BATTERY FAILURE PREDICTION

Manfred R. Laidig and John W. Wurst
BTECH, Inc.
Whippany, New Jersey

INTRODUCTION

The weak link in a standby battery-based emergency system is the battery. The batteries referred to here are either flooded(wet) cell type, or the valve-regulated type (VRLA). These batteries are typically used to power UPS systems, switchgear, oil pumps, telephone central office, outside plant areas, etc. They are used in processing plants, by utilities, financial institutions, transportation companies, in telecommunications, government offices, and the military. The battery is typically the last line of defense against total shutdown during power outages.

Experience has confirmed that storage battery failures cause more down time and service calls on emergency power systems than any other component. How can users be sure that their last line of defense, the backup battery, is sufficiently healthy to carry the intended load?

Until recently, the commonly used method to determine battery and cell health was to perform a load test. Although reliable, this method has proven to be cumbersome, time consuming, expensive, and risky. An alternative to load testing is the impedance comparison method. The technical basis description follows including test data.

BTECH Inc. has developed an on-line battery monitoring system which can detect developing battery, cell and cell interconnection problems before they can cause system failure. Comparison between individual measured cell impedance and the system average correlates with the ability to predict cell and system performance. Trended data, collected over time, permits this predictive technology to be automatically performed, and allows ample time for corrective maintenance to assure system up time.

DETERMINING BATTERY HEALTH - WHAT CAN GO WRONG?

Failure mechanisms in the backup battery power system are numerous and varied. They are driven by a host of external and internal influences. Manufacturing defects in new batteries sometimes avoid detection at the factory.

Table 1 Causes of Premature Battery Failure

Failure Mechanism	**Wet**	**VRLA**
Jar Case Cracks	X	X
Specific Gravity Changes	X	X
Electrolyte Level/Dryout	X	X
Excessive Temperature	X	X
High Cycling Rates	X	X
Defective Post Seals	X	X
Strap Corrosion	X	X
Plate Sulfation	X	X
Plate Growth (Dendrite Shorts)	X	X
Plate Deterioration/Separator Problems	X	X
Post/Connection Hardware Problems	X	X

Reversed plates, plate separation, seal separation and cracked cases have been reported. In the installation process, the installer could improperly torque connections causing damage to the case or a seal. The installer can also connect a cell in reverse, improperly crimp a connection, omit non-oxidizing grease from a joint and spill acid. When in service, high cycling rates leading to premature end of life conditions are common in UPS applications. Environmental conditions play a part in battery longevity with cell dry-out of VRLA batteries as a common failure mode. Table 1 summarizes

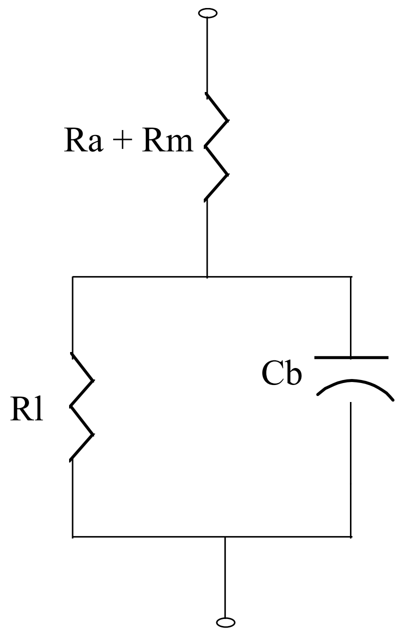


Figure 1 Model Battery Circuit

some of the causes of premature battery failure.

Is it possible to detect present and developing problems in battery backup systems early enough to allow corrective action? Can the total battery system be healthy and fully operational when called upon?

BATTERY TESTING AND PREDICTIVE ANALYSIS

Until recently, the accepted method of determining the health of a battery system was to disconnect it from service and perform a load test. Although the load test is an excellent method for use in determining the recent state of battery health, it does not provide ongoing protection for critical systems in between load tests. Typically, the load test requires a resistor bank and a method of measuring the voltage of each cell. Under load, cell voltage will decay at a rate proportional to the cell's health. Weak cells show early signs of voltage decay and at a greater rate. This voltage decay characteristic correlates very well with expected performance. The disadvantage of the load test, however, is that it is labor intensive and cannot be performed with the batteries on-line. Consequently, the test is infrequently performed. It is not uncommon to delay such testing beyond the IEEE 450 practice of five year interval discharge testing!

Given the above, it would appear advantageous if there were a way to perform continuous measurements of key battery parameters with the battery system on-line and collect this data automatically. Is there technology which would permit the automatic analysis of data and allow the prediction of failure before it occurs?

THE IMPEDANCE METHOD

Any device through which an electrical current will flow exhibits an impedance to that flow. In a lead-acid storage battery it happens that the dissipative or resistance portion of the impedance is the dominant factor, while the reactive portion is capacitive. Because the capacitor is so large, the capacitive reactance is quite small. Therefore, the terms "resistance" and "impedance" are sometimes used interchangeably when discussing batteries.

