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HIGH PERFORMANCE POWER MODULE FOR HALL EFFECT THRUSTERS

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Abstract

Previous efforts to develop power electronics for Hall thruster systems have targeted the 1 to 5 kW power range and an output voltage of approximately 300 V. New Hall thrusters are being developed for higher power, higher specific impulse, and multi-mode operation. These thrusters require up to 50 kW of power and a discharge voltage in excess of 600 V. Modular power supplies can process more power with higher efficiency at the expense of complexity. A 1 kW discharge power module was designed, built and integrated with a Hall thruster. The breadboard module has a power conversion efficiency in excess of 96 percent and weighs only 0.765 kg. This module will be used to develop a kW, multi-kW, and high voltage power processors.

Introduction

Hall effect thrusters (HET) provide the advantage of high thrust to power ratio at high specific impulse compared to other electrostatic devices. They are attractive for Earth orbital and deep space applications.¹⁻⁵ NASA Glenn Research Center (NASA-GRC) is currently developing new Hall thruster concepts including multi-mode and high power engines.⁶ In-house efforts concentrate on the development of the NASA-173M V.2 high voltage thruster and the NASA-457M high power thruster.⁷⁻¹⁰

NASA-GRC is simultaneously developing power processing technologies that facilitate the development of a high power/high voltage power processing units (PPUs). In state-of-the-art (SOA) HET systems, the PPU is the most complex, expensive, and massive component. For high power applications, efficiency is a

critical requirement for the PPU as a small reduction in efficiency could result in a large amount of additional waste heat to be rejected by the spacecraft, increasing thermal radiator requirements. This could have negative impact on a spacecraft as SOA radiator technologies have a specific mass exceeding 10 kg/kW.¹¹

A high efficiency, lightweight, 1 kW discharge power module was developed. This power module will be used to develop a kW-class PPU capable of operating in high voltage or high current modes for the NASA-173M V.2 thruster. In addition, the design will be used as the foundation for a multi-kW design targeted to a high power thruster like the NASA-457M. This paper documents the design and performance characteristics of the 1 kW discharge power module. Also, it presents the results of integration testing with a NASA-120M Hall thruster.

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Thruster Interface and PPU Specifications

A typical HET system consists of a thruster, PPU, and propellant feed system. The PPU is the most complex, heaviest and most expensive of all three components. A typical HET PPU, as shown in Figure 1, includes a voltage regulated discharge supply, which provides power for ionizing the xenon propellant and accelerating ions. The inner and outer magnets supplies are current regulated supplies that control the magnetic field in the HET. The cathode heater and keeper supplies provide constant current to the cathode heater to raise its temperature and for starting and maintaining cathode emission. Most PPUs also include auxiliary power supplies for control and feed system functions.

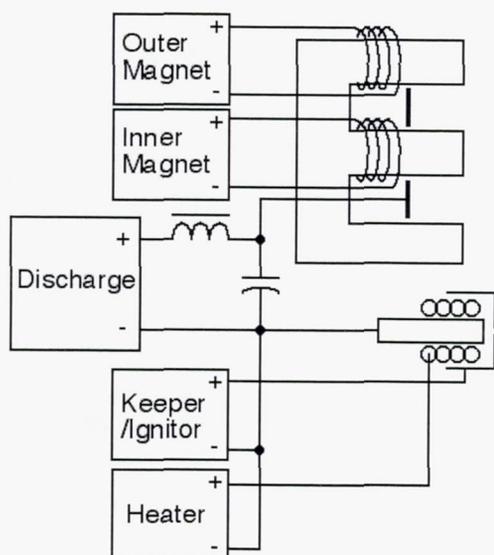


Figure 1. Electrical connections of typical HET PPU.

High power PPUs pose unique challenges to the designer. High current and voltage are difficult to manipulate efficiently using power semiconductor devices. As seen in many SOA kW-class Hall thruster PPUs, it is usually advantageous to use a modular approach.¹²⁻¹⁶ In this type of design, lower power modules are connected either in series and/or parallel to obtain higher total power. This reduces the amount of current processed by individual semiconductors, including diodes and MOSFETs, and also reduces the required voltage rating for diodes and capacitors. The

result of this is lower power losses yielding higher PPU efficiency. Another advantage of this type of architecture is that the switching of the MOSFETs in the individual modules can be staggered to reduce input and output ripples. This reduces filter requirements and could result in mass reduction for the PPU. In addition, modular designs allow the use of redundant modules for increased PPU reliability.

