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High Input Voltage Discharge Supply for High Power Hall Thrusters Using Silicon Carbide Devices

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Abstract

A power processing unit for a 15 kW Hall thruster is under development at NASA Glenn Research Center. The unit produces up to 400 V_{DC} with two parallel 7.5 kW discharge modules that operate from a 300 V_{DC} nominal input voltage. Silicon carbide MOSFETs and diodes were used in this design because they were the best choice to handle the high voltage stress while delivering high efficiency and low specific mass. Efficiencies in excess of 97 percent were demonstrated during integration testing with the NASA-300M 20 kW Hall thruster. Electromagnet, cathode keeper, and heater supplies were also developed and will be integrated with the discharge supply into a vacuum-rated brassboard power processing unit with full flight functionality. This design could be evolved into a flight unit for future missions that requires high power electric propulsion.

Introduction

Recent advancements in solar cell and deployment mechanisms could lead to the development of high-power solar arrays (Ref. 1). Using this power for electric propulsion will result in a high performance spacecraft capable of satisfying the requirements of the most demanding missions. A team of engineers from NASA Glenn Research Center (GRC) and the Jet Propulsion Laboratory (JPL) was chartered by NASA's Space Technology Mission Directorate (STMD) Game Changing Development (GCD) Program to develop a high-power solar electric propulsion (SEP) system to revolutionize future missions that require moving cargo or humans beyond Earth's orbit (Refs. 2 to 4). A critical part of an SEP system is the power processing unit (PPU) which processes power from solar arrays and converts it to the voltage and currents required for thruster operation. PPUs require much attention as they are the most massive and complex part of an electric propulsion system. Previous efforts to develop high power PPUs for electric propulsion have been challenging because of the difficulties in controlling high currents, noise and conduction losses (Refs. 5 to 7).

High voltage is advantageous for high power systems to reduce the current levels and minimize ohmic losses (Refs. 8 to 10). However, there is very limited availability of high-voltage, high-performance parts for space applications. Recent advances in solid-state power component technology have resulted in commercial availability of silicon carbide (SiC) transistors. These could enable the development of high power PPUs with higher input voltages by overcoming the performance limitations of state of the art silicon transistor technology. SiC has the potential of revolutionizing future PPU developments and enabling high-power SEP.

GRC is leading the PPU development effort for the STMD/GCD Program. The first phase of this effort consisted of a comprehensive trade study of power semiconductors. This study led to the selection of SiC MOSFETs as the transistor for a high voltage, high power PPU because they had the highest potential to achieve high efficiency and low specific mass. The second phase of the effort focused on the development of a breadboard 15 kW discharge supply to demonstrate the capabilities and functionality of

SiC in a high power converter design. The third phase of the effort is currently developing an entire PPU that includes most electrical functionality required for flight and starts to address form and fit of a flight unit. The goal is to develop a brassboard PPU to technology readiness level (TRL) 5 with a 300 V nominal input, and capable of operating in vacuum at high efficiency. This PPU will be integrated with a thruster to demonstrate a high performance design that can evolve into a flight SEP system and scaled to higher power.

The technical approach used in this development is to simplify the design wherever possible to avoid high recurring cost; use commonality at all levels including parts, circuits, assemblies, converters and modules; and finally, leverage as much experiences and lessons learned from other recent NASA development program like NSTAR, NEXT and HiVHAc (Refs. 10 to 13).

System Overview

A simplified block diagram of a typical Hall thruster system is shown in Figure 1. The most critical part of the PPU is the discharge supply because it processes 90 to 95 percent of the power into the thruster and regulates the high voltage for the main discharge to accelerate ions and produce thrust. The discharge supply also provides electrical isolation between the thruster and the solar arrays. The output filter in the discharge supply is critical for stable thruster operation because it provides current to the thruster to sustain discharge current oscillations. A PPU also provides power for the inner and outer electromagnets and the cathode keeper and heater. These are referred to as the auxiliary supplies. An input filter for the entire unit can be added to mitigate conducted emissions to the spacecraft power system and solar arrays. Also included in the PPU are input and output telemetry circuits to accurately assess system performance and protection circuits to safe the system in case of a fault. Finally, the PPU must have an interface to communicate with the spacecraft to relay system telemetry and receive commands.

