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Battery Model for the Extreme Ultraviolet Explorer Spacecraft

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This paper describes a battery model that has been developed to predict whether the Extreme Ultraviolet Explorer spacecraft batteries will support proposed loads for user-specified time periods (usually about 2 weeks). For given orbit, attitude, solar array panel, spacecraft load, and time period, the model is able to calculate minute-by-minute values for the net power available for charging the batteries plus minute-by-minute values for the voltage, current, and state of charge. The model's calculations are explained for the beginning-of-charge, constant-voltage charging, and discharge phases. A comparison of predicted values with telemetry data shows good correlation. The model can be adapted to changing spacecraft conditions through the use of empirical data from ground tests and telemetry, and the model can be customized for other spacecraft.

Nomenclature

A, B = amplitude constants
a, b = time constants, s
c/d = (total charge supplied to the battery)/(total charge removed from the battery) per orbit
D = solar-array-panel degradation factor
eff = energy conversion efficiency factor
I = battery current, A
I_0 = battery current at the start of the constant voltage charging phase, A
L = level of operation of the battery
P = power available to charge the battery, W
P_1, P_2 = maximum power produced by each solar array panel at the beginning of the mission, W
P_{sap} = power from the solar array panels, W
P_{sc} = power to the spacecraft load, W
R = distance between the sun and the EUVE spacecraft, AU
r = internal resistance of the battery, Ω
T = temperature of the battery, °C
t = time from start of constant voltage charging phase, s
V = battery terminal voltage, V
V_{limit} = maximum voltage of the battery that is allowed by the voltage limiter, V
y = time from EUVE launch, years
β_1, β_2 = angles between the sun's direction and the normal lines of the first and second solar array panels

Introduction

THIS paper describes a C-based battery model that has been developed to simulate the behavior of the three 50-A · h nickel–cadmium batteries that support the Extreme Ultraviolet Explorer (EUVE) spacecraft in its low Earth orbit. The model was originally developed to enhance the functions of the Explorer Platform Planning System (EPPS).[1] The EPPS is a C-based expert system that is used to schedule various EUVE activities at Goddard Space Flight Center.

The question of whether a spacecraft battery is going to support a proposed load is a recurring, fundamental question on every spacecraft. Spacecraft managers, instrument engineers, spacecraft engineers, power system engineers, and operations personnel are all interested in obtaining advance determination of the power system's ability to support a given load over a specified time period. With the battery model program described in this paper, they will be able to evaluate the success (or failure) of various power system scenarios before running them on the spacecraft. In addition, the model can be adapted to changing spacecraft conditions through the use of empirical data from ground tests and telemetry (TLM) data.

The EUVE battery model described in this paper is the first application of a generic battery model that can be customized for other spacecraft. The model has recently been customized to provide a prototype battery model for the Solar Anomalous and Magnetosphere Particle Explorer (SAMPEX) spacecraft, and the model is being customized for the Fast Auroral Snapshot Explorer (FAST) spacecraft.

Model Overview

This battery model was developed as a phenomenological computer program for the EUVE battery operated in the voltage-limit mode. Important battery characteristics provided to the model include a relationship between internal resistance and time and a relationship between emf and state of charge (SOC). The first relationship was determined before the mission using test data for the Gamma Ray Observatory (GRO) spacecraft batteries. The relationship between emf and SOC was determined at the beginning of the mission using TLM data and can be updated as needed. In addition, the model is provided with initial values of the battery voltage, current, and SOC, which are obtained from TLM data before each run. Then, for a user-specified run period, the model is able to use basic equations to calculate minute-by-minute values for the voltage, current, and SOC of the battery.

