ABSTRACT

Space Solar Power is a NASA program sponsored by Marshall Space Flight Center. The Paper presented here represents the architectural study of a large power management and distribution (PMAD) system. The PMAD supplies power to a microwave array for power beaming to an earth rectenna (Rectifier Antenna). The power is in the GW level.

INTRODUCTION

The Space Solar Power PMAD (Power Management & Distribution) is designed to process power from a solar array to the microwave planar antenna. This paper will describe an architecture for the PMAD. The power beaming and rectenna are beyond the scope of this paper.

The following Figure 1 shows one of the system concepts as a tower of solar arrays feeding a microwave planar array. Other array structures have been proposed but not analyzed to this extent.

The power level for this study is 3GW. It is generated by 340 solar arrays, approximately 10MW each.

System Description

The PMAD system is comprised of power processing electronics starting at the solar array farm and ending with the microwave antenna as shown in the following Figure 2. The solar array produces DC at a level of approximately 5000V. A resonant bridge converter generated a 10KHz sinusoid, three phase at 100KV for the 15 km down link cable. At the bottom of the cable, the three phase AC is transformer reduced in two steps to feed 80 VDC to the microwave antenna.

Trade Studies

The PMAD was designed to achieve minimum mass from the Solar array to the MMIC antenna array. Cable weight depends upon current and to lower the weight we are driven to high voltages.
The cable weight drove the selection of cable voltage. Weight is inverse with voltage. The design utilizes 100KV, three phase AC. This approach simplifies the upper and lower PMAD interface. A transformer can be used to transform the voltage without using solid state power conversion. An approach was show using conventional DC to DC infrastructure equipment. This has a very heavy weight penalty. Other approaches using Super Conductor cable is under study.

At the lower end of the tower, the transformer we encountered a second cable distribution weight problem. The Lower Transformer was elevated by 100 meters above the Antenna Array to avoid obstructing the antenna thermal radiation field of view by the size/temperature of the transformer module [See Figure 3]. With 3GW of power transmission, the transformer was estimated to be 300 degree C because of 5MW of internal dissipation.

With 1KVDC distribution, the cables were too massive, almost equal to the Antenna Converter weight total. This drove a choice of 10KVAC for the distribution cables. The lower transformer had included a 12 pulse rectifier. This was now placed in the Antenna Converter. The Antenna Converter grows slightly (16%) versus a Distribution cable gain of 90%.

The Antenna Converter sizing is based on the power required by the smallest replaceable segment. We used some design rules to establish the sizes and weights. This is shown in table 1.

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>500 w per lb</td>
</tr>
<tr>
<td>Volume</td>
<td>50 w per in³</td>
</tr>
</tbody>
</table>

Table 1  Power Supply
Design Factors

The assumption of 95% efficiency is possible with steady state operation with SSP. It is also necessary to reduce the thermal rise within the electronics. The density and volume factors preclude use of active cooling hardware. The module must be designed to radiate upward away from the antenna array.

The Antenna Converter contains a transformer to reduce the 10KV 3 phase AC to 500VDC with a 12 pulse rectifier. The second stage is a current fed DC-DC converter down to the 80VDC antenna grid. The converter was sized with state-of-the-art
factors listed in Table 1 and the results

<table>
<thead>
<tr>
<th>Transformer 3ph</th>
<th>4488W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>2 kg</td>
</tr>
<tr>
<td>Volume</td>
<td>8,503 cm³</td>
</tr>
<tr>
<td>Length</td>
<td>20.4 cm</td>
</tr>
<tr>
<td>Dissipation</td>
<td>105 Watts</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module Power</th>
<th>4488 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>4.1 kg</td>
</tr>
<tr>
<td>Volume</td>
<td>1,471 in³</td>
</tr>
<tr>
<td>Length</td>
<td>28.9 cm</td>
</tr>
<tr>
<td>Dissipation</td>
<td>224 Watts</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>6 kg</td>
</tr>
<tr>
<td>Volume</td>
<td>9,974 cm³</td>
</tr>
<tr>
<td>Length</td>
<td>21.5 cm</td>
</tr>
<tr>
<td>Dissipation</td>
<td>329 Watts</td>
</tr>
</tbody>
</table>

