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

- Outer Magnet
- Inner Magnet
- Discharge
- Keeper
- Heater
- Electromagnet
- Anode
- Cathode
Design Overview

- Discharge Module #1
- Discharge Module #2
- Auxiliary Supplies
- Input Filter Module
- Control Module
# Design Specifications

<table>
<thead>
<tr>
<th>Supply Type</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>PWM based on peak and average current control and an outer voltage control loop</td>
<td>60 kHz</td>
</tr>
<tr>
<td><strong>(Inner Electromagnet, Outer Electromagnet, Heater, and Keeper)</strong></td>
<td>Full-bridge converter with silicon MOSFETs</td>
<td>PWM based on peak and average current control</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
- V

Discharge Module #1
- V

Outer Magnet Supply
- V

Inner Magnet Supply
- V

Heater Supply
- V

Keeper Supply
- V

Input Filter Module
- V

Control Module
- V

High Voltage Power Supply
- V

Low Voltage Power Supply
- V

Control & Telemetry Filter

SCB Hardware Simulator

SCB PC Graphical User Interface

Cold Plate

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

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

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

Data Collection

Enable Switch

Telemetry

Flags

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, %

98.5%
98.0%
97.5%
97.0%
96.5%
96.0%

Output Power, kilowatts

3 4 5 6 7 8 9 10 11 12 13 14 15 16

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

SiC PPU Overall Efficiency vs. Output Power: 400 Vout

Efficiency = \frac{(Discharge Output Power + \sum Auxiliary Output Power + Housekeeping Power)}{(Low Voltage Power Input + 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></th>
<th>Test Conditions (full-scale value)</th>
<th>Line Regulation, %</th>
<th>Load Regulation, %</th>
<th>Ripple, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge Supply</td>
<td>Vout = 400 VDC (400 VDC)</td>
<td>2.90%</td>
<td>0.74%</td>
<td>1.25%</td>
</tr>
<tr>
<td>Inner Magnet Supply</td>
<td>Iout = 5 ADC (10 ADC)</td>
<td>0.08%</td>
<td>0.08%</td>
<td>0.08%</td>
</tr>
<tr>
<td>Outer Magnet Supply</td>
<td>Iout = 5 ADC (10 ADC)</td>
<td>0.03%</td>
<td>0.02%</td>
<td>0.20%</td>
</tr>
<tr>
<td>Heater Supply</td>
<td>Iout = 5 ADC (9 ADC)</td>
<td>0.08%</td>
<td>0.04%</td>
<td>0.20%</td>
</tr>
<tr>
<td>Keeper Supply</td>
<td>Iout = 2 ADC (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

For discharge supply, high voltage input varied from 250 – 330 VDC.
For auxiliary supplies, low voltage input varied from 23 - 36 VDC.

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

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

**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 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

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