2011 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
POWER AND MOBILITY (P&M) MINI-SYMPOSIUM
AUGUST 9-11 DEARBORN, MICHIGAN

HIGH TEMPERATURE SILICON CARBIDE (SiC) TRACTION MOTOR DRIVE

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ABSTRACT

Future Military ground vehicle power trains can benefit from a hybrid-electric drive approach, particularly in packaging flexibility where drive train components can be modular and conveniently distributed. Small component size and operation with high-temperature liquid coolant are essential factors in the flexible packaging concept. This paper describes the development of one component, a 220 kW traction motor drive for a hybrid-electric power train.

Challenging requirements for the motor-drive include power densities of at least 25 kW/liter and 15 kW/kg at 105°C coolant temperature. To achieve these densities, power modules capable of high-temperature operation were developed using SiC normally-off JFETs. This paper will discuss the unique custom packaging of the SiC JFET devices, as well as the arrangement of key components/packaging and thermal management issues.

INTRODUCTION

RCT Systems is in the process of developing a 220 kW silicon carbide based, liquid-cooled traction motor drive for use in tactical military vehicles. A key factor in the use of a motor drive in this application is the ability to operate with coolant temperatures as high as 105°C. This simplifies vehicle coolant loops and minimizes any necessary auxiliary systems. Another key factor is volume, since space on such a vehicle comes at a high premium. As a result, a power density threshold of 25kW/liter was set for this motor drive component. These two challenging and competing goals drive the development of advanced packaging techniques and a new, compact silicon carbide JFET power module.

SYSTEM REQUIREMENTS

The basic system requirements for this traction motor drive are as follows:

- Continuous operation at full power with a liquid coolant inlet temperature of 100°C to 105°C
- Coolant flow rate ≤6 GPM
- External ambient temperature range of -50°C to 55°C
- Power density threshold 25kW/liter
- Specific power threshold 15kW/kg
- Soft-start capability
- Capable of driving an IM or PM motor at 200 kW shaft power from a 650 VDC source in the motoring mode
- Capable of driving the motor at 200kW electrical power into the 650 VDC bus in the regeneration mode
- At least 95% inverter efficiency at full power
- Threshold volume is 8.4 liters, or 513 cu in
- Threshold weight is 14 kg = 30.8 lb

PERSPECTIVE

To provide some perspective on the challenging nature of the requirements, consider Figure 1. This figure shows a commercially produced, 250 hp traction motor drive for full-size (30,000lb GWVR) electric transit buses. The drive is designed to be mass produced in high volume on a semi-automated line. Such assembly techniques require that components and fasteners be installed along a single axis. The overall power density achieved for this drive, if auxiliary functions are not considered, is 7 kW/liter. The footprint for the equivalent function, but with a power density of 25kW/liter as required for this tactical vehicle application, is substantially smaller, as indicated in Figure 1 for comparison. Another way to look at this is to consider that the 8.4 liters that this drive must fit into is approximately the same volume as two standard reams of copier paper stacked on top of one another (8.5" x 11" x 5.5" total). The drive may weigh no more than about 1½ gallons of milk and must be "cooled" with liquid at a temperature exceeding the boiling point of water.

The high temperature of the "coolant," is typically associated with the cooling of engines, not power electronics. The 250 hp electric bus traction drive of Figure 1 was designed to be cooled with 60°C coolant. A temperature of 105°C does not leave much margin between it and the maximum operating temperatures of most military-grade electronics (125°C). Silicon carbide power devices offer some advantage in this regard since they can withstand significantly higher junction temperatures.

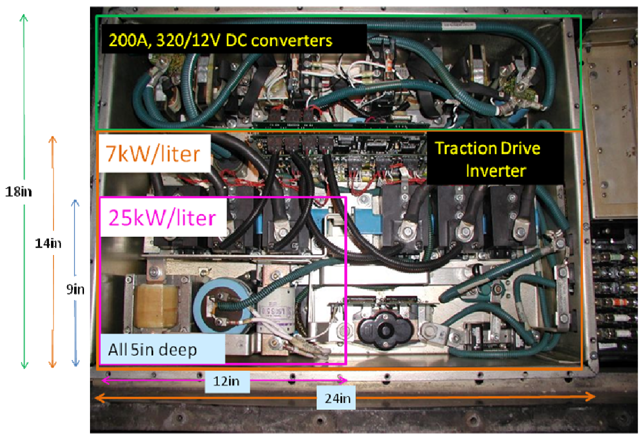

Figure 1: Power Density Comparison between Commercial Drive and TARDEC Requirements

