Design Considerations for High Power Spacecraft Electrical Systems

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Outline

• Space Power Challenge
• Background
• Trends is Space Power Requirements
• Future Space Systems
• Challenges and Driving Requirements
• Modular Power Systems
• Advanced Power Technologies
• Conclusions
• Credits
Space Power Grand Challenge

• Needs: Abundant, Reliable and Affordable Power
  – NASA’s future missions of science and human exploration require abundant, reliable and affordable energy generation, storage and distribution.
  – Power needs grow exponentially as we look at extending human presence beyond near earth.

• Problem: Today’s space power systems limit our ability to conduct human exploration beyond LEO.
  – Current spacecraft power systems key driving requirements become even more critical as we look at meeting growing power needs.
Background: Elements of a Power System

Power Generation:
- Solar Arrays
- Brayton Rotating Unit
- Stirling Radioisotope
- Fuel Cells

PMAD:
- Source Regulator
- Power Distribution
- Charge/Discharge Regulator
- Power System Control

Loads:
- Electric Propulsion
- Communications
- Instruments
- Actuators

Energy Storage:
- Batteries
- Flywheel
Background: Types of Space Power Systems

Technology used for a power system depends on power level and mission duration.
Traditional Space Power Systems

- Power Level $\leq 15$ kW
- PMAD Distribution Voltage $\leq 120$ V
- Custom systems created from one-of-a-kind components.
- Limited or no growth potential.
- Require extensive infrastructure for verification and operation.
- Limited or no autonomous operation.
International Space Station EPS

- **Power Source**
  - Largest ever space solar array
  - 8 solar array wings on space station (2 per PV module)
  - Nominal electrical power output ~ 30 kW per PV wing
    BOL for ~ 240 kW total power

- **Energy Storage**
  - 24 NiH2 Batteries NiH2
  - Nominal storage capacity is ~4 kW-hr

- **Power Distribution**
  - Power Level 75 kW
  - 8 power channels
  - Distribution Voltage
    - 116-170 V primary
    - 120 V secondary
Trends in Space Power Systems

- Power Requirements
- Autonomous Operation
- Reliability
- DDT&E Cost
- Operations and Logistics Cost

Mercury
Gemini
Apollo
STS – Space Shuttle
International Space Station
Manned Exploration Beyond LEO

1960 1980 2000 2020
Potential Future Missions & Applications

SEP Propulsion Stage

Deep Space Habitats

Space Outposts

Multi-mission Space Exploration Vehicle

Advanced Cryo Propulsion Stage
Challenges for Space Power Systems

- **Environment**
  - Radiation
  - Thermal
- **Cost**
- **Wide Range of Spacecraft Configurations**
  - Unique Requirements promotes “one of a kind” design.
- **Long Term Operation with minimal human intervention**
  - Health Monitoring
  - Power Management

- **Space Power System Design Drivers:**
  - Efficiency/Power density
  - Safety/Reliability
  - Radiation Hardness
  - Thermal requirements
  - Autonomous operation
  - Mass/Volume
  - DDT&E cost
  - Operations cost
Given these challenges

What should be our focus…
Modular Power System Concept

- Develop a set of modular power components that can be mixed and matched to meet “unique” requirements for different applications
  - Reduces DDT&E cost through design reuse
  - Reduces logistics cost across missions through reduction of vehicle unique components.

- “Monolithic” EPS functional units are replaced by collections of common “smart modules”.

- The power system can be “modularized” at various levels.
  - Module Level
    - Uses common devices with master-less intelligent controllers to create “smart modules” to build EPS functional units (converters, switchgear, batteries, etc.).
  - System Level
    - Integrate “smart modules” into sub-systems (power generation, storage, and distribution).
Modular PMAD - Hardware

Description

- Reusable building block(s) that can be configured in series and parallel arrangements for power management and distribution.

Key Issues to Address

- Mechanical packaging and interconnects.
- Low mass – complexity – parasitic.
- Control/configuration for multi-function, series, and/or parallel operation.

Key Benefits

- Reduced DDT&E and logistics costs.
- Enables high voltage/high power conversion and conditioning.
Modular PMAD - Controls
Intelligent Control Systems

Description
• Replaces a traditional, hierarchical control system with peer-to-peer cooperating elements with each power module for enhanced operational effectiveness.

Key Issues to Address
• Embedded controls in power elements.
• Collaborative agents in components for active power quality and stability control.
• Sensor web and distributed networks for health monitoring.
• Fault isolation and reconfiguration at the lowest levels.
• Reliable inter-module communication

Benefits
• Enhanced safety and reliability.
• Facilitates “plug & play” growth and system enhancement.
• Reduces cost of system verification and logistics.
PMAD - Power Distribution
High Voltage

Description
• AC or DC high voltage, > 300V, delivery of large power, >100kW, from source to load

Key Issues to Address
• Insulation stress.
• High current/power connectors.
• Corona management in certain environments.
• High current switching and fault control.
• Radiation tolerance.

