Performance of a High-Fidelity 4 kW-Class Engineering Model PPU and Integration with the HiVHAc System

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  - HiVHAc System
  - Thruster
  - XFS
  - PPU

• CPE/HiVHAc EM PPU
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  - Ancillary Module
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  - Control GUI

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  - Test Setup
  - Test Conditions
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• HiVHAc System Integration
  - Discharge Start-Ups
  - Throttling

• Future Plans
• Conclusions
Background: HiVHAc System

- NASA GRC is leading the technology development activities for the High Voltage Hall Accelerator (HiVHAc) propulsion system

- Substantial cost and performance benefits for certain types of Discovery-class science missions compared to SOA ion and Hall thruster systems

- The HiVHAc system consists of three elements:
  - Thruster
  - XFS
  - PPU
Background: HiVHAc Thruster

- Latest version of the HiVHAc thruster is the engineering development unit (EDU-2) developed by GRC and Aerojet
  - 3.9 kW discharge power
  - 2,700 s specific impulse at discharge voltage of 650 V
  - 58% efficiency
  - In-situ self-regulating discharge channel replacement mechanism
Background: Xenon Feed System

- Xenon flow control module (XFCM) was developed by VACCO Industries
- Joint effort between NASA and the Air Force Research Laboratory (AFRL) as a lightweight propellant flow control alternative for electric propulsion
- Inlet pressure range = 10 to 3,000 psia
- Flow range = 0 to 160 sccm
- Mass = 1.25 kg
- Dimensions = 19.5 x 7.0 x 7.5 cm
- Power < 1 W
- Flight qualification completed in 2012
Background: CPE/HiVHAc PPU

- Developed by Colorado Power Electronics (CPE) in Fort Collins, Colorado, with funding from NASA’S Small Business Innovative Research (SBIR) Program
- Four design iterations have been completed
  - Breadboard discharge module
  - Brassboard #1 demonstrated power converters
  - Brassboard #2 refined the electrical and mechanical design and made it more flight-like
  - Engineering model improved manufacturability and included a digital control interface unit (DCIU), electronics for XFCM, and rad-hard MOSFETs on one of two discharge modules
- All units were integrated with HiVHAc thrusters at GRC
- Brassboard units were tested for thousands of hours in vacuum
- EM unit performance was thoroughly characterized in vacuum
# CPE/HiVHAc EM PPU

<table>
<thead>
<tr>
<th>EM PPU</th>
<th>Discharge</th>
<th>Magnets (2)</th>
<th>Keeper</th>
<th>Heater</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Output Voltage</strong></td>
<td>200 – 700 V</td>
<td>2 – 10 V</td>
<td>5 – 40 V</td>
<td>1 – 15 V</td>
</tr>
<tr>
<td><strong>Output Current</strong></td>
<td>1.4 – 15 A</td>
<td>1 – 5 A</td>
<td>1 – 4 A</td>
<td>3.5 – 10 A</td>
</tr>
<tr>
<td><strong>Output Power Max</strong></td>
<td>4 kW</td>
<td>50 W</td>
<td>80 W</td>
<td>150 W</td>
</tr>
<tr>
<td><strong>Regulation Mode</strong></td>
<td>Voltage or Current</td>
<td>Current</td>
<td>Current</td>
<td>Current</td>
</tr>
<tr>
<td><strong>Output Ripple</strong></td>
<td>≤ 5%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Line/Load Regulation</strong></td>
<td></td>
<td>≤ 2%</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Input Voltage</strong></td>
<td>80 – 160 V (main) and 24 – 34V (housekeeping)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Modular design
  - Two discharge modules
  - One ancillary module
  - One DCIU module
- High voltage bus (HVB) input
- Low voltage bus (LVB) input
- MIL-STD-1553

- Thruster Power
  - Discharge
  - Inner Magnet
  - Outer Magnet
  - Keeper
  - Heater

- XFCM
  - Power
  - Control
  - Telemetry

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### Diagram:

- **HVB**
- **Thruster Power**
- **Housekeeping Power**
- **Telemetry**
- **1553**
- **LVBM**
- **XFCM Drive**
- **Aux Power**
- **DCIU**
- **Keeper**
- **Heater**
- **In Magnet**
- **Out Magnet**
Discharge Modules

- 3-phase LLC resonant converter
  - Wide range of operation
  - Very low filter requirements
- Two discharge modules operate in parallel
- Either module can operate as master and limit the current of the other module
- Output voltage and current regulation loops
- Discharge modules can deliver full power (4 kW) and any output voltage from 250 to 700 V and any input voltage
Ancillary Module

