Missouri University of Science and Technology

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6 Power Subsystem

6.1 Introduction, Background, and Purpose

The objectives of the power system are to acquire, store, and distribute power in a way that will sustain the operations of the mission. In order to achieve these objectives, a satellite power system must consist of the following components: a power generation system, an energy storage system, a power distribution system, and a power regulation system. For the MR SAT spacecraft, the power generation system will consist of solar panels and the energy storage system will consist of secondary batteries. Each of the major components of the electrical power system is discussed in further detail in its own respective section.

The two satellites (MR SAT and MRS SAT) are hexagonal in shape and solar cells will be placed on all six sides of the satellites. The size of the panels varies based on thruster and antenna placement. Batteries will be used to supply power while the satellites are in the Earth’s shadow.

6.2 Mission Constraints

<table>
<thead>
<tr>
<th>Requirement</th>
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<tbody>
<tr>
<td>The power system shall provide regulated 3.3, 5, 12, &amp; 24 V power buses.</td>
</tr>
<tr>
<td>The power system shall power on/off other subsystem’s hardware.</td>
</tr>
<tr>
<td>The batteries shall provide enough power storage to operate the satellite for a maximum of 40 minutes.</td>
</tr>
<tr>
<td>The power system shall provide a method for monitoring the power by the onboard computer.</td>
</tr>
<tr>
<td>The solar panels shall provide enough power to power the spacecraft while still charging the batteries in 1 hour.</td>
</tr>
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</table>

Table 2 MRS SAT Power Requirements

<table>
<thead>
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</tr>
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The batteries shall provide enough power storage to operate the satellite for a maximum of 40 minutes.

The power system shall provide a method for monitoring the power by the onboard computer.

The solar panels shall provide enough power to power the spacecraft while still charging the batteries in 1 hour.

6.3 Summary of Relevant Literature

- *Nanosat 6 User’s Guide, UN6-0001, Rev A*
  
The Nanosat 6 User’s Guide details the requirements and constraints of the Nanosat 6 Competition.

  
The book was used to provide an overview to the baseline design of the power system. It provided the necessary equations for the preliminary calculations. This book was also used to estimate the total power dissipation losses due to the converters and wiring.

The Internet also played a significant role in the power system research. Many other Universities’ satellite projects were examined, and their respective URL’s are listed in Section 6.7, Additional References.

6.4 Design and Analysis

6.4.1 Solar Cells

The solar cells to be used for the satellite pair were chosen based on price, efficiency, and ease of assembly. There were 132 triple junction CICs procured that are approximately 23% efficient for $40 each. The next cheapest option were double junction cells that were 21 percent efficient for $50 each, so we bought all of the remaining triple junction cells that were available. More recently, 25% efficient cells were acquired due to the

Each cell measures approximately 6.4cm x 4cm. They are CIC assembled cells, which include cover-glass, interconnects, and the cells. Diodes are built into the cells so when there is no sunlight the current cannot follow backwards and damage the cells. The assembly procedure for these cells is covered in detail in the assembly section. We only purchased enough CIC’s to power up the satellite. Additional cells will be purchased to complete the power system when assurance of a launch is received. The high cost of the cells makes it undesirable to build the entire system until we know for sure that it will go into space.
6.4.2 Power Requirements for MR SAT and MRS SAT

The power requirements are broken down by mode of operation and by spacecraft in document 06-002, M-SAT Power Budget.

6.4.3 Batteries

The batteries will be used to supply power while the satellites are in the Earth’s shadow and during peak power demand times. During worse case orbit of 98 minutes the satellites will spend approximately 30 minutes in the Earth’s shadow.

The batteries being used on the satellites are nickel cadmium (NiCd) batteries, specifically the Sanyo N-4000DRL. According to the cell specifications these batteries operate at a minimum acceptable voltage of 1.2 V (or 1.5 V fully charged), have a nominal capacity of 4000 mAh and require a normal charging current of 400 mA, which will charge the batteries in about 14-16 hours.

6.4.4 Array Design

The satellites have undergone major structural changes since entry into Nanosat 6 which greatly affects the solar array design. The main constraints on array design are the size of the satellites and thruster placement on MR SAT. The size of one string was determined using the maximum required voltage for each satellite.

On MR SAT each string of cells will be capable of producing 9.6 V. Each side of MR SAT will contain six strings of four cells. MR SAT will contain a total of 144 cells.