In a Hall thruster system, most of the power is processed by the discharge power supply. For example, on the NASA-173M thruster, discharge power is more than 96 percent of the total thruster power for most operating conditions.⁷⁻⁸ The remainder of the power is used by the magnets. Topology selection for the discharge supply is critical to obtain high overall PPU efficiency.

A summary of electrical specifications for the discharge power module is shown in Table 1. An input voltage range of 80 to 120 V was selected for this design. This is based on the assumption that a spacecraft that would use a high power HET system will have an unregulated, high voltage power bus. A nominal output voltage of 300 V was chosen for the output as many HET operate at this level. For higher voltage applications additional modules can be connected in series.

Table 1. Power Module Design Specifications

	Nominal	Range
Input Voltage	100 V	80 – 120 V
Output Voltage	300 V	100 – 350 V
Output Current	3.0 A	0.5 – 3.5 A
Output Power	≤ 1.0 kW	–
Output Ripple	≤ 5 %	–
Regulation	≤ 1 %	–
Efficiency	≥ 94 %	–

Discharge Power Module Design

At kW power levels, a full-bridge converter topology is very attractive. The advantages of this topology are low voltage stress on the switching transistors and good transformer utilization. In addition, in combination with phase-shift pulse width modulation (PWM)

control, “soft-switching” techniques can be used to reduce losses.¹⁷ Even though this technology has been used in the past for electric propulsion applications, the scope of this effort was to validate a simpler, more efficient, and lighter design.¹⁸⁻²⁰ Figure 2 shows a simplified schematic of this topology. A breadboard power module, as shown in Figure 3, was built to validate the electrical design.

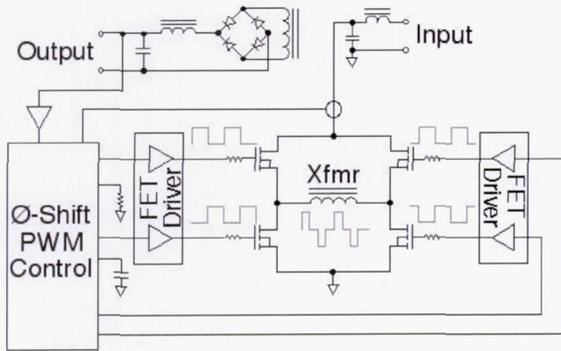


Figure 2. Block diagram of power module.



Figure 3. Breadboard discharge power module.

A switching frequency of 50 kHz was chosen as a compromise between mass and efficiency. The power transformer and filter inductors were built using ferrite cores for their low mass density and low core losses. A step up ratio of 1:3 was used to step up the nominal input

voltage of 100 V up to 300 V. Litz wire and winding techniques were used for the power transformer to reduce parasitics, skin and proximity effects. The MOSFET power stage and control circuitry were built using power and ground planes to reduce parasitic loop inductance and noise. The results of the efforts to reduce parasitics are reflected in the absence of transients in the primary voltage and current waveforms shown in Figure 4.

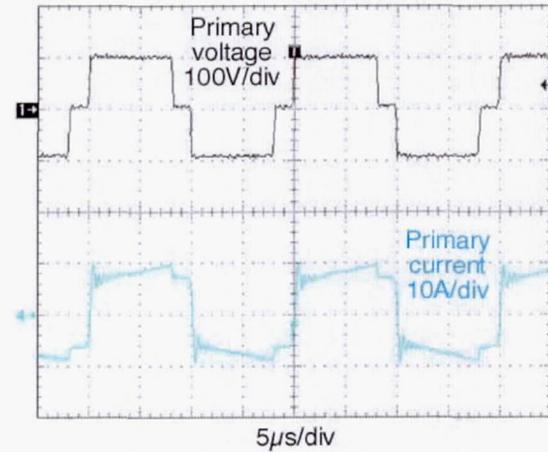


Figure 4. Primary voltage and current for the discharge power module.

Phase-shift PWM was implemented using a UCC3895 controller. This integrated circuit provides the necessary gate drives for the MOSFETs by phase shifting one half of the bridge with respect of the other. For this application, peak current mode control was used for its good short circuit protection. In addition, this controller provides other functions that are advantageous for this application. The current limit function limits the maximum current into the power module. In the case of an over-current condition, a “soft-stop” function disables the output for a programmable period of time and then restarts operation. Finally, a soft-start function ramps up the output at an adjustable rate which can be used to limit starting transients when starting a thruster.

Gate drives were implemented with IR2110 high and low drivers using a bootstrap circuit to isolate the floating MOSFET. Ultra-fast, ultra-soft recovery diodes with typical reverse recovery of 18 ns were used to reduce reverse

recovery transients and ringing which in addition reduce snubbing requirements. The output filter, which consists of an LC low-pass filter, was designed to meet the output ripple specification.