Key Benefits
• High voltage distribution reduces cable mass and ohmic losses.
• Minimizes power conversion which maximizes efficiency.

100ft Cable mass versus Source Voltage

100ft Cable Losses
operating in vacuum @ 77°F
PMAD - Advanced Components

Description
• Components that can withstand the harsh environments, wide temperature variations, and high radiation of deep space.

Key Issues to Address
• Development of Silicon Carbide and Gallium Nitrate semiconductors.
• High current/high energy density capacitors.
• Low loss magnetic materials that can withstand high temperatures.

Key Benefits
• Facilitates high voltage switching.
• Increased radiation tolerance.
• Ruggedness improves safety and reliability.
• Lower mass/higher energy density.
• Increased operating temperature range.

SiC Semiconductors

Advanced Capacitors
Power Generation: High Efficiency & Low Mass Photo-voltaic

State of Practice

- Current Systems: Crystalline Si Cells
  Triple Junction GaAs Solar Cells;
- Efficiency: Si Cells: 15%; MJ Cells: 31%
- Specific power: 50 to 100 W/kg
- Array stowage volume: 5 to 15 kW/m³

Advanced Solar Arrays

- 4-5 Junction Solar Cells; Quantum Dot Solar Cells; Thin-Film Solar Cells
- Efficiency > 50%
- Specific Power > 500 W/kg
- Array stowage volume > 100 kW/m³
Power Generation: Low Mass Solar Arrays

State of Practice
- Semi-rigid Deployment Mechanism
- Alpha and Beta Joints With Slip Rings or Roll Rings
- Truss Structure To Add Additional Solar Array Blankets
- Centralized Momentum Control

Advanced Solar Arrays
- Rigid Light Weight Deployment and Restowage Mechanism
- Lower Mass Pointing Mechanism Allowing Power and Thermal Transfer
- Integrated/Controlled Truss Structure With Distributed Momentum Control
Energy Storage: Batteries

State of the Art
- Ni-H2: 30 Wh/kg at the cell level, life > 10 years – ISS Application
- Li-Ion: 100 Wh/kg at the cell level, life > 5 years

Advanced Batteries
- Li-ion: 160 - 200 Wh/kg at the cell level for > 2000 cycles -- Rover / Lander application
- Li-ion: 270 Wh/Kg at the cell level for > 100 cycles – EVA applications
# Energy Storage
## Li-Ion vs. NiH2 Batteries

### Cell Characteristics

<table>
<thead>
<tr>
<th></th>
<th>ISS NiH2</th>
<th>140Ah Li ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated capacity</td>
<td>81 AH</td>
<td>134-144 A</td>
</tr>
<tr>
<td>Energy density</td>
<td>~65 wh/kg</td>
<td>~150 wh/kg</td>
</tr>
<tr>
<td>Discharge voltage</td>
<td>1.25 V</td>
<td>&gt; 3.6 V</td>
</tr>
<tr>
<td>Self discharge rate</td>
<td>~7% per day (20°C)</td>
<td>&lt; 0.05% per day</td>
</tr>
<tr>
<td>Cycle life in LEO (20%-30%DOD)*</td>
<td>~ 10 years (60,000-75,000 cycles) @ 20%-30% DOD</td>
<td>~ 10 years (58,000 cycles) @ 20%-25% DOD</td>
</tr>
<tr>
<td>Spec Cycle life</td>
<td>6.5 years @ 35%</td>
<td>10 years @ ISS power levels</td>
</tr>
<tr>
<td>Storage life</td>
<td>4 years</td>
<td>6 years</td>
</tr>
<tr>
<td>Overcharge</td>
<td>Tolerant</td>
<td>Controlled by 2 FT design</td>
</tr>
<tr>
<td>Total Energy Storage (Important for contingency operations)</td>
<td>8 kW-hr (Two ORUs combined)</td>
<td>15 kW-hr (One ORU)</td>
</tr>
<tr>
<td>Battery Weight</td>
<td>744 lbs (Two ORUs)</td>
<td>415 lbs (One ORU)</td>
</tr>
</tbody>
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Replacement of two NiH2 ORUs with one Li-ion ORU
Half the logistics flights
Fewer EVAs to replace batteries
Conclusions

• As human space exploration power needs increase, high power / high voltage systems will be required for future missions

• Power system technology development is critical for the future of human space exploration

• Spectrum of technology development will be needed to meet the increasing power needs of future manned missions
Credits

- Robert Scheidegger – NASA GRC
- James Soeder – NASA GRC
- Raymond Beach – NASA GRC
- Walter Santiago – NASA GRC
- Tom Kerslake – NASA GRC
- Penni Dalton – NASA GRC
- Jameka Humphrey – NASA GRC (SGT inc.)
- Azam Arastu – Boeing Space & Intelligence Systems