High Input Voltage, Silicon Carbide Power Processing Unit Performance Demonstration

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Introduction

- NASA’s Space Technology Mission Directorate (STMD) Game Changing Development (GCD) Program was focused on developing a high-power, high-voltage Solar Electric Propulsion (SEP) system to revolutionize future missions requiring moving cargo and humans beyond low earth orbit.

A 300-kilowatt spacecraft concept for human exploration of Mars
Introduction

• In support of the STMD GCD, NASA Glenn Research Center (GRC) and the Jet Propulsion Laboratory (JPL) were tasked with demonstrating a high-power electric propulsion string.
  – Hall Effect Thruster Technology Demonstration Unit
  – High Input Voltage Brassboard Power Processing Unit (PPU)

• This presentation focuses on the design, integration, and demonstration of the brassboard PPU.
  – The brassboard PPU leverages previous design work of a breadboard discharge supply with Silicon Carbide (SiC) power switching devices.
Introduction

• Today, STMD is still developing and demonstrating innovative in-space propulsion technologies.
• A proposed SEP Technology Demonstration Mission would use technologies developed under the GCD program to support the design and flight of a SEP spacecraft.
  – 50-kW class SEP spacecraft
  – Electric propulsion for primary in-space propulsion
Design Overview

PPU

Hall Effect Thruster
Design Overview
Design Specifications

<table>
<thead>
<tr>
<th></th>
<th>Maximum Output Power</th>
<th>Output Voltage Range</th>
<th>Output Current Range</th>
<th>Regulation Mode</th>
<th>Line/Load Regulation</th>
<th>Ripple</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge Supply</td>
<td>15 kW</td>
<td>300-400 VDC</td>
<td>37.5-50 ADC</td>
<td>Voltage</td>
<td>≤ 2%</td>
<td>≤ 5% peak-peak of regulated parameter</td>
</tr>
<tr>
<td>Inner Magnet and Outer Magnet Supplies</td>
<td>200 W</td>
<td>2-20 VDC</td>
<td>1-10 ADC</td>
<td>Current</td>
<td>≤ 2%</td>
<td>≤ 5% peak-peak of regulated parameter</td>
</tr>
<tr>
<td>Heater Supply</td>
<td>324 W</td>
<td>6-36 VDC</td>
<td>3-9 ADC</td>
<td>Current</td>
<td>≤ 2%</td>
<td>≤ 5% peak-peak of regulated parameter</td>
</tr>
<tr>
<td>Keeper Supply</td>
<td>90 W</td>
<td>10-30 VDC</td>
<td>1-3 ADC</td>
<td>Current</td>
<td>≤ 2%</td>
<td>≤ 5% peak-peak of regulated parameter</td>
</tr>
</tbody>
</table>
## Power Supply Design

<table>
<thead>
<tr>
<th>Description</th>
<th>Topology</th>
<th>Control</th>
<th>Switching Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Discharge Supply</strong></td>
<td>Two 7.5 kW power supply modules with the outputs connected in parallel externally</td>
<td>Full-bridge converter with paralleled SiC MOSFETS and a single bridge rectifier with SiC Schottky diodes</td>
<td>30 kHz</td>
</tr>
<tr>
<td><strong>Auxiliary Supplies</strong></td>
<td>Four separate power supplies; modular circuit board designs</td>
<td>Full-bridge converter with silicon MOSFETs</td>
<td>60 kHz</td>
</tr>
<tr>
<td>(Inner Electromagnet, Outer Electromagnet, Heater, and Keeper)</td>
<td></td>
<td>PWM based on peak and average current control and an outer voltage control loop</td>
<td></td>
</tr>
</tbody>
</table>
Control and Filter Design

• **Master Control Board**
  – Communication and control interface between the individual power supplies and the System Control Board (SCB)
  – Receives analog and digital commands from the SCB and analog and digital telemetry from the power modules and input filters
  – Generates PWM synchronization signals and the ignitor pulse command

• **System Control Board**
  – Provides a control interface between the PPU, the thruster propellant feed system, and the flight system
  – Currently under development at JPL

• **Input Filters**
  – Separate filters for each input power bus
  – Each filter consists of a differential low-pass stage and a common-mode inductor
Test Setup

Brassboard SiC Power Processing Unit

Discharge Module #2

Discharge Module #1

Outer Magnet Supply

Inner Magnet Supply

Heater Supply

Keeper Supply

Input Filter Module

Control Module

Cold Plate

High Voltage Power Supply

Low Voltage Power Supply

Control & Telemetry Filter

SCB Hardware Simulator

SCB PC Graphical User Interface

Chiller

Discharge Resistive Load Bank

Auxiliary Resistive Load Bank

KEY

- Low Voltage Power
- High Voltage Power
- Status and Command Telemetry
- Chiller Circulation Loop
- Digital Voltage Meter
- Current Shunt and Ammeter
Test Setup

• All of the instrumentation used for performance measurements during ambient testing was calibrated.

