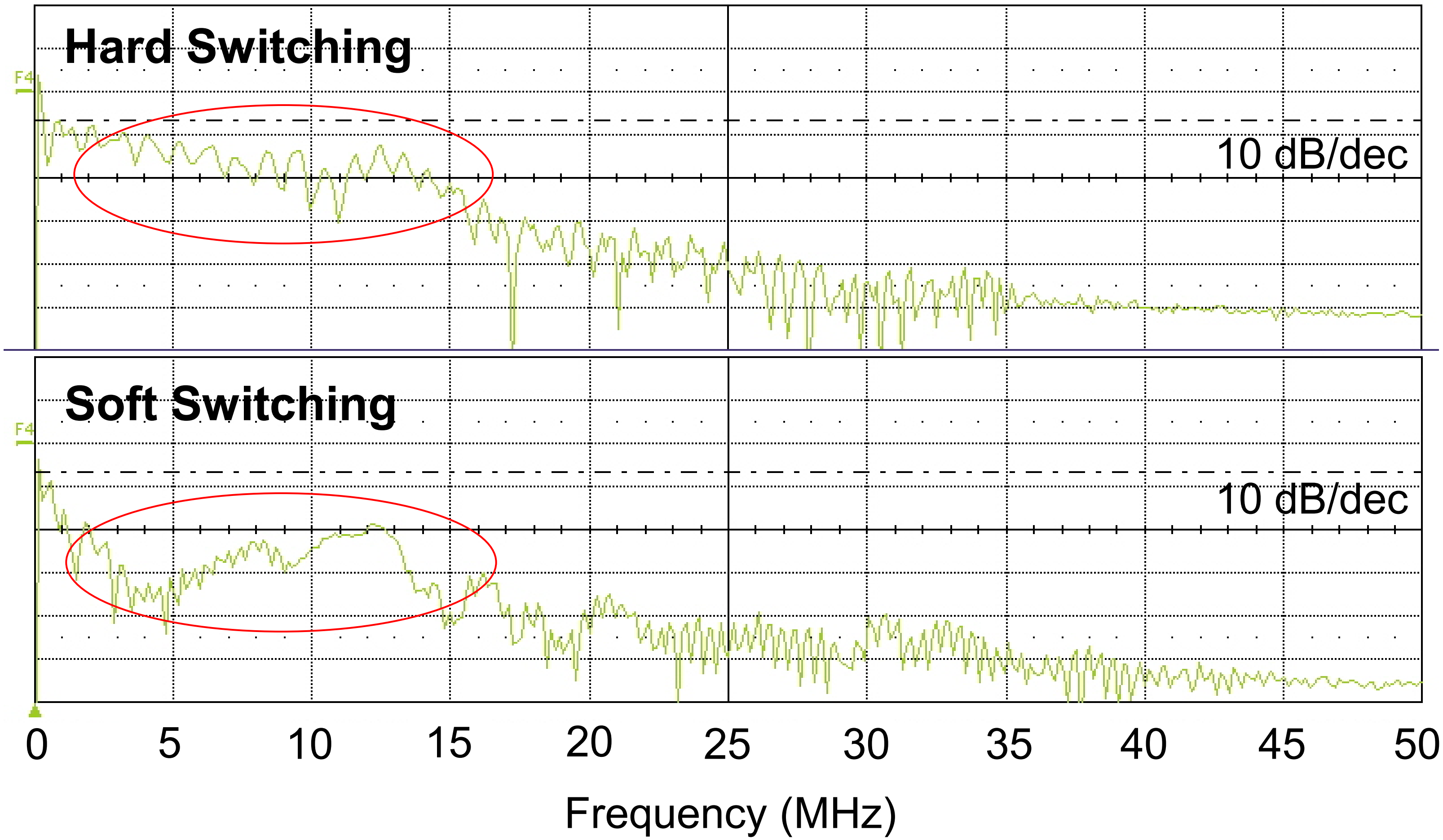
Gen-1 Soft-Switching Inverter

- Direct cooled module – no heat sink is required, but a custom-made water manifold is needed
- Large resonant inductor for initial conservative design

