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U.S. ARMY, BAE SYSTEMS P&S, and GE AVIATION JOINTLY EXECUTE AN M109A7 VEHICLE LEVEL DEMONSTRATION OF A GE SILICON CARBIDE CONVERTER

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ABSTRACT

The M109A7 Self-Propelled Howitzer (SPH) developed by BAE Systems is groundbreaking for its utilization of 610 Vdc high-voltage (HV) electrical power generation and distribution. When the vehicle entered development ten years ago, silicon based power conversion devices were a proven and effective technology to provide the demanding power needs of the new military platform. Since then, technological advances in Silicon Carbide (SiC) semiconductors have shown great promise in providing significant improvements to power density, efficiency, and operating temperature. When GE Aviation developed a prototype Silicon Carbide power converter which debuted at the 2014 GVSET Symposium, both TARDEC and BAE Systems, P&S recognized the benefit to evaluating and demonstrating the technology on the M109A7. In August 2016, the plan came to fruition when the joint TARDEC, BAE Systems P&S, and GE Aviation team successfully completed a series of demonstration tests showing that the technology could deliver on its promised improvements.

INTRODUCTION

The M109A7/M992A3 Paladin Integrated Management (PIM) program is the first Armored Brigade Combat Team tracked combat vehicle to integrate a high-voltage (HV) electrical power generation and distribution subsystem into its M109A7 SPH (shown in Figure 1) and M992A3 Carrier Ammunition Tracked (CAT) vehicles. Constantly increasing demand for electrical power drove the need for the size, weight and reliability improvements that a HV generation and distribution system can provide. The M109A7 is capable of providing 41 kilowatts of electrical power to the onboard systems while allowing for 50 percent reserve capacity for future expansion and addition of new capabilities.

Figure 1: The M109A7 Self-Propelled Howitzer

The original vehicle power system design came about through a collaboration between BAE Systems, Platforms & Services (P&S), York, Pennsylvania and BAE Systems, HybriDrive Solutions in Endicott, New York. From the start, there was an emphasis on modularity and the open-architecture systems approach so that future upgrades could be incorporated at the rapid pace of technological progress without the need for major system redesigns. Modular, open architectures are also important for promoting commonality across vehicle platforms, decreasing average unit production costs, and promoting industry competition.

The M109A7 Common Modular Power System (CMPS) includes a 610 Vdc HV bus and 28 Vdc Low Voltage (LV) bus and consists of a 70 kW HV generator, a 70 kW generator controller/inverter (GINV), two 12 kW Bi-Directional 610 Vdc to 28 Vdc DC-DC Converters (BIDIs), a HV Distribution Box, and three 28 Vdc Vehicle Control and Power Distribution Modules (VCDM). The 70 kW GINV and two 12 kW BIDIs provide the electrical power inversion and conversion for the CMPS. The GINV actively rectifies the generator AC voltage to +/- 305 (610 Vdc) and the BIDIs convert 610 Vdc to 28 Vdc. Figure 2 shows a high-level representation of the M109A7 Common Modular Power System.

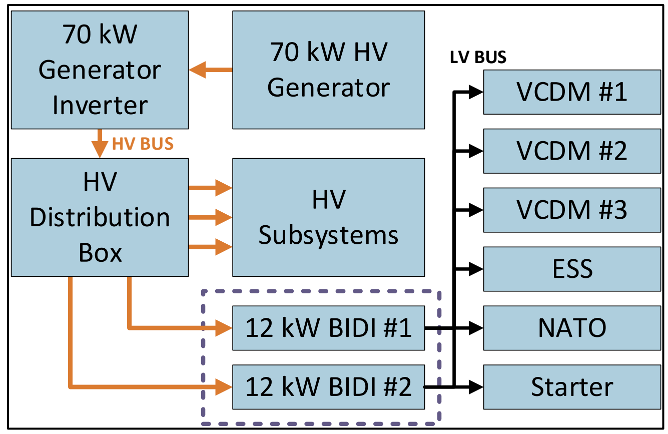

Figure 2: M109A7 Common Modular Power System Indicating Demonstrator Point of Insertion

