2014 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
VEHICLE ELECTRONICS AND ARCHITECTURE (VEA) TECHNICAL SESSION
AUGUST 12-14, 2014 - NOVI, MICHIGAN

HVDC POWER DISTRIBUTION AND CONVERSION COMPONENTS FOR NEXT GENERATION VEHICLES

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ABSTRACT

Electrical power system upgrades needed to fulfill mission objectives for next generation vehicles will require technology advances such as greater power density, increased functionality, and higher operating temperature. To meet these requirements, electrical power demands will exceed the capabilities of currently available low voltage power systems. High Voltage DC (HVDC) systems, e.g., 270 – 800 VDC, are being considered to meet next generation vehicle requirements, but these electrical power systems have the potential for extremely large fault currents in case of electrical equipment failure. Improved battery safety and intelligent Solid State Circuit Breakers (SSCB) and Solid State Power Controllers (SSPC) are needed to improve mission effectiveness, reliability, and personnel safety of next generation military and commercial ground, air, and sea vehicle electrical power systems. In this paper we present three enabling technologies developed by Creare: (1) an intelligent Battery Management System (BMS); (2) a fast-acting Silicon Carbide (SiC) SSCB; and (3) an intelligent SiC SSPC. All three technologies integrate into existing vehicle communications systems via CAN bus to support emerging system level management tools and power system architectures. Modularity and integration with existing and evolving system architectures is achievable through firmware upgrades, e.g., to support Stryker modernization, VICTORY, JLTV, and GCV architectures. The flexibility of these three key technologies provides advanced capabilities for a variety of applications including military and commercial ground, air, and sea vehicles.

INTRODUCTION

Electrical power system upgrades needed to fulfill mission objectives for next generation vehicles will require technology advances such as greater power density, increased functionality, and higher operating temperature. To meet these requirements, electrical power demands will exceed the capabilities of currently available low voltage power systems. High Voltage DC (HVDC) systems, e.g., 270 – 800 VDC, are being considered to meet next generation vehicle requirements, but these electrical power systems have the potential for extremely large fault currents in case of equipment or battery failure. Improved battery safety and intelligent Solid State Circuit Breakers (SSCB) and Solid State Power Controllers (SSPC) are needed to improve mission effectiveness, reliability, and personnel safety of next generation military and commercial ground, air, and sea vehicle electrical power systems.

Three enabling technologies are presented in this paper: (1) an intelligent Battery Management System (BMS); (2) a fast-acting Silicon Carbide (SiC) SSCB; and (3) an intelligent SiC SSPC. All three technologies integrate into existing vehicle communications systems via CAN bus to support emerging system level management tools and power system architectures. Modularity and integration with existing and evolving system architectures is achievable through firmware upgrades, e.g., to support Stryker modernization, VICTORY, JLTV, and GCV architectures. The flexibility of these three key technologies provides advanced capabilities for a variety of applications including military and commercial ground, air, and sea vehicles. Military and commercial vehicles outside the realm of U.S. Army platforms that will benefit from these technologies include More Electric Aircraft such as the Boeing 787 and the Joint Strike Fighter, the U.S. Navy Electric Ship program, Hybrid Electric Vehicles (HEV), and heavy construction equipment.

Creare’s military grade BMS was developed and field tested with an M3A3 Bradley Fighting Vehicle (BFV). This BMS provides accurate battery state information including State of Charge (SOC), State of Health (SOH), and State of Life (SOL). In addition, the BMS provides passive and active cell balancing, vehicle level communication feedback and control enabling intelligent system and mission power management, and operation from -50 to +71°C. The BMS uses a modular, universal architecture that supports any lithium-based chemistry, capacity, or configuration, and tests have demonstrated successful SOC estimates with three emerging lithium chemistries. This paper presents recent field test results showing the performance and accuracy of the BMS subject to a Silent Watch power profile in the BFV. The Silent Watch profile included vehicle start, powering of communications equipment, weapon turret movements, powering of warning systems, and vehicle environmental control activation at different time intervals. Two 24 VDC 6T NATO format 60 Ah battery packs were installed in the BFV’s electronics battery box in a 1S2P configuration. Results of these tests confirmed the accuracy of voltage, current, and SOC measurements to within a 5% error of the independent measurement.