Specifications

The design specifications for the high power PPU are summarized in Table 1. The discharge supply is required to operate from an input voltage range of 270 to 330 V and generate a maximum of 15 kW for the thruster at a voltage range of 300 to 400 V. This supply must regulate both output voltage and current to control steady-state thruster operation and limit current during fault or start-up conditions. The

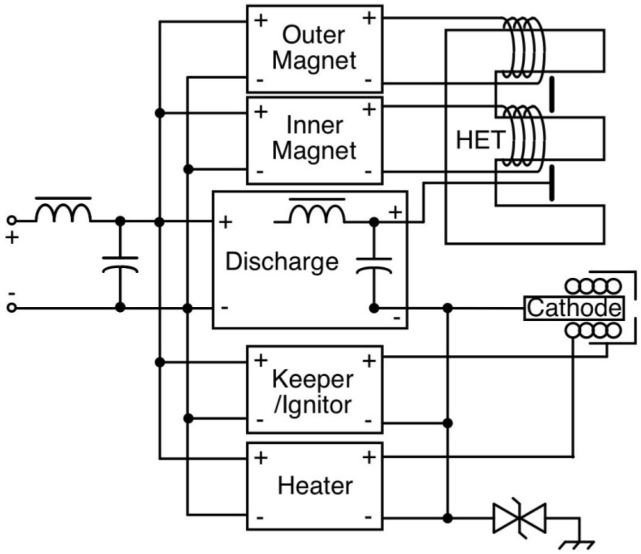


Figure 1.—Hall thruster PPU block diagram.

TABLE 1.—PPU ELECTRICAL SPECIFICATIONS

Electrical Specs	Discharge	Magnets	Keeper	Heater
Output Voltage	300 – 400 V	2 - 20 V	10 - 30 V	6 – 36 V
Output Current	37.5 – 50 A	1 - 10 A	1 - 3 A	3 - 9 A
Output Power	15 kW	200 W	90 W	324 W
Regulation Mode	Voltage or Current	Current	Current	Current
Line/Load Regulation	≤ 2%	≤ 2%	≤ 2%	≤ 2%
Ripple	≤ 5%	≤ 5%	≤ 5%	≤ 5%
Input Voltage	270 – 330 V	23 – 36 V	23 – 36 V	23 – 36 V

auxiliary supplies are required to operate from a 23 to 36 V input voltage range. This was selected so the thruster cathode can maintain operation during an eclipse by running the keeper supply from a standard 28 V battery backed-up power system. The auxiliary supplies require a variety of outputs but they do not exceed 36 V and 10 A and are required to regulate output current. All supplies must have better than 2 percent regulation and less than 5 percent output ripple. Finally, the cathode keeper must include a high voltage pulsed igniter to facilitate ignition.

Semiconductor Trade Study

One of the biggest challenges in developing high power electronics with high input voltages for space is the availability of radiation-hardened, flight-qualified power semiconductors such as transistors and diodes. Silicon (Si) MOSFETs have very good performance only up to a few hundred volts. Beyond that, performance degrades quickly and options are extremely limited. In fiscal year 2011, a comprehensive trade study of power semiconductors was conducted at GRC to evaluate and assess available options. At the time, components using new semiconductor materials, like silicon carbide (SiC) and gallium nitride, were becoming commercially available so these were considered in addition to standard Si parts. A selection of components from several vendors were characterized, compared and modeled using test circuits that simulated the conditions they would experience in a typical converter. Performance parameters such as on-resistance, switching loss, gate drive requirements and switching times were evaluated. The results indicated that for high voltage applications, SiC MOSFETs provided superior electrical performance over traditional Si devices. Commercially available 1200 V SiC MOSFETs have very high voltage ratings and much lower on-resistance than Si devices even at lower voltage ratings. They could facilitate building power converters with much lower specific mass. Another attractive feature is a very low gate capacitance that results in very high switching speeds for low switching losses. However, there are a few issues with these parts. First, SiC MOSFET technology had not been evaluated for use in a radiation environment or used in a power converter application in space. Also, their gates require to be driven to more than 20 V for the devices to be completely on. None of the space rated, rad-hard gate drive chips available can operate at this voltage.

