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IMPROVED PERFORMANCE AND SAFETY FOR HIGH ENERGY BATTERIES THROUGH USE OF HAZARD ANTICIPATION AND CAPACITY PREDICTION

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ABSTRACT

Prediction of the capacity remaining in used high rate, high energy batteries is important information to the user. Knowledge of capacity remaining in used batteries results in their better utilization. This translates into improved readiness and cost savings due to complete, efficient use. High rate batteries, due to their chemical nature, are highly sensitive to misuse (i.e., Over discharge or very high rate discharge). Battery failure due to misuse or manufacturing defects could be disastrous. Since high rate, high energy batteries are expensive and energetic a reliable method of predicting both failures and remaining energy has been actively sought. Due to concerns over safety the behavior of lithium/sulphur dioxide cells at different temperatures and current drains has been examined. The main thrust of this effort was to determine failure conditions for incorporation in hazard anticipation circuitry. In addition, capacity prediction formulas have been developed from test data. A process that performs continuous, real-time hazard anticipation and capacity prediction has been developed. [1] The introduction of this process into microchip technology will enable the production of reliable, safe and efficient high energy batteries.

INTRODUCTION

Each year millions of dollars are spent on lithium batteries for use in portable electronics equipment. Because of their superior rate capability and service life over a wide variety of conditions, lithium batteries are the power source of choice for many equipment applications. There is no convenient method of determining the available capacity remaining in partially used lithium batteries; hence, users do not take full advantage of all the available battery energy. In order to maintain readiness, users currently replace batteries on a conservative schedule. This practice results in the waste of millions of dollars in battery energy every year. In addition to the inability to determine the remaining capacity, high rate batteries are highly sensitive to misuse. To preclude this, safety devices are currently included in battery packs. Generally batteries contain three safety components: electrical fuses, thermal fuses and diodes. The electrical fuse protects the cells from sourcing too much current, the thermal fuse protects the battery pack from excessive heat and the diode shields primary cells from being charged. Charging primary cells can have catastrophic results. These devices are passive and provide maximum protection for all discharge scenarios, limiting the capabilities of the battery by imposing worst case protection for all discharge conditions.

It is a well documented and accepted that the available capacity in a lithium battery is a function of the conditions that the battery has been subjected. Capacity remaining is a complex function of current drain, temperature and time. Therefore a reliable method of predicting remaining capacity has been actively sought. [2-7] External devices are available for most battery systems. However these devices are, in many cases, not portable and imprecise. Therefore a continuous internal means of determining remaining capacity is desirable. Lithium/sulphur dioxide cell behavior at different temperatures and current drains have been examined. This examination has resulted in the establishment of discharge efficiency formulas. [2] Utilization of these formulas has given rise to a capacity prediction algorithm. In addition the safety aspects of electrochemical systems are a priority. [8-10] The concern over safety has lead to the incorporation of safety devices into batteries. [8] To achieve the full power potential of high energy batteries the development of active safety devices has been examined. Batteries are less tolerant to misuse the deeper they are discharged. Knowledge obtained through safety testing incorporated into microelectronics technology allowed the development of active safety devices. These devices designed to anticipate and detect hazardous conditions allow for increased power loads to be placed on the battery without the fear of failure.

EXPERIMENTAL

Lithium/sulphur dioxide cells, produced under government contract, were discharged at various temperatures and discharge rates. Cell discharge included typical as well as abusive conditions. Tests were temperature controlled using a Blue M, Model 1004-3B environmental chamber. Discharge rates were controlled using an internally fabricated constant current electronic load. This electronic load was designed to be a constant current load without forced discharge or external power supply aid. Test conditions were continually monitored and controlled with an ACROSYSTEMS Acro-400 data acquisition and control unit in conjunction with a personal computer. Acquisition and control software was internally generated. Temperature, discharge rate and cell voltage were continually recorded for analyses.

Typical discharge rates ranged from 0.02 $mAmp/cm^2$ to 10 $mAmp/cm^2$. This normalized discharge rate allowed for different cell sizes to be compared. The tests were conducted in temperatures between -40°C and 70°C. Cells were subjected to constant current discharge, pulse discharge and intermittent discharge. During pulse and intermittent discharge, conditions were varied as well as kept constant. Cell discharge capacity was determined at a two volt per cell cut off. The lithium/sulphur dioxide electrochemical system has an open circuit voltage of three volts. Cell discharge efficiency, determined by the ratio of delivered capacity to theoretical capacity, is graphically represented in Figure 1. [2] This set of curves can be described by a surface represented by Equation 1.