As the spacecraft moves into sunlight, a beginning-of-charge (BOC) phase begins, and the battery voltage is built up to the value imposed by the voltage limiter. A user-specified run period always begins at the start of a BOC phase of the battery charging cycle and usually runs for a 2-week period. After the battery voltage reaches the limiting value, the constant-voltage charging phase begins. During the constant-voltage charging phase, the charging current is gradually tapered so that the battery voltage is kept at the specified limiting voltage. Finally, as the spacecraft moves into darkness, the discharge phase begins.

Figure 1 shows the four main components of the model. In the first component, the power available to charge the batteries is calculated. At each instant, the power available to charge the batteries is the difference between the power supplied by the solar array panels and the power absorbed by the spacecraft load. During the BOC and constant-voltage charging phases, the solar array panels are usually

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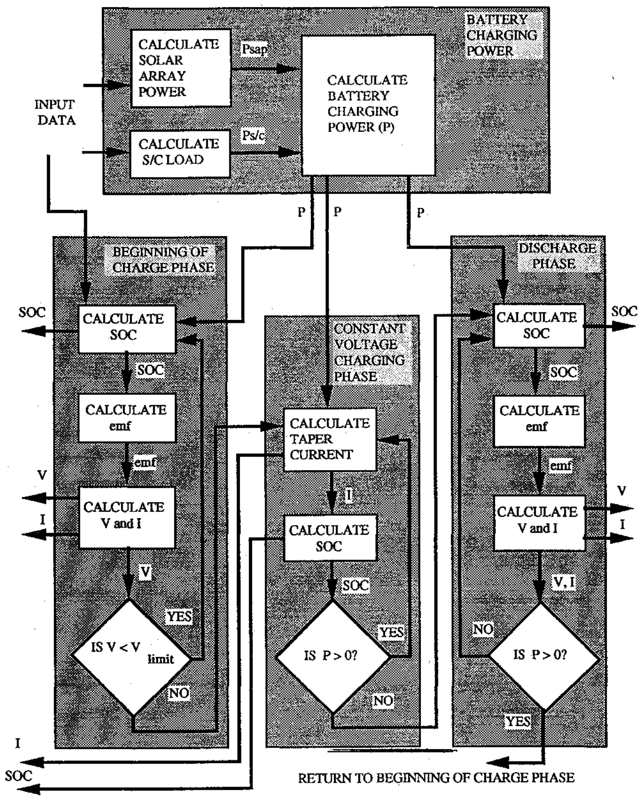

Fig. 1 Overview of the battery model.

able to provide power to charge the batteries. When this is true, the power available to charge the batteries is positive. During the BOC phase, the power to the spacecraft is limited by the solar array panels, whereas during the constant-voltage charging phase the power is limited by the voltage limiter (charge control) system. During the discharge phase, the power drawn from the battery is determined by the load, and the power available to charge the batteries is negative. The voltage and current profiles during the BOC phase and the discharge phase are driven by the battery characteristics. During the constant-voltage charging phase, the battery characteristics are not used and the voltage and current profiles are driven by the voltage limiter (charge control system). The functions and calculations of each of the four model components are described in the next four sections.

Battery Charging Power

The first quantity that the model calculates is the power available for charging the EUVE batteries. Input data for calculating the battery charging power include: start time of the run, stop time of the run, launch time for the spacecraft, maximum solar-array-panel power, solar-array-panel degradation factor, which solar array panels are operating, power conversion efficiency factors, orbit and attitude data, and spacecraft load information. The first step in calculating the power available for charging the EUVE battery is to calculate minute-by-minute values for the solar-array-panel power:

$$P_{\text{sap}} = (P_1 \cos\beta_1 + P_2 \cos\beta_2)D/R^2 \tag{1}$$

The NASA-GSFC Explorer Platform User's Guide[2] has provided solar-panel degradation information for the model. Next, minute-by-minute values for the power that is consumed by the spacecraft are calculated by combining the power consumed by all of the energy-absorbing activities, other than charging the batteries. Finally, these two power values are combined to provide minute-by-minute values for the power available for charging the spacecraft batteries.