Gen-2 Soft-Switching Inverter

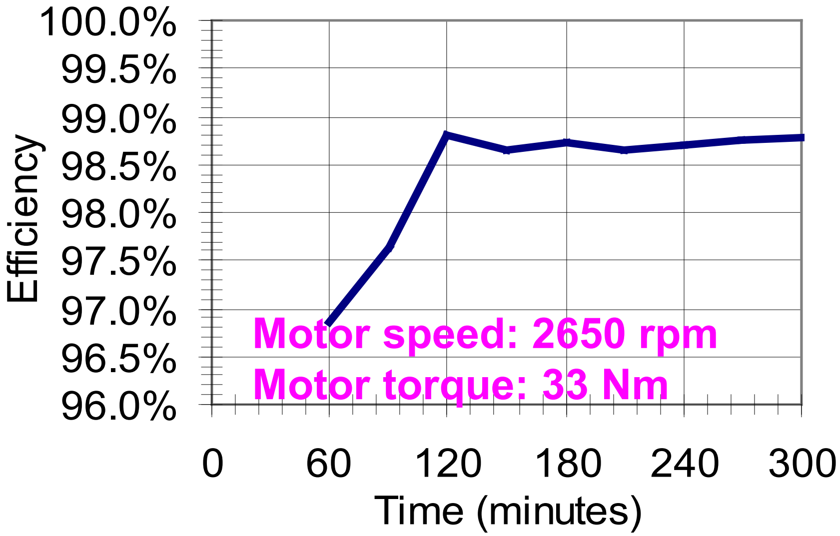
- Air- or liquid-cooled heat sink ➔ ease of mounting
- Reduced-size resonant inductor and integrated design
- Significant volume reduction to fit Azure inverter chassis.

Accomplishment – Common Mode EMI Reduction with Soft-Switching

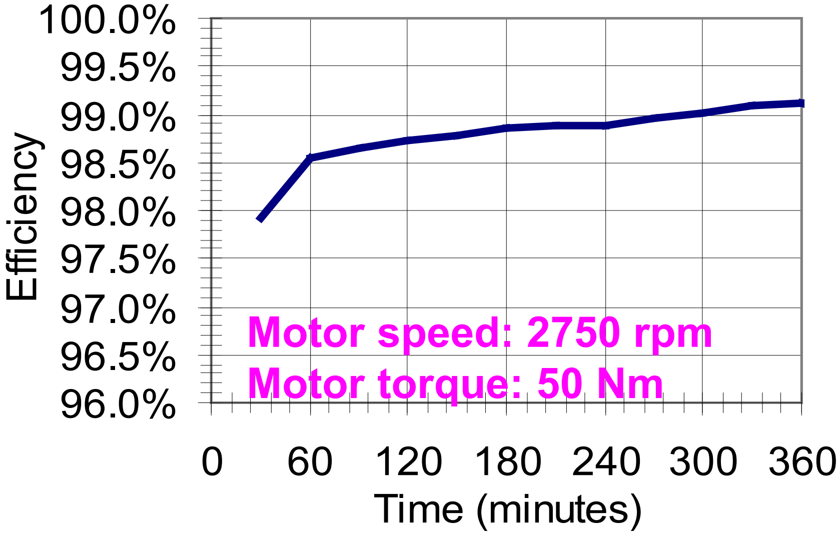


- FFT results show measured common mode (CM) EMI at the inverter output
- Soft-switching shows about 10 dB reduction across the entire frequency range, up to 50 MHz and more than 20 dB reduction between 3 and 6 MHz range

Accomplishment – 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.