SYSTEM DESIGN

A functional block diagram for the motor drive system is shown in Figure 2. The components and functions outside the dashed line are external to the motor drive itself. As with a typical motor drive, input contactors are included to connect and disconnect the drive from the DC input power supply – in this case, a 650 VDC vehicle battery bus. The input contactors will provide a "pre-charge" function to limit inrush currents as bus capacitance in the motor drive is initially charged when first connected to the battery bus. The motor drive contains an EMI filter to block switching noise from being transmitted to the input supply lines. Bus capacitance is included to reduce the source ripple voltage and provide the necessary system transient response. A 3-phase, 3-pole power bridge consisting of silicon carbide (SiC) junction field effect transistors (JFETs) provides the output power to the external motor. Each pole consists of two, dual SiC power modules in parallel. The power bridge is controlled by pulse width modulated (PWM) signals from a digital signal processor (DSP).

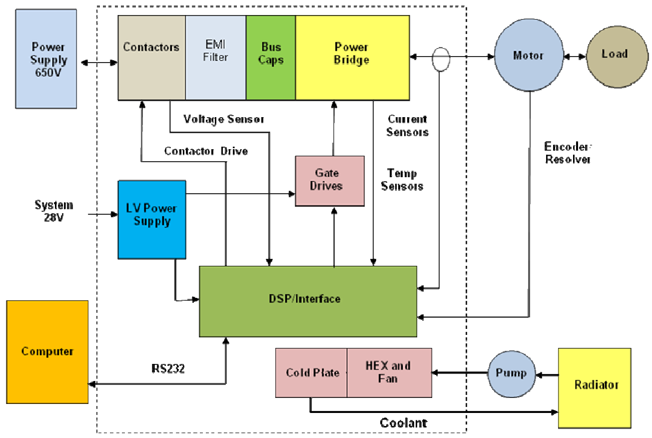

Figure 2: Traction Motor Drive Block Diagram

The power devices are connected to the DSP through a set of custom designed gate drives which provide voltage isolation and drive current for the gates of the JFETs. Feedback is provided to the DSP by 3 current transducers, a DC bus voltage sensor, and a number of temperature sensors located at critical points throughout the drive. The system includes a low-voltage power supply function to convert the 28 VDC control power input to levels such as +/-15V, 5V, and 3.3V to power the DSP and sensors. Finally, the system includes a custom designed cold plate for the liquid cooling loop, and an air to water heat exchanger for cooling the air inside the enclosure.

POWER MODULE DESIGN

The devices selected for this application are silicon carbide junction field-effect transistors (JFET) and Junction Barrier Schottky (JBS) silicon carbide diodes from SemiSouth Laboratories. A key characteristic of the silicon carbide diodes is that they exhibit almost zero reverse recovery loss. Multiple die of both JFETs and diodes are packaged in parallel by Silicon Power Corporation in one of their standard ThinPak® packages to provide the required current carrying capacity. Due to limitations on the number of die that can be packaged in one ThinPak®, the motor drive requires two ThinPak® modules in parallel per pole.

Each switch consists of sixteen 29A JFETs and eight 30A diodes. With a total load of 200kW (shaft) at 460V and 60Hz, the nominal phase current is 320Arms and 455A peak. The switching frequency selected is 20kHz. The resulting dv/dt and di/dt are 13kV/uS and 5kA/uS, respectively.

An equivalent circuit of the JFET switch is shown in Figure 3, and its transconductance characteristics are shown in Figure 4. The switching characteristics of a packaged module are shown in Figure 5. Note that an inherent Gate-Source diode limits the Gate-Source voltage that can be applied, and that a fairly significant gate current is required to initially turn on the device (50A), as well as to keep the device turned on (1A). This is in contrast to typical Insulated Gate Bipolar Transistors (IGBTs) which require very little current to keep the device turned on. This results in a slightly more complex and less efficient gate drive circuit for the JFETs.