The study also evaluated high-power Si and SiC rectifier diodes. Parts were primarily compared based on forward drop, reverse recovery characteristics and voltage and current ratings. A high-voltage SiC Schottky diode was the best choice for this application. The high voltage rating of 1200 V could enable building a discharge supply with minimum rectifier losses. Although their forward voltage drop and conduction losses were slightly higher than Si diodes, their lack of reverse recovery losses and “softer” turn-off resulted in better overall performance.

After selecting the best components for the application, the trade study evaluated various topologies and the optimum power level for individual converter modules. Three criteria drove the selection of the converter topology. First, topologies capable of processing high power so the PPU requires fewer discharge modules and have lower specific mass. Second, topologies with low voltage stress since a high input voltage was required for this design. Lastly, topologies with better transformer utilization were favored to minimize winding complexity and parasitic elements like leakage inductance that could be detrimental to converter performance. These led to the selection of the full-bridge converter topology. Also, a single full-bridge rectifier was selected for the output stage because of the large margin between the SiC rectifier diodes and the 400 V output required for this design and to minimize conduction losses.

After having selected components and topologies, the remaining question for the trade study was the power level for a single discharge module. Gate drive circuit capability, magnetics size and switching frequency influenced this part of the study. A module size of 7.5 kW was selected for this design to take full advantage of the SiC components. Also, a modest switching frequency of 30 kHz was chosen to minimize switching losses without the need of complex resonant switching circuits. Higher discharge power will be attained by paralleling modules.

PPU Design

PPU development was initiated by design, fabrication and testing of proof-of-concept breadboards of the main components of the PPU including the discharge and auxiliary supplies; input filters; a master control circuit; and a system controller. These elements are discussed below.

Discharge Supply

In fiscal year 2012, the PPU team at GRC started the development of a breadboard discharge supply with a 300 V nominal input using SiC components. The topology selected for this design was a full-bridge utilizing SiC MOSFETs and single bridge rectifier with SiC Schottky diodes as recommended by the trade study. A simplified schematic of the topology is shown in Figure 2. Peak-current pulse-width-modulation (PWM) was selected because it is simple to implement, protects against over-current faults and has a fast response to input and output voltage variations. An innovative gate drive circuit with transformer isolation and the ability to adjust the on and off gate voltages was developed so the switching performance of the SiC MOSFETs could be optimized. The main power transformer was designed on a ferrite core and using interleaving techniques on the primary and secondary windings to minimize leakage inductance. The final version of the transformer had less than 2.0 μH of leakage inductance which is small considering the size of the transformer.

Two 7.5 kW discharge modules were built and connected in parallel. A master control circuit processes the feedback to regulate both output voltage and current. It also provides clock signals and common controls. A photograph of the breadboard discharge supply is shown on Figure 3.

Auxiliary Supply

The auxiliary supplies provide thruster power for the inner and outer electromagnets and cathode keeper and heater. These are required to process between 100 and 400 W from a nominal input of 28 V. Although somewhat oversized for this application, a full-bridge topology was also chosen for these supplies to maintain commonality with the discharge supply, good transformer utilization, and scalability to higher power. Scalability can be advantageous as the system development matures. Since the Hall thruster being developed for this effort is also in early stages of development, separate electromagnet supplies were included to provide flexibility and better control. However, once the thruster design is matured, both electromagnets could be powered from a common supply. Implementing this should be relatively easy with the full-bridge topology. A center-tapped full-wave rectifier was chosen for reduced conduction losses at the lower output voltages. A simplified schematic of the power supply is shown in