Creare’s military grade SSCB provides very fast protection for batteries and electrical equipment in high current and high voltage electrical power systems. Bus voltages up to 800 VDC and currents up to 1 kA can be accommodated with fault isolation occurring within 10 μs. The SSCB is based on state-of-the-art SiC MOSFET modules, which have high voltage and high current capability, fast response, and good reliability, and replace slow response and limited-life electromechanical contactors commonly used for HEV protection. The SiC technology offers higher voltage blocking capability, a smaller package with greater power density, higher operating temperature, and higher throughput efficiency when compared to existing silicon (Si)-based technologies. The SSCB also provides modularity and flexibility through the onboard microcontroller and upgradeable firmware. This paper presents the design methodology necessary to adapt the SSCB to specific military platforms. Included are results that substantiate SSCB performance for various load currents and thermal environments, as well as an innovative approach to tailoring the characteristics of the SSCB trip point curve.

Creare’s military grade SSPC provides distributed protection for up to twelve (12) high voltage branch circuits (channels) with individual channel currents ranging from 50 – 350 A with ± 300 VDC split bus operation, for a total power throughput of 210 kW. The SSPC achieves revolutionary power density through the use of commercially available SiC MOSFETs integrated into a custom enclosure with innovative mechanical, electrical, and thermal management designs. The SSPC provides fast response (10 μs) electrical protection for the electrical power system loads through electrical isolation of a single channel or the entire SSPC. The key innovations are the modular and protective software features; the compactness of the design, which provides 1.2 kV of isolation between adjacent channels and substantial thermal cooling for the MOSFETs; and high temperature implementation of other circuit functions in addition to the SiC MOSFETs. The innovative software capabilities allow for increased capacity through the parallel combination of multiple channels on the SSPCs or across multiple SSPCs. In this paper we present and compare the design requirements of the SSPC for three cooling methods including passive air cooling, forced air cooling, and liquid cooling. We also present performance data for an initial subscale prototype SSPC and show that the SSPC far outperforms existing SSPCs which use silicon technologies in terms of size, weight, power efficiency, and cost.

BATTERY MANAGEMENT SYSTEM

Creare’s military grade BMS was developed and field tested with an M3A3 BFV in a program funded through U.S. Army-TARDEC. This BMS provides accurate battery state information including SOC, SOH, SOL, Power Availability (PA), pack current, cell voltages, and cell temperatures. It provides two programmable threshold protection levels against over-voltage, under-voltage, over-current, and over-temperature. In addition, the BMS provides passive and active cell balancing, vehicle level communication feedback and control enabling intelligent system and mission power management, and operation from -50 to +71°C. The BMS uses a modular, universal architecture that supports any lithium-based chemistry, capacity, or configuration, and tests have demonstrated successful SOC estimates with three emerging lithium chemistries.

In this paper we present the field test results under a Silent Watch profile performed on a BFV. The Silent Watch profile included vehicle start, powering of communications equipment, weapon turret movements, powering of warning systems, and vehicle environmental control activation at different time intervals. Two 24 VDC 6T NATO format 60 Ah battery packs were installed in the BFV’s electronics battery box in a 1S2P configuration. The 6T form factor modular pack comprises Creare’s BMS electronic assembly with twenty-four (24) prismatic lithium-iron-phosphate (LiFePO4) cells from A123 Systems (Nano-phosphate® AMP20M1HD-A cell). Internal and external views of the 6T pack are shown in Figure 1. Previous papers (i.e., [1], [2], and [3]) have described in detail this system and its laboratory performance results. Results of these tests confirmed the accuracy of voltage, current, and SOC measurements to within a 5% error of the independent measurement.

