Simulation of LEO Missions with NiH or LiIon Batteries Including Dead Bus Recovery using the Power Tools Suite EPS Simulation Codes

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The Power Tools Suite (PTS) has been under development at Lockheed Martin for many years and is being used in the simulation of several satellite programs. PTS includes a large library of models for the simulation of Electric Power System (EPS) components. These include various solar array (SA) cells, various battery cells (e.g. Nickel Cadmium, Nickel Hydrogen, Lithium Ion), different types of battery charging units and techniques, different harness, bus bar, and cable losses, and different load requirements (e.g. constant power or constant current). These models include the effects of light intensity (for SA), voltage, current, temperature, DOD (for battery cells), and aging. The simulation codes also include a sizing code and a dynamic simulation code. The sizing code determines the sizes of the battery and the solar array in order to satisfy the mission or sizing requirements. The dynamic code simulates the time-dependent behavior of the EPS over any given mission duration, such as either during a worst case scenario, or from pre-launch to final ascent. The time steps are user defined, and the user provides all of the time-dependent input variables and the required EPS loads as input. This paper discusses the application of the PTS Tools and Codes to a typical Low Earth Orbit (LEO) unmanned spacecraft using either Nickel-Hydrogen (NiH) or Lithium Ion (LiIon) batteries in the EPS. The use of a LiIon battery may require significant changes in the design of the EPS bus to satisfy the mission requirements for a particular LEO mission. Such changes are discussed as far as proprietary restrictions will allow. The impact of a possible new requirement "Dead Bus Recovery" on the EPS design is also addressed.

I. Introduction and Background

THE modeling of battery behavior during both discharging and charging is a major key in the simulation of electrical power system (EPS) behavior as used in space satellite missions today. Simulations of the operation of the EPS are extremely important in determining the sizes and capabilities of the solar arrays and the batteries to accomplish the mission objectives. Detailed EPS studies are required to provide specific maximum load power profiles at the Beginning-of-Life (BOL), at various mission stages, and at the End-of-Life (EOL) of the mission, to assure that the solar arrays and the batteries as designed will accomplish the mission objectives. In the past, so-called "engineering margins" or "wags" have been used to oversize both the solar arrays and the batteries, to insure that the EOL mission objectives will be met. Today, however, there is increased interest in predicting exactly how the EPS will operate from BOL all of the way through EOL, and even beyond the expected end of the mission. In fact, many satellites and space platforms today have been and are now operating well beyond their planned EOL mission characteristics, such as the Hubble Space Telescope. As more and more battery data are becoming available from both ground testing programs and actual satellite mission telemetry, it is now possible to create more advanced battery and EPS system component models that can reproduce this collected data and predict battery operation for various planned and anomalous mission conditions. It is now even possible to extend these models in to simulate other batteries of similar characteristics to predict their behavior.

Several simulation codes are being used by various aerospace industry leaders today to model the BOL to EOL transient behavior of the EPS for various missions. The Power Tools Suite (PTS) codes package has been under development at Lockheed Martin for several years. Descriptions of the development of this PTS code and its results have been presented at several IECEC and Space Power Workshop conferences in recent years.[1-8]

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II. The Updated Power Tools Suite (PTS) Code

The Power Tools Suite (PTS) codes package originated in the late 1990s for use in the Iridium Program and in other specific programs within Lockheed Martin.[9-11] The models and codes have been significantly updated several times during the past few years.

The updated PTS codes package has been used to support of several programs within Lockheed Martin, and will be continued to be used to do so in the future.[12-14] The PTS codes package contains a sizing code, a dynamic or time-dependent simulation code, and a library of various EPS Component models. These have all been written in Excel 2003 Visual Basic Macro coding (similar to FORTRAN or Basic) and allow modular use, clarity, ease of understanding, fast execution time, and the ability to used on any computer platform without any concerns for special workstation requirements and/or special software licensing agreements. They are all also upward compatible to both Excel 2007 and Excel 2010.