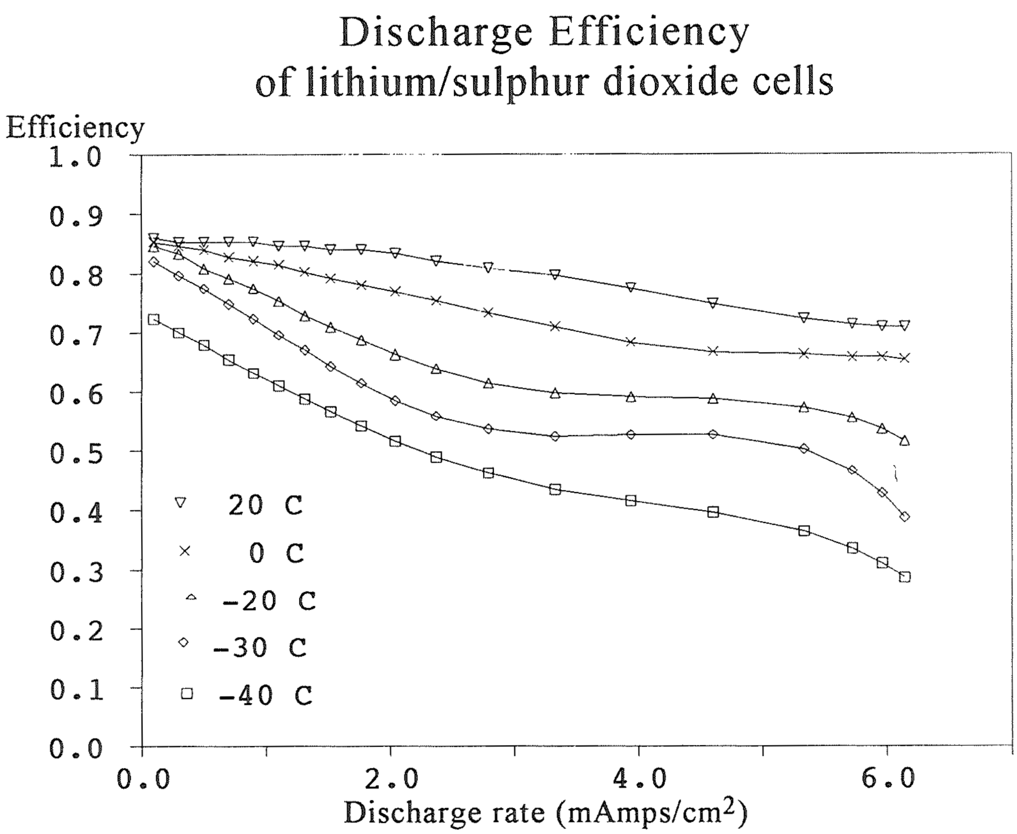

Figure 1. Graphic representation of relationship between discharge efficiency, temperature and constant current discharge rate for lithium/sulphur dioxide cells.

$$Ed = \sum_{x=0}^{3} \sum_{y=0}^{3} C_{x,y} \cdot i^x \cdot T^y$$

Equation 1. Polynomial fit of the surface relating discharge efficiency (*Ed*) to discharge current (*i*) and temperature (*T*).

Charging, forced over discharge and high current discharge are examples of abusive discharge conditions. These conditions generally lead to cell failure and were performed during the safety analysis. [10] Typical cell failure involves the opening of the cell's vent. In addition partially discharged cells were interrogated using DC pulse measurement and AC impedance spectroscopy using an impedance spectroscopy measurement system. The impedance spectroscopy measurement system included a Hewlett Packard HP9836 computer, a Schlumberger 1286 Electrochemical Interface and a Schlumberger 1250 Frequency Response Analyzer. [3] The effects of discharge rate, depth of discharge and temperature on cells were observed through the response to this stimulation. Data obtained during all tests were used to develop a capacity prediction algorithm as well as hazard anticipation circuitry.

DESIGN

The remaining capacity of batteries is often determined by a simple technique that monitors the coulombic drain (Amperes·seconds) from the battery. This information tells the user the capacity removed from the battery. When this information is subtracted from nominal capacity, remaining capacity can be determined. This technique is valid when discharge conditions remain constant. Variation in battery efficiency due to discharge conditions can result in large errors. Since discharge conditions of a battery are continually changing, it is desirable to utilize battery discharge efficiency on a continual basis. Designed capacity prediction circuitry calculates effective capacity removed from a battery based on discharge efficiency on a continual basis. In order to calculate effective capacity removed discharge rate, temperature and time must be determined. [2]

The voltage drop across a resistor is used as a current sensor. Unfortunately, there is valuable power wasted in the resistor when this approach is used. Another approach to monitor the battery's current drain is to use one of the components already incorporated in the battery. Using the diode as the sensor is not recommended because connecting anything across the diode would prevent the diode from performing its protective function. The voltage drop across a fuse is a function of the current passing through it and its ambient temperature. However variation in the fuse can cause calculation errors. Therefore a resistor with a value as low as possible is used.

