The Development of a 4.5kw Hall Thruster Propulsion System Power Processing Unit*†

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This paper describes the requirements, design, performance and development status of a 4.5KW Hall Thruster (HT) Power Processing Unit (PPU). The PPU provides conditioned power to operate and regulate the General Dynamics Space Propulsion Systems (GD-SPS), BPT-4000 class of Hall Thrusters. The detailed design and development effort is in support of the Hall Thruster Propulsion Subsystem (HTPS) program for the Lockheed Martin Company. The PPU design builds upon GD-SPS flight-proven Russian Hall Effect Thruster Test (RHETT) Power Processor and incorporates several new innovations to improve performance, reduce mass and increase system reliability along with increasing the output power to 4.5KW. The PPU design utilizes a current fed power conversion topology for improved immunity to single event upsets due to radiation. In addition, a single, patented design power supply, powers the Hall thruster cathode heater, cathode keeper, and magnet coils. High density packaging minimizes PPU mass and significantly helps to increase producibility and decrease cost.

Introduction

Lockheed Martin Space Systems Company (LMSSC) and General Dynamics Space Propulsion Systems (GD-SPS) are pursuing development of a Hall Thruster Propulsion System (HTPS) for a wide range of applications on geosynchronous earth orbiting satellites. The system currently under development is planned to be used for both orbit insertion from an initial geosynchronous transfer orbit and on-orbit stationkeeping and repositioning maneuvers. GD-SPS is responsible for the development and qualification of the Power Processor Unit (PPU), along with the Hall thruster, Xenon Flow Controller (XFC) and all associated integration tasks between these components. This paper provides a summary of the PPUs design, measured performance, development status and planned future activity.

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Background

As background for the PPU development effort GD-SPS has over ten years of experience developing power processing electronics for electric propulsion systems and has over 60 units currently in orbit operating with 100% mission success. Our 1.5KW flight Hall Effect Thruster PPU [1] (Figure 1) for the Naval Research Laboratories (NRL) Electric Propulsion Demonstration Module (EPDM) was designed, qualified in 1997 and successfully flown on the STEX satellite in 1998. This program provided a wealth of direct experience in understanding spacecraft and Hall thruster interface issues.

Further work was accomplished under a multi-year GD-SPS internal technology development program to further the development of a modular Power Processing Unit [2,3,4] to operate the BPT family of Hall Thrusters. This effort built upon the RHETT Power Processor and incorporated new features to improve performance, manufacturability and to reduce cost. This work resulted in a 2.5 kW HT system. The BPT System was successfully test fired at the GD-SPS Hall Thruster Test Facility in 1999 [4].

Figure 1 - GD-SPS RHETT Hall Thruster PPU

HTPS PPU Overview

This PPU is designed to provide all command, telemetry and power interfaces from the spacecraft to the BPT-4000 Hall thruster and the xenon flow control sub-system. The PPU provides regulated power to the Hall thruster for both startup and steady state operations. Commands and telemetry are communicated with the spacecraft utilizing a MIL-STD-1553B data link. Output voltage is regulated at commandable levels between 100 and 450 volts. Discharge power can be set using data link commands to operate up to 4.5 kW. Included in the PPU design are value drivers to operate two solenoid-holding valves in the XFC. The design of the PPU is largely based on technology developed under General Dynamic's internal development programs during the 1990s.

Development Status

At the time of this writing, the PPU development program has completed its preliminary design phase. This phase included the design, fabrication and testing of a complete PPU breadboard that is electrically identical to the flight PPU. Testing has successfully demonstrated all functional elements of the PPU design, using both resistive loads and flight like thruster and XFC components. System level testing utilizing a laboratory version of the BPT 4000 thruster and an Engineering Development Model (EDM) version of the XFC was successfully completed in March of 2001. System testing demonstrated startup, shut down, xenon flow control and PPU operation over the full power and voltage range. Bench level testing performed at both room and elevated temperature demonstrated all command and telemetry interfaces including start up, throttling and shut down sequences. PPU operating efficiency (total power in - total power out) has been characterized at both room and elevated temperatures. It has been demonstrated at greater than 93% at full power operation of 4.5 kW of discharge power at 300 volts output. Preliminary analyses have also been completed including thermal, structural, parts derating, radiation/survivability, reliability and FMECA. The preliminary design phase was culminated with a design review meeting, held in March of 2001.

In September of 2001 a second system level demonstration test will be performed using the breadboard PPU in conjunction with the flight configuration EDM thruster and EDM XFC. The objectives for this testing are to validate the PPU's compatibility with the flight configuration EDM thruster and tune the PFCV flow control electronics.

