

High Power Silicon Carbide (SiC) Power Processing Unit Development

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NASA GRC successfully designed, built and tested a technology-push power processing unit for electric propulsion applications that utilizes high voltage silicon carbide (SiC) technology. The development specifically addresses the need for high power electronics to enable electric propulsion systems in the 100s of kilowatts. This unit demonstrated how high voltage combined with superior semiconductor components resulted in exceptional converter performance.

I. Introduction

The NASA space flight program can be divided into manned and unmanned programs, setting the stage for advanced space transportation systems which includes, future space habitats, and spacecraft that can send humans deep into the solar system. Most spacecraft use solar arrays as the main source of power, except for those with relatively short flight duration using batteries or fuel cells or deep space probes designed for very long flight duration using radioisotope thermoelectric generators. As the vision for space exploration evolves power required for, spacecraft, space stations, and space habitats increases exponentially, thus creating the need for more efficient and revolutionary power technologies. NASA is investing in cutting-edge power technologies to enable human space exploration beyond its current limitations.

In 2011, the NASA Human Exploration Framework Architectures Team¹ (HEFT) introduced a capability-driven framework with a 300kW Solar Electric Propulsion (SEP) vehicle concept. Spacecraft buses with increasing power and decreasing mass will enable advanced electric and plasma propulsion spacecraft and decrease trip times to Mars and beyond. Solar array systems combined with solar electric propulsion have shown many potential benefits to the spacecraft developer when compared to chemical propulsion systems. The high specific impulse provided by electric thrusters substantially reduces the amount of propellant required to achieve a given mission. This mass savings can translate to reduction of spacecraft mass, reduced launch vehicle requirements, increased on-orbit lifetime, or increased payload.

Advances in solar array technology that produce more efficient and lighter solar arrays have enabled the notion of high power spacecraft as large as 300 to 1000kW class. Power systems of this magnitude will require higher voltage distribution and thus power

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components capable of operating at high voltage. In the case of solar electric propulsion, high voltage power converters are needed to process the power required by the thrusters.

In response to these technology needs, NASA's Office of Chief Technologist (OCT) approached the Glenn Research Center to study technologies with the potential to bring high voltage to reality. The study focused on semiconductor devices, mostly switching devices for power conversion. The study team investigated several switching technologies, both old and new. The results identified silicon carbide (SiC) MOSFETs as the most promising. At that time, commercial SiC switching devices were relatively new with little understanding of how they would perform when configured as a power converter. The team felt that the wide band-gap SiC device would be better suited for a radiation environment, therefore an easier transition to flight qualification. Armed with this information, a plan for a 15kW converter design was accepted by OCT to develop a breadboard high voltage, high power converter utilizing this new technology and demonstrate how high power propulsion could be realized.

At the time this development program started, the first practical, commercial-grade silicon carbide MOSFETs became available. CREE SiC MOSFET devices were selected as the switching device in combination with a SiC schottky diode to be used in the converter rectifier circuit. The MOSFET devices selected were 1200V, 42Amp CMF 20120D and 1200V, 54A schottky diodes C4D40120D. The power processor would operate from a nominal 300V_{DC} power bus. The power processor is designed to operate a discharge circuit for a high power Hall Effect Thruster.

II. Breadboard Development

It was determined that the power module was going to consist of two 7.5kW converters connected in parallel and operating with an input from 270 to 330V_{DC} and a variable output voltage from 300 to 500V_{DC}. The overall strategy for power converter breadboard design employs the full-bridge topology shown in Fig. 1. This topology is good for high power applications because it has low electrical stress on the power transistors and very good transformer utilization. Two (2) versions of the discharge were developed, the first design used single MOSFET devices in the full-