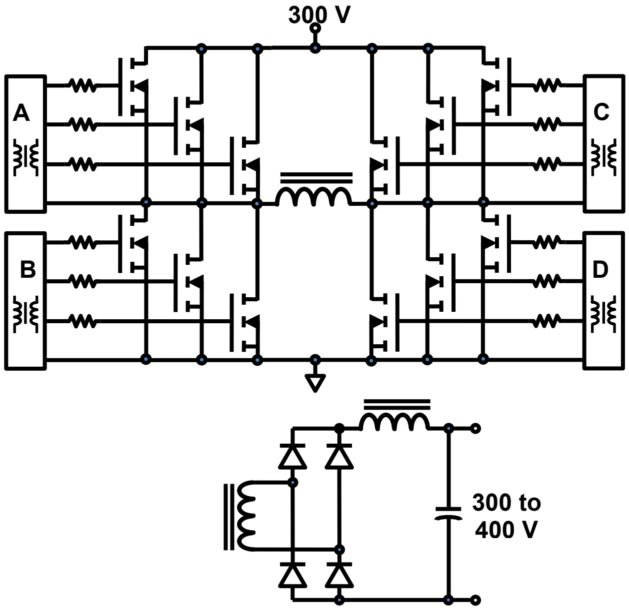


Figure 2.—Discharge module simplified schematic.

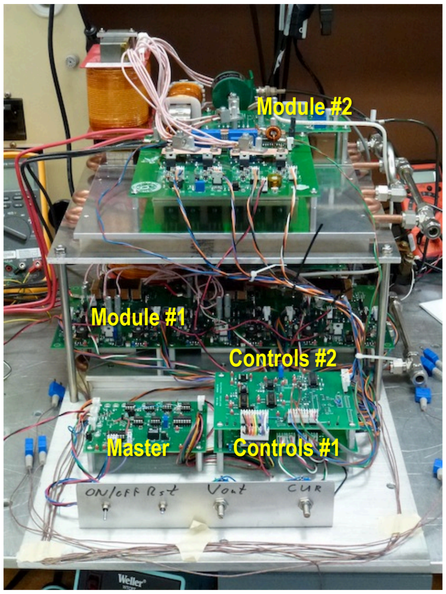


Figure 3.—Breadboard discharge power supply.

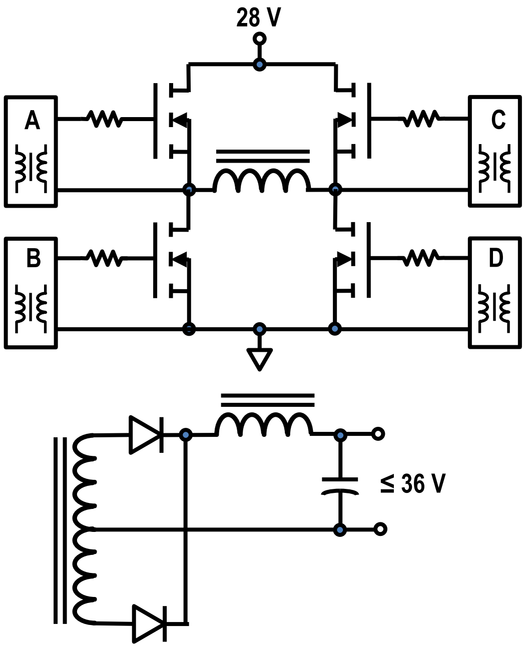


Figure 4.—Simplified schematic of auxiliary supply.

Figure 4. A common PWM control circuit and printed circuit board as used in the discharge module was used for the auxiliary supplies. Similar gate-drive circuit as in the discharge module was also used with some changes due to lower gate voltage and power requirements for the 100 V Si MOSFETs used in this design. A higher switching frequency of 60 kHz was selected to allow reduction in transformer and filter masses. The main power transformer was also built on a ferrite core with interleaved windings to minimize leakage inductance. There are two versions of the power transformer with identical primary windings and only a minor difference in secondary turns. One version is for the electromagnet supplies and the other for the heater and keeper supplies as they require about twice the output voltage as the magnet supplies. The only other difference between the auxiliary supplies is the output inductor and pulsed igniter used on the cathode keeper supply.

