Power System for the ALEXIS Satellite

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1.0 INTRODUCTION

ALEXIS is a 250 lbm satellite being built for the Department of Energy through Los Alamos National Laboratory. Its primary payload is an array of low energy x-ray telescopes. ALEXIS will be a sun pointer with a daily averaged power draw of 57 W.

The ALEXIS power system provides electrical power for the operation of the various satellite subsystems including payloads, guidance and control systems, and telemetry systems. The goal of the ALEXIS power system is to provide efficient power regulation with low mass, low cost, and reasonable reliability.

2.0 REQUIREMENTS

The ALEXIS satellite will draw a daily average of 57 W with a peak power draw of 156 W. This power is to be delivered at a nominal 28V. The satellite will be placed in a roughly 420 nm polar orbit and will be sun pointing, which translates into the satellite being in the sun from 63.6% to 100% of an orbit, depending on seasonal variations, with the solar panels pointed towards the sun. The satellite is being built for a 3 year operating lifetime.

For design and management purposes, ALEXIS has been split into 2 major components, the payload and the spacecraft. The payload is being built by Los Alamos National Laboratory and the spacecraft is being built by Astronautics. The majority of the daily average power draw, 42.5 W, is delivered to the payload through 4 independently switched power lines.
3.0 POWER SYSTEM COMPONENTS

3.1 System Overview
The components that make up the ALEXIS power system are solar cells, batteries, various voltage, current and temperature sensors, bipolar transistor switches, diodes, a timeshared processor, and the power control algorithm. These various systems will be described below.

3.2 Solar Cells
The solar cells used will provide power to the satellite as well as charge the batteries when in the sun. BSFR (Back Surface Front Reflection) solar cells where chosen for their high efficiency which is 13.5% at BOL (Beginning Of Life). These cells provide 0.16 W at 0.52 V. Less costly (and less efficient) cells require more surface area than is available. The solar cells will be mounted in strings of 71 cells on 4 deployable paddles and on the sunward facing end of the spacecraft. Table 3.1 lists the power this arrangement of cells delivers to the batteries and satellite for the darkest and lightest orbits and for BOL and EOL (End Of Life). The efficiencies are calculated by dividing the actual power output to the batteries and satellite by the maximum available power output from the solar panels.

<table>
<thead>
<tr>
<th>Power (W)</th>
<th>Efficiency</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BOL</td>
<td>EOL</td>
</tr>
<tr>
<td>100% Sunlight</td>
<td>109.9</td>
<td>77.8</td>
</tr>
<tr>
<td>63.6% Sunlight</td>
<td>69.3</td>
<td>55.3</td>
</tr>
</tbody>
</table>

Table 3.1
Orbit Averaged Power Generated by Solar Cells at 29 V

This arrangement of solar cells provides only marginal power at EOL, but additional power generating capacity could not be added without greatly increasing the cost of the solar arrays. A voltage regulator is being placed in line with output from the solar cells to limit the maximum voltage that will be applied to the bus. This is being done to prevent high voltages, which could
occur early in the spacecraft life with low paddle temperatures, from damaging any of the bus electronics (see Fig. 3.2).

Figure 3.2 Solar Paddle I-V Characteristics at BOL

3.3 Batteries

Energy storage for ALEXIS will be provided by 4 batteries each composed of 23 NiCd cells. As space qualified NiCd cells are extremely expensive, and the series of small satellites built by AMSAT have had good success using commercial grade NiCd cells, we are using commercial grade cells for ALEXIS. The cells we will use are the GEMAX C5 cells, which have, for commercial cells, a very high stored energy to mass ratio. The cells will undergo a series of preflight tests that will determine which cells will be used to assemble the batteries. Each battery has an energy storage capability of 40 W-hrs, and the use of 4 batteries will limit the maximum dod (depth of discharge) to 18% under nominal operating conditions. The use of four batteries allows one of the batteries to be taken off line for reconditioning without interrupting power to the satellite.

Battery failure can occur by one of three methods: individual cell degradation, cell short circuit, and cell open circuit. Although a cell open circuit failure would cause an open circuit for the whole battery, it occurs much less frequently than short circuit failure which only degrades the battery voltage. The reduction of cell capacity, which is the most frequent failure mode, can result in a cell being overcharged or in cell voltage reversal during discharge of the battery. This can lead to cell stress which could then result in an open or high impedance cell which would result in battery failure. To alleviate this problem, diodes are placed across each cell: two in the forward bias direction and one in the reverse
bias direction. Therefore, on discharge there will be a one cell plus one diode drop decrease in battery voltage and on charge, there will be two diode drops minus one cell voltage change in the battery voltage with an open circuited cell.