Beginning-of-Charge Phase

Each run of the model starts at the beginning of a user-specified BOC period when the spacecraft goes into sunlight and the power

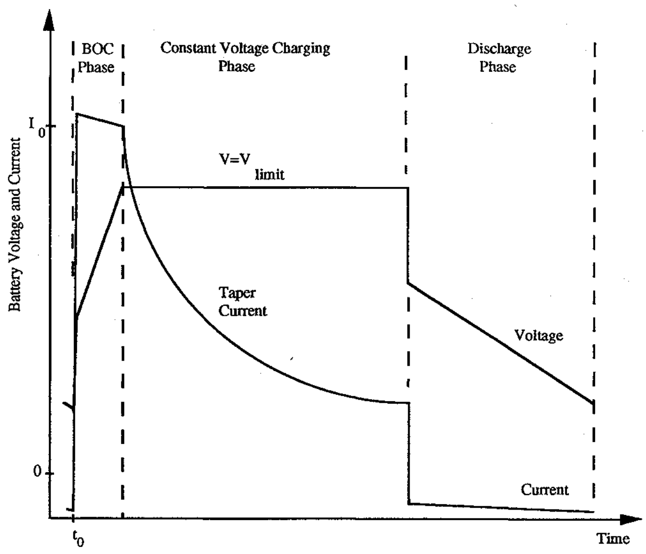

Fig. 2 Battery voltage and current over one orbit.

available for charging the battery becomes positive. First, the charging current at the start of the first 1-min interval is integrated over the interval to determine the SOC at the end of the interval. SOC is defined as the percentage of a specified charge level (e.g. 50 A · h) that the batteries have at any time. Initial values for battery voltage, current, and SOC obtained from observed telemetry (TLM) data before the run are used in the calculations for the first 1-min interval. Also, a correction factor called the charge-to-discharge ratio, which is defined as the ratio of the total charge supplied to the battery per orbit divided by the total charge removed from the battery per orbit, is applied to each 1-min interval of the charging phases to correct for the effect of charge leakage. Based on work by Madalinski,[3] the charge-to-discharge ratio as a function of the battery temperature used in this EUVE battery model is

$$c/d = 1.03 + 0.002T \tag{2}$$

Next, the empirical relationship between SOC and emf is used to calculate the emf at the end of the first 1-min interval, and the following two simultaneous equations are used to calculate the battery voltage and current at the end of the 1-min interval:

$$\text{emf} = V - Ir \tag{3a}$$

$$P = IV/\text{eff} \tag{3b}$$

A solution to these simultaneous equations for V is

$$V = \text{emf}/2 + [(\text{emf}/2)^2 + rP\text{eff}]^{\frac{1}{2}} \tag{4}$$

Finally, the value obtained for V is used to obtain the corresponding value for the current at the end of the first 1-min interval. These calculations for SOC, emf, V, and I are repeated for each 1-min interval of the BOC phase. In these calculations, the internal resistance of the EUVE battery is considered to change with time as

$$r = 0.038 + 0.022y \tag{5}$$

The relationship between internal resistance and time was based on GRO battery test data because the GRO data were available and the GRO and EUVE batteries have similar specifications.

Figure 2 schematically shows the form of the charging current and the battery voltage during one orbit. Initially, as the spacecraft goes rapidly into sunlight, the solar-array-panel power changes from zero to a positive value, which causes the battery current to change from a negative value to a positive value. As a result, the battery voltage has a jump of the order of 1–2 V, and then increases for the rest of the BOC phase. The BOC phase ends when the battery voltage has been built up to the value imposed by the voltage limiter.

Constant-Voltage Charging Phase

The constant-voltage charging phase begins when the battery voltage has increased to the value imposed by the voltage limiter (charge control system). This limiting value depends on the battery temperature and the user-specified level of operation of the battery in accordance with an equation that has been used for charge control systems on most Goddard Space Flight Center spacecraft[4]:

$$V_{\text{limit}} = 22[1.52 + 0.02(L - 8) - 0.00233T] \tag{6}$$

Here, the number 22 represents the number of series-connected EUVE battery cells, and the remaining factors in the equation pertain to the characteristics of each single cell.