The PTS dynamic code simulates the time-dependent behavior of the EPS by defining the EPS to be constructed of interlinked EPS components from the library. These components are then connected together to form the solar array circuits, battery circuits, bus circuits, and load circuits for the entire EPS. The wired EPS components then form the total EPS architecture under consideration. The current PTS dynamic code can automatically simulate the A2100 (battery regulated) bus design as well as the A2100M (battery dominated), LM700, and LM2000 bus designs studied and analyzed by Lockheed Martin. Additional bus designs have also been simulated.

A typical block schematic diagram of such a PTS EPS architecture is shown in Figure 1.[1] In this figure, each box connected in the EPS bus represents the effect of an individual EPS Component. The values shown within each box indicate the system values that would appear at specified times during a dynamic simulation. The data shown here are for example purposes only and do not represent any particular mission design.[1] The boxes at the top of the figure show additional data that may be of interest during the running of the simulation.

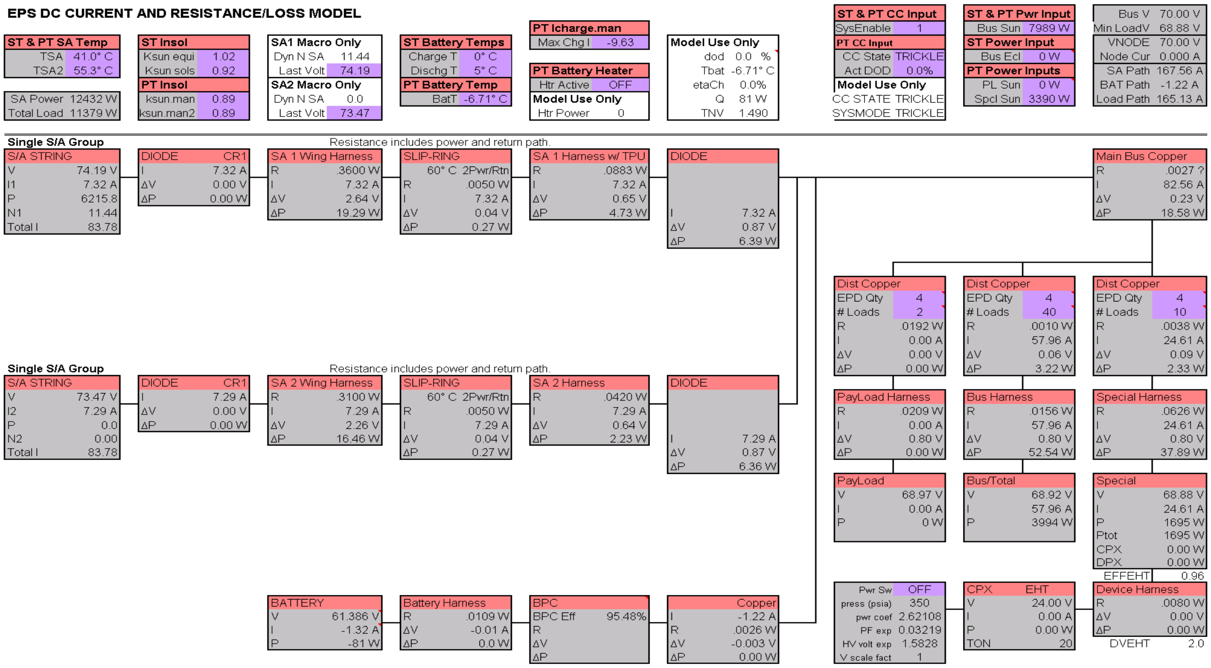

Figure 1. PTS Typical A2100 Bus EPS Architecture Model (Data for example use only)

The following abbreviations are used in Figure 1 to define various input and output variables: "S/A" or "SA" for "solar array", "SA1" for "solar array 1", "Batt" for "battery", "Batt_One" for "one battery", "BPC" for "battery power converter"; and "Payload", "Bus" and "Special" to identify the three possible loads on the EPS bus.