- Power supplies beside discharge needed for thruster
  - Inner magnet supply
  - Outer magnet supply
  - Keeper supply with pulse ignitor
  - Heater supply
- Single-phase resonant converters
- Similar power converter design
- Inner and outer magnet supplies are same design

V_{\text{max}} = 784 \text{ V}

Keeper Voltage: 100\text{ V / div}

80 \mu s/d\text{iv}
DCIU Module

- **DCIU**
  - Implemented by a reprogrammable field programmable gate array (FPGA)
  - Receives commands and transmits telemetry to control computer through a MIL-STD-1553B interface
  - Processes telemetry from power supplies and XFCM
  - Automatically controls the system
    - Cathode conditioning
    - Cathode ignition
    - Discharge start-up
    - Steady-state (discharge current close-loop control)
    - Throttle
    - Shutdown
  - Control parameters are programmable
    - Thresholds
    - Limits
    - Ramp rates
    - Delays and durations
  - Monitors operation and safes system in case of fault
  - Includes manual-mode operation for diagnostics

- **Auxiliary power supply**
  - Uses power from a low voltage bus (LVB) input to generate auxiliary or housekeeping power for the power supplies, XFCM, and DCIU

- **XFCM drive**
  - Drivers for micro-latching and piezo-control valves
  - Power for temperature and pressure transducers
CPE/HiVHAc EM PPU

- Modular design
- Dimensions = 38.6 x 23.2 x 16.3 cm
- Mass = 15.6 kg
System Control GUI

GUI for Cathode Ignition Sequence in “Auto-Mode” Control

GUI for “Manual-Mode” Power Supply Control
Functional and performance tests were conducted in air and vacuum.
Vacuum performance tests were conducted at baseplate operational limits of -20 and 50°C.
Integration with thruster and XFCM.
EMI characterization was conducted per MIL-STD-461C (CE01 and CE03).
EM PPU Test Setup

- **VF-70**
  - Dedicated for PPU testing
  - 0.6-m diameter by 1-m long
  - $< 1 \times 10^{-6}$ while operating PPU
  - Located next to VF-12

- **VF-12**
  - 3-m diameter by 10-m long
  - Cryo-pumped
  - $1 \times 10^{-5}$ Torr while operating thruster
Operating Conditions

<table>
<thead>
<tr>
<th>Discharge Voltage</th>
<th>Discharge Current</th>
<th>Magnet Current</th>
<th>Keeper Current</th>
<th>Thruster Power</th>
<th>HVB Voltage</th>
<th>LVB Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 V</td>
<td>1.4 A</td>
<td>2.4 A</td>
<td>1.0 A</td>
<td>0.31 kW</td>
<td>80, 120, 160 V</td>
<td>24, 28, 34 V</td>
</tr>
<tr>
<td>300 V</td>
<td>1.7 A</td>
<td>2.9 A</td>
<td>1.0 A</td>
<td>0.55 kW</td>
<td>80, 120, 160 V</td>
<td>28 V</td>
</tr>
<tr>
<td>400 V</td>
<td>2.5 A</td>
<td>2.8 A</td>
<td>1.0 A</td>
<td>1.03 kW</td>
<td>80, 120, 160 V</td>
<td>28 V</td>
</tr>
<tr>
<td>500 V</td>
<td>3.0 A</td>
<td>3.7 A</td>
<td>1.0 A</td>
<td>1.55 kW</td>
<td>80, 120, 160 V</td>
<td>28 V</td>
</tr>
<tr>
<td>600 V</td>
<td>2.6 A</td>
<td>4.0 A</td>
<td>1.0 A</td>
<td>1.62 kW</td>
<td>80, 120, 160 V</td>
<td>28 V</td>
</tr>
<tr>
<td>650 V</td>
<td>2.3 A</td>
<td>4.0 A</td>
<td>1.0 A</td>
<td>1.55 kW</td>
<td>80, 120, 160 V</td>
<td>28 V</td>
</tr>
<tr>
<td>200 V</td>
<td>7.5 A</td>
<td>4.0 A</td>
<td>1.0 A</td>
<td>1.56 kW</td>
<td>80, 120, 160 V</td>
<td>28 V</td>
</tr>
<tr>
<td>300 V</td>
<td>6.9 A</td>
<td>3.5 A</td>
<td>1.0 A</td>
<td>2.12 kW</td>
<td>80, 120, 160 V</td>
<td>24, 28, 34 V</td>
</tr>
<tr>
<td>400 V</td>
<td>7.4 A</td>
<td>2.4 A</td>
<td>1.0 A</td>
<td>2.99 kW</td>
<td>80, 120, 160 V</td>
<td>28 V</td>
</tr>
<tr>
<td>500 V</td>
<td>7.7 A</td>
<td>3.5 A</td>
<td>1.0 A</td>
<td>3.90 kW</td>
<td>80, 120, 160 V</td>
<td>28 V</td>
</tr>
<tr>
<td>600 V</td>
<td>6.5 A</td>
<td>2.7 A</td>
<td>1.0 A</td>
<td>3.93 kW</td>
<td>80, 120, 160 V</td>
<td>28 V</td>
</tr>
<tr>
<td>650 V</td>
<td>5.9 A</td>
<td>2.7 A</td>
<td>1.0 A</td>
<td>3.89 kW</td>
<td>80, 120, 160 V</td>
<td>24, 28, 34 V</td>
</tr>
</tbody>
</table>