At this time the detailed flight-like PPU design has been completed, including the mechanical packaging design, printed wiring board (PWB) layouts and a complete EDM PPU detailed drawing package. Fabrication of the EDM PPU is approximately 90% complete. All circuit cards are in various stages of assembly and functional testing. EDM PPU final assembly and functional testing will begin in September of 2001. During the 4Q01 and 1Q02, the EDM PPU will be subjected to all environmental testing required for qualification. This includes random and sine vibration, mechanical shock, EMI/EMC, ESD, thermal vacuum temperature cycling and Hall Thruster system testing using a flight configuration thruster and XFC. Following component level qualification testing, the EQM PPU will be utilized to support the remainder of the qualification thruster life test.

The fabrication and qualification testing of the Engineering Qualification Model (EQM) will follow a Critical Design Review (CDR).

MIL-STD-1553B Interface

The PPU communications is handled by a 1553B interface. This data link handles all commands except for input power isolation relay commands. The data link also handles all telemetry except for a single closed contact telemetry indication for the input auxiliary power relay. This approach greatly simplifies the PPU interface to the satellite. The command interface allows low level control of all functions that are not time critical. All critical timing is handled internal to the PPU. This approach allows the spacecraft computer to handle non-time critical sequencing and simplify the PPU design as well as allows good flexibility for system testing, troubleshooting and allows maximum flexibility to handle unanticipated thruster changes that could possibly occur on orbit.

Flow Control/Valve Drivers

Figure 2 shows a block diagram of the xenon flow control and the PPU drivers necessary to control the XFC. The XFC receives low pressure xenon from the system pressure reducer and controls the flow of xenon to the thruster and its cathode. The holding valves are driven with a pull in voltage of approximately 24 volts for 50 ms, and then held open with a lower voltage to reduce valve power dissipation. The PPU valve drive interface is protected against shorts in the valve drive interface. The xenon flow is split between the anode and cathode with about 95% of the flow provided to the anode and the remainder provided to the cathode. The proportional flow control valve is similar to a holding valve but it is designed to operate in a linear partially open mode as well as provide a second valve seat to prevent Xe leakage. The PPU provides a current to control this valve.

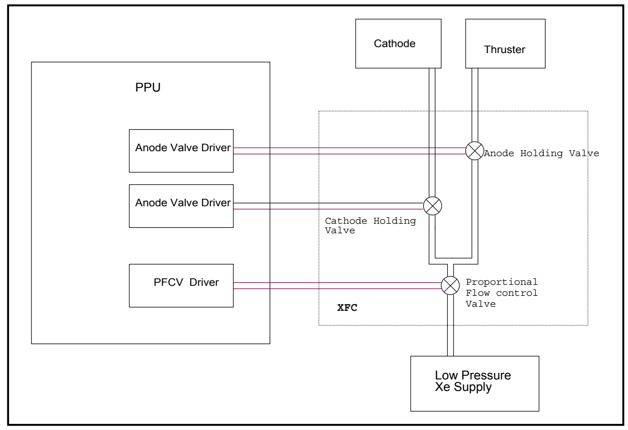

Figure 2 - Xenon Flow Control (XFC) and Valve Drivers

The valve current is controlled by a system feedback loop. In a Hall thruster, the increased xenon flow causes increased anode current. The anode current is approximately proportional to xenon flow.

Auxiliary Power Supply

The PPU has an internal auxiliary power supply that provides power to the internal circuitry and also power for operating the valves in the XFC. The design is a continuous mode flyback converter than converts power from the 70 volt input power to the necessary voltages needed for operation of the circuitry. This power converter has 6 outputs. Two of these are referenced to the input power return after the EMI filter and are used for powering the gate drives of the other power converters. The other outputs provide the necessary voltage for control and communication circuitry. Linear regulation provides +5V and +3.3V power for logic operation.

PPU Mechanical Design

The mechanical design of the PPU is shown in Figures 3 and 4 and has been optimized for electrical and thermal performance, mass and manufacturability. The overall PPU has dimensions of 0.4m x 0.43m x 0.108m (15” W x 17” L x 4” H) and has a mass of approximately 12.75 kg (28.1 lb.).