3.4 Processor

ALEXIS is unusual in the small satellite world as it will be flying a large number of microprocessors. On board the spacecraft alone there will be three 80C86 CPUs, and there are additional CPUs onboard the payload. We are taking advantage of the large computing power available to ALEXIS by running a near completely digital power management system. The CPU will sample the sensors approximately once a second and, will use the inputs from the various sensors to determine when batteries should be charged and at what rate, when to refresh a battery, and when to switch various pieces of equipment off, notably the 4 payload power lines. The CPU is also responsible for transmitting the spacecraft energy status to the payload to use in its own internal power management. CPU monitoring of the battery states, bus currents and voltages, and the spacecraft energy level allows better control than most independent regulators since a more complex algorithm can be used for critical charge control decisions and data on health and status of the batteries can be downlinked to the ground station where human control can be exercised and new control algorithms uplinked if necessary.

3.5 Sensors

A variety of sensors are required to provide information to the power control algorithm. The sensors that we have chosen to use will monitor voltage, current, and temperature for each of the 4 batteries, the current and voltage at the spacecraft bus, and the current flowing through each of the 4 payload power lines. The battery sensors will be used to determine a battery's state of charge and state of health. The other sensors will be used to track energy flow throughout the satellite and, as there is some sensor redundancy, provide limited checks on the sensors. If a sensor is positively identified as being bad, other sensor readings can be substituted for the lost sensor at reduced performance.

Each battery has its own independent set of sensors for voltage, current and battery temperature. (see Fig. 3.2). Since the current monitoring is bipolar, each voltage analog sensor output is referred to a voltage reference. The battery current is sensed through a 0.1 Ω resistor at the positive terminal of the battery by use of a differential amplifier circuit. The battery voltage is also sensed with respect to the voltage reference. Temperature sensing is done with a sensor who's current output is proportional to temperature. This current is then amplified through a transimpedance amplifier. All analog signal voltages are A/D converted through a MUX to a 10-bit A/D converter which is sampled through an I/O interface card by the CPU.
Each battery also contains three switches. These are for fast and slow charge, and for battery reconditioning. Fast charging will normally be used to recharge the batteries. When the battery is fully charged, the slow charge will be used to maintain the battery charge without overcharging. For reconditioning, both fast and slow charge switches will be off and a resistor will be switched in across the battery until the battery is nearly 100% discharged. After being discharged, the battery will be slow charged until its voltage is close enough to the bus voltage so that it can be switched to fast charge without lowering the bus voltage significantly.
3.6 Power Control Algorithm

The power control algorithm is the control for the entire power system. The flowchart below lists the major operations that are performed by the algorithm.

```
get_sensor_data
  sensor_sanity_check
    check_battery_health
      battery_switches
        power_shedding
```

The routines in get_sensor_data interrogate all of the sensors and temporarily store the values. A separate routine, run at a much lower frequency, stores sensor values for downlink to the groundstation.

Sensor_sanity_check compares the sensor readings with each other and some operational limits, and marks sensors that appear to be bad. Sensors that are marked as bad will not be used in any of the algorithms that follow. An example of the types of checks that are made is, if the satellite is in the dark (umbra), then the current flowing out of the batteries should equal the current flowing to the spacecraft and payload (within a tolerance).

In check_battery_health the sensor readings that have been taken are combined with the battery flags from the previous iteration to determine what the new battery flags will be. The various battery flags are:

```
ALIVE_AND_WELL
LIGHT_PROBLEM_2
DARK_PROBLEM
LIGHT DARK_PROBLEM_2
LIGHT_1
DARK VOC
LIGHT_2
DARK PROBLEM_1
DEAD
```

The ground can override the spacecraft and change any of the battery flags. The flag DEAD can only be activated by ground command. Any battery marked dead will have all of its switches opened and will be ignored by the spacecraft.

Note that in this routine, as in all of the routines, if a sensor reading is unavailable, the quantity in question will be estimated from the remaining sensors and/or the battery status in the previous iteration. The estimation is accomplished by changing the weighting coefficients used in determining the battery parameters from the sensor readings. Additionally, the ground can override the spacecrafts decisions on which sensor are still functioning normally.
Listed below is some pseudo code that outlines the major events that occur in this routine. The actual code is written in C.

```c
repeat for each battery {
  if (refreshing) {
    if (discharging && V_{battery} < V_{stop\_discharge})
      flag battery for refresh charging
    else if (charging && V_{battery} > V_{stop\_charge})
      flag battery for normal use
  }
  if (in\_the\_sun)
    test for light problems and flag if found (e.g. sinking excessive current).
  else
    test for dark problems and flag if found (e.g. not sourcing current).

  adjust permanent health flags based on past and current problems (if any).
  if a suspected problem has not reoccurred in the next orbit, remove the flag.
  calculate the energy (J) and current sum (A-hrs) for the battery.
}
```

Battery_switches uses the battery flags that were set in check_battery_health and the current battery temperature and voltage (with additional fallback to current summation), to determine what the state of the switches that connect the batteries to either charge normally, use a trickle charge, or discharge for refreshing should be. Again, what follows is pseudo code that outlines the major events that occur in the routine.

```c
repeat for each battery {
  if (battery flagged as having light and dark problems)
    open all switches
  else if (battery is to be refreshed - discharge) {
    close the discharge switch
    open both charge switches
  }
  else if (battery is to be refreshed - charge) {
    open discharge and fast charge switches
    close slow charge switch
  }
  else if (battery is ALIVE\_AND\_WELL or has no light problems) {
    open discharge switch
    if (okay\_to\_charge) {
      this function will be explained below
      close fast charge switch
      open slow charge switch
    }
    else {
      open fast charge switch
      close slow charge switch
    }
  }
  else if (battery has light problems) {
    close slow charge switch
    open discharge and fast charge switches
  }
}
```
Okay_to_charge is a function that returns TRUE or FALSE based on the evaluation of a matrix that uses the current state of the battery (voltage, temperature, estimate of dod based on current summation) and a series of weighting values that are based on the sensor health flags. The coefficients used in the matrix will be based upon data collected during the testing of the cells.

