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Integration Testing of a Modular Discharge Supply for NASA's High Voltage Hall Accelerator Thruster

Luis R. Piñero and Hani Kamhawi
Glenn Research Center, Cleveland, Ohio

Geoff Drummond
Colorado Power Electronics, Inc., Fort Collins, Colorado

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Glenn Research Center
Cleveland, Ohio 44135

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Glenn Research Center
Cleveland, Ohio 44135

Geoff Drummond
Colorado Power Electronics, Inc.
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Abstract

NASA's In-Space Propulsion Technology Program is developing a high performance Hall thruster that can fulfill the needs of future Discovery-class missions. The result of this effort is the High Voltage Hall Accelerator thruster that can operate over a power range from 0.3 to 3.5 kW and a specific impulse from 1,000 to 2,800 sec, and process 300 kg of xenon propellant. Simultaneously, a 4.0 kW discharge power supply comprised of two parallel modules was developed. These power modules use an innovative three-phase resonant topology that can efficiently supply full power to the thruster at an output voltage range of 200 to 700 V at an input voltage range of 80 to 160 V. Efficiencies as high as 95.9 percent were measured during an integration test with the NASA103M.XL thruster. The accuracy of the master/slave current sharing circuit and various thruster ignition techniques were evaluated.

Nomenclature

Eff	efficiency
Id	discharge current
Idm	discharge current master module
Ids	discharge current slave module
Pd	discharge power
Vd	discharge voltage
Vin	input voltage
Vpk	peak voltage

Introduction

Electric propulsion is critical for NASA's goals for solar system exploration and the study of planet Earth. Many missions can be enabled by state of the art electric propulsion systems and also by systems currently under development. Electric propulsion technology development activities are underway and are the responsibility of the In-Space Propulsion Technology (ISPT) Program, as part of NASA's Science Mission Directorate (SMD). The main focus of this program is NASA's Evolutionary Xenon Thruster (NEXT) ion thruster propulsion system (Ref. 1); however, ISPT is also developing the High Voltage Hall Accelerator (HiVHAc) thruster as a lower cost electric propulsion alternative for future cost constrained missions.

In 2004, the ISPT program conducted a study to quantify the potential benefit of using the NEXT propulsion system, which is nearing flight readiness; the NASA Solar electric propulsion Technology Application Readiness (NSTAR) ion thruster system, which is flight qualified; and a Hall thruster propulsion system with characteristics based on the HiVHAc thruster (Refs. 2 and 3). This study considered New Frontiers-Class science missions, that are currently cost capped at around $800 M, and Discovery-Class science missions, that are currently cost capped at around $450 M. The Hall thruster propulsion system was considered as part of this mission study due to advancements in Hall thruster technology that had occurred during the prior years. These advancements included increases in throttle-ability, specific impulse, and thruster efficiency (Ref. 4) and the successful demonstration of Hall thruster propulsion systems for primary propulsion applications (Refs. 5 and 6). The results of this assessment were that a Hall thruster system with these performance capabilities and the ability to provide total impulses approaching that of ion thruster systems provided substantial cost and performance benefits relative to the other advanced electric propulsion technologies for certain types of NASA's Discovery-Class science missions (Ref. 2). As a result of this study, the development of a Hall thruster with these characteristics was included as part of the ISPT's technology development portfolio.

To further advance the goal of developing a HiVHAc system, funding from a Small Business Innovative Research (SBIR) program was directed toward developing the power electronics necessary for such system. Colorado Power Electronics, Inc. successfully demonstrated in a Phase I effort the performance of a 1.0 kW discharge module that used a novel resonant topology capable of efficiently operating over a very wide operating range. This was demonstrated during an integration test at NASA Glenn Research Center (GRC) with an early version of a HiVHAc laboratory thruster. The Phase II effort then scaled up and refined the design to a 2.0 kW discharge module that could meet expected mission requirements. A brassboard discharge power supply comprised of two of these modules operating in master/slave parallel configuration up to 4.0 kW of output power was developed. This unit was designed to operate in vacuum and be conductively cooled through its baseplate. Integration testing was conducted at NASA GRC to characterize its performance, verify stable operation and to investigate ignition protocols. This paper summarizes the results of this integration test and upcoming work toward the development of a PPU for the HiVHAc system.