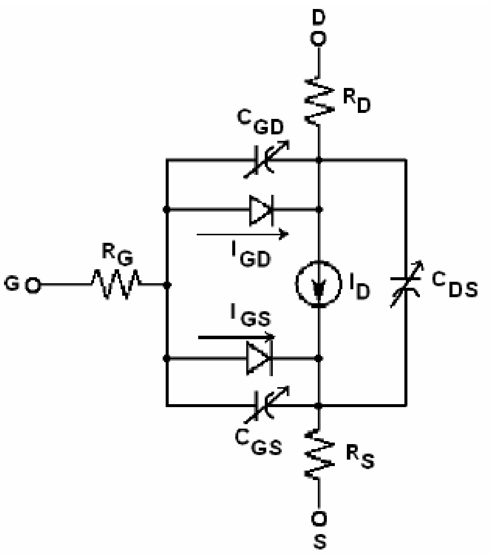

Figure 3: JFET Equivalent Circuit

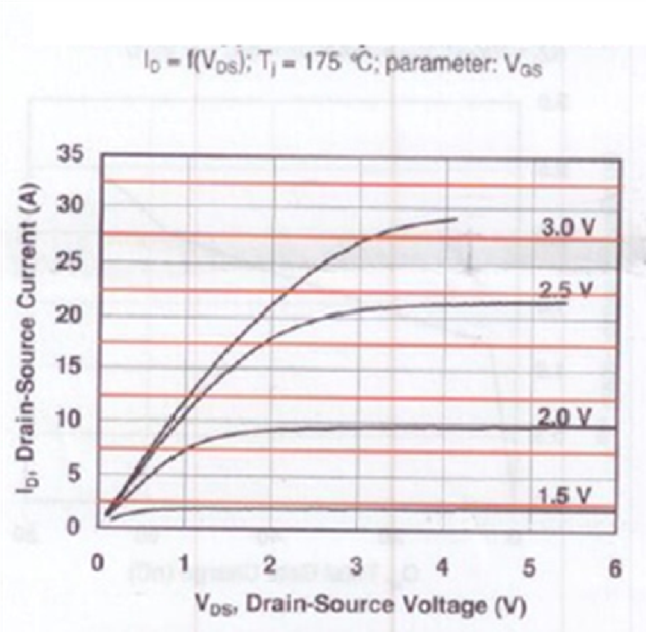

Figure 4: JFET Transconductance Characteristics

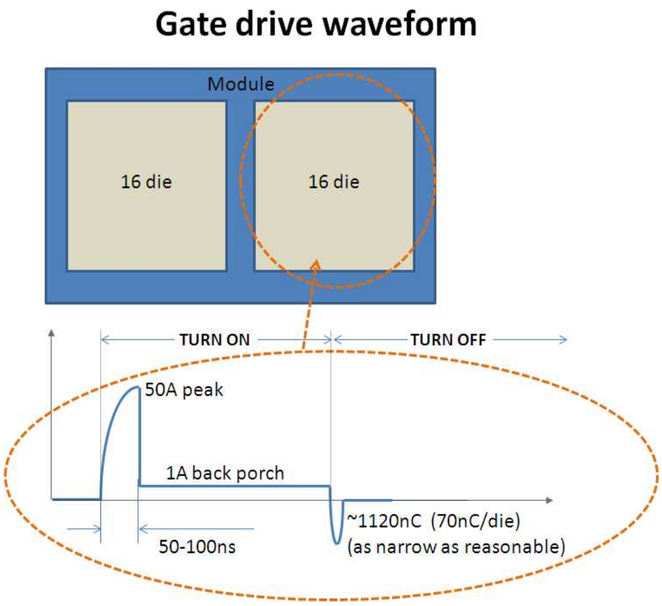

Figure 5: Module Switching Characteristics

GATE DRIVE DESIGN

Because of the unique drive requirements of the JFET switches used in this motor drive, custom gate drive assemblies were designed. Originally, it was planned to incorporate some, if not all, of the gate drive circuitry into the ThinPak® module directly. However, the required component volume and thermal limitations prevented this, and a separate gate drive circuit board was designed, connected to the switching module by means of a low-inductance flexible circuit board. Refer to Figure 6 for this arrangement.