SILICON CARBIDE (SiC) ENABLING TECHNOLOGIES

Silicon carbide semiconductors are enabling technologies that bring significant benefits to power conversion electronics. The two big advantages of SiC are lower switching losses and the ability to operate at higher temperatures. The wide band gap properties of SiC MOSFETs allow operation at much higher operating frequencies (5X) compared to silicon (Si) IGBTs. This in turn leads to smaller and lower weight magnetics typically used for isolation transformers, inductors/capacitors used in L-C output filters and input and output EMI filters. The high temperature properties of SiC devices facilitate reduced heatsink volume and weight or increasing power output capabilities for the same amount of cooling. The SiC MOSFETs developed by General Electric have been qualified to 200 °C operation. This high temperature performance is 50 °C higher than most silicon devices. To take full advantage of the high temperature capability of SiC versus Si devices, advanced packaging and system-level cooling methods can be employed to gain higher power density and increased reliability. On vehicles such as the M109A7, a big advantage to using higher operating temperature silicon carbide power devices could be the total elimination of the dedicated medium temperature electronics coolant loop and associated hardware, instead cooling all power electronics via the engine coolant loop. Doing this would lead to an overall weight savings, improved space claims, and significant reliability improvements.

EQUIPMENT UNDER TEST

For the on-vehicle demonstration, TARDEC provided a SiC based 15 kW unidirectional DC-DC converter developed by GE. The improvement in Size, Weight, and Power when compared to the existing silicon based BIDI is shown in Figure 3 and Table 1 below. It should be noted that because it was a prototype, the GE converter did not provide the full level of processing and memory, diagnostics, and system monitoring capabilities that a production BIDI is capable of.

Figure 3: Silicon Converter (left) vs. SiC Converter

Metric \ Technology	Silicon	Silicon Carbide	% change
Year	2011	2014	
Output Power (kW):	12	15	+25%
Weight (kg):	27	17	-37%
Volume (liters):	25	17.5	-30%

Table 1: SWaP Comparison Si Vs SiC

This converter is smaller and produces more power than a single existing BIDI. To fully meet the M109A7 vehicle level 28Vdc power requirement, the SiC converter power level needed to be able to provide 20kW. (Note: the M109A7 derived requirement including margins is 22kW of 28 Vdc power.) GE reported further testing resulted in this converter being capable of supporting 20 kW. Therefore, one SiC converter was determined to be sufficient for the demonstration to perform the function of the 28 Vdc power generation requirements of two existing production BIDIs.

The GE SiC converter has a smaller length and slightly larger width and has completely different interface connectors. To integrate the SiC Converter onto the vehicle, GE developed a fixture that replicated the existing BIDI chassis; picking up the mounting features at the front and rear of the chassis and all the front panel electro-mechanical interfaces. This allowed the SiC converter to be installed directly into the vehicle as if it were a single BIDI.

Figure 4: SiC Converter in Vehicle Fixture

Figure 4 shows the SiC Converter mounted in the fixture with I/O and instrumentation.

In the remaining volume, GE packaged I/O interface cables, current shunt for monitoring output load current and flow meters to monitor coolant pressure into and out of the Converter. Series and bypass valves and pressure gauges were used for these measurements to ensure adequate coolant flow would be provided to the GE SiC converter as well as ensuring coolant flow would not be impaired to the remaining existing M109A7 Common Modular Power System components.

GE modified the converter to enable manual operation of the unit from a remote location in the vehicle without interfacing to the M109A7 host control systems. A control box was provided with test points for monitoring output voltage and load current during the testing activity.

COLLABORATION AND TEST PLANNING

The purpose of this effort was to demonstrate and evaluate the performance of the SiC electrical power converter in a M109A7 Vehicle and at the same time demonstrate the modular, open architecture of the vehicle HV electrical power system. In order to successfully execute the demonstration, a partnership between BAE Systems P&S, TARDEC and GE was required leveraging the system knowledge of BAE Systems and the component knowledge of GE Aviation. The demonstration reinforced the vision that SiC Power Electronics is easily integrated in a production level combat vehicle.