Thruster Interface and PPU Specifications

Hall thrusters require five electrical inputs to operate. These are called the discharge, inner magnet, outer magnet, cathode keeper, and heater. The block diagram on Figure 1 shows the interface between the thruster and these power supplies. The discharge supply is the largest power supply in a PPU because it processes as much as 97 percent of the thruster power and provides high voltage for accelerating ions. This power supply drives a nonlinear, dynamic plasma load with large current oscillations (Ref. 7). High efficiency for this power converter is crucial to reduce power dissipation which can be one of the biggest impacts that an electric propulsion system imposes on a spacecraft.

On deep-space solar powered missions, solar array performance changes with heliocentric distance. Available power decreases with distance, so thruster power has to be throttled to maintain stable operation. For this reason, a PPU for the HiVHAc system must operate over a power range of 0.3 to 3.6 kW. This includes a discharge output range of 200 to 700 V and 1.4 to 5.0 A. Table 1 shows the throttling conditions required for the discharge supply.

Also, array voltage increases with distance and a PPU must still be capable of delivering output voltage. The PPU is therefore required to operate over an input voltage range of 80 to 160 V. Other HiVHAc PPU requirements include a low voltage power bus input that is used for powering internal circuits and passive cooling through its baseplate to maintain low complexity and cost.

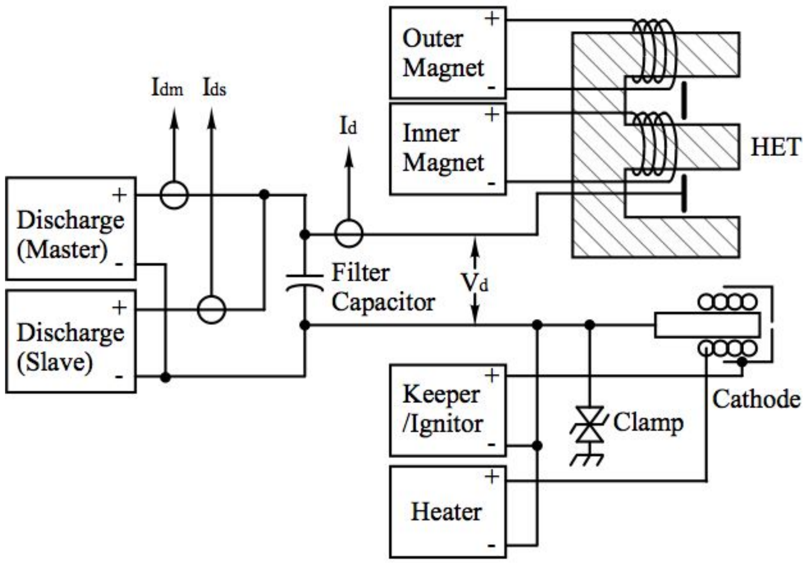

Figure 1. Block diagram of HiVHAc PPU and thruster interface.

TABLE 1.—DISCHARGE THROTTLING CONDITIONS FOR HIVHAC THRUSTER

Vd, V	Id, A	Pd, W
300	1.43	286
250	1.73	433
300	2.02	606
350	2.32	812
400	2.62	1048
450	2.92	1314
500	3.21	1605
550	3.51	1931
600	3.81	2286
650	4.11	2672
700	4.40	3080
700	4.70	3290
700	5.00	3500

