DC-DC CONVERTER FOR HALL THRUSTER PLASMA DISCHARGE

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Abstract

Busek has developed the key components of a 200 Watt Hall thruster propulsion system including the thruster, low power, low flow, hollow cathode and the discharge DC-DC converter which is the critical part of the thruster power processing unit (PPU). This paper will focus on the discharge converter and describe its design, and performance.

The converter is rated at 400 Watts, with a maximum output of 350 Volts or 1.25 Amps. Both voltage and current are real time continuously adjustable from zero to their respective maximums. An arbitrary number of these converters can be paralleled, offering modularity, redundancy and power scaling for application on a range of Hall thrusters from a few hundred watts to several kilowatts. Operational stability and an overall efficiency of 92% was demonstrated over a broad power range, first on a resistive load and then on the 200 Watt Hall thruster. Several thruster starting procedures were investigated with the magnet in series with the discharge and with the magnet powered independently. Anode to cathode electrical short was repeatedly induced to demonstrate the converter self protection features. The test results described in this paper include to the dynamic interaction of the converter with the thruster discharge.

Introduction

Military and commercial spacecraft designers and mission planners are now baselining Hall effect thrusters on a variety of satellites1,2,3 to perform station keeping, orbit repositioning and orbit raising. Examples include, the recently launched military technology demonstration satellite with a Hall thruster on board4 and several major commercial satellite communications systems including the French Skybridge and the American Teledesic/Celestri consisting of upwards of 60 satellite each. These large commercial constellations are planning to launch initial group of satellites with Hall thruster propulsion within the next two years.5

Concurrent with this proliferation of Hall thrusters, is the industry wide pressure to produce more capable, smaller and cheaper satellites, a trend forced by reduction in government funding, market driven competition in the commercial systems and technological/miniaturization advances in the electronic industry. This trend is analogous to the evolution in the computer industry, away from few costly mainframes to many low cost personal computers (PC) and finally to many networked PC’s that collectively outperform the main frame. The outcome of this evolution in the satellite industry is probably no longer in question for the same reasons experienced in the computer field. At the risk of over simplification, the reasons are lower costs and reduced risk in case of failure when an element in an autonomous distributed (instead of concentrated) system fails. This can be easily understood when one considers that the fastest growing class of satellites is used for communications in low Earth orbit where each satellite is essentially a computer driven switchboard in the sky. Studies, such as that performed by Barnhart et al.6 and focused on imaging instead of communications satellites, came to the same conclusions, confirming that small and micro satellites (< 100 kg) will proliferate and take over many functions now performed by large satellites. This trend toward small satellites requires the development of low power Hall thrusters.

The cost, weight and volume of a typical Hall thruster PPU dominates the Hall propulsion system. The PPU is typically heavier than the propellant management system, the thruster and the cathode combined and represents more than half of the system cost. Its weight and cost fraction increases as the Hall thruster size decreases because some of the PPU functions such as the control circuitry are power independent and remain fixed regardless of the thruster size.

Busek Co. Inc. pursued the Hall thruster development since 1991 primarily sponsored by the U.S. Air Force Research Laboratory. Selected low power Hall thrusters are described in Ref. 7. The USAFRL also sponsored this multiphased SBIR program focused on the development of a low power (~200 W) Hall thruster, propulsion system. Figure 1 shows a photo of the thruster and cathode assembly and Fig. 2 shows a photo of the breadboard. The system is described in Ref. 8 which emphasizes the thruster and the cathode. The breadboard is the subject of this paper.

