

Digital Control of High Temperature SiC Power Modules Utilizing HTSOI

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ABSTRACT

This paper describes a SiC based stackable DC/DC converter system capable of operating at high temperature. The system is capable of fault tolerance and complex power management. These functions require complex control; however, high temperature operation typically precludes the use of conventional control circuitries. Therefore, the present work seeks to develop an advanced digital controller capable of high temperature operation. This is accomplished by utilizing the currently available suite of High-Temperature-Silicon-on-Insulator(HTSOI) technologies.

INTRODUCTION

Development of high power systems for space applications is a time consuming and expensive process due to the extensive testing and qualification requirements. A change of the power system requirements often requires the re-design and re-qualification of the power system. A modular power system (illustrated in Figure 1) in which “standardized” modules could be connected in series and/or parallel in order to tailor the voltage, current and power of the system could address power scalability issues, avoiding

expensive re-designs; however, present modular power system approaches do not provide an optimal solution for space applications due to several drawbacks. (1) Modular solutions cannot, in general, address both the voltage and current scalability issues. (2) The increased part count of modular solutions hinders system reliability. (3) Modular solutions have lower efficiencies due to increased part count and added parasitic loads. (4) The power density of modular systems is reduced due to the increased interconnection and complexity.

This paper introduces a modular power system solution that addresses all of the mentioned drawbacks of present systems by combining the benefits of high-reliability emerging electronics technologies with advanced control and design methods. The developed power system is controlled by a distributed control method and a decentralized communication scheme, which allows for true modularity. The power system voltage, current and power can be scaled by the addition of modules.

In order to combat the inherent decreased power density of modular systems, high temperature operation of power and control components is sought. High temperature operation of control allows high levels of integration with power components, whereas high temperature operation of power components allows reduced cooling system requirements. High-temperature silicon-on-insulator (HTSOI) control components and silicon carbide (SiC) power devices become primary candidates for high reliability in such an environment.

This paper first details the design requirements for a modular power system. These requirements largely dictate the development of the standardized module (i.e., converter) power topology and control approach. The development of the required control approach and underlying hardware is then detailed. Limited part availability in the HTSOI library leads to innovative subsystems required for control functionality; these include isolated voltage sensors, gate drivers, and a digital processing core. Each of these subsystems is detailed. Following, high temperature operation of the system is explored. Finally, system performance is outlined.

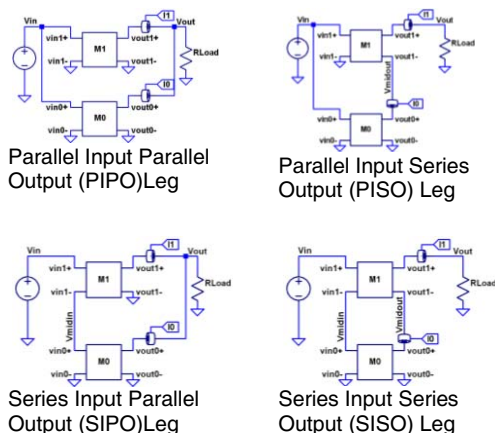


Figure 1. Four possible module leg connections.

MODULAR POWER SYSTEM REQUIREMENTS

The developed modular power system targets high reliability applications such as new high-power spacecraft power management and distribution modules (i.e., PMADs).

For initial system requirements and rating, the researchers consider a 120V/28V power system located in the international space station that will be used to recharge the crew exploration vehicle. Therefore, the developed modular power system input voltage is 120 V while the output voltage is 28 V. For the purpose of demonstration, the maximum rated power of the system is 1 kW.

The modular power system is composed of up to 8 standardized modules with a rated power of 140 W each. The modules are optimized to operate with two different input voltages, 60 V and 120 V, and two different output voltages, 14 V and 28 V, allowing for series and/or parallel connection of the modules' input and output terminals. Figure 1 displays the four possible system "leg" configurations, namely: parallel-input/parallel-output (PIPO), parallel-input/series-output (PISO), series-input/parallel-output (SIPO) and series-input/series output (SISO).

Additional requirements targeted were: (1) fault tolerance of up to two module failures, (2) uninterrupted supply of power during module fault and/or system reconfiguration, (3) minimum thermal management requirement, (4) high power density, (5) potential for high reliability and (6) potential for inherent radiation tolerance.