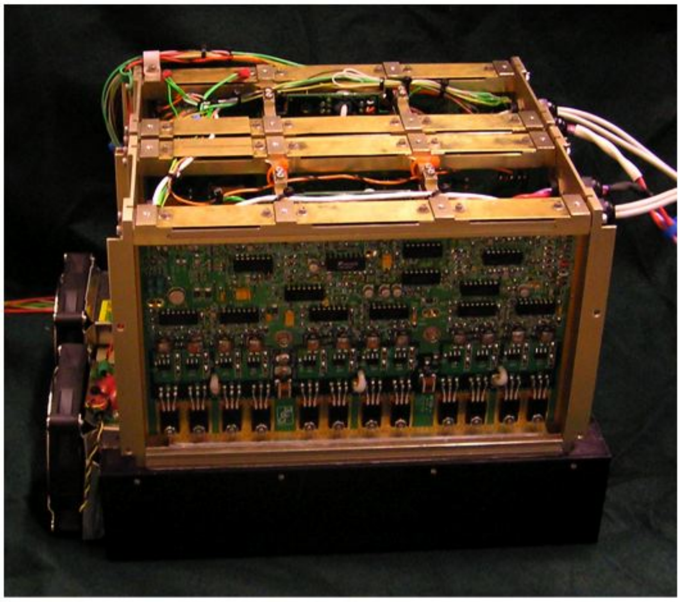

Figure 2. Photograph of the HiVHAc brassboard discharge power supply.

Discharge Power Module

Colorado Power Electronics, Inc. (CPE), under a Small Business Innovation Research (SBIR) contract with GRC, developed a brassboard, wide-range discharge power module for Hall thrusters. Traditional square-wave converters operate at high efficiency close to their maximum output power. As output power and/or voltage are throttled down because of power availability from solar arrays and thruster throttling requirements, efficiency decays very quickly. For this reason, PPUs are traditionally matched to a specific thruster to take advantage of the maximum efficiency (Refs. 8 to 10). In this design, a wide-ranging discharge power module operates at high efficiency over a wider operating range so it not only has the lowest power dissipation through a wider operating range but can also be used for a variety of thrusters. Two discharge power modules were connected in parallel in a traditional master/slave current sharing configuration to create a HiVHAc discharge power supply capable of processing up to 4.0 kW of discharge power. A photograph of this unit is shown in Figure 2. The modular nature of this design allows for scaling to higher power levels by adding more parallel modules.

Design

The HiVHAc discharge module uses a three-phase resonant converter (3PRC) comprised of three individual single-phase LLC converters (Ref. 11). This topology was selected for multiple reasons. Since it processes power more continuously, it exhibits lower ripple than single-phase converters and require smaller filter components. This effect is demonstrated in Figure 3 for the phase input currents. When the three individual currents are summed together, the total input current has a lower ripple than a single phase. Also, the resulting ripple frequency is six times higher than the switching frequency, simplifying filtering requirements. A 3PRC operating at an input of 100 V only requires 1 μF of input filter capacitance per kilowatt of output power. The LCC topology has an inherently wide load range capability because of transistor soft-switching, which results in low switching losses, at all operating points and the highest efficiency point occurs at the geometric mean of the load range. Similar resonant converters have been popular in the thin film plasma power conversion industry for many years.

A simplified diagram of the 3PRC is shown in Figure 4. With all three half-bridge transistors at 120° phase shift and 50 percent duty-cycle, the third harmonic is naturally cancelled, thus avoiding any third harmonic instability. This reduces the chance of load interaction and instability issues raised by negative plasma impedance loads. This topology can deliver full power over a 2:1 output voltage range. However, by using a voltage doubler and a current doubler this range can be individually increased by a factor of 2:1. A 4:1 voltage range was sufficient for the HiVHAc application so only the voltage doubler was used.

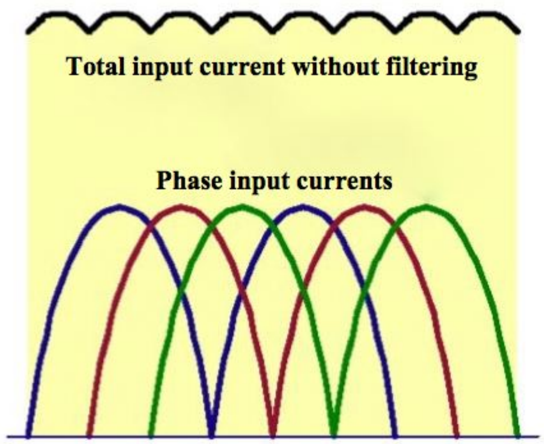

Figure 3. Three-phase resonant converter input currents.