Because the demonstration was performed on an existing M109A7 vehicle that was slated for future program needs, the team needed to take every precaution to ensure that no damage would occur to the vehicle hardware and that it was able to be returned to the same original configuration as before the test. Additionally, the team needed to observe rigorous hazardous-voltage design standards and precautions to ensure the safety of all involved test personnel.

Significant collaboration occurred between BAE Systems P&S, General Electric, and TARDEC leading up to the demonstration to ensure that the design was sufficiently matured. BAE Systems identified all relevant interface and performance requirements and communicated them to GE. The interfaces were tested and verified and a robust test setup and execution plan were in place to ensure total success on all fronts. BAE Systems completed software simulations to ensure that there was no potential for high-voltage differential link resonance in the system leading to an abnormal condition. GE performed extensive bench testing to ensure that the component was performing to expectations and met the parameters set forth by the BAE Systems vehicle subject-matter experts.

PRE-INSTALLATION TESTING

Considerable investigation was undertaken to ensure that the SiC converter was compatible with the existing 600 Vdc and 28 Vdc vehicle electrical systems. Performance requirements were verified at GE's facility prior to installation on the M109A7 vehicle. Operation over the expected input voltage range was verified at load currents up to 535 Adc (15 kW). Output voltage regulation and efficiency was tested at 15 different operating points. Table 2 shows the results of the testing.

Input Voltage (V)	Input Current (A)	Input Power (W)	Output Voltage 28V +/-	Output Current (A)	Output Power (W)	Efficiency (%)
641.1	0.003	1.923	28.122	0.00	0.00	
641.5	1.496	959.68	28.130	25.16	707.75	73.75
641.9	10.65	6836.24	28.102	225.00	6322.95	92.49
641.8	18.84	12091.51	28.076	399.94	11228.72	92.86
641.7	25.34	16260.68	28.053	536.11	15039.49	92.49
610.4	0.003	1.831	28.122	0.00	0.00	--
609.8	1.530	932.99	28.137	25.00	703.43	75.39
609.7	11.18	6816.45	28.110	224.80	6319.13	92.70
609.6	19.80	12070.08	28.086	399.70	11225.97	93.01
609.4	26.64	16234.42	28.066	535.84	15038.89	92.64
564.5	0.004	2.258	28.121	0.00	0.00	--
564.5	1.602	904.33	28.132	25.14	707.24	78.21
565.0	11.99	6774.35	28.106	224.97	6323.01	93.34
565.2	21.34	12061.37	28.023	399.92	11206.96	92.92
564.7	28.77	16246.42	28.064	535.91	15039.78	92.57

Table 2 - Line Regulation, Load Regulation, Efficiency

Low line operation demonstrated that the 28 Vdc output could maintain regulation down to 500 Vdc with 400 Adc load current applied.

Of particular interest was the effects on the 600 Vdc bus due to large transient loads on the 28 Vdc output of the Converter. Transient loads up to 400 Adc were applied and removed and the results were recorded. A bank of 24 Vdc lead acid batteries along with similar length / gage load cables were used to simulate the vehicle's 28 Vdc electrical system. Tests were performed with and without the batteries to evaluate the conditions described in MIL-Std-1275. In Figure 5, a step load from 0 to 400 A was applied. The load current was applied at a rate of 1000 A/mS.

Figure 5: Transient Load Performance; 0 A to 400 A step

The signals are identified as:
CH1 (Yel) = 28 Vdc Output Voltage
CH2 (Blu) = 610 Vdc Input Voltage
CH3 (Vio) = Battery Current
CH4 (Grn) = 28 V Output Current

The step load is applied over a 400 uS timeframe. The Converter is providing 400 A into an electronic load as well as charging current into the batteries as indicated by the negative current (-57 A) measured on channel 3. During the transient, the output voltage droop was only 1.2 Vdc and recovered in 500 uS. The minimum droop and fast recovery is due to the higher control bandwidth which is enabled by the higher switching frequency available when using silicon carbide devices. As seen in CH2 waveform, the effect of the transient load on the input voltage is minimal. Both input and output voltages stay well within the MIL STD limits while supporting the transient load requirements. In Figure 6, a step in load current from 400 A to 0 Adc (load shed) was applied.