To account for losses, one string on MRS SAT will be capable of producing 9.6 V. With the given dimension of the satellites, the MRS SAT panel will consist of one string of four cells on each side and a top panel of four strings with four cells for a total of 40 cells.

6.4.5 Power Electronics

The power electronics consist of two primary devices: the charge controller and the power regulation circuitry.

The charge controller provides the safety and logic for controlling the flow of power into the battery from the solar array. It is important that adequate protection is provided to prevent the batteries from overcharging and venting into the spacecraft as well as to ensure that the spacecraft stays alive. Without the batteries, there is no way for them to operate during the eclipse and are therefore severely limited in their ability to perform experiments and maintain a stable orbit. The charge controller circuitry monitors the temperature of the battery pack and monitors its voltage.
The power regulation circuitry handles the more sophisticated regulation of the power buses. This circuitry uses a highly efficient switch-mode method of regulation as opposed to a type which simply releases excess power as heat. The power regulation circuitry will be monitored by the onboard computer through the use of the 1-Wire® data bus and analog-to-digital converters (ADCs).

6.5 Power Calculations

The amount of power produced by the solar panels depends on several different parameters including the cell voltage, cell current, sun incident angle, temperature and ratio of the sun power density in space and on Earth. The relationship between the current and sun incident angle is shown in Equation 1.

**Equation 1: Relationship Between Sun Incident Angle and Current**

\[ I_s = I_a \cos \theta \]

Where \( I_a \) is current when theta is zero and theta is the sun incident angle. An angle greater than 85 degrees will not produce any power.

Equation 2 shows the relationship between the temperature and voltage.

**Equation 2: Relationship between Temperature and Voltage**

\[ V_{oc} = V_o - \beta \Delta T \]

Where \( V_o \) is the cell voltage, beta is the temperature coefficient (V/degree) for the cell. Error! Bookmark not defined. Beta used in the calculations was 0.065 abs %/°C.

Equation 3 shows the relationship between the temperature and current.

**Equation 3: Relationship between Temperature and Current**

\[ I_{sc} = I_o - \alpha \Delta T \]

Where \( V_o \) is the cell voltage, alpha is the temperature coefficient (A/degree) for the cell. Error! Bookmark not defined. Alpha used in the calculations was 0.065 abs %/°C.

The power calculations were performed assuming a voltage of 2.1 volts per cell and a maximum current of 290 mA. The maximum current was determined during testing. The power calculations were performed for an orbital period of 92 minutes with 28 minutes spent in the Earth’s shadow. The actually orbital period will vary. The worse case orbit will be 98 with 30 minutes spent in the Earth’s shadow. Tables 4 and 5 contain the breakdown of the voltage, current and power per side of MR and MRS SAT while the solar panels are capable of producing power.
Two sides of each satellite will not be producing any power during an orbital period. However, there is no way to determine which sides will not receive any sunlight. Therefore, solar panels will be placed on all sides of each satellite. These calculations also cannot accurately account for the fact that two panels will contain one less string of cells on MR SAT. In the power calculation sides one and four of MR SAT were assumed to have only 22 cells and side two, three, five and six contained 33 cells.

Table 6 contains the maximum current, voltage and power along with the minimum current, voltage and power while the solar panels are capable of producing power for each satellite.

The satellites currently need more power than the solar panels can provide. Therefore, the batteries will be needed to supply the extra power.
6.6 Building a Sample Panel

First a soldering jig must be built to protect the cells while soldering and to align the cells. The jig was to be built out of a plastic type material using rapid prototype technology available at Missouri S&T; however, after a failed attempt at rapid prototyping, a jig was machined from scrap material.

The next step is soldering the cells together. The cells were first cleaned, and then soldered together to form a string of five cells. Soldering was done using a Sn 62 wire. This wire contains 62.5% tin, 36.1% lead and 1.4% silver. This alloy is better than a pure mixture of lead and tin because the back of the cells and interconnects are silver plated. A soldering station with adjustable temperature is preferred, and a temperature of 650°F worked without damaging cells. Temperatures up to 750°F are acceptable.

Once the cells were soldered, the end terminations were soldered onto the final interconnects. These terminations serve as buses, and wiring going into the satellite will be soldered directly to the terminations. The terminations are made of Silver Kovar Ribbon, which is a very thin ribbon of Kovar, with a silver coating on the outside. This material was donated, and had to be cut to the desired size. This was also used for the extra interconnects needed on the ground end of the string.