Figure 5 shows a picture of a power module built on a printed circuit board (PCB). This version of the power module has the advantage of lower noise and transients from parasitics by using a multi-layer PCB. Also, it provides repeatability between multiple modules to be used in a high power unit. The module built on a PCB measures 22.5 cm by 21.0 cm and weighs 0.765 kg. The design uses only 102 components with a combined weight of 0.516 kg.

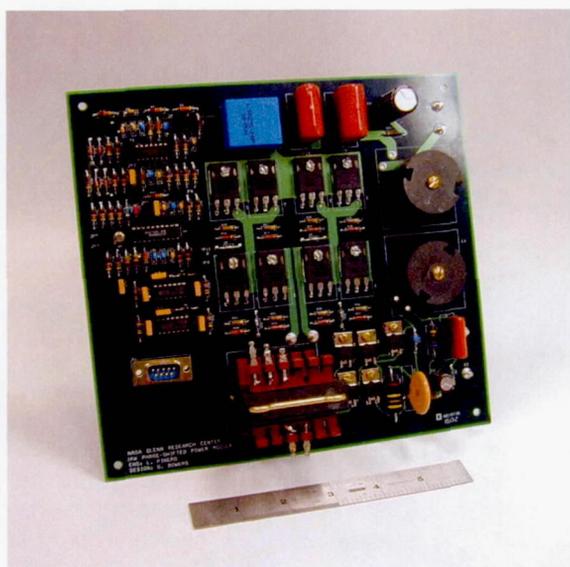


Figure 5. PCB Version of discharge power module.

Resistive Load Tests

The discharge power module was characterized using a resistive load at power levels from 0.1 to 1.0 kW and voltages of 240 and 300 V. Voltages and current were measured using a high bandwidth power analyzer. Efficiency was defined as the ratio of output to input power without including housekeeping power.

Figure 6 shows the efficiency as a function of output power for 300 V and 240 V output. Efficiency was better or equal to 96.0 percent at

300 V output, nominal 100 V input, and a power range of 0.3 to 1.0 kW. For a 240 V output, efficiency was higher than 93.7 percent for power levels from 0.1 to 0.7 kW.

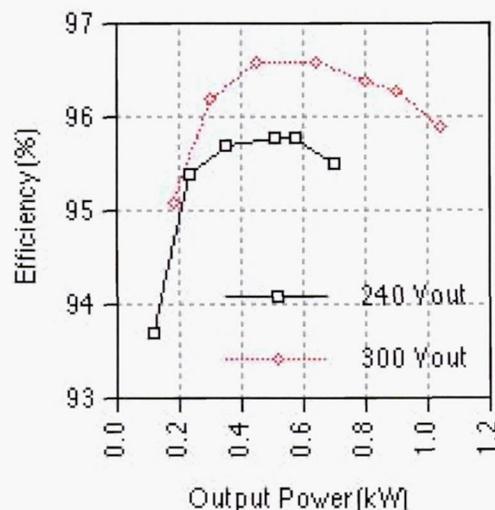


Figure 6. Efficiency as a function of output power at 300 V and 240 V at 100 V input.

Efficiency as a function of input voltage, with an output load of 100 Ω , is shown in Figure 7. For a 300 V and 240 V outputs, for any input voltage, efficiency was better than 95.7 percent and 95.0 percent, respectively.

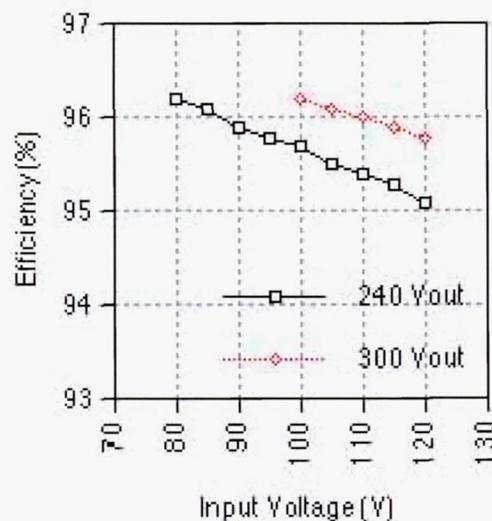


Figure 7. Efficiency as a function of input voltage at 300 V and 240 V into 100 Ω load.

Load and line regulation were tested by adjusting a resistive load or the input voltage at nominal operating conditions. They were defined as the ratio of output voltage change to nominal output voltage. For both cases, regulation was measured to be better than 0.2 percent. Also, a high-load and short circuit tests were conducted to verify operation of the current limit and soft-stop function. This was implemented by reducing the load resistance below nominal levels and by mechanically shorting the output. The power module survived both tests and the current limit and soft-stop functions performed properly.