Figure 6: Transient Load Performance; 400 A to 0 A step

The signals are identified as:
CH1 (Yel) = 28 Vdc Output Voltage
CH2 (Blu) = 610 Vdc Input Voltage
CH3 (Vio) = Battery Current
CH4 (Grn) = 28 V Output Current

The load shed occurs over an 800 uS period. An electronic load was used to provide a constant current 400 Adc load. The Load was disabled presenting a load shed event to the Converter. The output voltage increases less than 1 Vdc and recovers within 500 uS. As seen in CH2 waveform, the effect of the 400 A load shed event on the input voltage is minimal.

DEMONSTRATION SETUP

The demonstration occurred at the BAE Systems, York, PA facility. At this 143-acre industrial complex, BAE Systems designs and manufactures combat vehicles including the Bradley Fighting Vehicle, M88 Recovery Vehicle, and M109 Howitzers. The facility has the electronic test equipment available to perform detailed analysis and collect key data on the HV electrical system performance during the demonstration. The site also has a test-driving track, which is key to subjecting the equipment under test to the full gambit of thermal, mobility shock, vibration, and electrical loading profiles necessary to characterize the equipment.

The scope of the testing was to compare the power quality of the existing HV generation system with the prototype GE SiC Converter that would normally be performed by two BIDIs and document those results per the prescribed test plan. This includes ensuring the vehicle has sufficient amount and quality of 610 Vdc power while the GE SiC Converter 28 Vdc output is loaded or unloaded.

Complete safety standards and checklists were developed by BAE Systems personnel to ensure the safety of all personnel involved in the demonstration. Safety reviews were held to ensure all individuals conducting the HV testing were HV trained per BAE Systems standards, proper HV Personal Protection Equipment (PPE) was available and used appropriately throughout testing, proper setup of instruments, distances from vehicle and/or HV areas were maintained, and the test area was properly cordoned off to prevent entry of other personal into the HV testing area.

Complete fit-checks were performed in the vehicle to verify the form, fit and function of the vehicle fixture prior to testing. Figure 8 demonstrates the difference in space claim required for the single GE SiC converter when compared to the original two-BIDI configuration (Figure 7).

Figure 7: Original two-BIDI configuration (BIDIs stacked one on top of the other)

Figure 8: GE SiC converter in place of two BIDIs

TESTS PERFORMED

A stationary vehicle level DC Power Quality test was performed twice on the M109A7 vehicle. The first test was performed as baseline with the original two BIDI configuration and a second with the GE SiC converter installed in place of the two BIDIs.

Data collection was also performed at the output of the SiC converter to isolate observed ripple noise on the 28 Vdc bus and to determine if any high voltage link oscillations were occurring, which simulations showed not to be a concern.

The M109A7 vehicle with the SiC converter installed was then driven on the test track. The output voltage was monitored with a DVM attached to the remote control box and was being monitored 100% of the time. Several laps were performed at various speeds.

OBSERVATIONS AND TEST RESULTS

Interfaces with Vehicle

There were some initial issues installing the mechanical interface/adapter due to alignment issues with the existing locating pins, however, once the initial issue was resolved, the mechanical interface/adapter provided by GE worked well in the vehicle test environment. The SiC hardware fit within the allowed space claim without any physical interference to components around the installed location. The smaller space claim provided by the higher power density SiC hardware was evident when the hardware was installed in the vehicle and there was a noticeable open space where the top BIDI is normally installed in the vehicle.

Electronics Cooling

The GE interface allowed the SiC hardware to be cooled by the electronics coolant loop of the M109A7. Pressure measurements were taken during testing to ensure that there was sufficient coolant flow through the SiC converter for proper cooling. The measurements showed that flow was sufficient. No temperature measurements were taken during the testing.