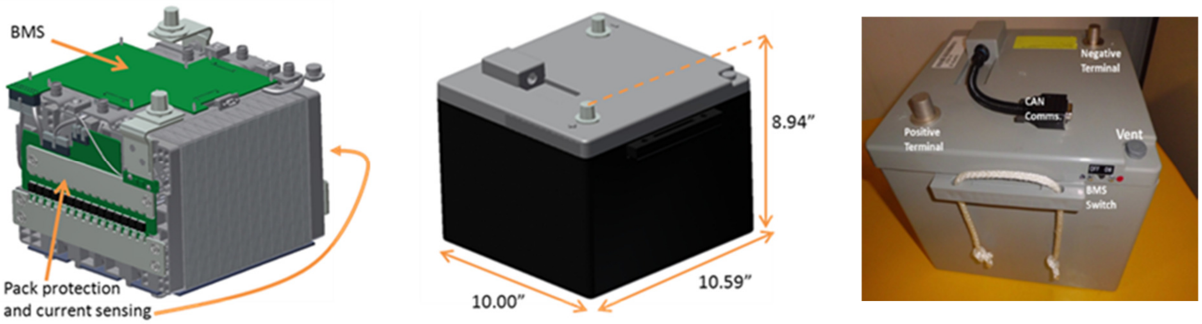

Figure 1. Creare's Universal Battery Management System integrated in a 6T pack form factor.

Execution of a Silent Watch profile was used to determine the performance of the BMS system under test. The objective was to determine how well the BMS compares with the measurements from an independent data acquisition system, as well as how consistent the tests are over multiple cycles in the same conditions. Two types of performance tests were conducted: (1) a test bench verification test; and a (2) vehicle test. The testing was completed in this order:

1. Preparation for Testing/Setup
2. Performance of Bench Testing
3. Installation of BMS/Battery Pack into BFV
4. Performance of Silent Watch Profile

The performance testing of the Silent Watch profile was conducted first with the current configuration of BFV's lead acid electronic batteries. This allowed for a baseline configuration sample to be developed. A second round of testing was conducted with two +24 VDC 6T battery packs installed in the BFV's electronics battery box.

The vehicle performance tests were performed under the Silent Watch power profile. A sequence of events were executed to conduct the Silent Watch test including boot-up to Combat State with an active turret, initiation and completion of the Silent Watch profile, and return to full operations with vehicle restart and battery recharge to 100% SOC. The results of these tests confirmed accuracy of temperature, voltage, and current measurements reported by the BMS as compared to the independent data acquisition system.

Figure 2 shows the pack voltage and current of one of the battery packs (referred to as Battery 1), and Figure 3 shows the corresponding SOC during the Silent Watch profile as logged by the BMS. The SOC responds well to the observed

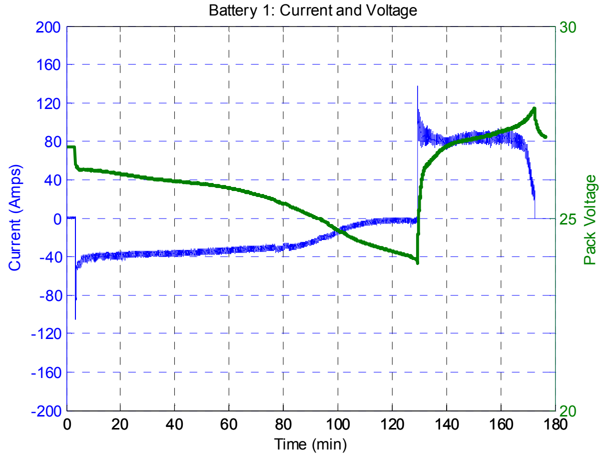

Figure 2. Pack voltage and current of Battery 1 during vehicle testing.

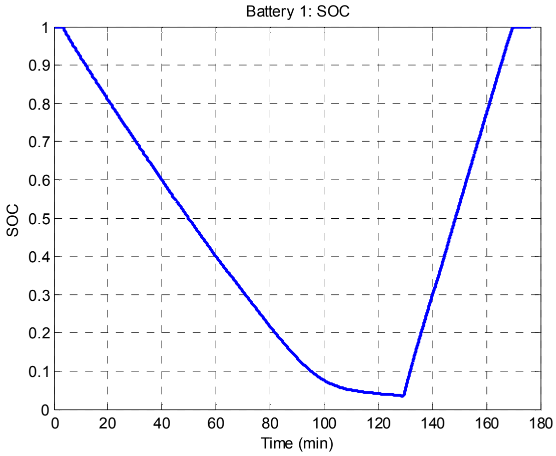

Figure 3. Pack SOC of Battery 1 during vehicle testing.