Finally, the voltage feedback loop of the power module was tested for stability. The results of these tests are shown in Figure 8. The power module has a bandwidth approximately 4.3 kHz, gain margin of 15 dB and phase margin of 73 degrees. This is enough to guarantee stability and provide good transient response.

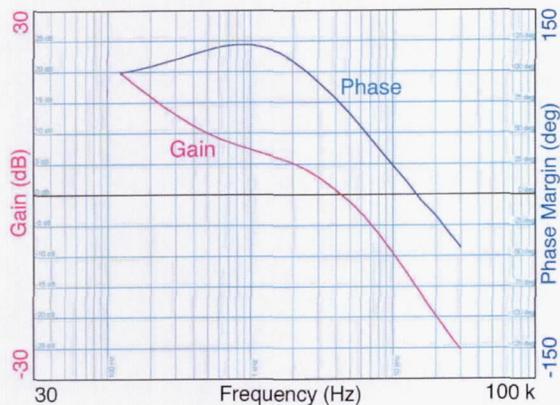


Figure 8. Power module feedback loop stability measurements.

Thruster Integration Tests

Thruster integration tests were conducted using a 3 kW-class, laboratory model NASA-120M Hall thruster. This thruster was developed by the NASA GRC Hall thruster program to serve as a test-bed for erosion diagnostics, capacitive discharge operation studies, and for investigation of the influence of channel parameters on operation. The thruster, depicted in Figure 9, has an outer diameter of 120 mm.

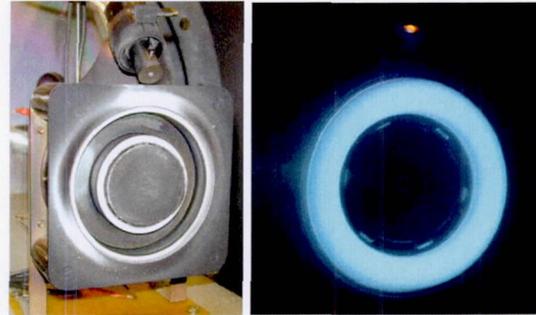


Figure 9. NASA-120M, 3-kW class laboratory model Hall thruster.

The NASA-120M performance is comparable to existing Hall thrusters of similar size. Table 2 shows the measured performance characteristics of the NASA-120M for operating conditions used in this experiment. The hollow cathode used for this test was manufactured by NASA GRC and was designed to operate up to 9.0 A. The cathode was operated at a mass flow rate of 0.8 mg/s.

Table 2. NASA-120M thruster operating conditions

Case	V _{dis} [V]	I _{dis} [A]	P _{dis} [W]	Anode [mg/s]	I _{sp} [sec]	Eff [%]
(1)	240	2.8	672	3.4	N/A	N/A
(2)	300	2.7	810	3.4	1409	41

The thruster was initially run using laboratory power supplies to verify its performance. The starting procedure consisted of starting cathode and main flow and the cathode heater and keeper supplies. After approximately 5 minutes, the cathode started at a 2.0 A keeper current and the heater was turned off. Then, inner and outer magnet supplies were turned on. Finally, the discharge supply was turned on and slowly adjusted from zero to the operating voltage.

In general, HETs exhibit characteristic discharge current oscillations during operation. The source of these oscillations is ionization phenomena in the discharge chamber. These oscillations have a fundamental frequency in the range of 10^4 Hz but also have components in the 10^6 Hz

range.²⁰⁻²² Traditionally, a “matching network” consisting of an LC low pass filter have been used between the thruster and the discharge supply. This filter supplies the thruster the ripple current it requires for start-up and steady-state operation. Also, it attenuates the oscillations into the discharge supply that can cause control instabilities and lead to power supply failure.²¹⁻²²

Figure 10 shows discharge current oscillations on the NASA-120M thruster operating at 300 V and 2.7 A. For this part of the test, only a 100 μ F capacitor was used at the vacuum feed-through since laboratory power supplies usually have over-designed output filters and do not have much difficulty running HETs. The frequency of the oscillations was approximately 25 kHz and the amplitude was in excess of 5.0 A. The large amplitude of the oscillations, compared to other Hall thrusters, was probably caused by operating the thruster at extremely low power. In addition, the magnet supplies were not set at optimum levels to minimize oscillations. Integration was conducted even at these non-optimized conditions as it presents a tougher challenge for the power module.

