Development of A “Smart” Power Processing Unit for Hall Effect Thrusters

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Abstract

A “smart” power-processing unit (PPU) for Hall effect thrusters was developed and tested. The PPU was designed to be universal and capable of powering most 1.3 kW class Hall thrusters. Included in the PPU are the main discharge supply, two auxiliary magnet supplies, cathode heater supply, and cathode keeper/igniter supply. Although the experimental PPU built uses a 28V input, the basic design can be used for input voltages up to 300V with some modifications. The PPU also contains a control unit that tracks the discharge current characteristics (i.e. DC discharge current and AC discharge current at the thruster input), mass flow rate, and thruster input power. The control unit uses a set of fuzzy logic optimizers and attempts to minimize the thruster DC input current for a fixed input voltage and mass flow rate. At the same time, the controller also attempts to minimize the AC discharge current oscillations. A weighted relationship between the AC and DC current is established by the optimization parameters defined by the user.

Introduction

As Hall effect thrusters have become “main stream” and are now the thruster of choice for many missions requiring onboard propulsion, interest in optimizing the power-processing unit (PPU) for both cost and performance has been increasing.[1] In many of the missions that could utilize Hall effect thrusters, the total thruster count is high and therefore the cost of the PPU becomes a major factor. To reduce this cost, research simplifying and reducing the total number of components in the PPU has been performed.

Although the design of the individual power supplies required to operate a Hall thruster is a challenging problem, the optimization of the supplies relative to cost and part count is an even more difficult problem. This is particularly when the interaction between the PPU and thruster are so tightly coupled.[2]

Another problem that has plagued many Hall thruster systems is that of optimally adjusting the inner and outer magnetic coils. While acceptable performance can be obtained with a constant set point on the current to the magnetic field coils, life tests have shown that as Hall thrusters age, their optimal B-field and thus their optimal magnetic field coil current settings change.[3]

PPU Requirements

The requirements of the PPU were written such that it would be “generic” as to the type of Hall thruster that it could power. This meant that the PPU would need six isolated power supplies consisting of a cathode heater supply (keeper heater), cathode keeper/igniter, magnet 1 and magnet 2, and the main anode supply. In addition, one non-isolated house keeping supply is included for internal power needs.

The PPU was designed around an input voltage of 24-32 V. The output voltage of the anode supply was adjustable up to 500V max at 1500W and was voltage controlled. The 500V output was chosen for higher Isp operation. The two magnet supplies and cathode heater supply are current controlled and can output 0-10 A up to 15 V. The cathode keeper/igniter can output up to 100V and is current limited at 0.75 A. As demonstrated in previous PPU designs, the igniter is built into the keeper supply by coupling a pulse winding onto the output filter inductor of the keeper supply.[4]

Although the specific supply requirements for the cathode are more dependant upon the type (manufacturer) than the other PPU supplies, the basic characteristics of the required supplies are similar. At worst, two output transformer and filter designs would be required to accommodate most cathodes currently being used with 1.5 kW Hall thrusters.

PPU Topology

Because the anode supply (main discharge) processes the greatest amount of power, the majority of the research effort was placed on optimizing this design. During the process of optimizing this design, several topologies were considered including resonate, semi-resonate, current fed push-pull, push-pull, and full bridge. After examining the possible topologies, it was decided to create two anode

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designs. One based upon a semi-resonate (zero current switching) topology and the other on a push-pull topology. These two topologies were determined to offer both performance and cost advantages over the other types considered. Because of the high input current, topologies having more than one switch in series on the input side were considered to suffer too low of efficiency, or too high of a cost.

Due to the relatively high step-up ratio (24 to 500 V), both anode designs utilize three modules with parallel inputs and series outputs. A diagram of the module connections is shown in Fig. 1. By connecting the outputs in series, the problem of voltage stress on the output diodes is minimized. Placing the outputs in series also allows the transformer to achieve better coupling and lower winding capacitance by minimizing the turns-ratio.

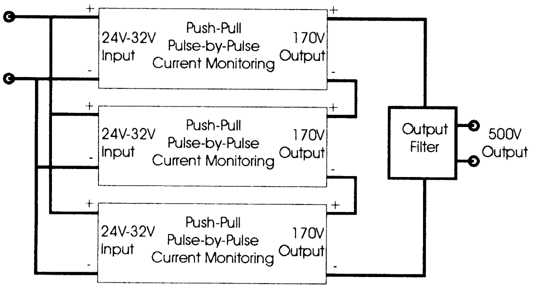

Fig. 1. Anode supply configuration.

After designing the anode around both topologies, the circuit simulation program PSpice was used to examine the dynamic characteristics of both designs. From the circuit simulations, it was determined that, for the particular input/output requirements we placed on this design, the push-pull topology was superior for maximum efficiency. A breadboard schematic of the anode supply is shown in Fig 2.

The feedback isolation circuitry used on the breadboard used a commercial isolation IC for simplicity. The next design iteration uses an input side current estimator and an additional sense winding on the power transformers. Although the accuracy of this method is worse than using a separate feedback circuit, the performance is more than adequate for Hall thruster operation and telemetry. The reduction in part count gives an inherent increase in reliability and a significant reduction in cost.