Fig. 1 Busek’s 200 W Hall thruster (BHT-200-X2B) with associated hollow cathode (BHC-1500)

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** Engineering Aide

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Hall Thruster is a Dynamic Load

From an electrical engineering point of view, the Hall thruster, schematically presented in Fig. 3, is a dynamic load. Its discharge impedance \( Z \) is inversely proportional to the discharge conductivity \( \sigma \) given by

\[
\frac{1}{Z} \sim \sigma \sim \frac{\sigma_\perp}{1 + \beta^2} \tag{1}
\]

where \( \beta \) is the Hall parameter and the subscripts \( \perp \) and \( \parallel \) indicate direction perpendicular and parallel to the applied radial \( B \) field, respectively. The Hall parameter in a useful Hall thruster is large relative to one and hence the discharge impedance is proportional to

\[
Z \sim R \sim \frac{B^\perp}{\sigma_\parallel n_e I_{\text{dis}}} \sim \frac{B^\perp}{\sigma_\parallel I_{\text{dis}}} \sim V_{\text{av}} \tag{2}
\]

where \( n_e \) is the electron number density in the plasma, \( R \) is the discharge resistance and \( V_{\text{av}} \) and \( I_{\text{dis}} \) are the discharge voltage and current. Thus the discharge resistance ideally increases as a square of the applied magnetic field and is inversely proportional to \( n_e \). However, the value of the \( n_e \) saturates at a level primarily determined by the supply of the neutral atoms into the discharge (propellant mass flow). If there is an insufficient number of neutrals to ionize, \( n_e \) cannot increase without violating the overall plasma neutrality and creating a space charge voltage barrier. Therefore, the discharge current saturates leading to a highly nonlinear \( V-I \) characteristics as shown in Fig. 4.

**Fig. 3 Schematic of a typical Hall thruster power connections**

**Fig. 4 Typical V-I characteristics of a Hall thruster**

For a PPU designer, it pays to examine the \( V-I \) characteristics of each particular thruster very carefully. Three areas require attention: (1) discharge starting, (2) discharge oscillations and (3) control techniques that tolerate negative \( V-I \) characteristics and rapid load impedance oscillations. These are discussed in turn.

**Discharge Starting**

Table 1 shows the viable starting procedure options (selected from many alternatives), assuming that the hollow cathode is operating with its discharge powered by the keeper supply (labeled \( V_k \) in Fig. 3), such that when a sufficient anode voltage and flow appear the main discharge will start.

Procedure #1 requires the simplest, fixed output voltage DC-DC converter. However the PPU as a whole gets more complex because it must broadly regulate the flow \( \dot{m} \) and the electromagnet current. Procedure #2 is ideal from the point of view of the thruster with a very benign, smoothly starting thruster. However it requires a more complex converter with continuously varying discharge voltage and magnet current which may be desirable in any case for off nominal operation. Procedure #3 may have a fixed output voltage converter and a simple flow control, but requires starting circuit that typically doubles the voltage on the anode (point 4 on \( V-I \)). This stresses all insulation and flow isolators (a component in the propellant supply line with its inlet side at ground level and exit side at high potential) and is the least favorable starting procedure from the point of view of the thruster. Procedure #4 is a subset of procedure #2 that results in a simple one-voltage-set-point converter which however requires over current protection.

Choosing one procedure over the alternatives will depend primarily on mission requirements. For example, if the thruster must perform constant power orbit raising (high thrust, low \( I_{\text{sp}} \) and station keeping (high \( I_{\text{sp}} \), low thrust) then the PPU must have adjustable discharge voltage and mass flow, making procedure #3 appropriate. Our breadboard is capable of starting options #1, 2, and 4. Option 3 would require separate ignition circuit.

**Discharge Dynamics**

The Hall thruster plasma discharge is known to be unstable and oscillatory. As an example we show in Fig. 5 the current and voltage waveforms of a Russian Hall thruster. The lowest frequency discharge current oscillations typically have the largest amplitude, often exceeding 100% of the DC value. This and other higher frequency oscillations, listed in Table 2, impact the discharge converter design, switching frequency selection and the converter output filter design.

As shown in Table 2, the discharge current fluctuations predicted with the so called predator/prey model result in the largest amplitude fluctuations. The mechanics of the process,
is based on the previously mentioned depletion of neutrals in the discharge zone, that are converted to ions and accelerated out; this creates an empty zone, that forces a reduction in current, followed by refilling of the void with much slower moving neutrals which then allows the discharge current to build up again. Because of the large amplitude and a frequency that is close to where most aerospace converters are switched (tens of kHz), it is important to select converter topology, and switching frequency that does not amplify or contribute to the plasma instability. The design of the output filter must take into account this frequency and also the higher plasma frequencies listed in Table 2 to prevent plasma disturbance propagation back into the converter.