During the constant-voltage charging phase, the charging current is tapered at a rate that will keep the battery voltage at the specified limiting value. McDermott[5] has shown that a double-exponential function provides a good fit with the experimentally measured taper current:

$$I = I_0(Ae^{-t/a} + Be^{-t/b}) \tag{7}$$

The parameters in the taper-current equation are adjusted empirically at the beginning of the mission to provide the best fit with the taper-current curve determined by TLM data. The constant-voltage charging phase continues as long as the power available to the battery remains positive. During this time, the charging current at the end of each 1-min interval is calculated from the double-exponential taper-current equation, rather than from the simultaneous equations used in the BOC phase, and the battery voltage has the limiting value. The SOC at the end of each 1-min interval is calculated by combining the SOC at the start of the interval with the integral of the taper current over the interval. The basic form of the battery current and voltage curves during the constant-voltage charging phase is shown schematically in the middle section of Fig. 2.

Discharge Phase

As the spacecraft moves from sunlight to darkness, the discharge phase begins and power is drawn from the battery to support the spacecraft load. First, the current is integrated over the first 1-min interval to determine the SOC at the end of the interval. Next, the empirical relationship between SOC and emf is used to determine the emf at the end of the first 1-min interval. Finally, the two simultaneous equations that were used in the BOC phase are used to calculate V and I at the end of the 1-min interval. These steps are repeated for each 1-min interval of the discharge phase.

The basic form of the battery current and voltage during the discharge phase is shown in the right-hand section of Fig. 2. Initially, as the spacecraft goes into darkness, the solar-array-panel power drops to zero, which causes the battery current to change to a negative value. As a result, the battery voltage has a drop of the order of 1 V. For the rest of the discharge phase, the battery voltage decreases steadily. The discharge phase ends when the spacecraft goes into sunlight and power from the solar array panels is supplied to the battery. At this time, the next BOC phase begins.

Comparison with Telemetry

Figures 3, 4, and 5 show comparisons between predicted and measured values for V, I, and SOC (respectively) for one complete orbit. The orbit selected occurred between 3:50 and 5:30 on day 16 of a 16-day run of the battery model program. Initial values of 28.0 V, −8.0 A and 93.0% SOC were used for the run. In these figures, the values predicted by the model are represented by solid lines and the experimentally observed TLM values are represented by individual data points with error bars. Overall, the predicted values are quite consistent with the TLM values. The small discrepancies that are observed may be due to uncertain input data provided to the model. For example, uncertain on and off times for the spacecraft heaters can cause an uncertainty in the battery current as large as 1 A per battery. In addition, discrepancies may be caused by modeling inaccuracies.

Figure 3 shows predicted and measured TLM values for the battery voltage for one orbit. The form of the voltage curve predicted by the model is seen to be generally consistent with TLM data, although the predicted values are lower than the measured TLM values by about 0.4 V during the BOC phase. This discrepancy could be due to inaccuracies in the model (e.g., the internal resistance value) or the algorithm that relates SOC and emf.

Figure 4 shows predicted and measured TLM values for the battery current for one orbit. The form of the predicted current curve is quite consistent with the observed TLM values, although there is a small discrepancy during the taper-current phase. This discrepancy could be due to an imprecise start time for the taper-current phase, which may be related to the 0.4 V discrepancy discussed in the previous paragraph. This discrepancy could also be due to inaccurate time constants in the taper-current equations.

Figure 5 shows the predicted and measured TLM values for the battery SOC for one orbit. The form of the predicted SOC curve is quite consistent with the observed TLM values, although there is a small discrepancy during the discharge phase section of the curve. The discrepancy seems to be related to an error that is magnified as the battery current is integrated over successive time intervals to obtain SOC values.