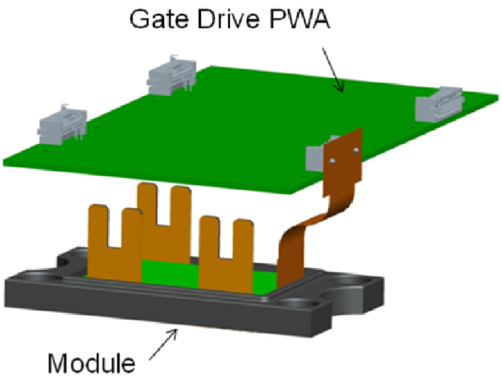

Figure 6: Gate Drive and Module Arrangement

Figure 7 shows the output of a PSIM® simulation of the gate drive design. A prototype of the circuit was manufactured, and subjected to continuous operational testing for greater than 75 hours at 125^{0}C ambient, driving full power into a dummy load at 20kHz and 50% duty cycle. Figure 8 shows the prototype gate drive hardware and its power supply, and Figure 9 shows the gate drive on top of the dummy load used for this test.

The waveforms measured during this testing are shown in Figure 10. A comparison with the simulation waveforms shows excellent agreement.

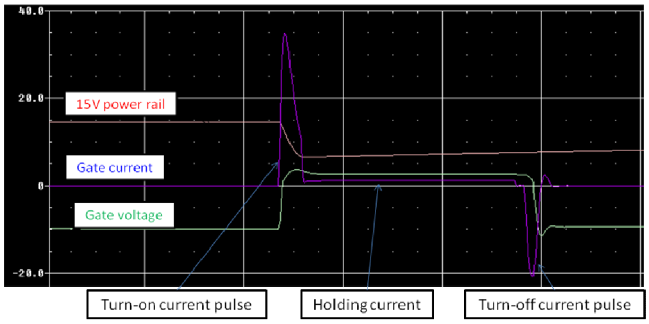

Figure 7: Simulated Gate Drive Circuit Waveforms

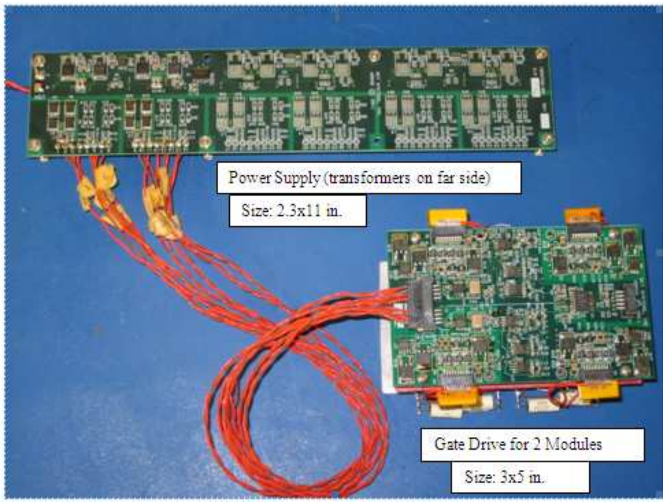

Figure 8: Prototype Gate Drive and Power Supply Hardware for Thermal Evaluation

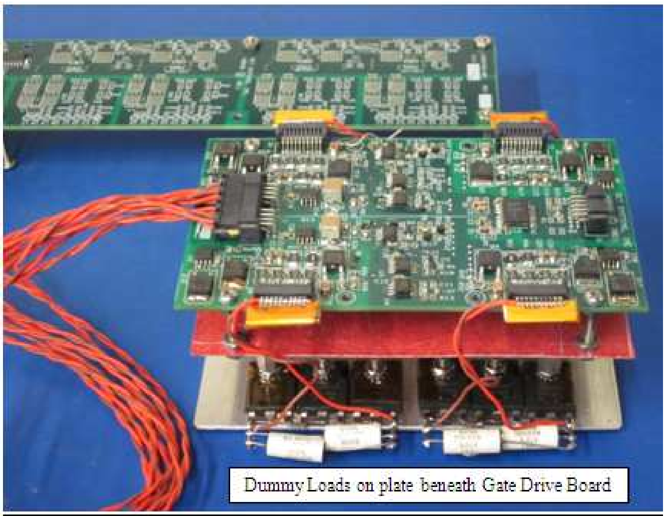

Figure 9: Prototype Gate Drive Hardware With Dummy Loads for Thermal Evaluation

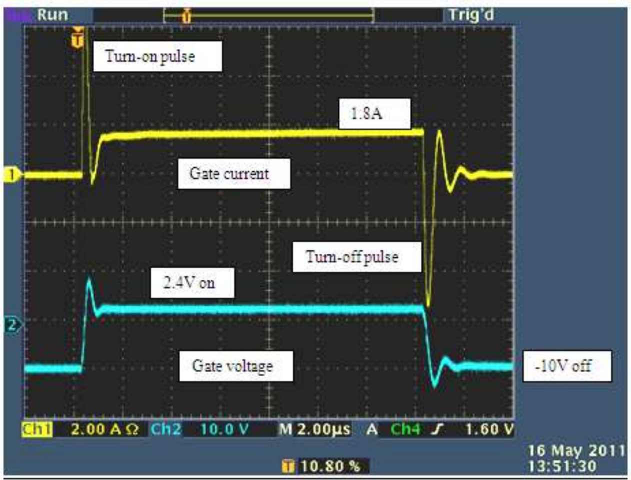

Figure 10: Measured Prototype Gate Drive Waveforms

COMPONENT SELECTION

In addition to the power modules and gate drives, other components of the motor drive require careful selection to meet the demands of this application. In particular, the DC bus capacitors have been specially selected. Typically, DC bus capacitors in a typical commercial motor drive might be power-dense and high capacitance electrolytic or film capacitors. However in this drive, due to the close proximity to the hottest components in the system, namely the power modules, in addition to the relatively high voltage requirements (1000VDC), those types of capacitors are not suitable. Ceramic capacitors are known to be capable of withstanding greater temperatures and voltages than electrolytic or film capacitors, but are not as power dense or as high in capacitance for their size. Capacitors manufactured by AVX utilizing X7R ceramic material in large "DIP" style packages have been selected to solve this need. These capacitors are rated