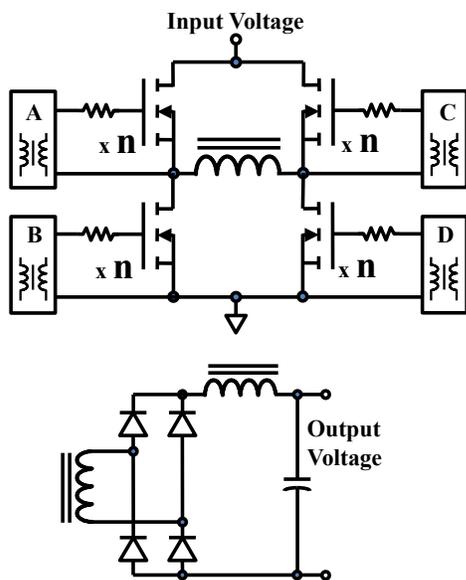


Figure 1. Full-bridge topology

Due to the thermal characteristics of the devices, a second version parallels the MOSFETs on each leg of the bridge. This increased the bridge power, reduced the overall parts count, and reduced the conduction losses on the transistors. Since these devices had never been used in this application, it was not clear how well the circuit would perform in either version.

Version 1 was built with the inverter stage using a single FET in each position and identical isolated drivers for each of the 4 FETs, essentially a 2.5kW converter design. Multi-layer stacked ceramic capacitors were used across the DC power input to absorb the current pulses, and a Hall Effect current sensor provided isolated sensing of

the total bridge current. This version required 3 of these inverter stages in parallel through a single power transformer.

Version 2 uses three MOSFETs in parallel on each leg of the bridge to reduce conduction losses, reduce the parts count, and meet the power needs for the 7.5kW circuit. A galvanically-isolated gate drive circuit provides 25 V and -5 V to the SiC MOSFETs. The gate drive voltages were used to fully turn on and turn off the SiC MOSFETs, therefore reducing switching and conduction losses.³ The main power transformer was built with a ferrite U-core using split windings, and filter inductors were built on amorphous metal C-cores.

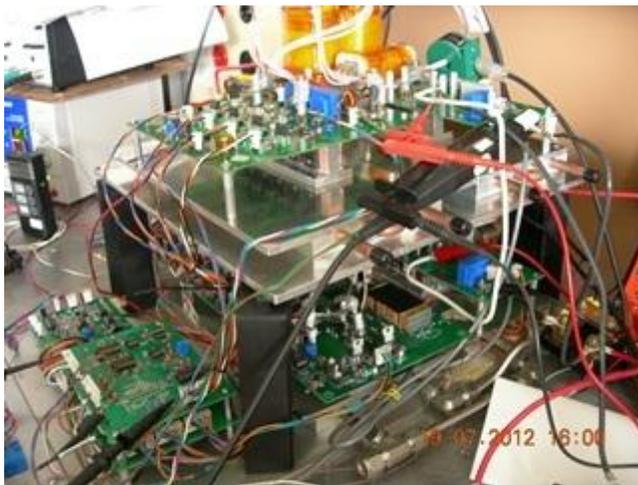


Figure 2 – Breadboard Converter

The breadboard discharge circuit was thoroughly exercised with both a resistive load and a test thruster. The team was encouraged by the performance of the breadboard. The performance was sufficient to warrant the development of a higher fidelity brassboard design with a thermal rejection design. Figure 2 shows both versions where Version 1 is on the lower coldplate and Version 2 is on the upper coldplate.

III. Brassboard Design

Design version 2 was chosen as the go forward architecture. A full bridge with parallel MOSFETS with a switching frequency of 30kHz. The overall strategy for the brassboard discharge was a modular design, and if more power were required, converters would be operated in parallel. The primary goal for the design was to focus on a robust electrical design, and less on the mechanical design or optimizing packaging. The next goal was to optimize the efficiency by making design choices that could provide the best efficiency performance. The unit has a thermal design using the chassis baseplate as the primary thermal path for cooling. Staying with the full bridge provides low voltage stress on the SiC transistors, good transformer utilization, and is easy to scale.