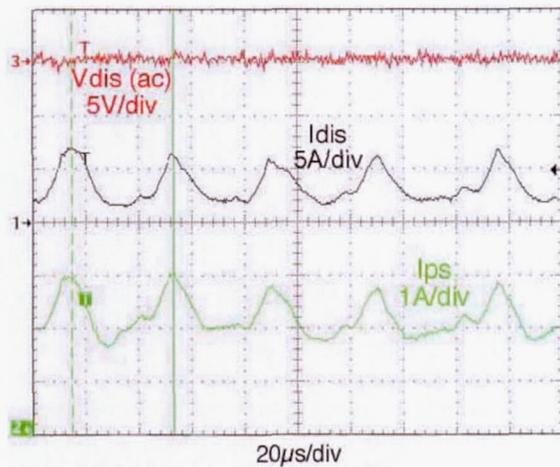


Figure 10. Oscillations during laboratory power supply operation with the NASA-120M thruster.

The power module was then connected at the discharge input to the thruster. The 100 μ F capacitor was removed and a matching network, consisting of an LC filter, was installed as shown in Figure 1. The values for the filter components were verified with computer simulation using a current source to model the HET discharge. Values of 10 μ F and 100 μ H were selected for the capacitor and the inductor, respectively.

The NASA-120M thruster was operated close to the power module maximum power and a lower power setpoint. Figure 11 show the current and voltage oscillations at the thruster and the module output current. Current oscillations were as high as 7.0 A_{p-p} or 260% of the DC value. Voltage oscillations were approximately 3.0 V_{p-p} or 1.0 percent at 300 V operation.

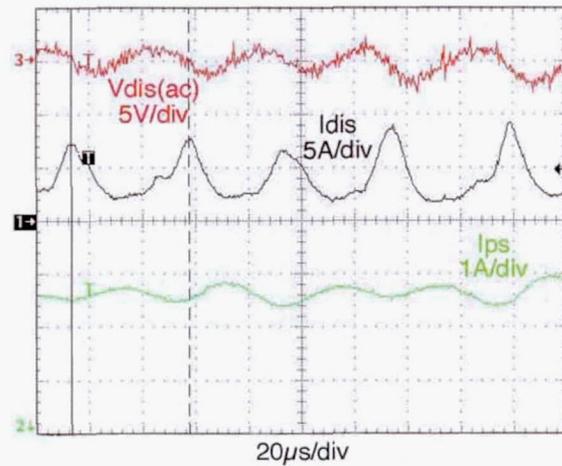


Figure 11. Oscillations during power module operation with the NASA-120M thruster.

The programmable soft-start function that was tested for thruster start-up. It provided a smooth start as shown on Figure 12. The output voltage jumps quickly to about 50 V where the thruster starts and current starts flowing. From there, the voltage builds-up to 300 V in approximately 450 ms. Multiple startups were successfully conducted at 300 V and 240 V output.

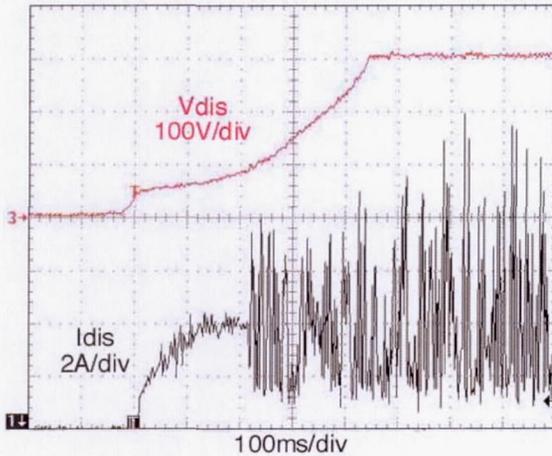


Figure 12. Thruster startup at 300 V using soft start function.

Conclusions

A breadboard discharge power module for HETs was designed and fabricated. The module uses a phase-shifted full-bridge topology operating at a switching frequency of 50 kHz to process up to 1.0 kW of output power. The mass of the power module is only 0.765 kg. Operating at nominal input and output conditions of 100 and 300 V, respectively, efficiencies in excess of 96.0 percent were measured. The discharge power module was successfully integrated with a NASA-120M Hall thruster. The module started and ran the thruster without difficulty even with large discharge current oscillations due to operation at off-nominal conditions.

This design will be used to develop kW-class PPUs by operating multiple modules in either parallel or series to process higher power and/or voltage. It will also be used as foundation for the design of multi-kW PPUs. This design should help reduce the mass of future HET systems and reduce their impact on spacecraft power and thermal system making HET propulsion systems more attractive for orbital and deep space applications.

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