The voltage across the resistor will be relatively small and must be amplified in order to bring it up to levels that can be processed. In addition the voltage drop will fluctuate, due to varying discharge loads. Therefore to maintain accuracy it is extremely important to continuously monitor the voltage across the resistor and store this information. One method of capturing this voltage is to use an integrator that would sum up the voltage over time. This summation represents an average current therefore the integration time should be minimal. The integrator can be of either analog or digital design; however, an analog integrator is far simpler to implement. An inexpensive method of integrating a voltage is to use a pair of PNP transistors and configure them as a conventional differential amplifier. A constant current source is needed to prevent changes in cell voltage from effecting the data being collected. Besides amplifying the resistor's voltage, the differential amplifier converts the voltage to a current. This current is used to charge a capacitor. The voltage developed across the capacitor represents capacity removed and is sensed by a comparator. The comparator and processor converts the analog voltage to digital data. [4]

The capacitor and resistor used in the circuit are tuned such that a threshold voltage represents one coulomb capacity removed. The capacitor is discharged by a switch controlled by the processor whenever the threshold voltage is achieved. This cycle is repeated each time one coulomb capacity is removed from the battery. An internal clock is used to record time for each cycle. Temperature data is acquired similarly, however amplification is not necessary. A current source whose output is a function of temperature is commercially available and inexpensive. [4]

The processor calculates current by calculating the ratio of one coulomb and the time required to perform the integration cycle. With current and temperature information the efficiency of the reaction can be calculated. Adjusted capacity removed (one coulomb/efficiency of reaction) is subtracted from the pervious capacity remaining, this value represents the current capacity available. For processors with limited computing power a look up table can be utilized without adding significant error. [1,4]

A control feature added to the processor enables hazard anticipation to be performed. This control requires the addition of voltage sensors across each cell and control elements within the battery. Example control elements include: micro controlled current suppressers and electronic fuses. A routine utilizing capacity remaining, temperature, discharge current and cell voltage is used to control the use of the battery. Examples of typical control include:

1) Allowable discharge current reduced as available discharge capacity decreases.
2) Load disconnected from battery when internal temperature reaches a preset level, allowing the battery to cool off.
3) Load permanently disconnected from load when the voltage of one cell in the battery drops below a preset level.

A simple version of battery control uses passive safety devices and an active safety device that permanently disconnects the battery from any load when hazardous conditions are detected.

Incorporated in the design is the ability to output to the user the information gathered and stored by the processor. A light emitting diode readout positioned on the battery will display to the user the remaining capacity in the battery. In order to conserve battery energy this readout is activated by a switch located on the battery surface. In addition a continual digital readout using the battery connector will output data to equipment. This output will allow for a real-time indication of the abilities of the batteries without removing the battery from the equipment. This output requires the equipment to have the ability to read and decipher the signals being outputted from the battery. [1]

Battery data output is achieved using a NMOS FET open drain with the source grounded. The serial data output has one start bit followed by eight data bits. The most significant bit of the data will be first and the data will represent a two character hexadecimal word. This hexadecimal word is used as a code that represents battery condition. Table 1 contains a listing of data codes and their meanings. In the output logical "0" is represented by high voltage and logical "1" is represented by low voltage. The data output will be provided every second at a bit transfer rate, in the order of, 800 bits per second. [1]

HEX CODE	INDICATION
00	00 percent capacity remaining in battery
01	01 percent capacity remaining in battery
...	...
0A	10 percent capacity remaining in battery
...	...
64	100 percent capacity remaining in battery
...	...
70	User activated shutdown
71	Battery group 1 cell 1 failure
72	Battery group 1 cell 2 failure
...	...
7A	Battery group 2 cell 5 failure
7B	Battery group 1 fuse activation
7C	Battery group 2 fuse activation
...	...

Table 1. Partial listing of output codes for a ten cell battery pack configured in two five cell strings.

Processor controlled circuitry that incorporates hazard anticipation, remaining capacity indication and data output has been designed. This circuit contains hardware and software for determining remaining capacity and control. The hardware is controlled by software, this makes the design suitable for different electrochemical systems and battery configurations.