to 125°C, 57Arms, 1000V, and come in packages with relatively high capacitance values. However, in order to achieve the capacitance values required for this motor drive, a large array of these capacitors on a custom circuit board with integrated busbars is necessary. These arrays can be seen in Figure 13. In order to withstand the thermal environment within the motor drive, all other components have been selected with a maximum temperature rating of at least 125°C.

THERMAL ANALYSIS

A detailed thermal analysis was performed to predict the maximum junction temperature, and the maximum allowable coldplate surface temperature under the worst case operating conditions. Based on manufacturer derived switching characteristics, losses in the power modules were estimated for both the motoring case and the regeneration case. In the motoring case, losses in the JFETs were estimated at 15W per die, and losses in the diodes were estimated at 2.75W per die. In the regeneration case, losses in the JFETs were estimated at 7.7W per die, and losses in the diodes were estimated at 15W per die.

The thermal impedance of the stack-up of materials forming the module (shown in Figure 11) was calculated based on the material properties, and an equivalent R_{th} of 0.96°C/W was calculated for the power modules. The Harvard Thermal® simulation model used in this calculation is shown in Figure 12. This calculated impedance predicts a 14.4°C rise in temperature from the coldplate surface to the JFET junctions. In order to keep the JFET junctions to a conservative 150°C, a maximum coldplate temperature of 135.6°C will be targeted.

The custom-designed coldplate was designed for an input coolant temperature of 105°C, with a 2.1°C rise from input to output using a 50/50 mixture of ethylene glycol and water at 6 gpm. The maximum surface temperature under these conditions at maximum load is estimated to be 130.7°C, within the thermal budget. The predicted efficiency at full load, considering the losses of all components is estimated to be 98.5%.