![Fig. 5 Discharge Voltage and Current waveforms showing current oscillations. Upper trace: Discharge Voltage, 20 V/div. Lower trace: Discharge Current, 1.25 A/div.](image)

**Discharge Control**

Most diffused plasma discharges are capacitive loads as is the Hall thruster. However, unlike other diffused discharges, the Hall thruster V-I characteristics contain positive, negative, and infinite dV/dI slopes (See Fig. 4). This places special requirements upon the control system/feedback loop stability and performance. This is especially true when the discharge, as a part of “normal” operation, oscillates at some tens of kHz, continuously sweeping the V-I characteristics from near zero to high current levels during each oscillation cycle.

Therefore the discharge converter must have a capacitive output, sized to maintain a low voltage ripple in the presence of oscillatory discharge. Additionally, the discharge converter control loop is designed to maintain the commanded average voltage or current depending upon the control mode. The control loops for both the voltage and current control modes are designed to have wide phase and gain margins resulting in a well damped transient response. This eliminates the risk of resonant response or interaction of the control loop with the discharge even when the plasma discharge oscillation frequency is near the loop crossover frequency.

**Discharge Converter Design**

Table 3 shows the major PPU/discharge converter specifications. The converter was designed to deliver up to 400 W to the thruster. To make it widely applicable, its output voltage is continuously variable from 0 to 350 V, adjusted in real time in response to an external analog signal. Furthermore, to make the breadboard a research tool in addition to being a discharge converter prototype, it was designed to provide continuously real time adjustable current form 0 to 1.25 Amps, also controlled by an external analog input signal. The user selects either voltage or current control or can preset maximum current while in voltage control. This capability, which may not be needed in most PPU’s, automatically provided a 1.25 Amp current limit and short circuit protection. (Short circuit protection is a mandatory feature in all PPU’s). The continuously adjustable current also facilitates easy control over many paralleled converters should a larger PPU for larger thrusters be needed in the future.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>( n_i )</th>
<th>( B )</th>
<th>( V_{as} )</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 → Nominal Starting at zero, increase ( n_i ) till ignition, then increase B with ( n_i ) to nominal</td>
<td>0 → Nominal Nominal (Point 3 on V-I)</td>
<td></td>
<td>Requires variable flow (( n_i )) control Upon start may result in large in rush current (on converter input side) One voltage set point converter - simple</td>
</tr>
<tr>
<td>2</td>
<td>Nominal</td>
<td>0 → Nominal Starting at zero, increase ( V_{as} ) till ignition, then increase B with ( V_{as} ) to nominal conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Nominal</td>
<td>Nominal Above Nominal (DC or Pulse)</td>
<td></td>
<td>Requires starting circuit with high voltage (point #4 on V-I) Stressing all insulators on thruster/cathode wiring and propellant feed lines isolators Simple discharge converter (one set point, dV/dt not relevant)</td>
</tr>
<tr>
<td>4</td>
<td>Nominal</td>
<td>0</td>
<td>0 → Nominal</td>
<td></td>
</tr>
</tbody>
</table>
Table 2 Frequency of discharge fluctuations in a typical Hall thruster