Accomplishment – Soft Switched Inverter Efficiency Measurement using Calorimeter

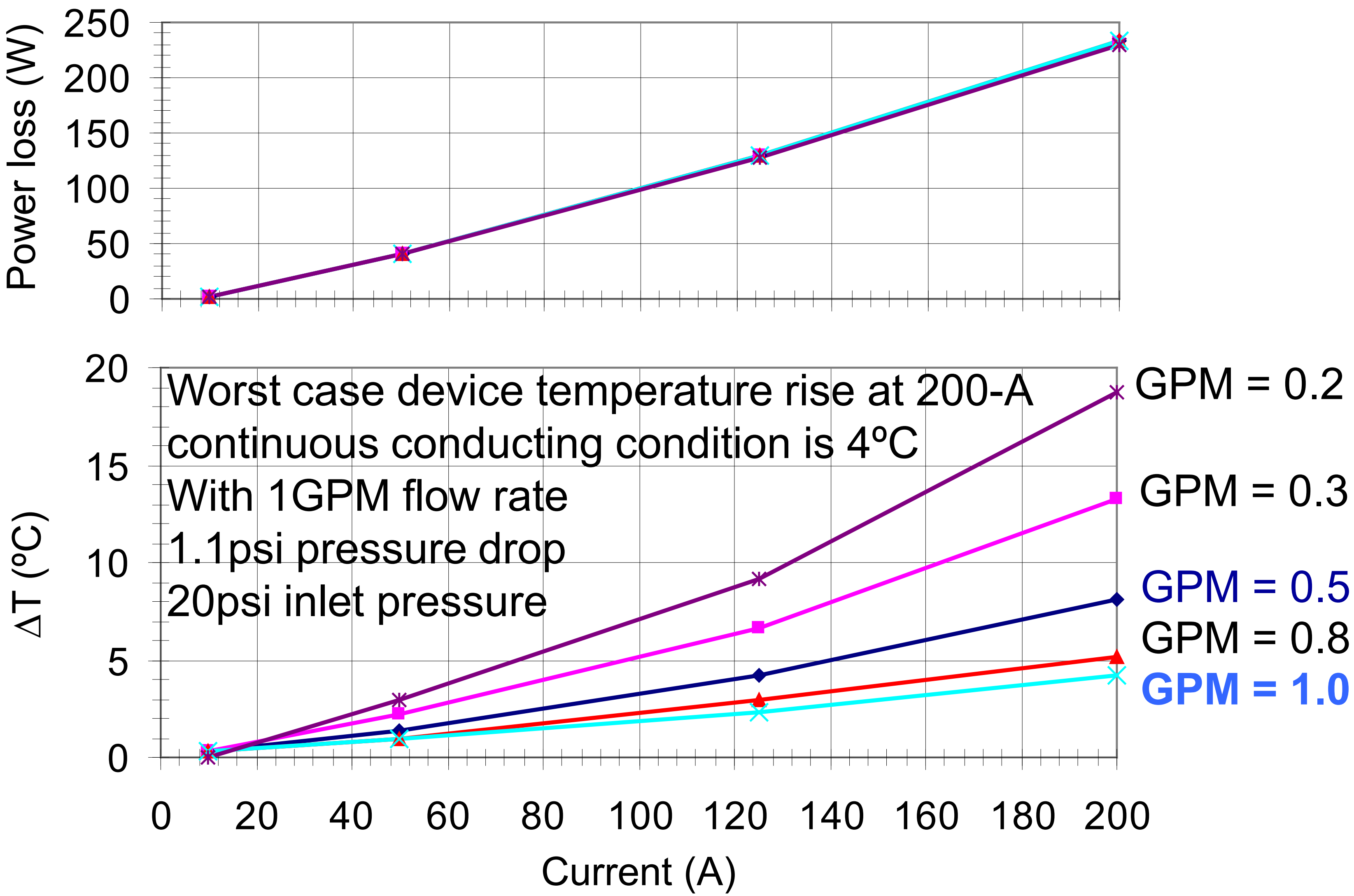
GEN-1 SOFT SWITCHED INVERTER CALORIMETER TEST RESULTS

Inverter Input (DC Link) Power Level	**Inverter Heat Loss**	Inverter Efficiency	Dyno	Speed Torque
17.5kW	**192W**	98.90%	Azure AC55	2750rpm 50Nm
12.5kW	**208W**	98.30%	Azure AC55	2650rpm 33Nm
27kW	**311W**	98.80%	Azure AC90	1600rpm 140Nm
-11.6kW (regen)	**202W**	98.30%	Azure AC90	-3800rpm 30Nm

HARD SWITCHED INVERTER CALORIMETER TEST RESULTS

Inverter Input (DC Link) Power Level	**Inverter Heat Loss**	Inverter Efficiency	Dyno	Speed Torque
15.4kW	**950W**	93.80%	Siemens	1300rpm 107Nm
19.7kW	**709W**	96.40%	Siemens	2400rpm 75Nm
23.7kW	**626W**	97.40%	Siemens	3400rpm 62Nm
-15.6kW (regen)	**643W**	96.00%	Siemens	-3000rpm 44Nm

Accomplishment – Temperature Rise of Main Device Q1/M1 under Different Coolant Flow Rates



Future Work

- Efficiency and EMI Testing with Gen-2 Soft-Switching Inverter
- Perform In-Vehicle Testing with Soft-Switching Inverter
- Complete More Efficient and Lower Cost Gen-3 Modules
- Manufacturability and Cost Analyses

Preparation for In-Vehicle Testing

Summary

- Variable timing control is successfully developed for high efficiency over a wide load range. The Gen-1 soft-switching inverter successfully demonstrates 99% efficiency, which was verified with calorimeter measurement.
- Worst-case junction temperature rise is less than 4ºC even with just 1-GPM coolant flow rate.
- Soft switching shows 10dB EMI reduction across entire frequency range and >20dB reduction between 3 and 6MHz
- Gen-2 soft-switching module can be cooled by either air or liquid. As compared to Gen-1 module, the Gen-2 soft-switching module demonstrates
  - Parasitic inductance reduction by 79%
  - Cost reduction by 84%