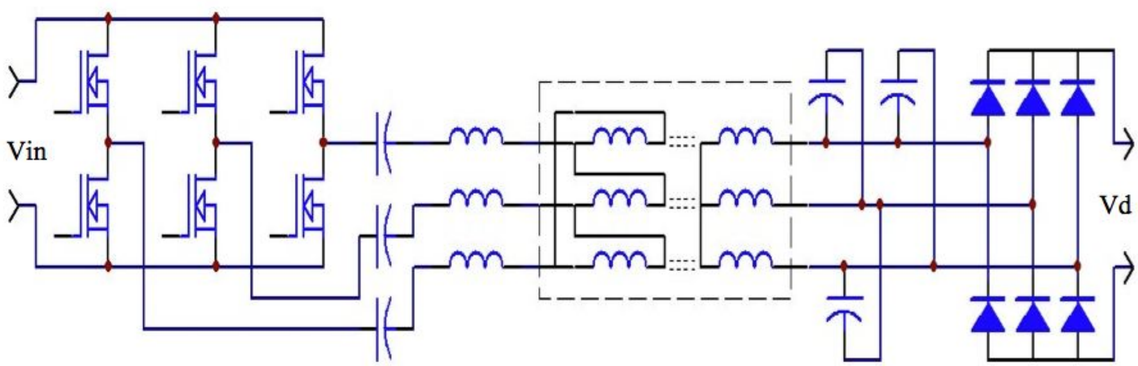

Figure 4. Simplified diagram of 3-phase resonant converter.

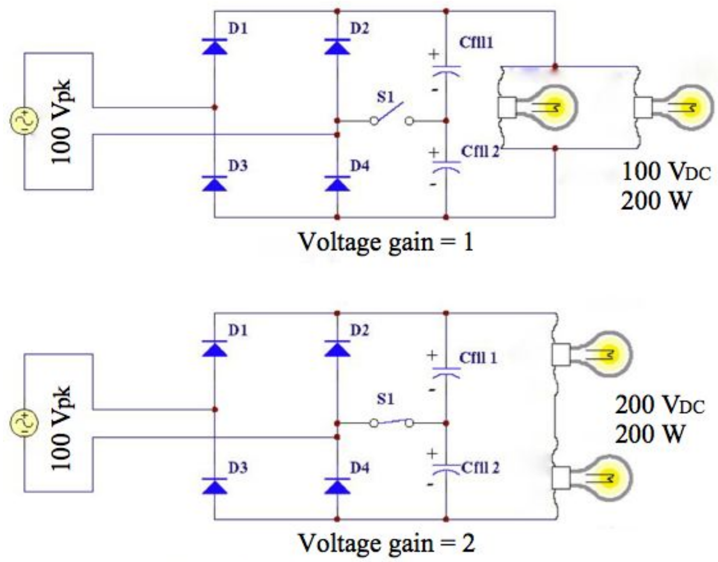

Figure 5. Voltage doubler circuit.

A simplified diagram of a voltage doubler output circuit is shown in Figure 5. The switch S1 is practical for one-time user selectable ranges. However, for quality electronic power conversion, there should be no moving parts in the electrical circuits. By careful selection of frequency dependent components, the switch S1 is replaced with passive components. It is important to emphasize that the 4:1 output voltage range is achievable in a continuous manner.

The HiVHAc discharge supply can operate in voltage or current control to regulate its output. The output voltage or current can be continuously adjusted from 0 to 700 V and from 0 to 20 A, respectively. It can deliver full load (4.0 kW) power at any output voltage between 200 and 700 V and input voltage between 80 and 160 V. So at an output of 700 V, it can deliver an output current of 5.7 A, and at an output of 200 V, it can deliver up to 20.0 A. For this reason, this converter can be applied to a wider variety of thrusters without the necessity of re-qualifying the design.

Thruster Integration

Integration tests were conducted at NASA GRC to characterize the performance of the brassboard discharge power supply, verify stable operation with a dynamic thruster load, and ensure that the master/slave current sharing circuitry performs well during ignition and steady-state conditions.

Thruster

The integration test was conducted with the NASA-103M.XL laboratory thruster. This thruster incorporates an innovation that enables a more than two-fold increase in lifetime relative current SOA Hall thrusters. The performance of the NASA-103M.XL thruster was experimentally evaluated. The total efficiency was between 0.33 and 0.55 and the a specific impulse between 1,062 and 2,779 sec at input power levels between 0.3 and 3.5 kW, respectively (Ref. 12). In addition, the thruster has undergone wear testing primarily to demonstrate the life extending innovation. To date, the thruster has been operated for 4,731 hr at a discharge voltage of 700 V demonstrating its life extending innovation. For the first 3,623 hr, the thruster was operated at 3.5 kW. For the next 1,108 hr, the thruster was operated at a power level of 3.1 kW (V_d = 700 V and I_d = 4.4 A). Figure 6 shows a photograph of the thruster after 4,731 hr of operation (Refs. 13 and 14).