<table>
<thead>
<tr>
<th>Instability Type</th>
<th>Associated With</th>
<th>Frequency Estimate</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic</td>
<td>Transit time of neutrals through discharge chamber with sonic velocity $c_s$</td>
<td>$\approx \frac{c_s}{L} = 20 \text{ kHz}$</td>
<td></td>
</tr>
<tr>
<td>Predator/Prey$^{10}$</td>
<td>Combined transit time of neutrals and ions</td>
<td>$\approx \frac{1}{2nL} \sqrt{c_sc_s} = 27 \text{ kHz}$</td>
<td>Large discharge current amplitude, that could exceed DC value</td>
</tr>
<tr>
<td>Ionization</td>
<td>Transit time of ions from ionization location to outside of thruster</td>
<td>$\approx \frac{c_l}{L} = 1.4 \text{ MHz}$</td>
<td>Superimposed on predator/prey oscillations</td>
</tr>
<tr>
<td>Azimuthal Waves</td>
<td>Electron azimuthal transit time</td>
<td>$\approx \frac{(V/L)}{\pi dB} = 3 \text{ MHz}$</td>
<td></td>
</tr>
<tr>
<td>Plasma Electron Oscillations</td>
<td>$= \left( \frac{nq^2}{m_eB_e} \right)^{1/2}$</td>
<td>$= 1 \text{ GHz}$</td>
<td></td>
</tr>
<tr>
<td>Electron Cyclotron Oscillations</td>
<td>$= \frac{qB}{m_e} \approx \text{ few kHz}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Assumes: Typical 1kW class Hall thruster, singly ionized Xe, neutral speed $c_s$=300 m/sec, ion speed $c_l$=21 km/sec (given by $V_{dis}$=300 Volts), discharge cavity length $L$=0.015 m, discharge cavity diameter $d$=0.1 m

Table 3 Discharge converter major specifications

<table>
<thead>
<tr>
<th>Nominal</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage (Volts)</td>
<td>28</td>
</tr>
<tr>
<td>Output Voltage (Volts)</td>
<td>300</td>
</tr>
<tr>
<td>Output Current (Amps)**</td>
<td>0.66</td>
</tr>
<tr>
<td>Output Power (Watts)</td>
<td>200</td>
</tr>
<tr>
<td>Output Current Ripple (-)</td>
<td>&lt;5% Resistive Load</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>50 kHz</td>
</tr>
</tbody>
</table>

*Operator selects V or I Control  **Short circuit protected to $I_{max}$

The power topology selected for the converter consists of a buck derived pulse width modulated full Mosfet bridge followed by a dual bridge seriesed rectifier shown schematically in Fig. 6. Phase shift control is used for pulse width modulation of the Mosfet bridge in order to obtain resonant transitions for maximum efficiency. A switching frequency of 50 kHz was selected as a compromise between switching losses and size of the magnetics. A separation from the expected frequency of the plasma discharge fluctuations was considered to be a small factor in switching frequency selection because our control loop is designed for wide phase and gain margins.

The primary bridge configuration is especially suited to high voltage and high power operation because it limits the voltage stresses on the Mosfets to the actual input line voltage. In addition to eliminating corona risk, this allows selection of lower resistance ($R_{down}$) Mosfets than would be possible with a push-pull or forward converter topology. Further advantage of the bridge is its compatibility with resonant transition phase shift modulation. This modulation technique significantly reduces switching losses at high power levels. Additionally, since the gate drive waveforms are always symmetrical square waves, isolated gate drive signals are easily coupled to the bridge from an isolated control circuit using transformers. The rectifier consists of ultrafast, high voltage diodes in a dual seriesed bridge to lower device stresses during reverse recovery.

The planar winding power transformer uses a combination of printed wiring board and flat sheet metal (copper) windings. Planar construction offers important features such as low skin effect losses and parameter repeatability. The flat conductors provide excellent current distribution at high frequency yielding lower conductor losses at high currents than would be obtainable with a conventional toroidal device using magnet wire. Planar devices are also free of fabrication variables and yield the repeatable leakage inductance that is important to resonant transition switching.

![Fig. 6 Hall thruster discharge power supply/DC-DC converter schematic](image)

The converter must deliver isolated and well-regulated power from the primary to the secondary side. It also must provide precise control of secondary voltage and consistent with our goals, must provide precise programmable control of the maximum output current as well. This requires that the sensing circuits of the secondary be capable of proper operation with output
voltages between the nominal output and near zero volts which would occur as a direct result of a shorted output load.

Including a separate low power DC/DC bias converter, powered from the 28 VDC main input bus, allows the complete PWM control circuit to be referenced to the secondary side while making its operation independent of the state of the main converter. The bridge gate drive transformers provide the required isolated feedback to the main converter's primary side. This results in inherently high noise immunity while avoiding the use of optical isolators and their associated radiation intolerance. The bias converter does not require precise regulation and therefore does not require secondary feedback. It does however, provide imperviousness to the operational state of the main power converter and possible thruster plasma oscillations.