Master Controller

The master controller includes several internal control functions for the discharge modules, the auxiliary supplies, and the overall PPU. It generates 30 and 60 kHz clock signals for PWM used by the power converters. The discharge supply output voltage and current feedback circuitry also resides in the master controller. It also contains various fault protection circuits, interlocks and fault flags for thruster anomalies. All controls, output setpoints, and telemetry signals are generated or routed through the master controller on the way to the system control board (SCB) described below.

Input Filter

The PPU has two independent inputs. The 300 V input provides power for the discharge supply and the 28 V input powers the auxiliary and housekeeping supplies. Each one has its own input filter consisting of a differential low-pass stage and a common-mode inductor. The filters are damped to mitigate overshoots during transient conditions. The filters have cut-off frequencies around 5 kHz so they provide enough attenuation at the switching frequency. The 28 V input filter PCB also includes a commercial off the shelf power supply for housekeeping power to provide bias voltages for internal circuits. Input voltage and current signals are generated to be included with telemetry.

System Control Board

The SCB controls the PPU and the propulsion system. The SCB communicates with a user computer through a transformer isolated Mil-Std-1553B interface. It provides users control over power supply and feed system outputs and displays telemetry and fault flags from the PPU master controller and propellant feed system. The SCB uses a field programmable gate array (FPGA) and additional digital circuitry to generate control signals in response to user commands and to “translate” telemetry for the operator. The SCB is being developed by JPL.

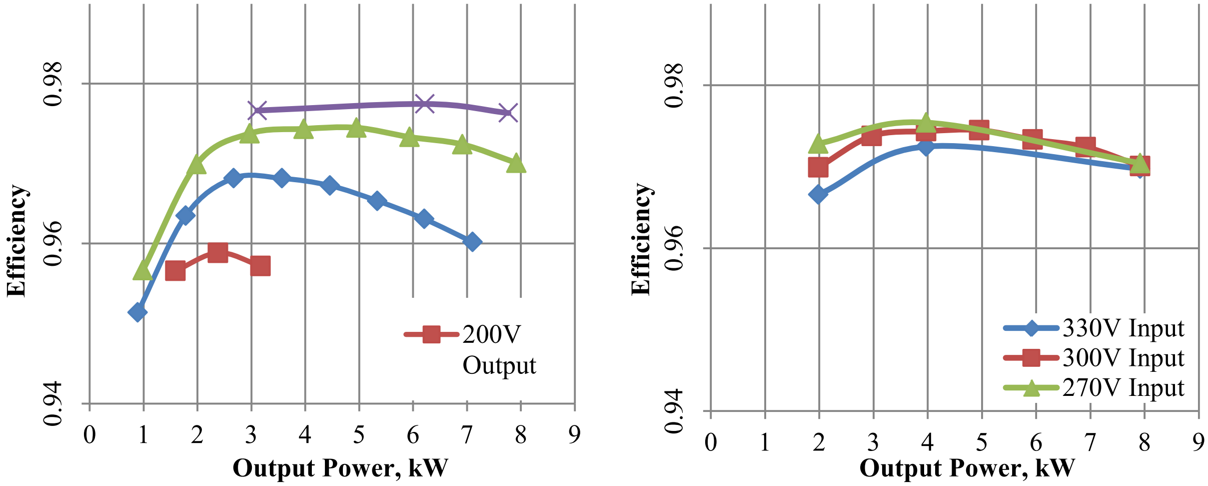
Test Results

Both the discharge module and auxiliary supplies were tested to verify that the hardware meets design specifications including input and output range, loop response, efficiency, regulation and overcurrent protection. Testing was conducted using a resistive load and digital multi-meters to measure input and output voltages and currents.