currents applied to the battery pack. For example, consider the first 80-minute duration during which the pack is discharged from 100% SOC down to 20% SOC. The time averaged discharge current was 34 A for 80 minutes, which corresponds to an actual SOC of 24%. The BMS reported the SOC within 4% at 20%. To charge the battery from 5% to 100% SOC should require 43 minutes at a current of 80 A. Figure 3 shows the SOC increase from 5% to 100% in 40 minutes (130 minutes to approximately 170 minutes). These results show accurate voltage, current, and SOC measurements in a vehicle environment, which were compared to the results obtained with the independent data acquisition system. The packs were also used to subsequently start the vehicle and performed well for that task.

SILICON CARBIDE SOLID STATE CIRCUIT BREAKER

Creare is developing an extremely fast SiC-based SSCB rated for high voltage, current, and power. This SSCB allows large loads to be isolated quickly, enabling the move to greater electrical power system capacity. With an increased maximum operating temperature, our SSCB can be installed in harsh environments, such as engine compartments, with minimal demand on vehicle thermal management systems.

SiC MOSFETs are the device of choice for SSCBs that protect high voltage, high current power systems. The SiC MOSFET advantages include low on-state losses when compared to other devices, exceptionally rapid switching speed, 1,200 V blocking voltage, and high operating junction temperature. Cree guarantees operation to at least 150°C, and there is adequate data available to suggest that operation is possible as high as 300°C. The high operating junction temperature of the SiC device, combined with the ability to reduce MOSFET switch on-state resistance to a minimal level by paralleling devices, permits the reduction of on-state losses and simplifies thermal management in high ambient temperature environments such as combat HEVs. Another advantage of the MOSFET device, compared to an IGBT, is the inherent bidirectional ohmic conduction characteristic of the switch. This latter feature permits reverse current flow in the presence of regenerative or charging current flow without additional gating of the power switching device. The features of the SSCB, advantages over other approaches, and benefits to the warfighter are summarized in Table 1.

Table 1. Features, Advantages, and Benefits of Creare's SSCB

Feature	Advantages	Benefits
SiC-based Solid State Protection	• Higher temperature operation than silicon SSCBs • Faster response than electromechanical protection • Longer life than relays and contactors	• Simplify thermal management • Free up vital vehicle space for additional mission capability • Improve vehicle and personnel protection and safety • Lower life cycle costs • Intelligent control, monitoring, and diagnostics
Scalable and Modular	• Broad application	• Reduce cost • Simplify logistics
High Current (1,000 A), High Voltage (600 V), Fast Response (10 µs)	• Satisfies needs for all military ground vehicles	• Limit damage due to high fault currents • Minimize lifecycle costs
-55°C to +125°C Operation	• Full MIL-SPEC capability	• One design meets all needs • Locate anywhere in vehicle, including engine compartment

The SSCB is currently at TRL4. We designed, fabricated, and tested a first generation, proof-of-concept, 1.2 kV, 200 A SSCB (Figure 4), demonstrating excellent performance [4]. Our SSCB has distinct advantages over existing electro-mechanical contactors, fuses, and silicon-based SSCBs including much faster response time (< 10 µs), higher temperature operating capability (125°C environment), much better cycle life and reliability, and more flexible reset capability. The most pressing requirement is for a switch that can break kA-level fault currents within several µs, before the currents exceed allowable ratings. Unlike electromechanical relays, which can be destroyed by even one such breaking event, the solid-state switch will have longer life expectancy and offer advanced capabilities such as soft-start, inrush limiting, reclosing, and smart power system management. We are currently fabricating a second generation prototype 1.2 kV, 1.0 kA SSCB that will be evaluated and demonstrated under typical operating conditions and with prototypical systems to advance the technology to TRL 8. Table 2 compares the key design criteria of the first and second generation products.