The brassboard converter design features include PWM control, peak-current-mode control, cycle-by-cycle current limit and shoot-through protection, voltage and current mode output regulation, and soft start control. SiC Schottky diodes were used as the output rectifier for their high voltage capability and reverse recovery. Ideally since the unit is designed for a space application, parts selections would be parts with path-to-space qualified devices. In this case, with the SiC parts being so new, there are no space-qualified components, although all other parts have a path to flight. Figure 3 shows the end product of the modular brassboard SiC power unit. This unit is designed to operate a Hall effect thruster (HET) and is electrically fully functional.

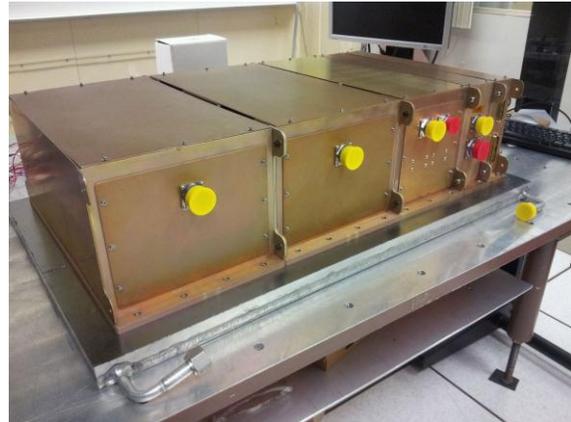


Figure 3. 300V SiC Power Unit

It is anticipated that a packaged flight design will reduce the mass by 25% compared to state-of-the-art (SOA) units.

III. Brassboard Testing

Testing was conducted to validate the operation and performance of the 300 V SiC brassboard unit. Performance parameters such as regulation, ripple, telemetry and setpoint accuracy were validated for various input and output voltages and power levels. Inputs and outputs were instrumented to measure DC performance. A digital oscilloscope with current probes was used to measure and characterize input and output ripples. Temperature was monitored using thermocouples to measure operating temperatures. The converter load was a resistive load bank to simulate steady-state operation and transients. Total efficiency was calculated as the ratio of all power outputs to all power inputs.

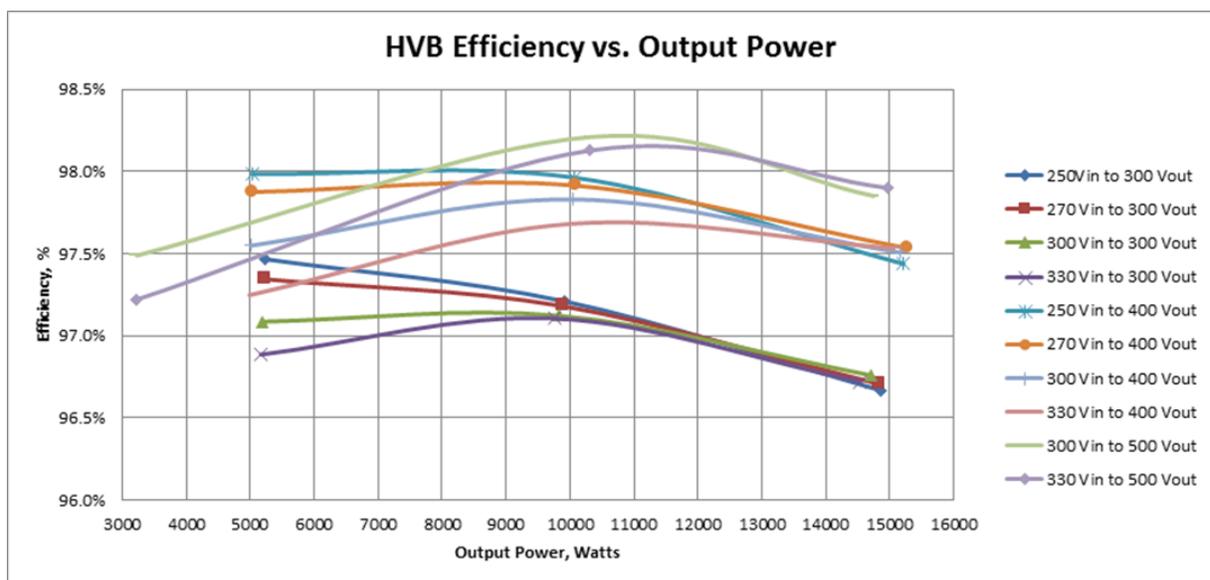


Figure 4. 300V SiC Converter efficiency vs. total output power for several voltages