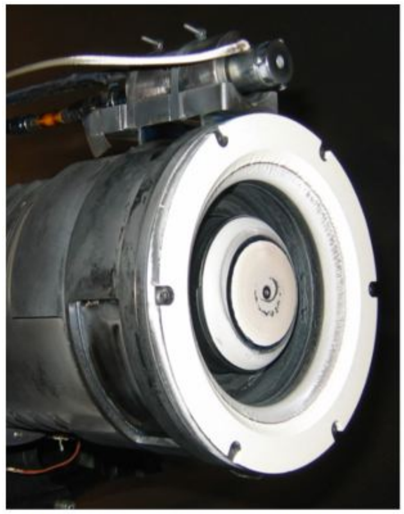

Figure 6. Photograph of the NASA-103M.XL thruster after 4,731 hours of testing at 700 V.

Test Setup

The discharge power supply was used to operate the NASA103M.XL thruster in vacuum facility 8 at NASA GRC. Xenon flows into the thruster were regulated by a laboratory feed system that independently controlled main and cathode flows.

Input and output voltages and currents, including individual module output currents, were measured using digital multimeters. These data were used to calculate discharge supply efficiency, line regulation and current sharing accuracy. A digital oscilloscope was used to measure the AC components of the discharge voltage and current as well as the individual module currents as shown in Figure 1.

The discharge supply was designed as a brassboard unit and it was conductively cooled. Its baseplate was mounted on a commercially available cooling plate connected to a water/glycol circulator that removed waste heat.

Current Oscillations

The HiVHAc thruster was operated throughout its entire throttling range. The operating conditions for the discharge supply are shown in Table 1. During the test, typical Hall thruster current oscillations were observed as shown in Figure 7 for full power conditions. The magnitude of these oscillations was as high as 12 A peak-to-peak with a fundamental frequency of approximately 25 kHz. The discharge current oscillations were measured downstream of a 4 µF filter capacitor while the module current were measured upstream. The lower magnitude on the module current oscillations suggests that most of the discharge peak-to-peak current was supplied by the filter capacitor.

Efficiency

The efficiency of the discharge power supply was characterized while operating the thruster over a wide range of output voltages and power levels. Efficiency was calculated as the ratio of output to input power of the discharge supply and did not include housekeeping power. Figure 8 shows a plot of efficiency versus output power for a variety of input voltages. For the 80 V input case, the efficiency is higher than 95 percent for output power levels higher than 1.8 kW and higher than 94 percent for outputs higher than 1.0 kW. Small reductions are observed at 120 and 160 V inputs. Figure 9 shows a plot of

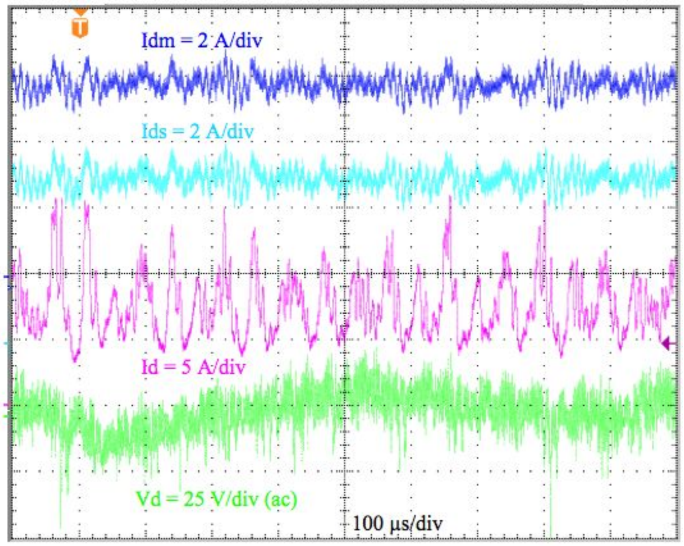

Figure 7. Discharge voltage and current oscillations.