The next section discusses the development of a standardized module using these two new electronics technologies.

DEVELOPMENT OF A STANDARDIZED POWER MODULE

The standardized power module prototype (displayed in Figure 2) is composed of a power and a control stage. Figure 3 shows the power stage which is formed by several blocks, namely: power topology components (power switches, inductor, transformer, capacitors) and bypass relays. Several converter topologies were investigated; ultimately, the symmetrical half-bridge topology was selected due to its flexibility.

POWER STAGE DEVELOPMENT

The researchers utilized the now emerging SiC power devices as the main power switches of the system. As a wide bandgap material, SiC power devices have demonstrated excellent high temperature functionality, far beyond the 150 °C limit of Si devices [1]. This, in turn, allows for an increase of the power density by minimizing the cooling requirements of the modules. The

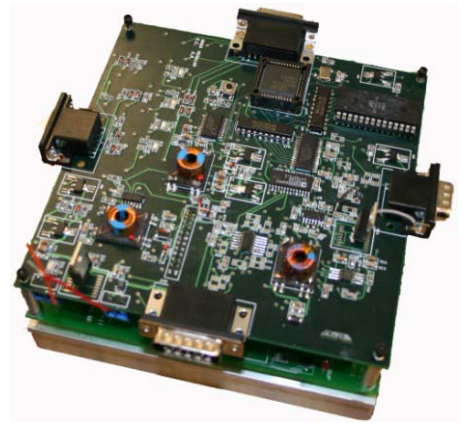


Figure 2. Complete standardized prototype module.

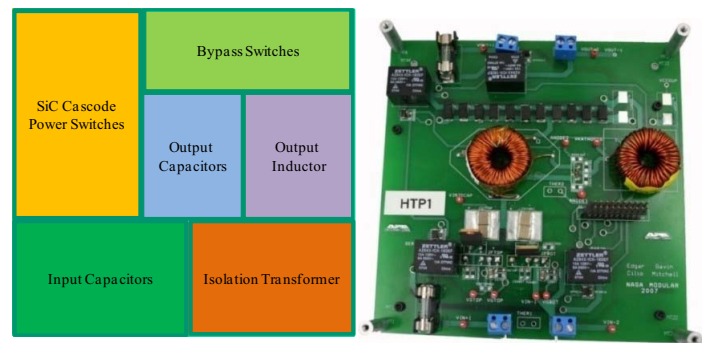


Figure 3. Module power stage (block diagram and hardware).

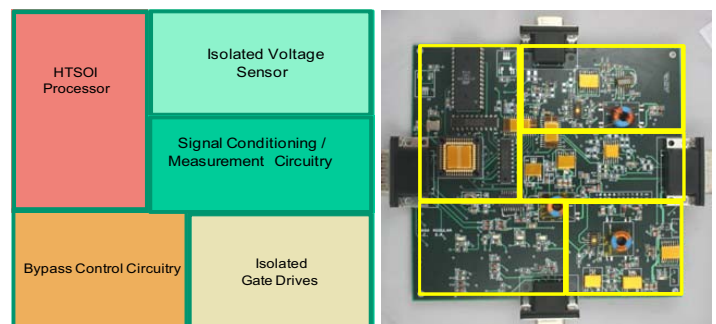


Figure 4. Module control stage (custom HTSOI packages shown right).

minimization of system cooling requirements can counter the lower power densities that regular modular approaches achieve due to an increase in component count (i.e., added transformers, inductors, capacitors, connecting hardware, etc.). Additionally, SiC power devices are under investigation for increased radiation hardness, and several publications indicate potentially significant advantages over silicon components in this arena [2-3]. This could also minimize shielding and hence increase power density. These qualities make SiC power devices particularly appealing for space based power systems. The selected SiC power switch for this application was a 1200V / 5A SiC cascode device manufactured by SiCED. The cascode structure combines a SiC JFET with a Si MOSFET in a single

package. SiC cascodes combine the high voltage blocking and low on resistance characteristics of the SiC JFET with the normally-off characteristic of the MOSFET to yield a high-voltage, low on-resistance, normally-off power device. Note, radiation tolerance and temperature performance of this device is certainly hindered by the addition of the silicon MOSFET; ambient operational temperature was limited to 140 °C for this reason. However, proper MOSFET de-rating or new monolithic SiC solutions, such as normally-off JFETs now under development, will soon mitigate this issue [4]. For further details of the SiC JFET cascode structure, see [5].