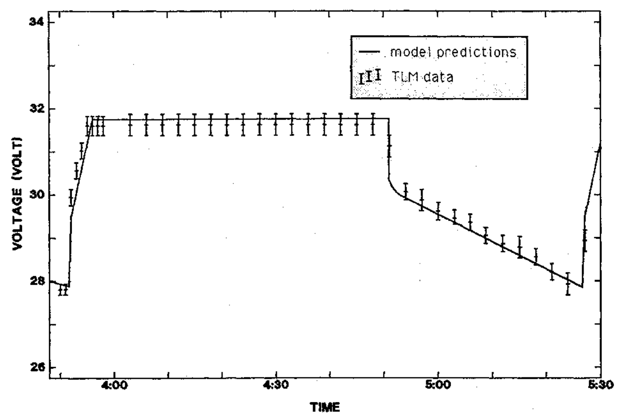

Fig. 3 Predicted and observed voltage 16 days after start time.

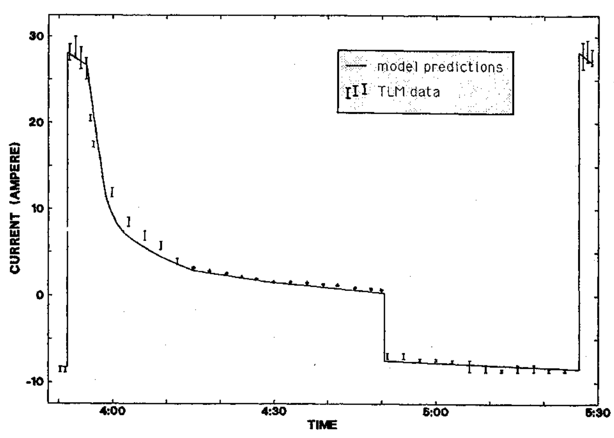

Fig. 4 Predicted and observed current 16 days after start time.

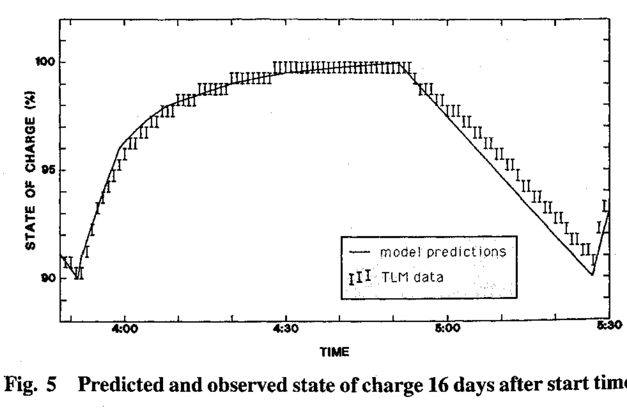

Fig. 5 Predicted and observed state of charge 16 days after start time.

Conclusions

The battery model is able to predict voltage, current, and SOC values that are quite consistent with observed telemetry data for a user-specified run period. Small inconsistencies in the results may be due to uncertain input data to the model or inaccurate parameters and algorithms in the model. The main purpose of the battery model is to predict whether the EUVE battery is going to support a proposed load, or whether a particular spacecraft load would cause the battery state of charge to fall below a safe level. Currently, there are no problems operating the EUVE batteries within safe limits. However, as the solar array panels and the batteries get older, it is expected that the model will become a more important tool for that purpose. In addition, this generic battery model can be applied to other spacecraft.

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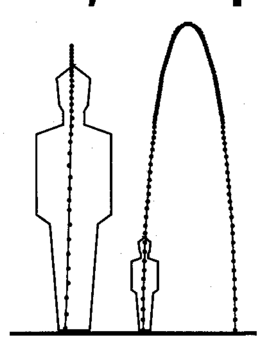

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