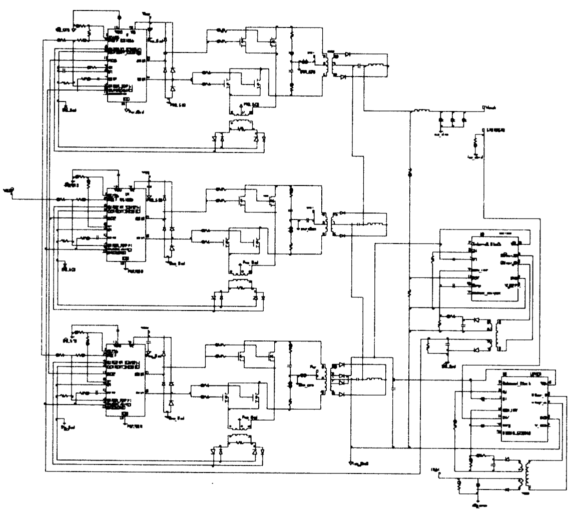

Fig 2. Breadboard schematic of the anode supply.

The loop bandwidth of the feedback control was selected based upon Hall thruster data (TAL and SPT) showing that the majority of the power spectrum of current oscillations is between 1 kHz and 100 kHz, under normal operating conditions. To minimize the interaction between the thruster and the PPU, the loop bandwidth was designed around 100 Hz. Because the PPU contains large input filters to minimize conducted EMI onto the main power buss, the 100 Hz bandwidth will easily track input variations and fluctuations.

The push-pull anode design was laid out on a two-layer printed circuit board (PCB) with 4 oz copper power traces. Although the PCB was not optimized for size and heat transfer, the controlled ground plane that a PCB offers is essential for proper power electronics operation. The magnetic components were also designed and built at this stage. Again, the magnetic components were not optimized for size or heat distribution at this point.

The PCB was then populated and tested using a dynamic DC load. All components used on the breadboard PPU were best in class commercial grade with space-qualified equivalents. Although not discussed in this paper, the other PPU supplies were designed and built (with the exception of the cathode heater supply) using a method similar to the anode supply.

Following the bench testing, the breadboard PPU was tested on an SPT-100 Hall thruster at NASA Glenn RC. During these tests, the magnetic field coils were operated independently of the discharge supply, thus allowing better optimization of the thruster's operating characteristics (minimized current oscillations). Fig's. 3 and 4 show the startup voltage and current traces of the main discharge (at the thruster and after the output filter). Note the staged startup voltage level. Each section of the anode supply has independent level controls that allow each section to turn on sequentially and in a controlled manner. In the example presented in Fig.4, the first section was initially stepped to 90% and slowly ramped to 100%. Section two was then stepped to 75% and then to 100%. Finally, the last section was stepped to 50% and held constant.

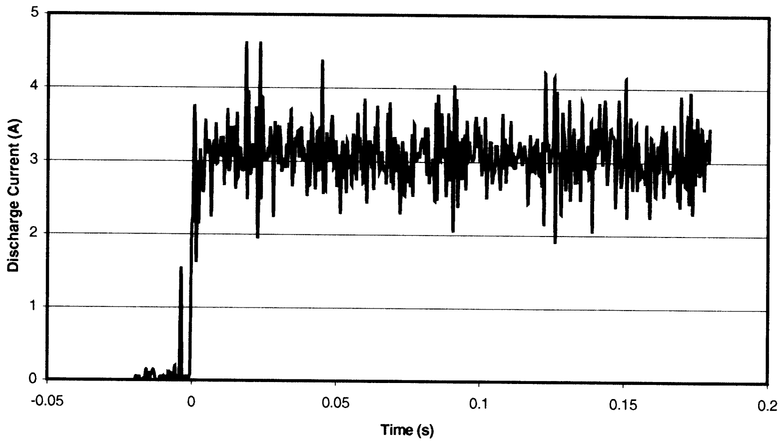

Fig 3. PPU discharge voltage of an SPT-100 during startup.

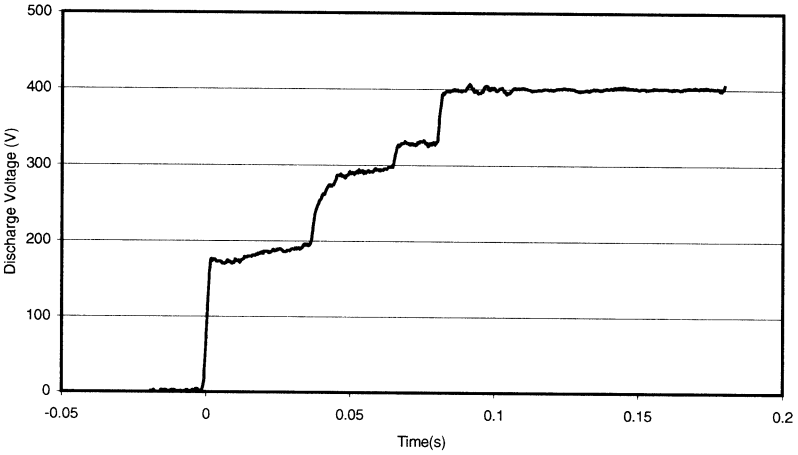

Fig 4. PPU discharge current of an SPT-100 during startup.