Power_shedding also uses the battery flags that were set in check_battery_health as well as the estimated energy of each battery. In this routine, the energy available to the spacecraft is compared against the energy needed to get the spacecraft through the umbra, which will be uplinked periodically from the groundstation. Based on this comparison power to the payload is left on, shed (turned off), or turned back on. There are 4 separate power lines to the payload which are switched on or off independently. Another routine passes an energy status variable to the payload for use in its own internal power management. A payload power line may be masked off, which will result in that line being turned off and then ignored until the ground commands otherwise. Additionally, power lines may be requested on or off by the payload for system reset or power management independently of ground commands. Below is some pseudo code that covers the major points in the power_shedding routine.

```
repeat for each battery {
    if (battery is capable of fast charge)
        energy = energy + battery_energy
}
energy_level = 100 * energy / FULL_ENERGY

repeat for each payload power line {
    if (payload request line off)
        disconnect power line
    else if (power line flagged as SHED) {
        if (energy_level > shed_marker + hysterisis) {
            connect power line
            flag power line as OK
        }
        else
            disconnect power line
    }
    else {
        if ((energy_level > shed_marker) && timer not started)
            connect power line
        else if (timer not started) {
            issue warning to payload
            start timer
        }
        else if (timer has timed out) {
            disconnect power line
            flag power line as SHED
            reset timer
        }
    }
}
```
The code that will run on the spacecraft does have the capability for taking a battery offline, but does not have the ability to begin a refresh. The refresh routine is initiated upon ground command. Ground commands can override any of the decisions made on board the spacecraft, if necessary. All of the code is being written in C using Think C™ on a Macintosh IIcx.

4.0 Conclusion

The power control system for ALEXIS illustrates an important concept in the design of small satellites, graceful degradation. Graceful degradation means designing a system so that if a key component is lost, the spacecraft can continue to function at reduced performance by utilizing a different mechanism to perform that function, be it a sensor, actuator or whatever. An example of this would be designing a guidance and control algorithm to be able to maintain the satellite attitude after loss of a sun sensor by using measurements from a coarse sun sensor designed for sun acquisition. Because small satellites typically cannot afford the cost or mass involved in making key systems redundant, they generally have a lower reliability than conventionally sized satellites. Part of this reliability loss can be recovered by careful system design, utilizing graceful degradation. The components in the ALEXIS power system that can degrade gracefully are:

**Batteries:** loss of one or more batteries will increase depth of discharge, probably resulting in a shortening of operating life, but the satellite will be able to continue functioning.

**Battery switch loss:** the most likely failure is an open switch, which will mean the loss of either one charging mode or the refresh discharge. The battery will be able to continue operating either with less control over charging or without the ability to refresh.

**Payload power line switch loss:** as there are 4 payload power lines, the loss of 1 switch will result in the loss of roughly 25% of the experiment, but the remaining 75% will be able to operate normally or perhaps even more often which might the actual amount of the loss.

**Sensor loss:** As described above, if a sensor is lost, other sensor readings will be used to estimate the quantity that can no longer be directly measured.

**CPU loss:** ALEXIS will have 3 CPU's which will not be run at full capacity. If a CPU is lost, whatever tasks it was performing will be transferred to the remaining CPUs.

The power control system for ALEXIS has several advantages over conventional power control systems. They are: the charging circuitry is relatively simple, the overall system mass is low, the total cost of the power system is low, and digital control gives a powerful and flexible control system. Although this system has very few parts which are redundant, the total system reliability is still acceptable because the system will degrade gracefully with loss of most components. This system also has several disadvantages. Because all of the current information is in software, a CPU reboot will cause all of the current information to be lost. This is not catastrophic, as the default settings will emphasize spacecraft survival, turning on the payload and other systems only when it determines there is sufficient energy to do so. Additionally, the algorithm will quickly determine if there is anything significantly wrong and take corrective measures. Finally, the groundstation will be able to uplink to the spacecraft the last set of health and parameter data that...
was downlinked during the next communication. Another disadvantage is that the power system cannot be completely tested independently of other spacecraft components such as the CPU, memory, and other spacecraft software. We feel that the disadvantages of using software to perform all of the power management and charge control are more than offset by the system's flexibility, which includes the ability to uplink battery and sensor health flags, change the algorithms parameters, including the voltage-temperature curve used to determine battery voltage charge limit as well as various system set points, and even the ability to uplink entirely new code if desired.

Reference