Breadboard Discharge Module Performance

A 7.5 kW discharge module was tested to validate electrical performance. The module is capable of delivering full power at output voltages from 300 to 400 V for input voltages from 270 to 330 V. It has the capability of operating up to 500 V at nominal input or at lower output voltages at reduced power. Figure 5a illustrates the efficiency of the discharge module as a function of output power for a variety of output voltages at a nominal 300 V input. Figure 5b illustrates efficiency as a function of output power for a 300 V output for the entire range of input voltages. Efficiency at full power conditions was between 96 and 97 percent and was as high as 97.5 percent at 4 kW output power. Line and load regulation is better than 1.0 percent for the entire range of inputs and outputs. The output voltage ripple was lower than 1 percent at full power conditions while running into a resistive load.

The control loop of the discharge module was compensated to ensure stability while operating a Hall thruster. Figure 6 shows the gain and phase plot for the discharge module voltage loop. The bandwidth of approximately 1 kHz, gain margin is approximately 12 dB, and a phase margin is about 90°, provide adequate stability margin and response for this application.



a) 300 V input b) 300 V output

Figure 5.—Breadboard discharge module efficiency.

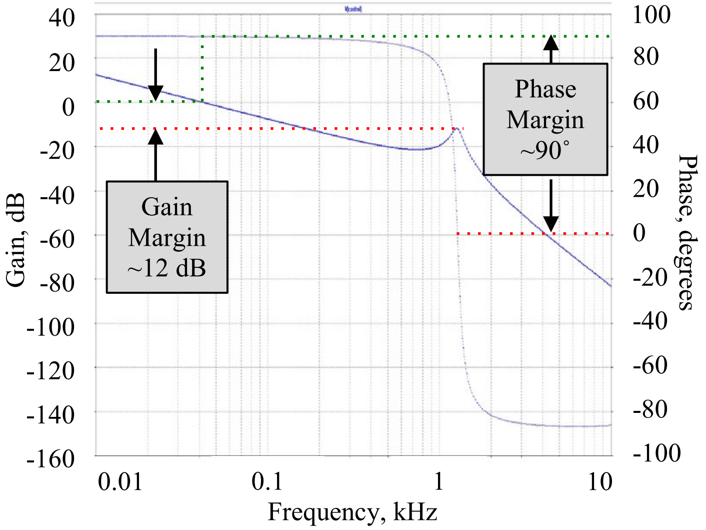


Figure 6.—Discharge supply voltage loop response.

Breadboard Discharge Supply/Thruster Integration

The 15 kW breadboard discharge supply was tested with the NASA-300M 20 kW Hall thruster in VF-5 at NASA GRC. The purpose of the test was to verify stable operation throughout the entire range of operating conditions. One of the most important issues to validate is the ability of the power supply to drive the large discharge oscillations that can occur during thruster operation. If the discharge output filter is not properly designed, it could result in large voltage oscillations and unstable operation of the discharge supply.

During the integration test, the thruster was operated from 3 to 15 kW at 300 and 400 V output from a nominal 300 V input. Efficiencies in excess of 97 percent were measured. The two discharge modules shared current within 0.1 A of each other at all operating conditions. Measured current oscillations had a frequency of approximately 40 to 50 kHz and a peak-to-peak magnitude of 5 to 10 A depending on thruster operating conditions. The worst-case voltage oscillations had a peak-to-peak magnitude of less than 5 V at full power. Figure 7 illustrates these oscillations at full power conditions.