Table 2

Antenna Converter Sizing

appear in Table 2 below.
The antenna Converter must be closely attached to the 64 element module to minimize the loss and voltage drops in the 80 volt MMIC input power bus. With the estimated power needs of the 64 element panel, we calculate a volume of 9,974 cm³ or a cube 21.5 cm on a side. We also calculate a thermal loss of 329 watts. This thermal loss must be radiated outward, preferably away from the antenna. This is a difficult packaging problem. The first approach was to position the power converter on the 64 element array panel.

We see in Figure 4, the converter covers most of the array sub panel. This blocks the thermal radiation from the MMICs.

An idea is to reduce the aspect ratio of the converter. For example, the converter could be squeezed into half of the thickness with twice the length or 10.5 by 42 cm. This covers 29% of the radiating surface of the antenna segment. This is clearly a difficult design challenge for the high interface voltage.

Results and Conclusions

Three primary challenges exist for SSP PMAD:
- Mass Less than 1kg/kw
- Voltage Greater than 1KV
- Temperature 300 degree C

These challenges interact. We are driven to small boxes to keep within the mass allocation. This causes the temperature to rise because no active cooling – the mass allocation includes everything the PMAD requires.

An estimation of the overall PMAD mass is tabulated below in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>kg</th>
<th>kg/kw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array Converters</td>
<td>3,362,061</td>
<td>1.06</td>
</tr>
<tr>
<td>Upper Transformer</td>
<td>88,712</td>
<td>0.03</td>
</tr>
<tr>
<td>3 phase cable</td>
<td>1,463,049</td>
<td>0.46</td>
</tr>
<tr>
<td>Lower Transformer</td>
<td>88,712</td>
<td>0.03</td>
</tr>
<tr>
<td>Distribution Cables</td>
<td>390,296</td>
<td>0.12</td>
</tr>
<tr>
<td>Antenna Converters</td>
<td>2,890,909</td>
<td>0.91</td>
</tr>
<tr>
<td>Total</td>
<td>8,283,740</td>
<td>2.61</td>
</tr>
</tbody>
</table>

Table 3 PMAD Mass

The overall factor of 2.61 in the table 3, above, exceeds the allocation of 1kg/kw.
Clearly we have a challenge to reduce mass. A beginning challenge is to build a 300 degree C power converter with less than 1kg/kw density. The Array Converters and the Antenna Converters are the largest components of the mass distribution.

PMAD for SSP is a difficult challenge but no less than the other issues for SSP. We have 20 years to full deployment to work through the myriad of issues and design challenges.

Acknowledgements

This worked was done under funding of Space Solar SERT contract from MSFC through Boeing, Huntington Beach. I wish to thank Mark Henley, Seth Potter and James McSpadden (Boeing Seattle) for the many hours of technical discussions.

List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>PMAD</td>
<td>Power Management And Distribution</td>
</tr>
<tr>
<td>SSP</td>
<td>Space Solar Power</td>
</tr>
<tr>
<td>MMIC</td>
<td>Monolythic Microwave Integrated Circuit</td>
</tr>
<tr>
<td>GW</td>
<td>Gigawatt, $10^9$ watts</td>
</tr>
</tbody>
</table>
• Architecture & Concepts
• Backside Thermal View
• Solar Array Interface
• Transformer design & risks
• Twelve pulse rectifier
• Antenna(80V) Converters
• Distribution Cables
• Weight analysis
• Summary & Conclusions
- Transmitter always faces Earth
- Trollis framework fixed to transmitter
- Individual panels rotate to face Sun