- Operating conditions of resistive load cover entire operating range of the HiVHAc thruster
- Power supplies were independently tested in some cases to cover the actual operating range of the power supply (i.e. 200 V / 15 A)
- PPU as operated at the baseplate operational limits of -20 to 50°C
## CPE/HiVHAc EM PPU Performance

<table>
<thead>
<tr>
<th>Specification</th>
<th>Test Results</th>
<th>Test Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telemetry Accuracy</td>
<td>≤ 2% of FS</td>
<td>Discharge ≤ 1.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Keeper ≤ 2.7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Magnet ≤ 1.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heater ≤ 2.0%</td>
</tr>
<tr>
<td>Set point Accuracy</td>
<td>≤ 2% of FS</td>
<td>Discharge &lt; 0.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Keeper ≤ 2.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Magnet ≤ 0.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heater ≤ 1.7%</td>
</tr>
<tr>
<td>Line Regulation</td>
<td>≤ 2%</td>
<td>Discharge ≤ 0.01%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Keeper ≤ 3.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Magnet ≤ 0.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heater ≤ 0.7%</td>
</tr>
<tr>
<td>Load Regulation</td>
<td>≤ 2%</td>
<td>Discharge ≤ 0.05%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Keeper ≤ 0.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Magnet ≤ 0.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heater ≤ 1.9%</td>
</tr>
<tr>
<td>Efficiency</td>
<td>≥ 95 % at FP</td>
<td>Discharge: 86–96%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Keeper: 47–80%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Magnet: 57–86%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heater: 57–87%</td>
</tr>
<tr>
<td>Output Ripple</td>
<td>≤ 5 %</td>
<td>Discharge ≤ 0.7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Keeper ≤ 3.3 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Magnet ≤ 0.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heater ≤ 1.0%</td>
</tr>
<tr>
<td>Transient Response</td>
<td>n/a</td>
<td>Discharge ≤ 8 ms</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Keeper ≤ 4 ms</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Magnet ≤ 10 ms</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heater ≤ 8 ms</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>-20 to 50℃</td>
<td>-20 to 50℃</td>
</tr>
</tbody>
</table>

- Electrical specifications were met with margin with exception of the keeper telemetry accuracy and regulation.
- Improvements for these circuits have been developed and will be implemented in the next design iteration.
CPE/HiVHAc EM PPU Efficiency

- Efficiency at full power was 95%
- Efficiency was > 90% from 1 to 4 kW
- Variation over entire input voltage range was approximately 0.5%
- Variation over entire temperature range was approximately 0.5%
System Integration Test

• Integrate the PPU with the XFCM
  - Demonstrate control of latching valves
  - Demonstrate control of the piezo-control valve
  - Demonstrate telemetry was received

• Integrate the PPU, XFCM and thruster
  - Demonstrate cathode ignition
  - Demonstrate discharge start-ups
    ✓ “Hard” mode
    ✓ “Glow” mode
  - Demonstrate close-loop on discharge current
    ✓ Steady-state
    ✓ Throttling
Discharge Start-Up

“Hard” Mode

- **T = 0s**
  - Cathode ignited and operating off keeper supply
  - Anode PCV OPEN command
- **0 < T ≤ 12s**
  - Anode flow ramps up
- **T = 12s**
  - Discharge and magnet supplies ON command
- **12s < T ≤ 22s**
  - Discharge current ramps up
  - ~20% overshoot
- **22s < T ≤ 60s**
  - Close-loop adjusts flow to take discharge current to setpoint