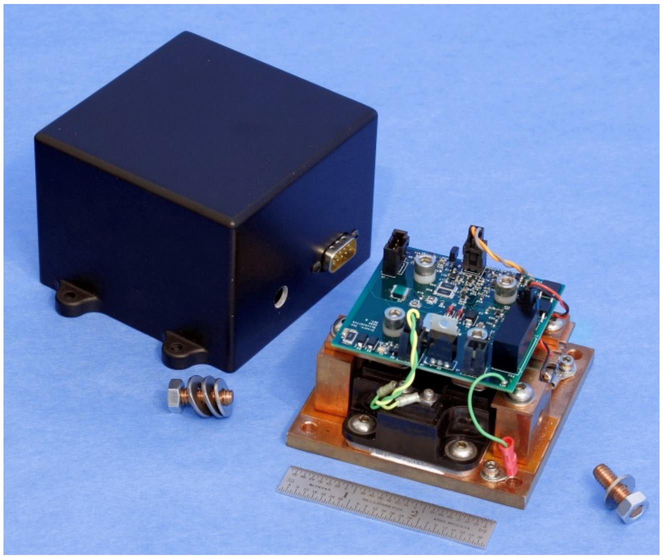

Figure 4. Complete SSCB assembly.

Table 2. Summary of Prototype Requirements by Generation		
Parameter	1^{st} Generation	2^{nd} Generation
Functional Purpose	Replace conventional electromechanical relay for the purpose of protecting HEV electrical systems and battery packs.	
Primary Feature	Limit fault current via fast switching.	
Features	Fast switching. Remote input control and status output. Ability to handle regenerative and charging currents. Can be used for dual bus protection.	
Voltage	1,200 V	1,200 V
Forward Current	200 A	500 A continuous 1,000 A for 10 seconds
Reverse Current	100 A	60 A continuous 120 A maximum
Response Time	20 µs	10 µs
Case Temperature	75°C	100°C

SILICON CARBIDE SOLID STATE POWER CONTROLLER

Creare's military grade SSPC provides distributed protection for up to twelve (12) high voltage branch circuits (channels) with individual channel currents ranging from 50 – 350 A with ± 300 VDC split bus operation, for a total power throughout of 210 kW. Note that the SSPC designs presented here support protection for both sides of the split bus. The SSPC achieves revolutionary power density through the use of commercially available SiC MOSFETs integrated into a custom enclosure with innovative mechanical, electrical, and thermal management designs. The SiC technology provides the same benefits to the SSPC as seen in the SSCB. The SSPC provides fast response (10 µs) electrical protection for the electrical power system loads through electrical isolation of a single channel or the entire SSPC. The key innovations are the modular and protective software features; the compactness of the design, which provides 1.2 kV of isolation between adjacent channels and substantial thermal cooling for the MOSFETs; and high temperature implementation of other circuit functions in addition to the SiC MOSFETs. The innovative software capabilities allow for increased capacity through the parallel combination of multiple channels on the SSPCs or across multiple SSPCs.

In developing this product, we compared the design requirements for passive air cooling, forced air cooling, and liquid cooling and showed that the SiC approach outperforms existing SSPCs, which use silicon components. Figure 5 shows (left to right): (1) heat sink fins and natural convection cooling (largest), (2) heat sink fins and forced convection (smaller), and (3) liquid cooling (smallest). The thermal design required optimization of key thermal management components including the heat sink fins, liquid flow heat exchanger, and thermal interface materials. To achieve the desired thermal performance, we optimized these components while varying the number of SiC MOSFETS used for each channel in the SSPC. For the natural convection fins, we optimized the height and length and determined the width of the fin array needed to meet the SiC MOSFET heat dissipation requirements. Increasing the number of MOSFETS for each channel reduces the current per device and therefore significantly reduces the I^2R heat dissipation of each MOSFET device as well as for each channel.

For the trade study presented here, we assumed a maximum allowable SiC MOSFET junction temperature of 175°C and an ambient temperature of 125°C. Although SiC devices are capable of operation at temperatures of 200°C or above, long-term reliability has not yet been established for these temperatures. At a junction temperature of 175°C, we expect good reliability of the MOSFET device, so we are using that condition as our design condition. The rightmost design in Figure 5 is representative of a well-optimized 12-channel SSPC that operates at 125°C ambient temperature with 105°C coolant and unidirectional protection of two buses (+/-300 VDC) with a current rating of 350 A. Two 12 oz. soda cans are shown for visual size comparison of the various cooling approaches. These designs are well optimized thermally and mechanically.

