BUS HIGH CURRENT BATTERY MODEL

Prepared by

J. P. Kajs and R. C. Zowarka, Jr.

Presented at
The 6th Electromagnetic Launch Symposium
The Institute for Advanced Technology
Austin, Texas

April 28-30, 1992

Publication No. PR-155

Center for Electromechanics
The University of Texas at Austin
Balcones Research Center
Bldg. 133, EME 1.100
Austin, TX 78758-4497
(512) 471-4496

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J.P. Kajs and R.C. Zowarka

Center for Electromechanics
The University of Texas at Austin
Balcones Research Center, Mail Code 77000
Austin, TX 78712

Abstract: An empirical model for voltage and equivalent series resistance (ESR) has been developed for lead acid batteries used as a pulsed power source. During the design of the Battery Upgraded Supply (BUS) for Eglin Air Force Base, the Center for Electromechanics at The University of Texas at Austin (CEM-UT) developed a model for the batteries to be used in this system. BUS is a 5 MA, 500 MJ inductive power supply charged by batteries for use as a railgun power supply. There will be thousands of batteries in this system, with various configurations used to obtain the desired current levels. BUS is designed to reach peak current in a few seconds followed by a 5 s test. The batteries will individually be operated at current levels up to 2,500 A. This use is substantially different from normal battery use and little data is available on battery characteristics in this type of application.

A series of tests were performed to determine the driving voltage and ESR of the batteries for discharge times from 2 to 10 s and current levels from 500 to 2,500 A. A model for voltage and ESR were obtained from these tests. The methods used and sample data from the tests are presented. The main factors affecting battery voltage and ESR are discussed, followed by the models developed for the batteries tested.

INTRODUCTION

The Battery Upgraded Supply (BUS) for the Air Force Armament Laboratory, Eglin Air Force Base will be a 5 MA peak current, 500 MJ of inductive energy power supply. This power supply will maintain the 5 MA level for 5 s and is to be built using commercial lead acid batteries. This power supply is to be used as a railgun power supply to drive a variety of railguns. During the initial design it was determined that the electrical characteristics of the batteries would significantly affect the overall performance of the system. Reference [1] notes that for a battery model using only resistance, the resistance must be current dependent with the higher currents requiring higher resistances. Battery testing was done to determine a voltage droop function and resistance function for the 20 pair Pulsar™ batteries.

The work was supported by Air Force Armament Laboratory (AFATL/SAH), Eglin Air Force Base, contract number FO8635-90-C-0152.

COMPARISON OF BUS TO BPS

The initial Battery Power Supply (BPS) at Eglin Air Force Base was built using conventional lead acid batteries. Considerable knowledge about the operation of large high current battery power supplies has been found as a result of BPS. The BPS operates at peak battery currents up to 2,000 A [1] and at peak system currents up to 2 MA. At the high current levels the most common failure mode of the batteries is inter-cell connections [2]. Since the battery failures had become more prevalent during later high current testing, a battery which eliminates the inter-cell connections (the Pulsar™ battery) was chosen as the primary choice for the BUS. A drawing of a Pulsar™ battery is shown in Fig. 1. The Champion Switch™ automotive battery is a commercially marketed Pulsar™ battery. The Pulsar™ batteries can be made with various numbers of pairs: the more pairs the larger the battery. A 20 pair Pulsar™ battery was chosen mainly because these were the largest Pulsar™ batteries which would fit comfortably in the existing battery trays. The internal resistance of the present BPS batteries is in the range of 3.5 to 5 mΩ [1]. The manufacturer quotes an internal resistance of approximately 2.5 mΩ for the 20 pair Pulsar™ batteries [3].