The overshoot discharge current shows the hysteretic behavior of the PCV
- Can be minimized by optimizing the PID controller parameters

Start up timing and magnitudes can be changed through sequence parameters
Discharge Start-Up

“Glow” Mode

- T = 0s
  - Cathode ignited and operating off keeper supply
  - Anode PCV OPEN command

- 0 < T ≤ 3s
  - Anode flow ramps up

- T = 3s
  - Discharge and magnet supplies ON command

- 3s < T ≤ 7s
  - Discharge current ramps up
  - Discharge supply operating in current-mode at current limit setpoint

- 7s < T ≤ 12s
  - Close-loop ramps down flow rate to take discharge current to setpoint
  - ~20% undershoot

- 12s < T ≤ 50s
  - Close-loop adjusts flow to take discharge current to setpoint

- The overshoot discharge current shows the hysteretic behavior of the PCV
  - Can be minimized by optimizing the PID controller parameters

- Start up timing and magnitudes can be changed through sequence parameters
Throttling

- $T = 0 \text{ min}$
  - Thruster operating at approximately 500 V / 2.0 A / 1.0 kW
- $0 < T \leq 50 \text{ min}$
  - Discharge current increased approximately 1 A increments to 3.5 kW
- $50 \text{ min} < T \leq 90 \text{ min}$
  - Small adjustments in current
- $T = 90 \text{ min}$
  - Discharge current reduced to ~ 6.5 A
  - Discharge voltage increased to 600 V
  - Thruster operating at full power of 3.9 kW
- $90 \text{ min} < T \leq 140 \text{ min}$
  - Thruster throttled down to 1.8 kW
- $T = 140 \text{ min}$
  - Thruster off

The overshoot and undershoots in discharge current at transitions can be minimized by optimizing the parameters of the PID controller.

Discharge oscillations were nominal during test.

PPU was also successfully integrated with a SPT-140 using the same test setup.

- Kamhawi, H., et al., “Integration Test of the 4 kW-Class HiVHAc PPU with the HiVHAc and the SPT-140 Hall Effect Thrusters,” AIAA-2016-4943.
Future Plans

- Prototype Demonstration Unit (PDU) PPU
- Next iteration of PPU based on EM PPU electrical and mechanical design
- Output specifications were changed to enable operation of other commercial thrusters
  - Discharge power
  - Magnet voltage and current
  - Heater voltage and current
- Input voltage range was changed to satisfy power requirements of commercial spacecraft busses and NASA missions
- Additional functionality:
  - Magnet reversal
  - Independent discharge module control
  - XFCM inlet heater power to enable high flow rate
  - Health status flags
  - Safety interlocks and lockouts
  - Telemetry
    - Input
    - Discharge ripple
  - Correct minor issues identified during EM PPU testing

<table>
<thead>
<tr>
<th>PDU PPU</th>
<th>Discharge</th>
<th>Magnets (2)</th>
<th>Keeper</th>
<th>Heater</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Voltage</td>
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<td>5 – 40 V</td>
<td>1 – 13 V</td>
</tr>
<tr>
<td>Output Current</td>
<td>1.4 – 15 A</td>
<td>1 – 7.5 A</td>
<td>1 – 2 A</td>
<td>3.5 – 21 A</td>
</tr>
<tr>
<td>Output Power Max</td>
<td>4.5 kW</td>
<td>108 W</td>
<td>80 W</td>
<td>210 W</td>
</tr>
<tr>
<td>Regulation Mode</td>
<td>Voltage or Current</td>
<td>Current</td>
<td>Current</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

- All parts will have flight equivalents or will have path to flight qualification
- Will be built using flight processes and procedures
- Analyses:
  - Stress
  - Thermal
  - Structural
  - Worst-case
  - Radiation assessment
Conclusions

- The CPE/HiVHAc EM PPU was successfully tested
- Most electrical requirements were met with margin
- Total efficiency as high as 95% at full power was measured
- Performance was measured at operating temperature extremes of -20 and 50°C
- Integrated with VACCO XFCM and HiVHAc thruster to demonstrate close-loop control on discharge current with anode flow
- Successfully demonstrated ignitions, start ups, and throttling
- A PDU PPU is under development will have additional functionality, will better capture NASA and commercial needs, and will get the design closer to flight-qualification.
Questions?