Figure 4 shows an efficiency plot of two high power converters in parallel, as seen in Figure 3, as a function of output power for several output voltages.⁴ Testing demonstrated converter efficiencies greater than 98%, well beyond the expected results. The efficiency was better than 96.5% for the entire power range from 3 to 15kW.

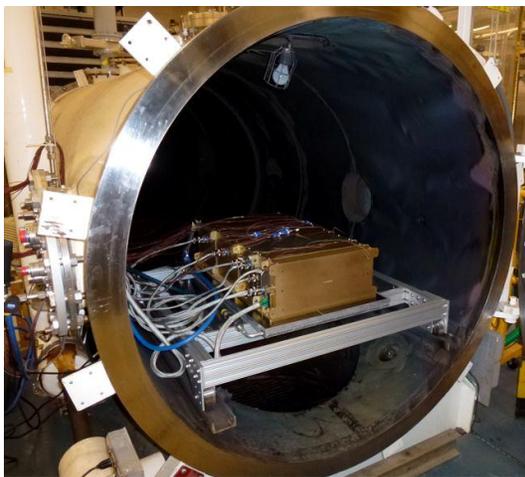


Figure 5. 300V SiC PPU in vacuum testing

Ripple, regulation and telemetry were within the expected goals. Measurements revealed a temperature rise of about 30 °C in the main power transformer and output inductor for the power converter which is within derating guidelines. The temperature rise of other components was less than 20 °C.

Performance tests were repeated in a vacuum environment to validate the thermal design. Figure 5 shows the unit installed in the GRC vacuum facility. The power unit was mounted on an aluminum water-cooled baseplate to conductively reject heat. The converter was operated at baseplate temperatures at 5, 25, 50 °C.⁵

IV. Conclusion

Combining high input voltage and high performance switching components resulted in a power converter with a peak efficiency greater than 98% with an expected reduction in mass of 25% from state-of-the-art. The development demonstrated a fully functional 15kW converter that can be utilized for solar electric propulsion system with the development of flight qualified SiC parts.

What started out as a high power converter design demonstration resulted in a high power, high efficiency converter design. The extremely high efficiency has additional positive effects that ripple through spacecraft platform. For a proposed 300kW propulsion system, the thermal load produced by the SiC unit would equate to 6kW as opposed to a 24kW load with a state-of-art efficiency. This is a huge reduction in thermal system mass. In addition to the mass savings from the thermal system is the mass saving from the power generation system. The spacecraft can carry 18kW less of solar array. All the mass saving then reduces the wet mass in the form of less propellant.

This development has demonstrated the mass and efficiency advantage by the use of silicon carbide technologies combined with high voltage in power conversion applications. These gains can be greatly utilized for space power applications if radiation hardened space rated components were available. NASA Glenn Research Center (GRC) had performed preliminary heavy ion testing of select commercial SiC MOSFET and diodes. The outcome of the testing produced failures in all the test samples. NASA is currently investing resources to further test and studying the component failures to better understanding the failure mechanisms. Understanding the failure mechanisms can lead to recommendations for modifications in the manufacturing of the components to make them less susceptible to failures. It is our hope that the manufacturing community can help develop qualified parts for space.

For NASA to pursue high power systems such as high power solar electric propulsion then high voltage and high efficiency power distribution and power processing is crucial. Therefore the development of qualified high performance space rated electronic components as discussed in this paper will be essential.

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