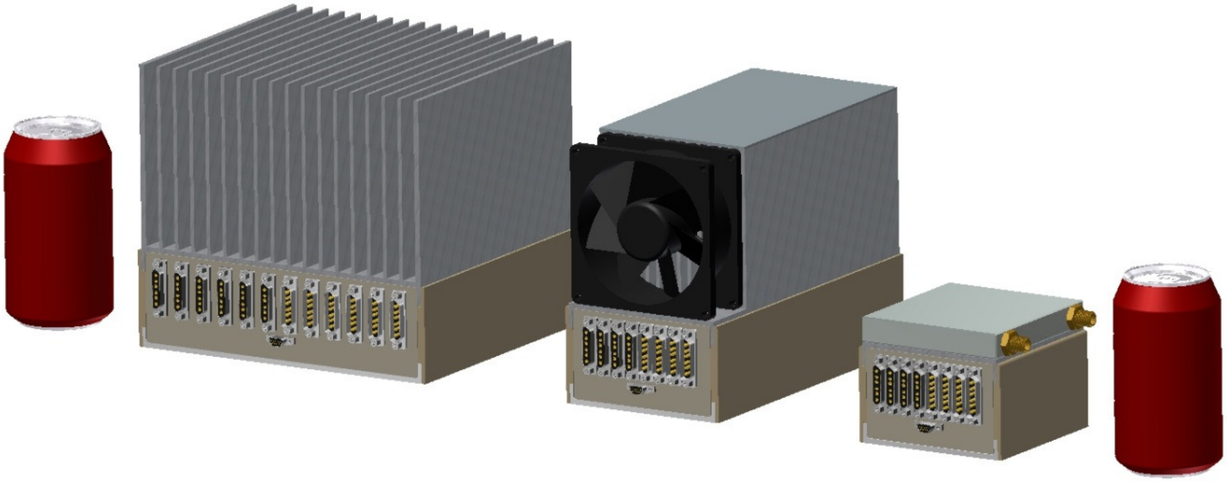

Figure 5. SSPC cooling options. From left to right: SSPCs with passive air cooling, forced air cooling, and liquid cooling. These packages are well optimized designs supporting 12 channels with a total current capacity of 350 A on a split bus at ±300 VDC (210 kW). Two 12 oz. soda cans are shown for visual size comparison of the various cooling approaches.

We also evaluated and optimized a Si-based MOSFET SSPC design concept to compare size, weight, and cost with the SiC technology. To make a fair comparison, we identified two state-of-the-art Si MOSFETs with similar current and voltage rating to the SiC MOSFETs. Both Si MOSFETs have similar on-state resistances to one another, although it is much higher than the SiC MOSFET, and the MOSFET package geometries are nearly identical. The maximum rated junction temperature of the Si MOSFET is 150°C, although the allowable drain current limit goes to zero amps at that temperature, so the device must actually be operated at lower temperatures. Consequently, although we allow Si MOSFET junction temperatures of up to 125°C for the purpose of this comparison, the allowable current is much lower than the maximum datasheet rating. This will further increase the number of MOSFETs needed and corresponding package size. To make this comparison, we designed the Si MOSFET SSPC to produce the same power dissipation as the liquid cooled SiC MOSFET SSPC. The designs resulting from the thermo-mechanical analysis of the two MOSFET technologies show that the Si-based SSPC is almost 20 times larger than the SiC-based SSPC. This is due to the much higher on-state resistance of the Si MOSFETs and corresponding larger number of devices required for a given current.

We fabricated and tested the thermal and electrical performance of the SiC SSPC to verify intelligent circuit protection and validate thermal and electrical models. A photograph of the first generation, four channel prototype SSPC is shown in Figure 6. For the prototype SSPC, we used commercially available cold plate and electronics components to reduce cost for the proof-of-concept device. To evaluate the prototype, we conducted thermal and electrical tests including temperature rise, turn-off response, soft-start demonstration, and current-overload protection for constant and pulsing overload conditions.