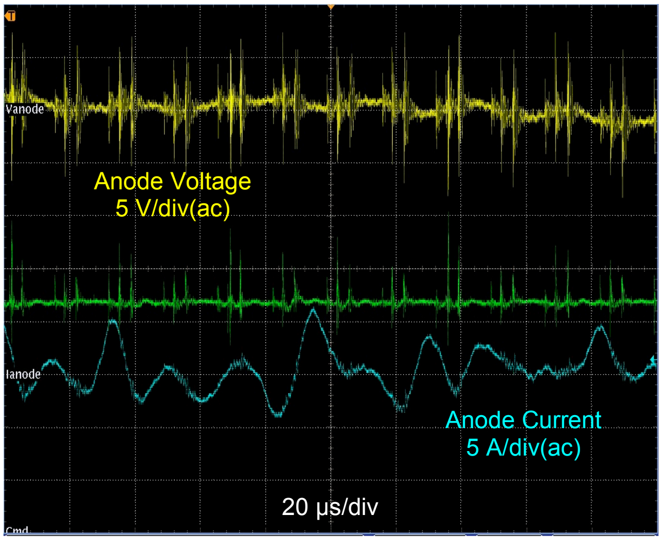


Figure 7.—Discharge oscillations with NASA 300-M thruster.

Breadboard Auxiliary Supply Performance

An auxiliary supply was tested to validate electrical performance. It was tested in the electromagnet configuration because the magnet supplies have to operate continuously during steady-state thruster operation. The supply is capable of delivering up to 200 W of power at an output current of 10 A for an input voltage range of 23 to 36 V. Efficiencies in excess of 92 percent were measured when operating at full power. Line and load regulation was better than 1 percent and output current ripple was lower than 3 percent for the entire operating range.

Brassboard Development

Brassboard PPU Design

After demonstrating functionality with the breadboard power supplies, the effort focused on design and fabrication of a brassboard version of the PPU. The goal was to develop a unit capable of operating in vacuum while maintaining the high efficiency demonstrated with the breadboard power supplies. This would require to address the thermal design of the unit and provide an iteration on the electrical design to include additional circuitry for telemetry and fault protection. This design could then be transferred to a contractor to evolve it into a flight design with full form, fit, and function.

The brassboard PPU consists of interlocking modules that supply a variety of functions. The height and depth of the modules were fixed and the width was adjusted to accommodate various modules. Figure 8 illustrates a drawing of the PPU that consists of two discharge modules, an auxiliary module, an input filter module, and a system control module.

The PPU was designed to reject waste heat through its baseplate. The thermal design approach consists of mounting large power components like MOSFETs, rectifier diodes, transformers and inductors on heat sinks that mount directly onto the baseplate. This maintains the parts with the most power dissipation at the lowest possible temperature within the unit. PCBs rely on internal thermal planes to reject waste heat from components and into a heat sink also attached to the baseplate. Thermal models were developed to validate the thermal design approach and verify that critical components like magnetics and the SiC semiconductors would operate below their temperature limits. Figure 9 shows the implementation of this design approach for the discharge module. The module consists of subassemblies for the discharge full-bridge inverter, power transformer, output rectifier and output inductor.

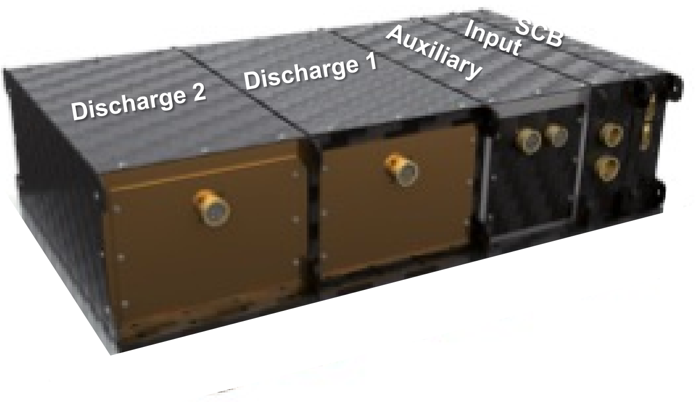


Figure 8.—Brassboard PPU.