• Resistive load banks were used to simulate the thruster loads for both the ambient and vacuum testing.
Test Setup

- Thermal Laptop
- Brassboard PPU
- Cold Plate
- Chiller
Test Setup

- Thermocouple Wires
- Brassboard PPU
- Oscilloscope
- Calibrated Digital Multimeters
- Data Logger
- Aux. Load Bank
Test Setup

- Power Supplies
- Discharge Load Bank
- System Control Board Simulator
Test Setup

Data Collection

Flags

Telemetry

Enable Switch

Set Points
Test Setup

KEY
A: GRC Vacuum Facility 8 (VF-8)
B: HP-300V-PPU
C: Cooling Plate
D: Test Table
E: Tank Feedthroughs

• Vacuum tank pressure was controlled by a separate facility control system to ≤ 10^{-5} Torr
Performance Results

SiC PPU Overall Efficiency vs. Output Power: Nominal Input

Efficiency = \( \frac{\text{Discharge Output Power} + \sum \text{Auxiliary Output Power} + \text{Housekeeping Power}}{\text{Low Voltage Power Input} + \text{High Voltage Power Input}} \)
Performance Results

SiC PPU Overall Efficiency vs. Output Power: 300 Vout

Efficiency = \frac{(\text{Discharge Output Power} + \sum \text{Auxiliary Output Power} + \text{Housekeeping Power})}{(\text{Low Voltage Power Input} + \text{High Voltage Power Input})}
Performance Results

Efficiency = \frac{(\text{Discharge Output Power} + \sum \text{Auxiliary Output Power} + \text{Housekeeping Power})}{(\text{Low Voltage Power Input} + \text{High Voltage Power Input})}
Performance Results

SiC PPU Overall Efficiency vs. Output Power: 500 Vout

\[
\text{Efficiency} = \frac{\text{Discharge Output Power} + \sum \text{Auxiliary Output Power} + \text{Housekeeping Power}}{\text{Low Voltage Power Input} + \text{High Voltage Power Input}}
\]

Output Power, kilowatts

Efficiency, %

98.5%
98.0%
97.5%
97.0%
96.5%
96.0%
96.44%
96.71%
97.0%
97.5%
98.0%
98.5%

97.94%
97.86%
97.72%
97.67%

300 Vin to 500 Vout
330 Vin to 500 Vout
### Performance Results

<table>
<thead>
<tr>
<th>Test Conditions (full-scale value)</th>
<th>Line Regulation, %</th>
<th>Load Regulation, %</th>
<th>Ripple, %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Discharge Supply</strong>&lt;br&gt;Vout = 400 VDC&lt;br&gt;(400 VDC)</td>
<td>2.90%</td>
<td>0.74%</td>
<td>1.25%</td>
</tr>
<tr>
<td><strong>Inner Magnet Supply</strong>&lt;br&gt;Iout = 5 ADC&lt;br&gt;(10 ADC)</td>
<td>0.08%</td>
<td>0.08%</td>
<td>0.08%</td>
</tr>
<tr>
<td><strong>Outer Magnet Supply</strong>&lt;br&gt;Iout = 5 ADC&lt;br&gt;(10 ADC)</td>
<td>0.03%</td>
<td>0.02%</td>
<td>0.20%</td>
</tr>
<tr>
<td><strong>Heater Supply</strong>&lt;br&gt;Iout = 5 ADC&lt;br&gt;(9 ADC)</td>
<td>0.08%</td>
<td>0.04%</td>
<td>0.20%</td>
</tr>
<tr>
<td><strong>Keeper Supply</strong>&lt;br&gt;Iout = 2 ADC&lt;br&gt;(3 ADC)</td>
<td>0.01%</td>
<td>0.02%</td>
<td>0.80%</td>
</tr>
</tbody>
</table>