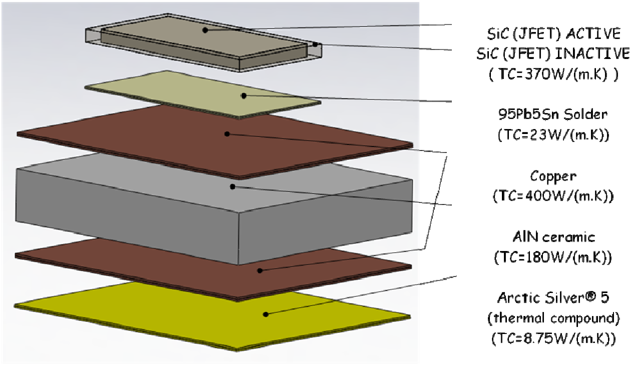

Figure 11: Stack-up for Thermal Analysis

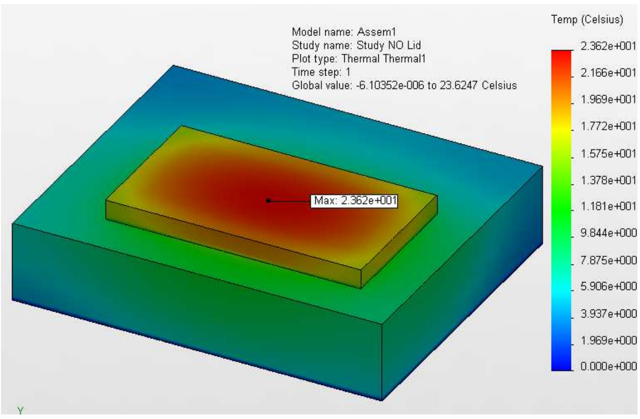

Figure 12: Thermal Analysis Model

PACKAGING

In order to meet the stringent volume constraints of this motor drive design, a number of unique packaging techniques are utilized. In standard commercial designs, the typical practice is to mount components on a single side of a coldplate. In this project, in order to maximize the available cooling surface, and to somewhat segregate the hottest components (SiC switches) from other more temperature-sensitive components, components are mounted on both sides of a custom-designed coldplate. The coldplate is a high efficiency, aluminum brazed assembly that makes use of technology developed for the commercial electric bus powertrains. The coldplate itself divides the assembly into two compartments. One compartment, depicted in Figure 13, contains the SiC switches, gate drives and high temperature DC link capacitors. The compartment on the opposite side of the coldplate, depicted in Figure 14, contains the remaining components, including the power supply board, digital signal processing board, contactors, EMI filter and air to liquid heat exchanger.

One factor limiting the power density of the system is the required creepage and clearance distances necessary to withstand the required hi-pot test voltage for circuit to chassis isolation. Insulation of busbars, use of insulation barriers, careful orientation of components for optimum power flow, and selection and specific orientation of fasteners were some of the techniques used to minimize internal volume.

Figure 15 shows the external view of the packaged motor drive. Busbar connections are provided for input DC power as well as output AC power to the motor. A single circular military style connector is used for the interface to the low-voltage control power, and user interface and controls. Swage-style fittings are provided for the coolant interface. Current projections indicate a final system weight of 30.3 lb.