The numerical solution scheme used within the dynamic code allows stable and accurate iterative numerical solutions within each dynamic time step for the given EPS components and the given user defined EPS architecture. Also, these codes are written to follow the standards set forth in both the 2006 "AIAA Draft EPS Standards Review Document," and the book by Bauer, "Batteries For Space Power Systems."[15-16]

III. Battery Models

The PTS Component Library includes all of the models that are available for use in the EPS Simulations. These models include detailed simulations for various solar array cells, battery cells, battery efficiencies, battery recharging algorithms, other non-linear EPS components such as diodes, cables, wire, and harnesses. Many battery cell models are able to chosen by the user, including nickel-hydrogen (NiH) and lithium ion (LiIon) battery cell models. Typical characteristics of these battery cell types of interest are given in Table 1 below.

Table 1. NiH and LiIon Battery Data

Company	Eagle Pitcher	SAFT	(Units)
Label	RNH 90-3	VL44E(L)	
Nameplate	90	44	Ah
Weight	4.76	2.54	Lbs
Length	9.71	9.65	In
Diameter	3.55	2.12	In
Temperature	-5 to 10	10 to 35	Deg. C

The voltage characteristics of the NiH and LiIon battery cells are very similar. Typical curves as reported by various researchers and as modeled in the PTS EPS Component Library are shown below for Beginning-of-Life (BOL) conditions in Figures 2 and 3. Figure 2 shows typical NiH data that has been publically reported for use in various mission, and Figure 3 shows data from a publically released SAFT LiIon model (44 Ah cell).

These data and additional battery data and modeling information for LiIon batteries are now recently becoming available. Many LiIon cell designs and operational data especially for LEO operation have been recently reported at the April 2010 Aerospace Space Power Workshop.[17-23] Although many battery cell designs are being offered, several mission contactors have already chosen their specific cell design and operational tolerances for use in their own particular mission.

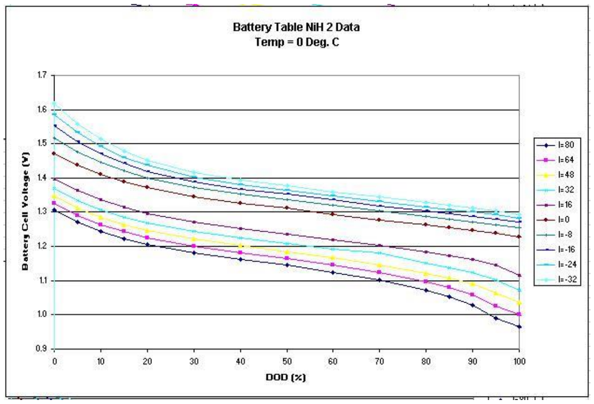

Figure 2. Typical NiH Battery Voltage Characteristics at BOL Conditions

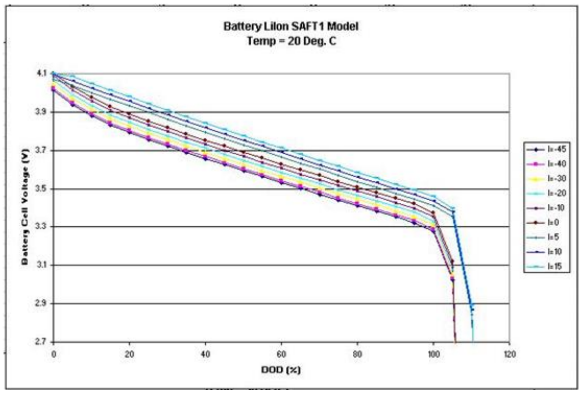

Figure 3. Typical LiIon Battery Voltage Characteristics at BOL Conditions

IV. Factors Affecting EOL Battery Operation

There are many factors that can affect End-of-Life (EOL) operation in both NiH and LiIon battery cells, as listed in Table 2. For Low-Earth-Orbit (LEO) missions, all of these factors play a significant role in the design and the sizing of the EPS.