Operational temperature was considered when selecting power stage passive components. There are four important components that are particularly challenging for high temperature operation; they are the input (half-bridge) capacitors, output capacitor, power transformer, and output inductor.

Several capacitor technologies can be used depending upon the temperature of operation of the final module. High-temperature solid tantalum capacitors operate up to 150 °C. High-temperature X7R, X8R, and wet tantalum capacitors can operate up to 200 °C. Based on capacitance and voltage requirements, 120 V and 4.7 μ F X7R type capacitors were selected for the half-bridge capacitors. X7Rs offer relatively good performance up to the target maximum temperature of operation (140 °C), meeting the voltage requirements, and are available in 1 μ F capacitance values (compared to ~ 0.1 μ F for X8Rs for the same voltage levels.) Similarly, solid tantalums were selected for the lower voltage, higher capacitance requirement at the output. Wet tantalums were avoided due to their poor ESR.

Magnetics design for high temperature operation is challenging as well, however, more material options are available. Based on software analysis, the researchers determined Nanoperm and Finemet materials to be the best option for high temperature operation of the power transformer. These materials have crystalline structure which can achieve higher permeability, higher saturation flux density, higher Curie temperature, and lower core losses than the amorphous materials. Powder based cores were considered for inductor materials. Powder cores are made out of fine powder particles of different alloys. The coating of these particles with an insulating material controls the size of the “air gap”. The powders are then pressed into various core shapes under high pressure. The small air gaps distributed evenly throughout the core reduces the effective permeability of the core and increases the amount of DC current that can be passed through the winding before saturation occurs.

Magnetics Inc. produces powder core materials under the names Molypermalloy Powder (MPP), Kool Mu, and High Flux. The Curie temperature for these powder cores is 500 °C; however, as in the case of the tape wound core, the coating is guaranteed only to 200 °C.

As a result, continuous operation at 200 °C has no damaging effects on these types of cores

CONTROL STAGE DEVELOPMENT

The control stage of the standardized module was developed utilizing HTSOI electronics. The researchers incorporated HTSOI into the design of the modules because it has many advantages over bulk Si that make it a good candidate for deployment in a space mission. The smaller current requirements make SOI ICs highly desirable for space applications since low power operation is required from all electronic systems. In general, HTSOI devices are more resistant than Si to certain radiation activated latch-up events. They also exhibit leakage currents that are reduced by 100-1000 times at high-temperatures when compared to bulk Si devices [6]. This property can reduce the size and weight of the cooling needed—a highly desirable characteristic in weight sensitive applications such as space missions. Lastly, the smaller charge collection area of the bulk SOI results in increased Single-Event-Upset immunity, which with proper design techniques, has proven to contribute to improved radiation hardness [7]. Current suppliers of high temperature SOI components are Honeywell and Cissoid, with most of the commercial set of components rated to 225 °C for up to five years and in some cases up to 300 °C for a year.

While HTSOI part selection is limited, it is adequate to perform many of the functions required for advanced DC/DC converter control. Honeywell currently produces the largest HTSOI portfolio under its HTMOS product line. The line includes the HT1104 quad operational amplifier, the HT1204 quad analog switch, the HTNFET, capable of 60V/1A, HT506 (16:1) and HT507 (2x8:1) analog multiplexors, the HT6256 32k x 8 static RAM, and the HT83C51 microcontroller. Cissoid produces operational amplifiers, analog to digital converters, LDO voltage regulators, 555 timers, and newly qualified N-type and P-type MOSFET devices. Cissoid devices are produced in the German XFAB HTSOI process. Additionally, Atmel currently produces select power device gate drivers on its new BCD-on-SOI process. High temperature Atmel devices are rated to 200 °C.

DIGITAL PROCESSING CORE

Figure 4 displays a block diagram of the developed control circuit, in which the Honeywell HT83C51 microcontroller forms the core of the HTSOI processor “block”. The main function of this section is the control and communication of the module. All control and communications (such as interfacing with local peripherals such as gate drives, ADCs, bypass controls, as well as other modules) occur within the HT83C51 IC with periphery ICs (three eight-bit latches and a memory IC [i.e., EEPROM] providing critical internal functionality support.

An EEPROM is required for non-volatile program storage. Legacy HT83C51 systems have made use of