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Fig. 1. Pulsar™ Battery Construction

EMPIRICAL BATTERY MODEL

The two most relevant battery characteristics from battery literature are internal resistance and practical discharge capacity. Practical discharge capacity is defined as the time or coulomb amount at which the terminal voltage of a battery falls below a given voltage under a constant current load [4]. Capacity is dependent on construction, maintenance, age, current level, temperature, and history of use. The only equation for capacity which has found wide application is Peukert's equation which is:

$$I^n t = C$$

where I is battery current, t is time, and n and C are empirically derived constants determined from discharge data. For small currents n approaches 1 and for large currents n approaches 2 [4]. These batteries will not be used in a constant current mode. However, as long as the current levels over which the model is concerned can be considered large the rate of voltage droop should be proportional to t^2 .

Since a significant portion of battery modeling is done using empirical models, the derivation of an empirical model was the logical method for obtaining the BUS battery model. To ensure the relevance of the model for the intended use, the testing was performed at current levels and time intervals close to those which the BUS will operate. These models should be good for 20 pair Pulsar™ batteries used at roughly 500 to 2,500 A and from 2 to 10 s.

There are a fairly large number of factors which affect the battery characteristics. An incomplete list of these various factors follows. A possible numerical model is given for each of these factors. The models all have unknown coefficients which must either be analytically derived from the individual battery construction or empirically derived. If one were designing batteries for pulse power duty rather than just modeling existing batteries, then a more detailed test program and model would probably be desired.

Factors Affecting Battery Voltage

1) *Changes Due to Discharge.* For an individual cell, the voltage can be calculated from

$$E_h(mV) = 676.26 - 73.595x - 30.531x^2 - 30.552x^3 - 12.054x^4$$

where

$$\begin{aligned} E_h &= \text{cell voltage} \\ x &= \log(m_2) \text{ where } m_2 \text{ is molality of sulfuric acid [4]} \end{aligned}$$

This is a fairly complicated expression. However, it becomes more complicated because the molality at the electrodes is the important parameter. As a result of the water diffusing away from the electrodes after the chemical reaction occurs, a diffusion process is also occurring. Due to this, the Peukert model has been tried.

$$dV = -K_1 \int I^n dt$$

where K_1 and n are to be derived experimentally.

2) *Battery Temperature.* As the temperature of the electrolyte increases the cell voltage increases according to the equation [4]:

$$E_t = E_o + aT + bT^2$$

where

$$\begin{aligned} E_t &= \text{temperature dependent voltage model} \\ T &= \text{temperature of battery} \\ a, b &= \text{temperature coefficients dependent on electrode and electrolyte materials} \end{aligned}$$

The temperature is a result of the heat of the chemical reaction and ohmic heating. The amount of reaction is dependent on coulombs extracted. The reaction is endothermic so it absorbs heat.

$$dT = -K_2 \int Idt$$

For small changes in temperature the resistance of the battery is approximately constant. Heating is then proportional to I^2 , so

$$dT = -K_3 \int I^2 dt$$

However, as discharges are performed even at levels of 1 to 10 A, the batteries heat up. Thus, at levels of hundreds of amps, the cooling can be ignored.

$$dV = K_4 \int I^2 dt + K_5 \int I^4 dt$$

3) *Polarization Voltages.* A lumped sum of the diffusion overvoltage, reaction overvoltage and crystallization overvoltage. These will decrease the useful battery voltage but again the function is unknown, however a current dependent change is expected.

$$dV = -f(I)$$

Factors Affecting Battery Resistance

1) *Electrolyte Concentration.* As the electrolyte decreases in concentration the resistivity increases for sulfuric acid solutions near the concentrations at which batteries are operated [5]. For small changes in concentration:

$$dR = K_6 \int Idt$$

2) *Battery Temperature.* As the electrolyte temperature is increased the resistivity decreases for sulfuric acid. The lead and connectors increase in resistance with increased temperature. From other tests the battery resistance decreases with increased temperature. For small changes in temperature, the change in resistivity is linear with a change in temperature [8], this can be approximated as:

$$dR = -K_7 \int I^2 dt$$

3) *Sulfate Formation.* As the electrochemical reaction takes place, non-conducting lead sulfate is formed at the surface of the electrodes and thus creates a smaller cross-sectional area for the current to pass through at the surface of the plates. For small percentages of the electrode area covered:

$$dR = K_8 \int Idt$$

Models to be Derived

$$V_{model} = V_{init} - K_1 \int I^n dt + K_4 \int I^2 dt + K_5 \int I^4 dt - f(I)$$

$$R_{model} = R_o + (K_6 + K_8) \int Idt - K_7 \int I^2 dt$$

Measurements for Empirical Model

To determine a valid model, a set of tests were performed with the Pulsar™ batteries. Since the BUS will operate at peak current for 5 s and will take approximately 4 to 5 s to reach peak current, a nominal battery discharge should last 10 s. The tests were done for 15 s to stress the batteries beyond their normal expected duty. The test setup is shown in Fig. 2. The switch is an ordinary automotive starter contactor with a metal oxide varistor (MOV) in parallel to absorb the arc upon opening to reduce contact wear. The contactor was opened and immediately closed 5 times during the test to measure the internal battery voltage as the test progressed. A schematic identifying the measured parameters is shown in Fig. 3. The assumption was made that the internal battery voltage labeled V_{int} in Fig. 3 cannot change instantaneously since it is dependent on the charge separation of the two electrodes and can only change as a

Fig. 2. Schematic of Measurements Taken During Tests

Fig. 3. Schematic of Measurements Taken During Tests

result of diffusion and a chemical reaction. Therefore, the battery voltage at the instant when the current goes to zero was taken as the driving voltage. To determine the internal resistance, this driving voltage minus the voltage just prior to switch opening is divided by the current. Fig. 4 shows a typical set of battery current and voltage signals taken during one of these interruptions with V , V_{int} and I marked.

$$R = \frac{V_{int} - V}{I}$$

As can be seen from Fig. 4 the battery voltage rises a significant amount in the approximately 120 ms which the contactor is open. The voltage increase is caused by the diffusion process of the acid toward the electrode surface and is larger for the higher current tests. The difference in current prior to opening compared to after reclosing is

Fig. 4. Sample Voltage and Current Measurements During Interrupt

measurable, however the contactor resistance is not exactly the same for each closure. Fig. 5 shows a typical test for the entire 15 s test period. These tests were done with various load resistors to obtain results at approximately 500, 1,000 and 2,000 A. These models are based upon approximately the first 100 tests performed on the batteries. These first 100 tests consisted of approximately 17 tests on three of the batteries and six tests on each of the other 15 batteries. Most of the testing was performed at the higher current levels since the peak performance of the BUS uses the batteries at the higher current levels.

Empirical Voltage Model

The initial estimate was that the battery voltage would decrease linearly with the charge removed from the battery. This corresponds to $n = 1$ in the Peukert equation. With a

Fig. 5. Sample Battery Test Measurements

Fig. 6. Voltages Measured vs. Coulombs Output.

constant current drawn from the battery, the voltage does drop approximately linearly with time. This would suggest a voltage model which followed the following function

$$V = V_o - K \int Idt$$

The voltage data shown in Fig. 6 is somewhat difficult to interpret by itself. To aid in developing the model, a running average of the voltage vs. coulombs was performed to give a set of representative voltage vs. coulombs curves. Fig. 7 shows the running averages for the data taken during the 500, 1,000, and 2,000 A tests vs. coulombs removed with a straight line which approximates the 2,000-A tests. The curves in Fig. 7 are derived directly from the data plotted in Fig. 6.

Fig. 7. Running Averages of Voltages vs. Coulombs

This model was deemed inadequate because though the voltage droop was approximately linear with coulombs, the slope of this droop was current dependent. Different values for the constants would be necessary for the different current levels. When it was observed that the voltage decreased faster for the higher currents, it was decided to try the other extreme of the Peukert equation, $n = 2$, thus

$$V = V_o - K \int I^2 dt$$

An action integral normally involves the integral of I^2 with respect to t and is often used in heating and melting calculations for fuses. Fig. 8 shows the voltage plotted vs. the action.