The mission duration for a LEO mission is usually near 5 years, and may be longer. The cycle life can be on the order of 30,000 cycles. The average Depth-of-Discharge (DOD) during a mission may vary, and can be from 10 percent to 50 percent (relative to the battery nameplate capacity). The Average DOD per cycle may also be a relative term, meaning how far the capacity changes within each cycle, whereas the maximum DOD per period could be constant maximum value during the lifetime. The average cell temperature plays a significant role, and is estimated to be 20 to 30 deg. C for some LiIon cell EPS designs. The charging voltage cutoff is also a significant

Table 2. Factors that can Affect EOL Battery Operation

- Life of Mission
- Cycle Life
- Average Depth-Discharge per Cycle
- Average Maximum DOD per Period
- Average Cell Temperature
- Charging Voltage Cutoff
- Taper Charging Current
- Trickle Charging Current
- EOL Capacity Fade
- EOL Solar Array Degradation

parameter, as it is then used to define the maximum State-of-Charge (SOC) of the cell after a recharge (SOC = 100 – DOD, with both DOD and SOC in %). Any EPS having a charging voltage cutoff lower than the maximum voltage of the battery cell will probably always result in changing the battery cell to less than 100% SOC, i.e. less than full. The exception occurs during taper current charging. After the charging voltage cutoff is met, the charging current is reduced to keep the voltage at, near, or lower than the voltage cutoff as the battery is recharged. During this taper charging period, the charging current is “tapered,” much like a decreasing exponential, until the battery cell voltage reaches its zero charging current value. After this taper charging period, trickle charging may be used to keep the battery voltage constant, due to internal battery power losses, in the form of heat.

V. End-of-Life EPS Design Concerns

During the design of the EPS from BOL through EOL, care must be taken to address all of the factors listed in Table 2 above. Particular attention is now addressed to the value of the charging current after the charging voltage cutoff has been reached, usually called taper charging current. Various test procedures and simulations have shown that during this taper charging period, as much as 1.0 to 3.0 Amp hours of capacity can be added to a battery cell. Assuming a design for a 1.0 Ah addition, for a 90 Ah NiH cell, this amounts to only a 0.11% capacity addition. However; for a 44 Ah LiIon cell, a 1.0 Ah addition amounts to a 2.27% capacity addition – which can make a significant EPS design impact on a per cycle basis!

The effects of a charging cutoff voltage using a SAFT LiIon cell model at BOL are shown in Figures 4 and 5. Figure 4 shows simulated results of the maximum charging current at BOL that is allowed to reach a charging cutoff voltage of 4.1V, and Figure 5 shows similar results for a charging cutoff voltage of 3.9V. It is seen that a charging cutoff voltage lower than the maximum voltage of the cell will result in lower allowable charging currents at high states of charge, and will also lower the maximum possible state of charge of the cell.

The effects of the added capacity during this taper current charging are shown in Figures 6 and 7. Figure 6 shows simulated results using the same LiIon cell model at BOL to obtain the constant voltage during recharging, for different constant charging currents, assuming a voltage cutoff of 3.85 V at 20 degrees C. It is noted that when these curves are each multiplied by their corresponding charging rate “n”, then they overlap. The area under the curve, after the taper begins and for a certain range, is then the capacity added during that taper charging period. This added capacity is then found to be dependent on the cell temperature, decreasing with increasing temperature, as shown in Figure 7.

Figure 8 illustrates the effects of capacity removal on a per cycle basis for a simulated LEO mission. This mission assumes a hypothetical LEO orbit having cycles of 30 minutes eclipse, 60 minutes sunlight, 16 orbits or cycles per day, full sun insolation on the solar array cells, with an EPS composed of one 44 Ah LiIon cell, no internal power losses, a constant power addition during sunlight, a constant power use during eclipse, and no power use during the last two cycles. The sunlight and eclipse power requirements have been chosen to produce the baseline case SOC as shown, which is designed to refill the cell to at least 100% after each day (of 16 cycles). Removing 2% (0.88 Ah) of the cell capacity from this baseline case results in almost filling the cell after a day (to 99.7% SOC). However, removing 4% (1.76 Ah) of the cell capacity from this baseline case results in a final SOC of only 87.4%, and a similar further significant SOC degradation of the cell in future cycles and days. Thus, the question arises: Should the expected capacity that would be added during taper current charging be included in the EPS baseline design? Some customer agencies have said “no”; reasoning that it should be excluded from the design in order to balance out other possible capacity losses that may occur on a per cycle basis, such as cell charge imbalance during charging.