RESULTS AND DISCUSSION

Breadboard circuits were fabricated to test the validity, accuracy and operation of the design. The breadboard allowed for quick software changes to accommodate different cell configurations. The breadboards incorporated both hazard anticipation and passive safety devices. Operation tests were performed using 'D' size and '1/3 C' size lithium/sulphur dioxide cells. Cell configuration included: Two five cell strings discharged in parallel and one, five and ten cell strings discharged in series. During discharge temperature, voltage and current were monitored independent of the circuitry. Discharge conditions for the validity checks were the same as described in the experimental section of this paper. Discharges were halted at random depth of discharge.

To evaluate the operation of the hazard anticipation, single cell and multi-cell batteries were stressed with known failure modes. Tests were considered successful when the circuit disconnected the battery and no cells within the battery vented. Evaluation of the capacity prediction algorithm was performed by recording the predicted remaining capacity of partially discharged batteries. The batteries were then discharge at a rate of 5 mAmps/cm^2 at 25°C. The capacity delivered was then compared to the capacity of a fresh battery at this discharge condition. The fresh battery capacity was determined by a twenty battery average. The results of this comparison is shown in Figure 2. Figure 2 shows a prediction error of ±5% with a median value slightly skewed to the negative. A negative error denotes a low capacity remaining prediction. [2]

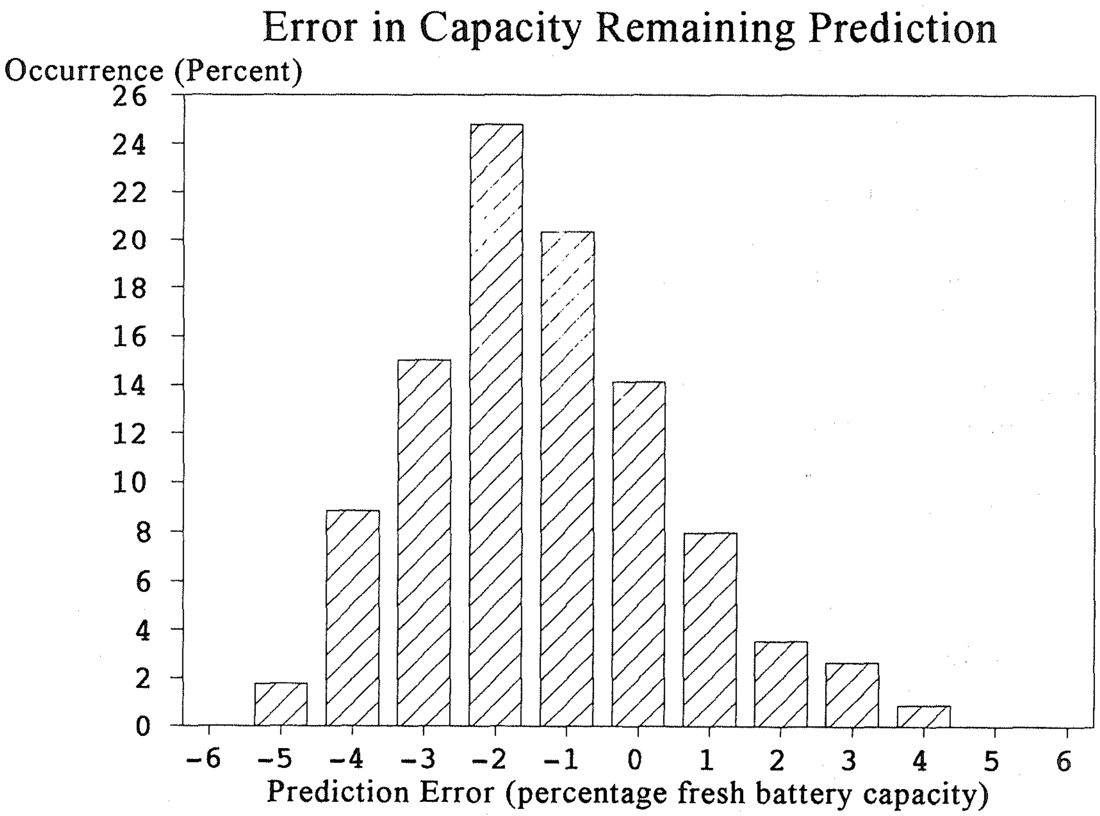

Figure 2. Distribution of error in capacity remaining prediction.

Data output capability was performed using a developmental radio. Tests showed that the data supplied from the battery was able to be read and interpreted by the radio. The radio was then capable of displaying this information to the user. These results combined with the low capacity remaining prediction error and successful hazard anticipation results shows that the incorporation of hazard anticipation and capacity prediction provides the means for more efficient utilization of battery energy by the user.

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