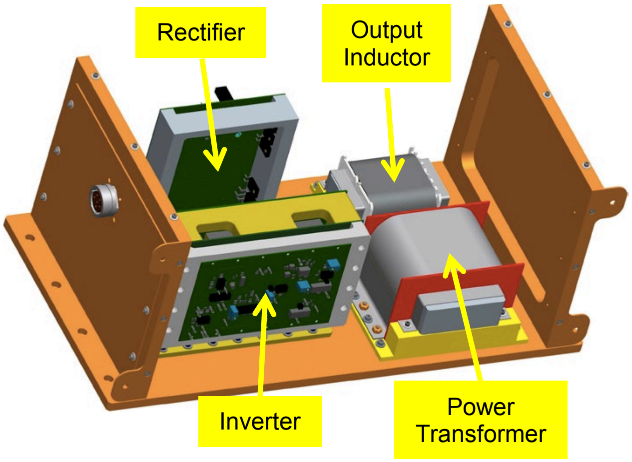


Figure 9.—Brassboard discharge module.

Brassboard DDU Design

In a direct-drive system, electrical power from a power source, like solar arrays, is fed directly into the discharge in a Hall thruster. This eliminates the need for a discharge supply making the system potentially more efficient and lightweight. The direct-drive unit (DDU) contains the power electronics necessary to operate a direct-drive system (Ref. 14).

Another goal of this development effort is to develop a DDU. It will be developed by leveraging PPU modules like the auxiliary module, the input module, and the SCB. However, in place of the two PPU discharge modules is a single DDU discharge module that houses a discharge filter to control ripple current from the thruster and a high-voltage switch to isolate the thruster from the power source and extinguish short circuit faults. In this design, a mechanical relay will be used as an isolation switch but in the future a hybrid switch that combines a relay and semiconductor devices could be implemented to improve reliability and transient response.

JPL has been conducting experiments with a 10 kW solar array to investigate technical issues associated with direct-drive. Some of the biggest challenges of direct-drive are the effect of discharge current oscillations on the various spacecraft systems, how to handle ignitions, transients and faults, and how to force current sharing when operating multiple thrusters. One outcome of their effort is the development of techniques and algorithms to control operation of Hall thrusters in a direct-drive system. The algorithms will be included in the SCB for the DDU to control the entire Hall propulsion system.

SiC Component Radiation Testing

A parallel effort was initiated to evaluate the radiation tolerance of the SiC power devices being used to develop the PPU and other parts used in the design that are not space qualified. Personnel from NASA GRC and Goddard Spaceflight Center (GSFC) are conducting dose rate testing at GSFC facilities and heavy ion radiation testing at Texas A&M University. The most critical parts for this application are the SiC MOSFETs and diodes that are being used for the power converters. SiC MOSFETs from various vendors are being evaluated as well as SiC JFET and super junction transistors (SJT). Also, two critical components of the gate drive circuit developed for this effort are being evaluated.

Future Work Plan

Once the brassboard PPU and DDU assembly is completed, they will be subjected to a thorough performance test using a resistive load. Then the PPU will be integrated with a Hall thruster at GRC and the DDU will be tested at JPL. Lastly, the PPU will be tested while operating in vacuum. Thermal data will be collected to validate thermal models and investigate the thermal capability of the design. The PPU will then be redesigned to optimize thermal performance, mass, volume and structural design for vibration environment.

Conclusion

NASA GRC is leading the development of a 15 kW Hall thruster PPU with a high input voltage. A comprehensive trade study of power semiconductors concluded that SiC was the superior choice for this application because it overcomes the performance limitations of state-of-the-art Si components. The discharge supply consists of two parallel 7.5 kW modules that use SiC MOSFETs and diodes to process power from a nominal input voltage of 300 V into an output of 400 V. The breadboard discharge supply demonstrated efficiencies in excess of 97 percent and was successfully integrated with the NASA-300M 20 kW Hall thruster. Power supplies for the electromagnet, cathode keeper and heater functions were also developed and tested. A brassboard PPU with most functionality required for flight and capable of operating in vacuum is being developed using a modular approach and common design elements to mature the PPU to TRL 5. A brassboard DDU is also being developed using common PPU modules. Once fabrication is completed, the PPU and DDU will undergo performance testing on resistive load and with a Hall thruster. The technology could then continue its evolution toward a flight ready design. This game changing technology has the potential of revolutionizing future PPU developments and enable high power SEP.

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