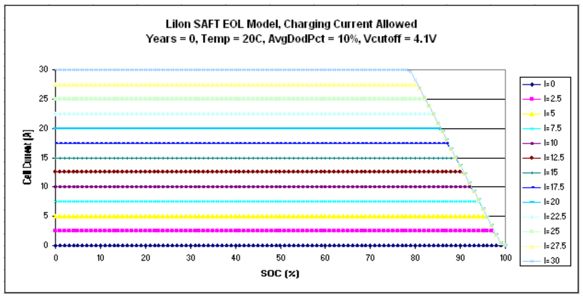

Figure 4. LiIon Model Charging Current Allowed with Vcutoff=4.1V for Different Charging Rates

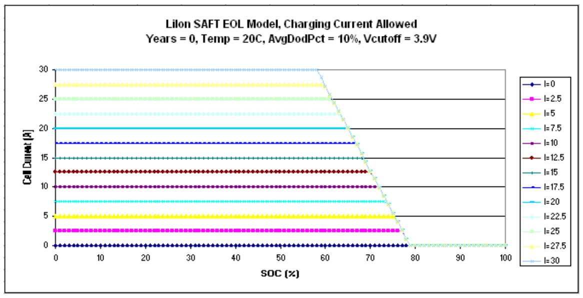

Figure 5. LiIon Model Charging Current Allowed with Vcutoff=3.9V for Different Charging Rates

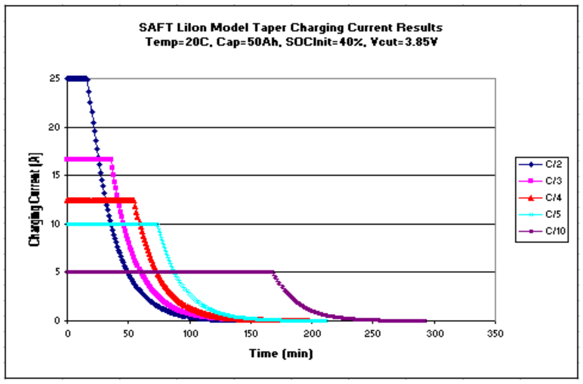

Figure 6. LiIon Model Taper Charging Current Results for Different Charging Rates

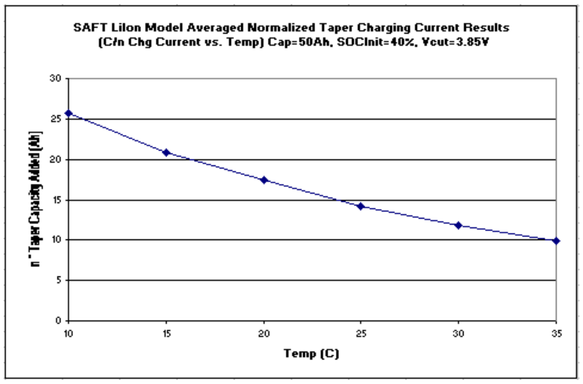

Figure 7. LiIon Model Normalized Capacity Added During Taper Charging vs. Temperature

The effect of capacity loss over the life of the mission is also important, and appears to be much less than the taper charging effects. Estimates have been reported that LiIon cells are expected to lose about 15% of their capacity over a 5 year mission, assuming an average DOD of about 20% per cycle. This of course must be taken into account in the design of the EPS. This equates to only a 0.0006% capacity loss per cycle, or a loss of 0.023 Ah per cycle, or 0.36 Ah per day. The cumulative effect of this slow yet important capacity loss over EOL is illustrated in Figure 9.