The SSPC achieves a turn-off time with a 20 A rated channel within 10 µs. The SSPC provides soft start ramp-up time of about 20 ms, and allows programmatic increase or decrease of the charge-up rate of the gate to source voltage to increase the soft start-up time if desired. The SSPC provides current overload protection based on a charge pump accumulator and an I^2t threshold. Validation of the current overload protection validates both the current sense and the firmware digital logic. We performed over-current tests at constant current overloads of 200%, 350%, 450%, 650%, 850%, and 1100% of nominal current. An example over-current test result is given in Figure 7 for a 20 A rated channel that has been downwardly programmed by the user to a current limit setting of 15 A. A variety of programmable settings can be modified on the SSPC through a graphical user interface that communicates with the SSPC via a standard CAN bus. We measured trip time for each of the over-current conditions and plotted the results.

Figure 8 shows the results of the current overload experiments (symbols) relative to the ideal trip threshold (pink line) and the upper and lower limits of acceptance (orange and green lines). The SSPC tripped at precisely the trip threshold for all but the 1100% over-current condition, and always tripped within the threshold limits. An example of I^2t current overload protection with a pulsing current is shown in Figure 9. In this case we applied an overload current of 150% with a rapidly pulsing current. The accumulator increases starting at roughly 3 s when the first overload pulse occurs. Between pulses, the accumulator decays at a rate proportional to $I_{rating}{}^2t$, as indicated by the decreasing portion of the accumulator curve. The accumulate/de-accumulate cycle repeats until the accumulator reaches the I^2t threshold at 10 s. This test simulates an intermittent partial short to ground.

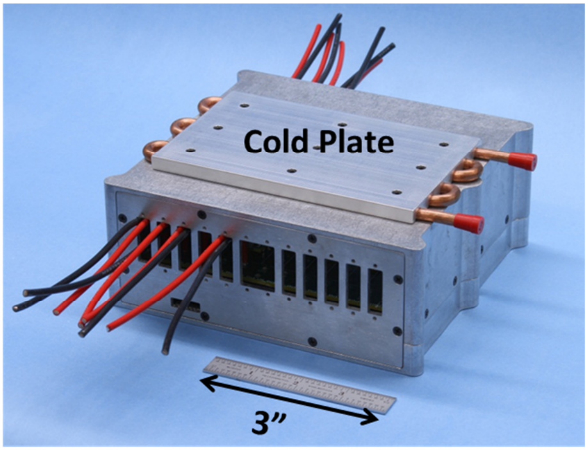

Figure 6. SSPC prototype assembly.

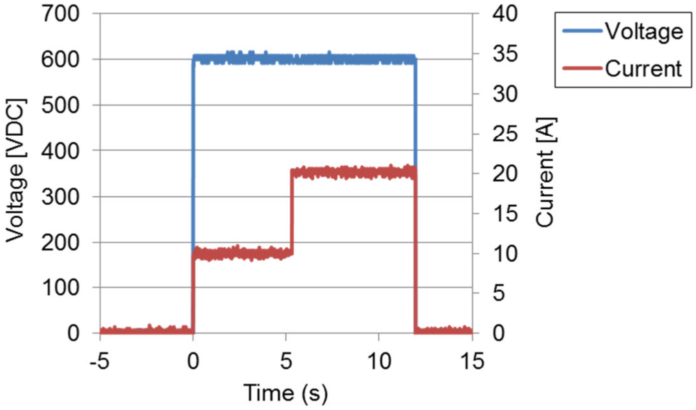

Figure 7. High voltage current overload (130% channel current rating).

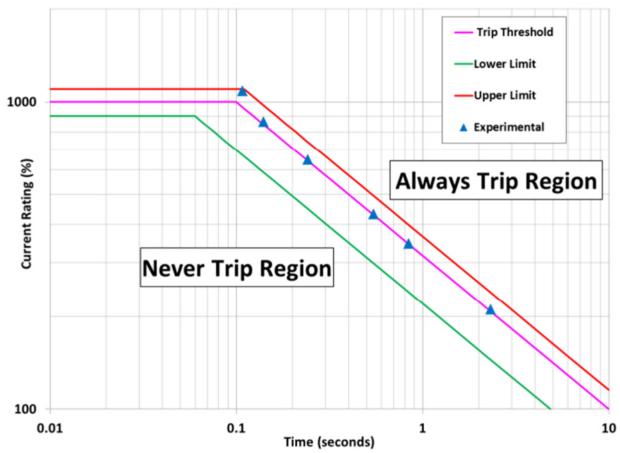

Figure 8. I^2t expected (lines) vs. actual (symbols).