The PWM control circuit is based upon the Unitrode UC1879 Phase Shift Controller IC. This IC is capable of operation at frequencies up to 300 kHz. Note that a 300 kHz full bridge converter produces an output ripple frequency of 600 kHz, and is comparable in many respects to a 600 kHz forward converter.

Parts were selected based upon their potential for upgradability to space qualified or qualifyable components. The use of non-bipolar or CMos components was avoided unless known radiation tolerant full temperature range parts are available. Commercial plastic power mosfets and other plastic encased semiconductor components were used in the breadboard upon verification of the availability of hermetic radiation tolerant parts which are essentially equivalent. General components selection was based upon the availability of similar or equivalent components with a military/space temperature range of -55 to +135°C.

The breadboard was constructed using a flat aluminum baseplate that can serve as a heat path for conduction cooling inside a vacuum chamber and in an ambient room environment. The breadboard was designed to require no active cooling when operating in air. The baseplate dimensions are 11.5 x 9 x 3/8", as visible in Fig. 2. Excluding the baseplate, but including all mounting hardware and connectors, the converter weighs 975 grams.

**Breadboard Tests with Resistive Load**

Table 4 lists the converter detail specifications requirements versus the actual measured performance. The converter performance characteristics with resistive load are presented in Figs. 7 through 11. As shown in Fig. 7, the breadboard efficiency plotted as a function of output power (at several constant output voltages) exceeds 92% over the power range of interest from 150 to 350 Watts. Efficiency versus output current, shown in Fig. 8, exceeds 90% for all discharge currents over 0.5 Amps and voltages over 250 Volts. As mentioned previously, these efficiencies include control power taken off the 28 VDC input. These results were achieved despite the dual seriesed rectifier bridge which doubles the number of diodes and hence losses. (Dual bridge was employed to minimize rectifier stresses during their reverse recovery). The extra rectification losses were compensated by minimizing switching losses (resonant switching was demonstrated) and by careful design of the planar transformer.

![Fig. 7 Discharge power converter efficiency versus output power](image)

![Fig. 8 Discharge power converter efficiency versus output current](image)

Maximum output voltage versus input voltage is plotted in Fig. 9. It is seen that the converter can safely tolerate a 21 Volt input voltage (7 volts below nominal) and still achieve its specified maximum output of 350 Volts.