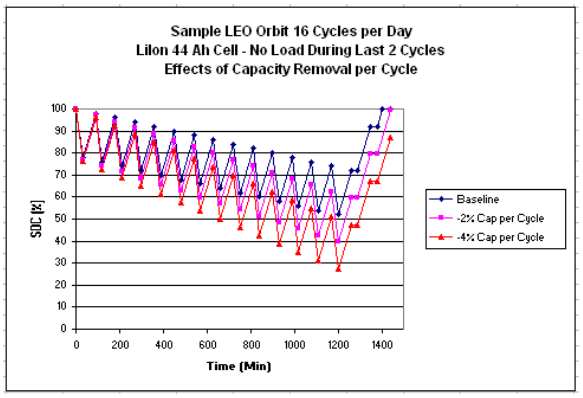

Figure 8. Sample LEO Simulation of LiIon Cell with Capacity Charging Losses per Cycle

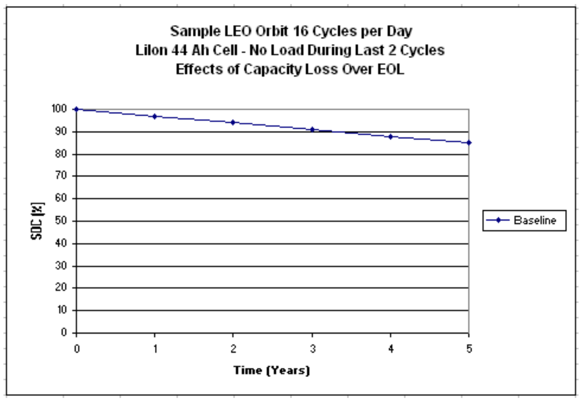

Figure 9. Sample LEO Simulation of LiIon cell with Capacity Charging Losses over EOL

It is to be noted that these simulations have assumed that the beginning SOC and the SOC after cell recharging have each been 100%. Real missions typically design for a BOL SOC of 70% to 80%, and the actual SOC after recharging to a "full battery condition" will be limited by the charging voltage cutoff and other EPS design considerations (as illustrated in Figure 5).

VI. Dead Bus Recovery Concerns

A new area of concern in the design of EPS systems for LEO missions is that of "Dead Bus Recovery." Another related design topic is that of "Dead Bus Avoidance." The concept of a Dead Bus Recovery is to design the EPS in a specific manner in order to allow it to recover from a state of being "dead;" i.e. from a total shutdown, which could include loss of power or loss of battery capacity. The concept of Dead Bus Avoidance is to design the EPS in order to insure that a Dead Bus never occurs. Both approaches have merit, and both approaches will have significant impact on the overall design of the EPS.

For the purposes of simulating the EPS to size, design, and simulate the operational behavior of the batteries and other EPS components, it is necessary to define the overall range of system operation. Past discussions at the Aerospace Space Power Workshop in 2009 and 2010, have proposed that the lowest temperature possible for a Dead Bus Recovery will be at -40 C, as lower temperatures will adversely impact any semiconductor chips and disallow communications or computerized operations. Therefore, in order to simulate the operation EPS under these conditions, detailed models are needed for all of the EPS components at these low temperatures, and at temperatures ranging up to the normal expected operating temperatures. Also, the effects of heating and of changing temperature gradients will also be needed. More EPS component data is needed, especially for various battery cells, before accurate simulations can be made in these regions.

VII. Conclusions

The Power Tools Suite (PTS) codes package has been under development at Lockheed Martin to provide EPS Component Models for various mission analyses. Missions simulated include LEO, MEO, GEO, and deep space missions at both BOL and EOL conditions. These models and codes are also being used to design and to predict the operation of LEO satellites using heritage nickel hydrogen and new lithium ion battery cells. The designs of such systems include the consideration of many various loss factors that can have a significant impact on the operation of the EPS. In particular, the operating temperature, design life, and possible capacity losses in using a LiIon battery cell are very important considerations that must be included in the EPS design for the baseline mission. Additional attention must also be made to include the capabilities of dead bus avoidance and/or dead bus recovery. Such possible design changes may impact the design of the EPS system components and the sizing of the satellite's power systems.

Acknowledgments

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