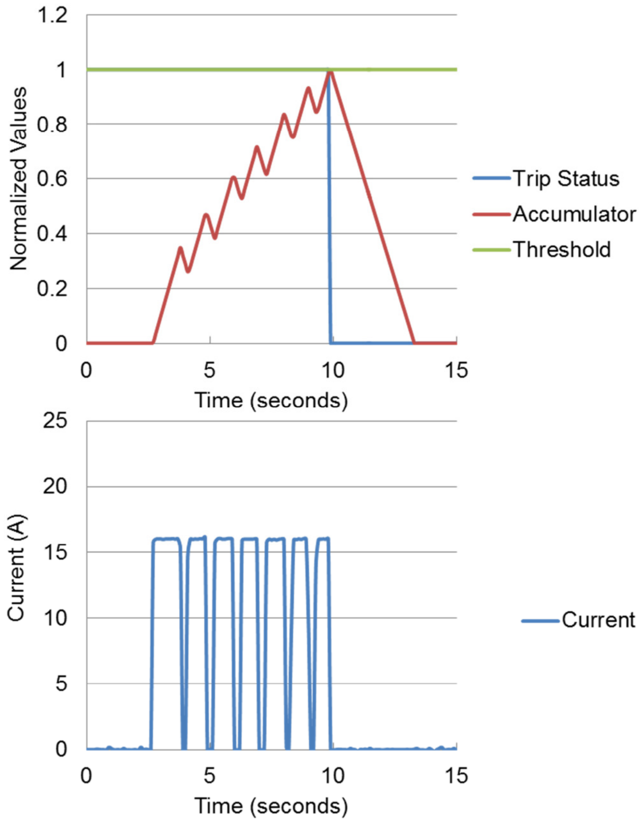

Figure 9. Pulsing current trip (150% channel current rating).

CONCLUSIONS

We have presented three technologies that will improve the safe and reliable operation of HVDC distribution and electrical power conversion systems for next generation ground, air, and sea vehicles.

First, we presented an advanced lithium-based Universal BMS that is capable of accurate SOC, SOH, SOL, and PA estimation, along with active and passive cell balancing, protection, and communication features in a wide range of thermal environments. This technology has proven SOC estimates to within 5% accuracy and was field tested with a BFV in a Silent Watch mission scenario.

Second, we presented a high power 1.2 kV/200A SiC MOSFET SSCB for the protection of military vehicle electrical power systems. We demonstrated response times of less than 10 µs, operational ambient temperatures higher than 125°C, and a current density of 0.4 A/cm^3. Our next generation design will achieve a much greater current density of 12 A/cm^3 by accommodating up to 2,000 A in a 10 in^3 package.

Finally, we presented a high power SSPC with 350 A total current rating at ±300 VDC (210 kW). We evaluated a number of design concepts to compare size and performance, including three cooling options, and showed that liquid cooling provides enormous space savings. We also showed that a conventional Si MOSFET based approach results in a package that is roughly twenty (20) times the size of a comparable SiC approach. We demonstrated basic functionality with a first generation prototype at bus voltages of up to 600 VDC, continuous currents up to 20 A per channel, and peak transfer power of 12 kW. We verified over-current trip times consistent with the I^2t settings at current overloads of 200%, 350%, 450%, 650%, 850%, and 1100% of nominal current, and we verified over-current trip times with pulsing current loads. In all cases, we verified activation response time is less than 10 µs, and we demonstrated soft start capability with a nominal ramp-up time set to 20 ms, which is programmable via the CAN interface and easily changed.

Each of these technologies is modular and adaptable to a variety of system platforms and architectures through upgradeable software. The intelligent BMS, fast-acting SSCB, and multi-channel SSPC will enable substantially increased power capabilities in next generation military and commercial ground, air, and sea vehicles.

ACKNOWLEDGMENT

The support and guidance of the U.S. Army SBIR Office and TACOM Research, Development and Engineering Center (TARDEC), in particular the Technical Monitors David Skalny, Wes Zanardelli, George Hamilton, and Kevin Sharples, are gratefully acknowledged.

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