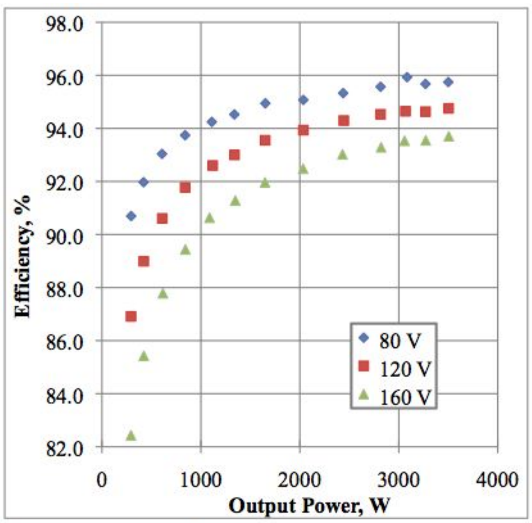

Figure 8. Plot of efficiency versus output power.

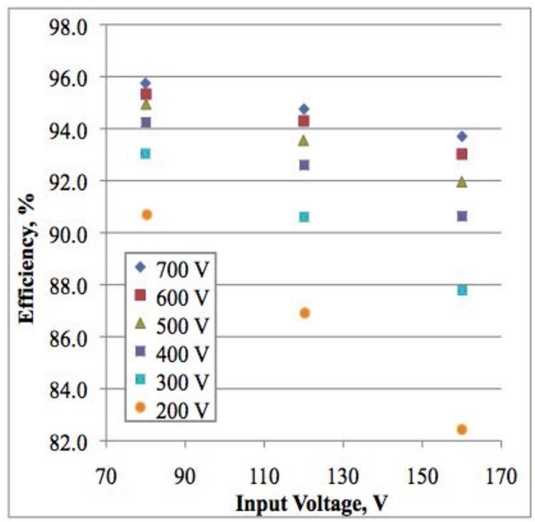

Figure 9. Plot of efficiency versus input voltage.

efficiency versus input voltage for a variety of output voltages. Once again, the effect of input voltage on efficiency is quite obvious primarily because at higher input voltages duty cycles are proportionally reduced resulting in lower power per cycle for a fixed switching loss.

Current Sharing

When power supplies are used in parallel, they have the advantage of modularity, redundancy and distributed heat loads and electrical stress. However, they have to be forced to share the load current. There are several passive and active techniques to accomplish this and their efficacy is proportional to their complexity. For the HiVHAc discharge supply, the two modules operate in parallel using a master/slave current sharing configuration. With this technique, the master module sets its output current level and commands the slave module to match that same level.

To evaluate the efficacy of this technique, the current through the master and slave discharge modules was individually measured with multimeters throughout the entire test while operating at all throttling conditions. The error of the current sharing was calculated as the ratio of the difference between the master and slave currents to the average module current. Test results showed that for all operating conditions in the throttle table, the current sharing operated with an average error 5.5, 7.7, and 8.7 percent for input voltages of 80, 120, and 160 V, respectively. As expected, the highest error of 11 percent occurred at the lowest power condition (V_d = 200 V, I_d = 1.4 A and V_{in} = 160 V) and progressively improved at higher power levels. The lowest error was observed at full power condition (V_d = 700, I_d = 5.0 A and V_{in} = 80 V) where it was 1.5 percent.

Ignition

The first step in igniting the HiVHAc thruster is starting the cathode. After this, two different techniques are used to complete the ignition. With the first technique, the magnets and flows are turned on to their steady-state conditions, followed then by the discharge supply. This technique requires simple controls but can have a high inrush current and can induce high electrical stress. With the second technique, the flows are turned on to their steady-state values and then the discharge supply is turned on with a limit on maximum discharge current. This establishes a low voltage glow discharge until the magnets are ramped up to smoothly complete the ignition.