As pointed out in a previous section, good bandwidth and stability are important to DC-DC converter performance. Figures 10 and 11, show the measured loop gain and phase performance for the respective voltage and current control modes. Although stability criteria in terms of phase and gain are somewhat arbitrary, some generally used guidelines are to have a minimum worst-case gain margin of 10dB and minimum worst case phase margin of 30 degrees. The measured PPU nominal gains and phase margins for the voltage and current modes meet or exceed 17dB and 75 degrees, respectively. These levels assure worst case end of life and operating conditions margins well in excess of the guidelines.
### Table 4 Discharge Power Converter Specification Requirements vs. Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
<th>Performance</th>
<th>Test Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input Requirements</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DC Input Voltage</td>
<td>24 to 35 VDC</td>
<td>21.6 to 45 VDC</td>
<td>Vo=350VDC, io=0.7A</td>
</tr>
<tr>
<td>Full Performance Survival:</td>
<td>0 to 40 VDC</td>
<td>0 to 45 VDC</td>
<td>Vo=350VDC, io=1.25A</td>
</tr>
<tr>
<td><strong>Output Requirements</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output Voltage</td>
<td>0 to 350 VDC</td>
<td>0 to 358 VDC</td>
<td>23&lt;Vin&lt;35, Vo=200, io=1A</td>
</tr>
<tr>
<td>Line Regulation:</td>
<td>&lt;0.01%</td>
<td></td>
<td>0&lt;io&lt;1.25A, Vo=200, Vin=28</td>
</tr>
<tr>
<td>Load Regulation:</td>
<td>0.01%</td>
<td>Untested</td>
<td>Vin=35, io=1.25A, Vo=200V</td>
</tr>
<tr>
<td>Temperature Regulation:</td>
<td>&lt;5%</td>
<td>1%</td>
<td>Regulates to Setpoint</td>
</tr>
<tr>
<td>Output Ripple Voltage</td>
<td>&lt;5%</td>
<td>Untested</td>
<td></td>
</tr>
<tr>
<td>Output Current Range:</td>
<td>0 to 1.25A</td>
<td>0 to 1.27A</td>
<td>23&lt;Vin&lt;35, Vo=200, io=1A</td>
</tr>
<tr>
<td>Line Regulation:</td>
<td>0.20%</td>
<td>Verified</td>
<td>0.2&lt;Vin&lt;350, io=1, Vin=28</td>
</tr>
<tr>
<td>Load Regulation:</td>
<td>0.25%</td>
<td>Verified</td>
<td></td>
</tr>
<tr>
<td>Temperature Regulation</td>
<td>&lt;5%</td>
<td>Untested</td>
<td></td>
</tr>
<tr>
<td>Output Overload</td>
<td>Protection Required</td>
<td>Regulates to Setpoint</td>
<td></td>
</tr>
<tr>
<td><strong>Control and Adjustability</strong></td>
<td>Required</td>
<td>Verified</td>
<td>Vo=300V, io=0.67A</td>
</tr>
<tr>
<td>On/Off Control</td>
<td>Required</td>
<td>Verified</td>
<td></td>
</tr>
<tr>
<td>Output Voltage Control</td>
<td>Required</td>
<td>Verified</td>
<td></td>
</tr>
<tr>
<td>Output Current Control</td>
<td>Required</td>
<td>Verified</td>
<td></td>
</tr>
</tbody>
</table>

#### Efficiency
- **85% Minimum**
- **92%**

#### Operating frequency
- **40 kHz Minimum**
- **50 kHz**

#### Electrical Isolation
- **Input to Output:** 10 MegOhms Min
- **Input to Chassis:** 10 MegOhms Min
- **Output to Chassis:** 10 MegOhms Min

#### Temperature Range
- **0 to 70°C**

*Bias Converter (Semiconductor Circuits, Inc.) leakage under evaluation

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**Fig. 9** Discharge Power Converter. Maximum Available Output Voltage vs. Input Voltage

**Fig. 10** Discharge Converter Loop Gain and Phase Margin Voltage Mode

**Fig. 11** Discharge Converter Loop Gain and Phase Margin Current Mode

**Breadboard testing on a 200W Hall thruster**

During the initial checkout of the converter on several of our 200W developmental thrusters, the converter operated in both voltage and current control modes, up to the maximum output voltage (350V/35V), current (1.25A) and a maximum power of about 300W (limited by the thruster, not the converter). We also demonstrated by shorting the anode to cathode that the converter simply runs up against its preset maximum current limit and continues to operate. Since those initial tests, we have used the breadboard routinely for all types low power of thruster development testing without any problem and without a single failure in the breadboard.

In the most recent tests, we used the breadboard to power the BHT-200-X2B thruster and its hollow cathode BHC-1500 shown in Fig. 1. The schematic of the
Most data were collected on a PC based data acquisition system (DAS) and high frequency data were collected on a storage oscilloscope (LeCroy 9304). This 200 MHz scope is capable of storing the data on its own floppy disk (for post test transfer to the PC) and also performs data analysis such as fast Fourier transform on the stored data. The Fourier transform results are then displayed on the scope screen and/or transferred to the PC.

With the converter breadboard delivering 200W at 300 volts to the thruster (nominal operating conditions), the oscilloscope was used to record the discharge current and voltage, and perform fast Fourier analysis on both signals. The results are shown in Figs. 13a,b over a range from DC to 200 kHz. The voltage amplitudes are less than 2 Volts and therefore are a very small fraction of the 300 VDC applied voltage. Maximum amplitude occurs at 42 kHz which corresponds approximately to the predator/prey oscillations discussed in Table 2 (the calculated predator/prey frequency for the BHT-200 thruster is about 60 kHz). The 47.5 kHz peak may be part of the same oscillation. The cause of the 82.5 kHz and the 125 kHz peaks is unknown but could also be considered as some exponentially decaying harmonic of the 42 kHz base.