### EQUATION

| Line Regulation = \[
\frac{\Delta Regulated\ Output}{\Delta Input\ Voltage}\] | VARIATION
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>For discharge supply, high voltage input varied from 250 – 330 VDC</td>
<td>For auxiliary supplies, low voltage input varied from 23 - 36 VDC</td>
</tr>
</tbody>
</table>

| Load Regulation = \[
\frac{\Delta Regulated\ Output}{Nominal\ Regulated\ Output\ Value}\] | VARIATION
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>For each supply, load resistance was varied from 30% to 100% of the full load capability of the supply.</td>
<td></td>
</tr>
</tbody>
</table>
## Performance Results

### Brassboard SiC PPU Thermal Result Summary

**High Voltage Input:** 300 VDC  
**Low Voltage Input:** 28 VDC  
**Discharge Output Voltage Setting:** 400 VDC, **Discharge Output Power:** 15 kW

<table>
<thead>
<tr>
<th>Component Temperature</th>
<th>Ambient Steady State Temperature, C Baseplate at 25 C</th>
<th>Vacuum Steady State Temperature, C Baseplate at 25 C</th>
<th>Vacuum Steady State Temperature, C Baseplate at 50 C</th>
<th>Vacuum Steady State Temperature, C Baseplate at 5 C</th>
<th>ΔT (Vacuum-Ambient) Baseplate at 25 C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge Module 2, Inside Transformer Windings</td>
<td>54.6</td>
<td>67.3</td>
<td>97.2</td>
<td>61.4</td>
<td>12.7</td>
</tr>
<tr>
<td>High Voltage Bus Input Filter Differential Inductor</td>
<td>47.6</td>
<td>66.2</td>
<td>81.5</td>
<td>51.5</td>
<td>18.6</td>
</tr>
<tr>
<td>Housekeeping Power Supply, DC-DC Converter</td>
<td>38.8</td>
<td>53.8</td>
<td>73.2</td>
<td>36.5</td>
<td>15.1</td>
</tr>
<tr>
<td>Discharge Module 2 Transformer Case</td>
<td>45.9</td>
<td>52.5</td>
<td>74.8</td>
<td>35.2</td>
<td>6.6</td>
</tr>
<tr>
<td>Discharge Module 2 SiC MOSFET</td>
<td>33.3</td>
<td>35.3</td>
<td>58.8</td>
<td>16.3</td>
<td>2.0</td>
</tr>
<tr>
<td>Low Voltage Bus Total Input Current Sensor</td>
<td>33.1</td>
<td>45.6</td>
<td>64.8</td>
<td>27.7</td>
<td>12.4</td>
</tr>
<tr>
<td>Discharge Module 2 Gate Drive Board</td>
<td>35.9</td>
<td>42.2</td>
<td>64.3</td>
<td>24.3</td>
<td>6.4</td>
</tr>
<tr>
<td>Discharge Module 2 SiC Output Rectifier Diode</td>
<td>38.7</td>
<td>40.6</td>
<td>64.1</td>
<td>21.5</td>
<td>1.9</td>
</tr>
<tr>
<td>Discharge Module 2 Baseplate Temperature</td>
<td>25.6</td>
<td>26.7</td>
<td>50.1</td>
<td>6.9</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Performance Results

• Integrated Thruster Demonstration
Forward Work

- NASA’s Glenn Research Center with support from the Goddard Space Flight Center has investigated the ability of commercially available SiC devices to survive the space radiation environment.
  - *To date, none of the SiC components under test have passed all of the required space environment radiation tests.*
- On-going research seeks to better understand and analyze the failure modes of SiC power devices in order to develop space-qualified devices for future NASA missions.
Conclusion

• SiC components and high voltage design contributed to the superior performance demonstrated by the 15 kW brassboard SiC PPU under ambient and vacuum conditions.
  – Peak PPU overall efficiencies in excess of 97% at full-power in ambient test environment
  – All component temperatures within 30C of baseplate in ambient test environment
  – Vacuum performance results consistent with ambient performance results
  – Integrated test demonstrated compatibility with a technology demonstration unit Hall Effect Thruster

• Future work is necessary to demonstrate that SiC power devices can withstand the space radiation environment.
Acknowledgements

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• **Engineers, Designers, and Technicians** at NASA Glenn Research Center who contributed to the success of these development efforts.