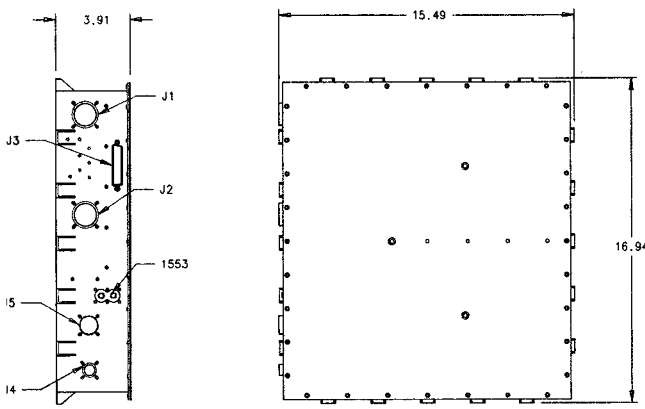

Figure 3 - HTPS PPU Envelope Dimensions

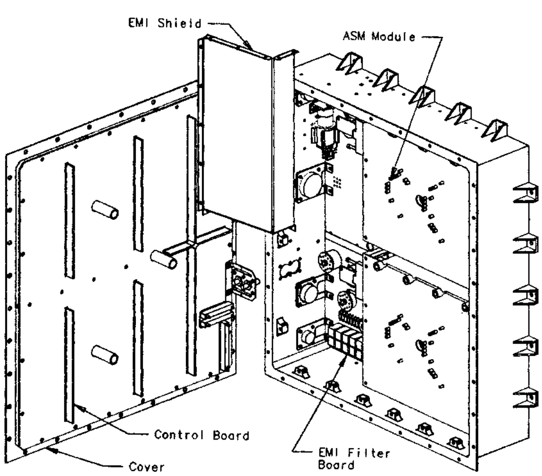

Figure 4 - HTPS PPU Mechanical Design Overview

Verification Approach

In addition to good engineering design practices, the power and control circuits utilized in the PPU have been analyzed using SPICE simulation. In particular the Anode Supply Module simulation was used as an aid in understanding losses and designing ways to reduce them. The results of these simulations were also compared to actual test data and became a guideline for further design enhancement. Typical operation of the ASM is provided in the test data from the breadboard PPU shown in Figure 5 and illustrates basic operation of the two ASMs in the PPU.

V_{in} VDC	I_{in} ADC	V_{out} VDC	I_{out} ADC	P_{in} Watts	P_{out} Watts	Efficiency %	Load ohms
			Dual Supply				
71.04	17.93	148.45	7.84	1273.64	1164.44	91.43	18.93
70.90	31.23	197.77	10.39	2213.85	2055.17	92.83	19.03
70.51	68.18	295.76	15.26	4807.50	4513.59	93.89	19.38
70.84	16.71	197.98	5.46	1183.55	1081.11	91.34	36.26
70.41	36.24	295.91	8.07	2551.48	2388.17	93.60	36.67
71.10	67.88	394.88	11.49	4826.48	4537.17	94.01	34.37
			Single Supply				
69.98	35.85	396.86	5.96	2508.40	2366.91	94.36	66.54
70.08	12.58	191.41	4.30	881.54	823.64	93.43	44.48
70.39	6.61	97.23	4.32	464.99	420.03	90.33	22.51
70.31	3.48	47.16	4.40	244.35	207.36	84.86	10.73
69.99	2.00	23.02	4.39	139.99	101.09	72.21	5.24
70.34	0.27	0.33	5.53	18.70	1.83	9.78	0.06

Figure 5 - Anode Supply Test Data

The output of the ASMs under dual and single modes of operation is given for operation at outputs of 150VDC to 400VDC and at power levels up to 4.5kWs. In addition, the single ASM performance is shown under overload and short circuit modes of operation.

Test Results/Performance

Figure 6, illustrates the PPU breadboard overall operational characteristics at 400VDC output and shows an overall operating efficiency of greater than 93%.

400V @ 4500W							
Board	Output Voltage	Output Current	Output Power	Input Voltage	Input Current	Input Power	Efficiency
Anode Supply A	400.00	5.63	2250.00	70.00	34.01	2380.95	0.945
Anode Supply B	400.00	5.63	2250.00	70.00	34.01	2380.95	0.945
AUX Supply	Variable	Variable	NA	70.00	0.53	37.00	0.870
Master Cntrl Board	NA	NA	NA	NA	NA	10.00	NA
Magnet	39.96	3.33	133.07	70.00	2.21	154.73	0.860
Heater	NA	NA	NA	NA	NA	NA	NA
Keeper	NA	NA	NA	NA	NA	NA	NA
PFCV	Variable	Variable	0.70	NA	NA	NA	NA
Valve Driver	Variable	Variable	3.10	NA	NA	NA	NA
Total			4636.87			4963.63	0.934

Figure 6 - Performance of PPU at 400VDC Output

Conclusions

Utilizing the experience of our previous electric propulsion power processor work and through the application of design innovations, GD-SPS has successfully developed and demonstrated an improved performance, 4.5 kW Hall Thruster Power Processor Unit. This design has completed preliminary design, breadboard fabrication and testing, and has undergone a full-up Hall thruster system demonstration test. All test results to date meet or exceed all of the established design requirements and have demonstrated all interfaces and stability with the BPT-4000 HT and XFC. Qualification of the HTPS PPU is planned to be begin in the 4Q01 and any progress will be reported on in future proceedings.

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