Vehicle Operation with SiC Converter

The vehicle was able to be driven (Figure 9) and the 28 Vdc equipment appeared to be fully operational with the 28 Vdc bus being powered by the GE SiC converter for the full duration of the test. The 28 Vdc bus regulated within operational limits for the duration of the driving test and the vehicle functioned as expected without incident. This demonstrated the ability of the SiC hardware to power and regulate the 28 Vdc equipment in the vehicle test environment without any noticeable concerns or issues. This was the main objective of this Silicon Carbide demonstrator.

Figure 9: The M109A7 with Installed SiC Converter Driving on the Test Track

Transient Response

200 amp and 400 amp external 28 Vdc step loads were applied from the front NATO while the vehicle was operating and the SiC demonstrator held regulation within MIL-STD-1275D for these load transients. In addition, 15 amp step loads were applied to the 610 Vdc HVDB output with the SiC demonstrator again holding regulation within MIL-STD-1275D on its output for these 610 Vdc line disturbances.

High Frequency Noise

It was clear that the observed noise on the 28 Vdc vehicle bus was significantly higher with the SiC converter than the baseline testing with the original BIDIs installed. The 28 Vdc bus ripple measurements exceed the MIL-STD-1275D standard of 2V near the 12.5 MHz frequency. The conclusion is that the noise on the 28 Vdc bus is higher using the SiC than with the BIDIs and it is not known whether this could potentially negatively impact the vehicle's Radiated Emissions and EMI/EMC interoperability.

Environmental Requirements Not Assessed

The testing did not assess the full range of environmental requirements/conditions that the M109A7 vehicle is expected to operate through during a normal mission and thus, the performance of the SiC hardware in those environments is not known. The following is a subset (not a full list) of vehicle requirements that were not assessed during the testing:

- Vibration requirements due to off-road driving
- Gunfire shock
- Low and High temperature environments
- Water submersion
- NBC decontamination
- Exposure to engine compartment fluids
- EMI/EMC interoperability with communications equipment, CREW II, etc.

EMPHASIS FROM AN OEM PERSPECTIVE

Electrical power generation, integration challenges and space allocation led the BAE Systems electrical power generation, conversion, distribution and management Integrated Product Team (IPT) to select a dual 610 Vdc/28 Vdc solution. At this point, combat vehicle electrical power generation requirements continue to increase due to integration of electrical/electronic add-on kits, converting hydraulic maintenance required subsystems to very low maintenance and higher efficiency electrical subsystems and directed energy weapon integration.

The identified electrical power requirements continue to increase electrical power generation and distribution requirements. These requirements create a need for cost effective innovative solutions in increased electrical power density in the same volume of current silicon (Si) power electronics solutions. Silicon Carbide (SiC) technology is looking promising as a cost effective innovative solution to meet combat vehicle system integrator's increased electrical power generation, conversion, distribution and management integration challenges. SiC technology is receiving very serious consideration for current modernization and future military combat vehicle electrical power systems.

CONCLUSIONS

The effort demonstrates the effectiveness of flexible, open-architecture vehicle system designs coupled with fast-paced technological advancements of on-board vehicle systems. The joint TARDEC, BAE Systems, and GE Aviation team collaboration proves that modular power systems are easily upgraded and adapted to meet ever-increasing power demands and improved power density and cooling capabilities.

The SiC converter shows great promise for providing a lighter and smaller electrical power generation source for the warfighter. The voltage regulation was adequate to power the low voltage electronics while operating the M109A7 vehicle in place of the BIDI converters in the test environment. The transient response of the SiC converter performed well in the test environment. High Frequency noise was observed during the testing and it is not known whether this could present issues with EMI/EMC interoperability and emissions. Additional testing would be required to verify that the SiC power converter complies with the full range of environmental conditions that the M109A7 vehicle would encounter during field operations.

In the end, the demonstration successfully met all of the objectives of the test plan set out at the onset. The M109A7 vehicle proved to be an ideal candidate to test new technologies in high-voltage power electronics. The team gained key knowledge about the application of new SiC hardware to a military platform. TARDEC, BAE Systems P&S, and GE Aviation (Figure 10) continue to work to together to find ways to advance high-voltage electrical power systems to keep the US Army on the cutting-edge of technology.

Figure 10: The joint TARDEC, BAE Systems P&S, and GE Aviation Team