The HiVHAc thruster was successfully ignited using both techniques. Figure 10 shows the results of the first technique. The discharge voltage rises and then drops when current starts flowing into the thruster. Once the discharge supplies catches up with the transient, the voltage builds up again until it reaches steady-state. It is important to notice that even during this transient operation, the master and slave modules shared the load current very accurately. Figure 11 shows the result of the glow discharge technique. The discharge current steps up to the current limit value of 3.0 A, set by the current control on the discharge supply, while the discharge voltage is about 50 V. As the magnets are manually ramped up, the discharge voltage increases to its steady-state value. One more time, it can be observed that the discharge modules evenly share the load current. This technique had lower transients on the discharge current but can only be used because the discharge power supply has the capability of limiting its output current. The selection of a starting technique for the HiVHAc thruster will be done at a later date.

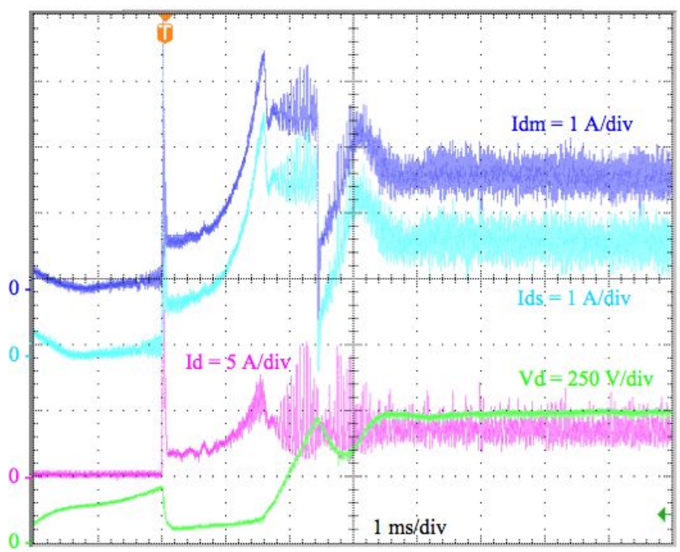

Figure 10. Ignition with magnets on.

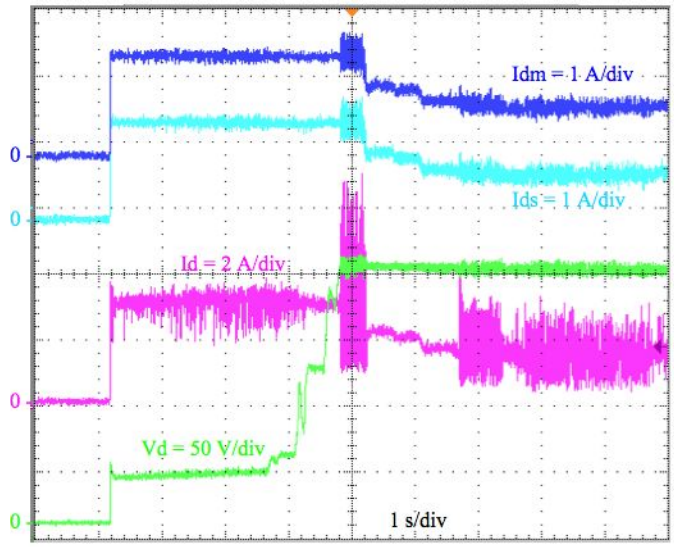

Figure 11. Ignition with magnets off.

Conclusion and Future Work Plans

A brassboard discharge supply was designed, fabricated and tested with the HiVHAc thruster. This design consists of two 2.0 kW modules that operate in a parallel master/slave configuration. An innovative three-phase resonant converter topology with a voltage doubler was used, resulting in very high efficiency for a very wide range of input and output operating conditions. Performance was measured during an integration test with the HiVHAc laboratory thruster NASA103M.XL at NASA GRC. Efficiencies close to 96 percent were measured for high power conditions and higher than 94 percent for power levels higher than 1.0 kW. Current sharing between the two modules was better than 11 percent. Successful ignitions with magnets on and off were characterized. Even during transient operation during a thruster ignition, current sharing between modules was maintained.

Planned future work with this discharge supply includes operation in vacuum and a long duration test with an engineering model thruster. Also, the other power supplies necessary for a HiVHAc PPU including the inner and outer magnets and cathode heater and keeper will be designed and built. Once these are completed, all the critical elements will be available to assemble a HiVHAc PPU.

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14. ABSTRACT
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