Fig. 12 Schematic of the Experimental Setup

Fig. 13 Fourier analysis of (a) discharge voltage at nominal operating conditions and (b) discharge current at nominal operating conditions

Fig. 14 Fourier Analysis of the discharge curves from DC to 60 MHz
The discharge current spectrum in Fig. 13b contains much more white noise with some current peaks close to the frequency of the voltage peaks in Fig. 13a. The 47.5 kHz voltage peak is not present in the current spectrum but its multiple (labeled 96 kHz in Fig. 13b) is present. This 96 kHz peak however, may also originate in the converter which switches at 50 kHz and therefore full bridge topology should result in 100 kHz switching transients. The most significant difference between the voltage and the current spectrum is that the current AC amplitude exceeds the DC value of 0.660 Amps and therefore $\Delta V_{dc}/V_{dc} \geq 1$ while $\Delta V/V_{dc} \approx 0$. This is not unlike the behavior observed by others using larger Hall thruster as shown in Fig. 5.

Above 200 kHz there are no peaks in the voltage spectrum but there are several interesting peaks in the discharge current spectrum at 1.09 MHz, 18.2 MHz and 20.1 MHz as shown in Fig. 14. The small peak at 1.09 MHz may indicate some ionization instability or azimuthal wave. The 18.2 and 20.1 MHz peaks have too high frequency for an azimuthal wave and much too low for plasma electron oscillations. Their origin is therefore unknown, offering an interesting challenge for the plasma physics researcher, which is not purely academic because the thruster lifetime may be dependant in part on the stability of the discharge. This can be understood by realizing that the amount of sputtered material is proportional to $I_{th} V_{dc} (V_{dc})$, where the $V_{dc}$ (typically 80 Volts) is the threshold sputtering limit. The greater the $V_{dc}$ (or $I_{th}$) amplitude the faster the thruster erosion. However, it is also possible, that these high frequency oscillations do not originate in the plasma, but are caused by ringing in the converter during switching transients. This appears unlikely, because we have performed similar Fourier analysis on signals obtained by powering a 450 $\Omega$ resistor (containing small parasitic inductance) with the converter at the same 300 Volts, 200 W output power and these signals did not contain the same peaks. Low amplitude peaks were present at approximately 11, 18 and 20 MHz. It must, however, be stressed that measurement of MHz level signals in a physically large circuit due to the size of the vacuum tank, (many meters of wire acting as an antenna), are difficult to perform accurately and repeatably and are prone to common mode problems.

Conclusion
A 400 Watt, DC-DC converter breadboard was developed to power a Hall thruster discharge. The converter was designed to operate from 28Vdc input (+15/-4 Volts) and deliver a maximum of 350 Volts or 1.25 Amps to the thruster discharge. Both the output voltage and the current are real time adjustable, via an externally provided analog signal, from zero to the respective maximums. Any number of converters can be paralleled to power a large Hall thruster, providing modularity and/or redundancy. These features make the converter operationally flexible and widely applicable.

During extensive testing, over about a two-year period, the converter breadboard performed as designed without any detectable flaw and met or exceeded all specifications. The breadboard is now used routinely for various developmental tests of low power Hall thrusters. The major results are:

1. Efficiency of 92% was demonstrated over a power range form 150 to 350 Watts. This includes housekeeping power, which was derived from the 28 Volts DC input.
2. The converter successfully powered several different nominally 200 W Hall thrusters from start up (as low as 10 Watts) to full power at up to 300 Watts.
3. Several start up modes were successfully tested with the thruster magnets in series with the discharge and powered separately.
4. The converter successfully operated in current control mode, and voltage control mode through intentionally induced short circuit (anode to cathode) conditions.
5. The converter tolerated significant discharge current oscillations with Fourier transform peaks at frequencies from about 40 kHz to 20 MHz and did not appear to excite or aggravate any plasma/discharge instabilities.

Acknowledgments
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References