Fig. 9 shows the running average of the voltages vs. action plotted with the a curve fitted voltage model. For the range of test conditions which were observed during this testing, the following model seems to accurately describe the battery voltage

$$V_{model} = 11.85 - 21.67 \times 10^{-9} \int I^2 dt$$

The temperature dependent part was not included because a good temperature measuring technique has not found.

Empirical Resistance Model

Battery resistance is temperature dependent. The batteries heat up measurably during the tests, but since battery resistance drops with an increase in temperature, a decrease in resistance would be expected during the tests. Since the resistance increases during the tests, the other factors such as changes in electrolyte concentration and sulfate formation are more dominant factors. These both indicate that the resistance should change as a function of coulombs out of the batteries.

Fig. 8. Voltages vs. Action.

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Fig. 9. Running Averages of Voltages vs. Action

The data shown in Fig. 10 shows that the resistance for 500, 1000, and 2000 A all fall approximately along the same curve. If the resistance is plotted vs. action, the data for the different current levels begins to split into three distinct groups as the voltage data does in Fig. 6. The battery resistance model was derived as

$$R_{model} = (2.35 + 35 \times 10^{-6} \int I dt) \text{ m}\Omega.$$

This model is shown with a running average of the resistance in Fig. 11.

7201.0089

Fig. 10. Resistance vs. Coulombs.

Measurement Errors

The digitizers used for measurements are rated as accurate within $\pm 0.5\%$ of full scale. For the voltage ranges used, this gives the voltages as accurate within ± 0.1 V. For the currents, the accuracy is ± 24 A. The base CVR calibration is 1% as well.

Fig. 11. Resistance Average and Model vs. Coulombs.

The voltage data shown in Fig. 8 falls mostly within this ± 0.1 V error band. The change in open circuit voltage is mainly due to a decrease in electrolyte concentration at the plate surfaces. Because the overall electrolyte concentration is changed very little during these tests, the voltage rises as the electrolyte concentration equalizes. This voltage rise is faster as the measured voltage decreases which adds more error for the measurements further to the right in Fig. 8.

The measured resistance errors can be estimated for a 500 A discharge assuming a 2.5 mΩ actual resistance.

$$V_{closed} = 12 - (500)(2.5m\Omega) = 10.75 \text{ V}$$

$$R_{measured} = \left[\frac{(12 \pm .1) - (10.75 \pm .1)}{500 \pm 24} \right] \pm 1\% \\ = (2.53 \pm .52) \pm 1\% \text{ m}\Omega$$

The resistance data shown in Fig. 10 falls mostly within a ± 0.5 mΩ error band. There are additional errors which are due to the voltage rise mentioned earlier which can account for most of the other points.

During testing, the resistance of the batteries decreased from near 2.4 mΩ at the beginning of the test program to near 1.8 mΩ after 30 to 40 high current discharges. The current into the same resistive load increased significantly from the beginning of the test program to the end of the test program. The resistance model was a moving target which depended

upon how many tests had been performed on a battery. The battery resistances were expected to decrease during our testing period as the electrodes became more porous. The option of adding more test data and effectively filtering out errors was not feasible due to time constraints. After the resistance model was derived, the voltage and resistance models were combined and the performance of the resultant battery model was compared to actual battery test data. The model was developed using the data from the early tests and as a result, the model performed well compared to the early tests. Because battery resistance dropped by approximately 25% from the early tests to the later tests, the model consistently underpredicted output current and terminal voltage when the model was compared with data from later testing. It was decided that to ensure that the BUS would reach its design goals, the initial higher resistance battery model would be used during initial system design. Use of this battery model in the design of the BUS resulted in an increase in the number of batteries required to obtain system goals over a simpler 2.5 mΩ resistance model.

CONCLUSION

An empirical battery model has been developed to model a Pulsar™ 20 pair battery for the BUS. The model can be used to predict the performance of Pulsar™ batteries as long as the currents are around 500 to 2,500 A and the timeframes are from 2 to 10 s. This model should be capable of being expanded to other sizes of Pulsar™ batteries once the scaling equations are verified. The model can probably also be extended to other types of lead acid batteries operated under high current conditions if the constants for the equations are empirically derived.

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