Complete Shadowing at Noon

Partial shadowing between 10:00 am and 2:00 pm and between 10:00 pm and 2:00 am

No shadowing at other positions

500 meter Transmitter

20 km

3 km

Trollis

Small Bearings and Slip Rings

Solar Panel

When flat, space between Solar Panels is equal to Width of Panel

Sun

3/20/00

SSP PMAD - Thomas Lynch / Boeing
Integrated Symmetrical Concentrator

1.2 gW Delivered

Abacus Concept

Prismatic abacus frame supports lightweight solar concentrators

Arrays of lightweight Fresnel concentrators

Primary Mirrors (36 per Clamshell)

Solar Array

Transmitter Array

Docking Ports

Transmitter Radiator

Nadir provides Earth tracking

Azimuth roll-ring

Radiators mounted on back of transmitter

3/20/00

SSP PMAD - Thomas Lynch / Boeing
Backside thermal view

- Remote locate PMAD
- Design for cold underside PMAD surface
- Effect of cable heating?

PMAD Tower

Temperature ~200°C

Tower Support Structure

Lower PMAD Assembly

100KV 3 phase Cable
Hot Thermal Surface ~ 5MW

"Cold" Surface ~16 meters

Power Cable One of "N" cables <5°

Desired Radiation View obstruction

80V Converter

Antenna - front side

3/20/00

SSP PMAD - Thomas Lynch / Boeing
Solar Array

Peak Power Tracker
10.9MW

1000VDC

3 phase Inverter
10.4MW

1000VAC

100KVAC

Startup Vsense and phase adjustment for maximum power transfer
Transformer analysis

RF at Antenna 2.86E+09 watts
Antenna efficiency 90.0%
DC to Antenna 3.18E+09 watts

\[ N_p = \frac{E \times 10^8}{4.44 \, f \, B_m \, A_e} \]

<table>
<thead>
<tr>
<th>Stage1</th>
<th>Conversion to 10KV</th>
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<tbody>
<tr>
<td>Primary Voltage</td>
<td>100000 Vrms</td>
</tr>
<tr>
<td>Primary Current</td>
<td>93.5 Arms</td>
</tr>
<tr>
<td>Secondary Voltage</td>
<td>10000 Vrms</td>
</tr>
<tr>
<td>Secondary Current</td>
<td>934.6 Arms</td>
</tr>
<tr>
<td>Frequency</td>
<td>10000 Hz</td>
</tr>
<tr>
<td>Bmax</td>
<td>5000 gauss</td>
</tr>
<tr>
<td>Area of core</td>
<td>50 cm²</td>
</tr>
<tr>
<td>Stacking Factor</td>
<td>80% (1 mil tape)</td>
</tr>
<tr>
<td>Effective core area</td>
<td>63 cm²</td>
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<tr>
<td>Core dimension</td>
<td>7.9 (sq core)</td>
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<tr>
<td>Core Length</td>
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<tr>
<td>Core volume</td>
<td>27835 cm³</td>
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<tr>
<td>Steel weight</td>
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<tr>
<td>Core weight</td>
<td>359 lbs</td>
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<table>
<thead>
<tr>
<th>Primary</th>
<th>Secondary</th>
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<tbody>
<tr>
<td>Turns</td>
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<td>Wire Size</td>
<td>4</td>
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<tr>
<td>Wire Area</td>
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<tr>
<td>Insulation fill factor</td>
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<tr>
<td>Winding Area</td>
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<tr>
<td>Window Fill Factor</td>
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<tr>
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<td>wire volume</td>
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<tr>
<td>Wire Weight</td>
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<tr>
<td>Transformer Weight</td>
<td>542</td>
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<tr>
<td>Transformer Volume</td>
<td>788,316</td>
</tr>
<tr>
<td>Core Loss, W</td>
<td>35,900</td>
</tr>
</tbody>
</table>
• Leakage inductance of $\sqrt{10} : 1$ ratios (x2)
• Corona, interwinding & distribution
• Dielectric voltage stress
• Core dissipation
• Interface to 100KV lines
• Potting or Oil filled
• Operation at 200°C
Advantages