This startup profile is only an illustrative example of the circuit's capability and would not be considered a realistic startup sequence. Fig 5 shows the voltage and current waveform of the main discharge during normal, stable operation.

Adaptive Controller

As mentioned previously, work on incorporating a smart control unit within the PPU is being performed. Several approaches can be taken to optimize the operating set point of a Hall thruster's PPU. In this study, the control inputs were limited to the average current of the main discharge and the RMS current minus the average current of the main discharge (approximately the AC component of the discharge current). The control output is the magnetic field coil current (only one magnet supply is adjusted by the controller and depends upon the thruster type).

The average discharge current is derived from the input current monitor used internal to the PPU anode supply. Because of the output filter and matching network between the anode supply input and the thruster, the AC component is measured using a simple AC coupled current transformer placed between the matching network and the thruster.

Internal to the control unit are a set of input constants that define the parameter space of the controller. These constants set the maximum acceptable AC value of the discharge current (I_{AC}) around which the control unit will try to minimize the average discharge current (I_{avg}). That is, if the controller finds a setting that increases I_{AC} but offers lower I_{avg} and maintains I_{AC} below its threshold, the settings are used. Likewise, if I_{AC} is above the acceptable threshold, the controller moves to reduce I_{AC} below this threshold.

Another level that the input constants set is the operating slope on which I_{avg} and I_{AC} will work. This parameter determines the ratio of percentage change of I_{avg} to I_{AC} that the controller will optimize around. This feature allows the controller to select an operating

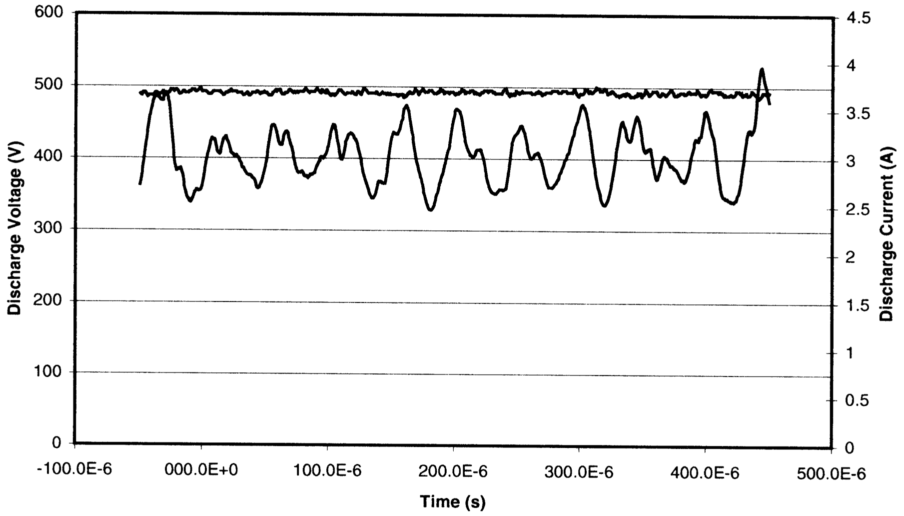

Fig 5. PPU discharge voltage and current during stable operation of an SPT-100.

point that offers significantly lower I_{AC} while increasing I_{avg} only slightly. The relative levels of "significantly" and "slightly" are to be determined by the user for a particular application or mission stage.

The final parameter that the input constants dictate are the control limits and neutral operating point. The control limits are simply the range of the magnetic field current that the controller is allowed to use. The neutral point is simply the nominal operating point of the thruster and is the point that the controller will begin to optimize around.

To simplify the control algorithm some important assumptions were made about the thruster's characteristics. The first and most important is that both I_{avg} and I_{AC} have only one local minimum within the control range and thus are monotonically increasing on both sides of this point (excluding the control end points). Other assumptions of lesser importance is that the thruster reaches a steady-state condition within the time constant programmed into the controller (i.e. thruster has reached thermal equilibrium) and all other operating parameters of the thruster are stationary (i.e. voltage and mass flow are constant).

Conclusions

A "generic" low-cost PPU was developed for use with Hall effect thrusters. The PPU is capable of operating most types of Hall thrusters in the 1.5 kW class. The electrical efficiency of the PPU is greater than 94% with all supplies included. Research on improving the magnetic components is continuing. This research is directed at reducing the mass and cost of the main transformers and on better heat dissipation techniques.

Because the controller is still in early development, operational data on laboratory Hall thrusters are minimal. Future work includes verification of the controller on several Hall thrusters at various ages and a quantization (thrust measurement) of the efficiency gain that a controller such as this can add to a propulsion system. The ability to set the operating power level of a Hall thruster is also being added. This simply involves adding two additional inputs (desired power and output voltage) and one additional output (mass flow setpoint).

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