High Input Voltage, Silicon Carbide Power Processing Unit Performance Demonstration

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Outline

• Introduction
• Design Overview
• Design Specifications
• Test Setup
• Performance Results
• Forward Work
• Conclusion
• Acknowledgements
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><strong>Discharge Supply</strong></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><strong>Inner Magnet and Outer Magnet Supplies</strong></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><strong>Heater Supply</strong></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><strong>Keeper Supply</strong></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><em>(Inner Electromagnet, Outer Electromagnet, Heater, and Keeper)</em></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
Discharge Module #2
+
-
Discharge Module #1
+
-
Discharge Resistive Load Bank
+
-
Outer Magnet Supply
+
-
Inner Magnet Supply
+
-
Heater Supply
+
-
Keeper Supply
+
-
Discharge Resistive Load Bank
+
-
Outer Magnet
+
-
Inner Magnet
+
-
Heater
+
-
Keeper
+
-
High Voltage Power Supply
+
-
Low Voltage Power Supply
+
-
Control Module
+
-
Input Filter Module
+
-
Control & Telemetry Filter
+
-
SCB Hardware Simulator
+
-
SCB PC Graphical User Interface
+
-
Cold Plate
+
-
Chiller
+
-
Auxiliary Resistive Load Bank
+
-
Brassboard SiC Power Processing Unit
+
-
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
- Calibrated Digital Multimeters
- Brassboard PPU
- Oscilloscope
- 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, %

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, %

- 250 Vin to 300 Vout
- 270 Vin to 300 Vout
- 300 Vin to 300 Vout
- 330 Vin to 300 Vout

Output Power, kilowatts

**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: 400 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

SiC PPU Overall Efficiency vs. Output Power: 500 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

<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> Vout = 400 VDC (400 VDC)</td>
<td>2.90%</td>
<td>0.74%</td>
<td>1.25%</td>
</tr>
<tr>
<td><strong>Inner Magnet Supply</strong> Iout = 5 ADC (10 ADC)</td>
<td>0.08%</td>
<td>0.08%</td>
<td>0.08%</td>
</tr>
<tr>
<td><strong>Outer Magnet Supply</strong> Iout = 5 ADC (10 ADC)</td>
<td>0.03%</td>
<td>0.02%</td>
<td>0.20%</td>
</tr>
<tr>
<td><strong>Heater Supply</strong> Iout = 5 ADC (9 ADC)</td>
<td>0.08%</td>
<td>0.04%</td>
<td>0.20%</td>
</tr>
<tr>
<td><strong>Keeper Supply</strong> Iout = 2 ADC (3 ADC)</td>
<td>0.01%</td>
<td>0.02%</td>
<td>0.80%</td>
</tr>
</tbody>
</table>

**EQUATION**

\[
\text{Line Regulation} = \frac{\Delta \text{Regulated Output}}{\Delta \text{Input Voltage}}
\]

**VARIATION**

For discharge supply, high voltage input varied from 250 – 330 VDC

For auxiliary supplies, low voltage input varied from 23 - 36 VDC

\[
\text{Load Regulation} = \frac{\Delta \text{Regulated Output}}{\text{Nominal Regulated Output Value}}
\]

For each supply, load resistance was varied from 30% to 100% of the full load capability of the supply.
# Performance Results

## Brassboard SiC PPU Thermal Result Summary

<table>
<thead>
<tr>
<th>Component Temperature</th>
<th>Ambient Steady State Temperature, °C</th>
<th>Vacuum Steady State Temperature, °C</th>
<th>Vacuum Steady State Temperature, °C</th>
<th>Vacuum Steady State Temperature, °C</th>
<th>ΔT (Vacuum-Ambient)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseplate at 25°C</td>
<td>Baseplate at 25°C</td>
<td>Baseplate at 50°C</td>
<td>Baseplate at 5°C</td>
<td></td>
</tr>
<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 30°C 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

• **Co-Authors**: Luis Pinero, Robert Scheidegger, Michael Aulisio, Marcelo Gonzalez, and Arthur Birchenough

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