- Simplicity
- Rugged & robust
- Excellent power factor

10KVAC

From Lower Stage Transformer

Phase 1
Phase 2
Phase 3

500VDC

12 phase summation

Antenna Converter

To MMC Array

3/20/00

SSP PMAD - Thomas Lynch / Boeing

80V

10
• Architecture
  80 VDC output
  10KVAC input to 12 Pulse Rectifier
  500VDC into 80V converter
  4488 watt module for 64 MMICs
  Current limit to 80V grid
  Redundancy with "N+1" converters per module
  Weinberg topology
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<td>Length</td>
<td>28.9 cm</td>
</tr>
<tr>
<td>Weight</td>
<td>9.0 lbs</td>
</tr>
<tr>
<td></td>
<td>4.08 kg</td>
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<td>Dissipation</td>
<td>224.4 Watts</td>
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Assumptions:
- 10KV 3 phase AC input
- 80VDC output at 4488W

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State-of-the-Art

PMAD Modules
Temp. °C
6 Guage Round Wire in Vacuum
0 °K background

ISS Rating:
150A/cm²

Temperature, °C
-200 -100 0 100 200 300 400 500
Current, Amperes
0 10 20 30 40

3/20/00
SSP PMAD - Thomas Lynch / Boeing
Could double ISS Current Rating with Flat Wire

6 Guage Flat Wire in Vacuum with 0°C Sky

64A = 300A/cm²
Assuming use 300A/cm² current density with flat wire
935 Amperes at 10KVDC per cable

<table>
<thead>
<tr>
<th>Antenna Distribution Cables</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Qty</strong></td>
</tr>
<tr>
<td>Hot</td>
</tr>
<tr>
<td>Return</td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>

- Trade must be done to evaluate use of smaller cables
- Radiation occlusion from dark sky from other structures
- Adjacent cables cloud view of dark sky
- Careful attention to termination of small cables
At 3.18 GW to 500 meter Antenna

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<td>2.61</td>
</tr>
<tr>
<td><strong>Issue</strong></td>
<td><strong>Straw man</strong></td>
<td><strong>Risks</strong></td>
</tr>
<tr>
<td>----------------------------</td>
<td>--------------------------------------</td>
<td>---------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Cable Voltage</td>
<td>100KV</td>
<td>Corona, plasma, cable weight</td>
</tr>
<tr>
<td>Power cable Topology</td>
<td>Single Cable, 3PH 10KHz AC drive</td>
<td>Weight, Spaghetti distribution, Feed access, coupling &amp; drive</td>
</tr>
<tr>
<td>Array Voltage</td>
<td>1KV and higher</td>
<td>Corona, rotary joints</td>
</tr>
<tr>
<td>Grounding, plasma, corona</td>
<td>Exterior surfaces of PMAD to be at structure ground</td>
<td>Insulator interface degradation &amp; failure due to voltage gradients</td>
</tr>
<tr>
<td>Command &amp; Control</td>
<td>Autonomous status &amp; control from each node</td>
<td>Failure analysis, distribution imbalance</td>
</tr>
<tr>
<td>MTBF &amp; MTTR</td>
<td>Careful topology design trades and mechanical interface design</td>
<td>Connector interfaces prevent disassembly</td>
</tr>
</tbody>
</table>

3/20/00
SSP PMAD - Thomas Lynch / Boeing
Temperature ———— 300°C
Mass ———— 1.0 kw/kg
Voltage ———— Corona
• Re-visit weight on all fronts
• Tower termination at antenna
  – PMAD interface & distance from antenna
  – Thermal radiation shield for antenna
  – Wire distribution to antenna
• Invest in PMAD R&D