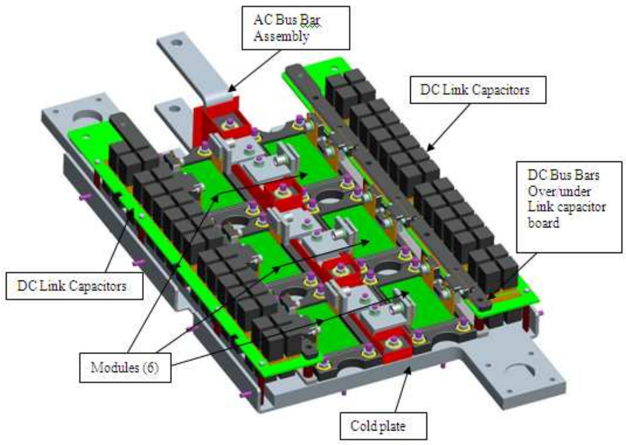

Figure 13: Cold Plate Components, Top View

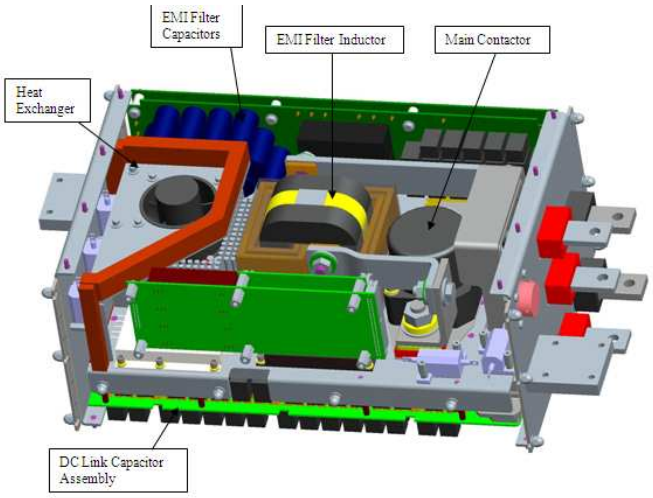

Figure 14: Motor Drive Package, Internal, Bottom View

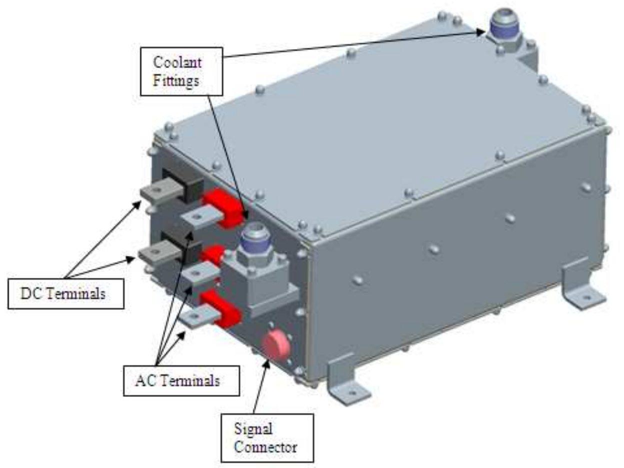

Figure 15: Motor Drive Package, External

PROGRAM STATUS AND TEST PLAN

The program described herein is currently in the manufacturing phase, having completed preliminary and critical design reviews and recently released manufacturing drawings. Power modules are currently being produced and are scheduled for delivery mid-summer of 2011. Assembly will be completed in late summer. Testing will be completed in the fall, with delivery to TARDEC later in the year.

Testing will be performed in several stages. The module manufacturer, SPCO will conduct testing at the module level at 25^{0}C and 150^{0}C. These tests will consist of on-resistance vs. gate voltage, measured breakdown voltage (leakage at 1000V), measured turn-on and turn off switching energy, and verification of the dv/dt performance.

Testing at RCT Systems at the motor drive level will consist of basic system integration and functional testing, thermal validation testing, transient testing to determine the maximum transient output current and power for durations of 1 second and 10 seconds, and efficiency map testing to measure the efficiencies across the operating range of the converter. Testing will include bidirectional (motoring and generating) dynamometer testing using a 200 kW induction motor. The starting condition for all tests will be rated power, with stabilized, 100^{0}C coolant at the inlet.

After delivery, TARDEC will conduct a series of system-level integration tests in their System Integration Laboratory. Test results will be reported at next year's GVSETS conference.

ACKNOWLEDGEMENT

RCT Systems gratefully acknowledges the support of the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) Ground Vehicle Power & Mobility (GVPM) Directorate under an award from TARDEC BAA W56HZV-05-R-BAA1 Topic #20 “High Temperature Silicon Carbide (SiC) Power Electronics”.

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Mr. Wagner is Vice President of Engineering for RCT Systems with over 28 years experience in electronics and electro-mechanical product design and development. His experience includes power electronics, signal conditioning, data acquisition, digital design, microprocessors, and programming. Mr. Wagner has extensive experience in the deployment of heavy-duty electric and hybrid-electric power trains for use in transit buses, and the associated battery-charging infrastructure. Mr. Wagner is a member of the Industry Advisory Board for the Florida State Center for Advanced Power Systems (CAPS), and a member of the Steering Committee for the Electric Power Research Institute (EPRI) National Electric Vehicle Infrastructure Working Council. He is a registered Professional Engineer, and a member of the IEEE. He holds BSEE and MSEE degrees from Lehigh University.

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Mr. Mahoney is Vice President, Business Development, RCT Systems. A Vietnam veteran, he served for 30 years in the US Navy as an Engineering Duty Officer. Relevant tours include Chief Engineer on a Destroyer; Head Design Division, Pearl Harbor Naval Shipyard; Director, Naval Sea Systems Command (NAVSEA), Hull, Mechanical and Electrical group, responsible for all non-nuclear ship mechanical and electrical systems and components. He was the first Program Manager for the Zumwalt (DDG-1000) Class guided missile destroyer. He was head of the Naval Postgraduate School Naval/Mechanical Engineering program, and Professor of Naval Construction and Engineering at MIT. He holds BS & MS ChemE degrees from Iowa State University, as well as SM Nuclear Eng and Ocean Eng degrees from MIT. He is a registered Professional Engineer.

ABOUT RCT SYSTEMS

RCT Systems is a leading developer of high power, high power density power electronics, motors and drives for demanding applications in the defense and aerospace sector. RCT Systems is the former Applied Technology division of the Satcon Technology Corporation which was sold to a group of private investors in January of 2010. RCT maintains a staff of over 40 industry leading engineers, scientists, and technicians and has 16,000 square feet of manufacturing, laboratory and office space located in Linthicum, Maryland near the Baltimore Washington International Thurgood Marshall Airport (BWI). RCT is an ISO 9001:2008 registered company.