Once the strings were completed, wire was soldered directly to the end terminations. The wire chosen is a space rated military spec MIL-27500 Tefzel AWG22 - 4 Conductor Shielded Cable. Once the wire was soldered on, connectors could be soldered to the end of the wire. However, the wire may need to be fed into the satellite before the connectors are attached. The connectors also must follow very specific guidelines, and can not contain certain alloys that outgas in space. The recommended 4-pin connectors from www.powell.com are JF2S2S45 and JF2P2P95. Since these are not available until a large order is received, similar connectors were used for the prototype. These are not space rated and will not be used on the actual satellite panels.

The cells are currently ready to be attached to a panel through an extensive lay down procedure. This procedure must be done in a 100,000-class clean room. This process requires a vacuum assembly and an oven which the MR SAT team has not yet procured. The following is a short summary of the procedure for completing the panel. A plot of the cells must be made to help place the CIC strings exactly as desired on the panel. The panel is made of honeycomb aluminum, and is raised above the side of the satellite. First, Kapton tape is applied to the honeycomb aluminum panel, which serves as an electrical insulation. Next, a primer is applied where each CIC will be placed. Then, an adhesive covers the primer completely. Since silicon outgases in space, the space rated CV-10-2568 adhesive must completely cover the primer. Also, the adhesive must be mixed and placed in a vacuum under 25 inHg of pressure for about 10 minutes to remove any air pockets before applying.

A stainless steel sheet form with CIC cutouts is placed on the panel, and the adhesive is placed inside the cutouts, as shown in the figure below taken from Utah State
University’s lay down procedure document. The adhesive is then smoothed out. The form helps keep the same thickness to the adhesive everywhere, and helps create a flat smooth surface. Extra adhesive must then be applied to the end terminations.

![Figure 1: Stainless Steel Cutout](image1)

The CIC strings are then put into place on top of the adhesive. Then the panel is placed in a pan and vacuum bagged. A vacuum is attached which places the panel under around 1 inHg of pressure. The panel then must be put into an oven for curing for approximately 4 hours at 65°C.

![Figure 2: Vacuum Bagging](image2)

After the panels are completed, it is necessary to test them all again and to check for cracks.
6.7 Testing

The cells were tested separately to determine approximately how many ‘good’ cells were purchased. A ‘good’ cell produces around 2.4 volts open circuit and a short circuit current of over 280 milliamps. The first round of testing was performed on September 7 and 12, 2005. On September 7, 2005, a few of the cells were tested in the senior design lab to determine a testing method. On September 12, 2005, a grow light was used to simulate the sun in the lab in hopes of providing a consistent testing environment. The grow light produced better results than using the fluorescent lights but not as good as testing the cells outside in the sun. On October 4, the cells were tested outside. About 108 ‘good’ cells were identified. All of these cells gave a very similar short-circuit current and open-circuit voltage. As the sun got higher in the sky, the current increased to around 310 mA.

On September 21, 2005, five cells that individually produced approximately the same current were soldered together. Table 7 contains the open circuit voltage and short circuit current values of the individual cells.

Table 6: Individual Cell Open Circuit Voltage and Short Circuit Current

<table>
<thead>
<tr>
<th>Cell</th>
<th>Open Circuit Voltage (V)</th>
<th>Short Circuit Current (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.36</td>
<td>270</td>
</tr>
<tr>
<td>2</td>
<td>2.40</td>
<td>285</td>
</tr>
<tr>
<td>3</td>
<td>2.37</td>
<td>270</td>
</tr>
<tr>
<td>4</td>
<td>2.38</td>
<td>273</td>
</tr>
<tr>
<td>5</td>
<td>2.36</td>
<td>265</td>
</tr>
</tbody>
</table>

The measured open circuit voltage for the string was 11.5 and the current was 250 mA. The voltage was close to the expected 11.87 volts. The current was lower than the expected 265 milliamps. While testing the individual cells it was discovered that the current varies greatly according to how the cells are directed towards the sun and the sun positioning in the sky. The lower current is likely a result of testing the array in slightly different sun conditions. The measurements for the string of five cells shown in Figures 4 and 5 were taken on a different day.

Figure 3: Array Voltage
6.8 Conclusion and Current Status

Enough solar cells have been acquired to build several of the solar panels for both satellites. The power electronics need to be designed. The new double battery box for MR SAT has been designed but not manufactured.

6.9 Additional References

- http://www.cubesat.auc.dk/index1.html
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- http://engineering.dartmouth.edu/~dartsat/
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