THE CIRCUIT

The generic representation of a battery circuit is illustrated as Figure 1. The metallic resistance incorporating terminal post, strap, grid and grid paste is represented as Rm. Ra is the resistance of the electrochemical path comprising the electrolyte and separator. The capacitance of the parallel plates is represented by Cb and roughly measures 1.3 to 1.7 Farads per 100Ah of capacity. This in turn is shunted by a non-linear resistance contributed by the contact resistance of plate to electrolyte. Although more sophisticated models exist, this illustration will suffice as reference material for the following discussion.

When measuring the resistance of a lead-acid cell by AC methods, the precise number obtained is influenced by the AC frequency used to make the measurement. However, below 1000 Hz, the differences are small. By the use of an on-line impedance monitor, it is possible to look for changing cell float voltage and cell impedance values which signals that the internal cell is changing. Given this type of application, the user doesn't care whether the impedance number the monitor returns exactly matches the number obtained by a manually operated diagnostic impedance test sets. The on-line monitor will be comparing any given measurement, either with the average of all the measurements made at that time or with the same cell's base line value measured months or years earlier. Therefore, long term stability is very important as an indication of cell performance and health.

BTECH equipment uses 220 Hz as the measurement frequency and, with the help of some filtering, avoids the effects on the measurements of the power frequency and its harmonics. Other manual diagnostic instruments use different frequencies and will get slightly different numbers, but there is no known significance to these differences. DC methods of impedance testing should be avoided since they require a significant discharge from the cell in order to obtain repeatable readings. This results in a long measurement cycle, if done manually, since the battery string must recover before moving to the next cell. Float condition measurements with an AC measurement device have proven to be the most consistent and repeatable method to date.

Impedance values will change but the reasoning may be different for flooded and for valve-regulated cells. For instance, resistance increases as the charge is depleted, or as the specific gravity drops. Resistance also changes inversely with temperature. These characteristic are the same for both types of cells. On the other hand, a flooded cell can lose a lot of water (through dissociation and loss of hydrogen & oxygen) before its resistance will rise noticeably, whereas a "starved electrolyte" cell can lose very little water before a significant resistance change begins to signal that something is wrong.

Similarly, when heavy charging causes gas bubbles to form in a flooded cell, the resistance rises because the effective plate area has been reduced temporarily, but the pressure regulating valve in the "maintenance-free" cell makes bubble formation difficult, so little effect on resistance is seen in this type of cell from this cause.

VRLA cells provide unique challenges as to how their "health" can be ascertained.

- First, the specific gravity cannot be measured.
- Second, the need for water cannot be visually observed, nor can water be added.
- Third, many aspects of cell deterioration that are visually diagnosed in flooded cells, because their cases are usually transparent, are denied in valve regulated cells because these containers are opaque.

In VRLA cells, diagnosis and correction are relatively simple. When the resistance rises more than a selected percentage above the average:

- Check the cell connections, and clean and re-torque as necessary.
- If the connections are OK, determine if an equalizing charge (used very sparingly on VRLA cells) is permissible, or individually charge this one cell.
- If no permanent improvement is obtained, replace the cell (or unit). It is either drying out or some metallic aspect of the cell is deteriorating. No other corrective action is possible.

As an aside, it should be noted that the float voltage of VRLA cells tends to remain within the manufacturer's acceptable limits; even when the cell has serious problems. Cell voltage under stabilized float conditions is an unreliable indicator of a cell's health or condition! VRLA cells also tend to float at their self prescribed level. The use of cell balancing techniques will depolarize the cell in order to make the numbers correct but do little for the performance level. If the battery string is healthy impedance wise, the proper float current will maintain the cells.

Flooded cells' resistance anomalies are more difficult to analyze because more factors influence the readings and because more options are available for correcting the problems.

- Cell connections are always suspect and even more so in flooded cells because post seals tend to be less effective. Also normal venting of the cell leads to acid spills causing external corrosion. Check, clean and retorque connections as necessary.

- Avoid taking impedance readings for perhaps 36 hours after an equalizing charge. The higher voltage charge will generate gassing along with bubble formation on the plates and lead to biased impedance measurements.
- Consider that uniform float voltage is a necessary but insufficient condition for cell health. Generally, if it is below 2.17 volts, the specific gravity (and therefore charge level) will be low, requiring equalizing or separate cell charging. When this cell has returned to normal voltage and has stabilized for some hours, measure its impedance and compare with other cells. If it is still out of line, consider replacing the cell.
- Visually inspect the cell for corroding internal plate interconnects, for plate distortion, for excessive shedding of active material accumulating at the bottom of the cell, etc. These conditions naturally register an increased resistance.

As a practical matter, temperature effects may play a minor role. Many battery rooms are climate-controlled to prevent loss of battery life from overheating and loss of battery capacity from cold temperatures. Where the temperature is quite uniform, the method used to trend impedance values is not critical. However, for installations where the battery is subject to significant temperature swings, the average comparison method is recommended because it eliminates effects of temperature. All the cells should be within a few degrees of each other during the brief time of a measurement cycle. While their resistance may go up and down in response to daily temperature changes, the cell impedance values relative to each other will be maintained.

The following are some examples of impedance changes as functions of charge level - temperature, physical distress (cell freezing), capacity reduction of two cells in a group of six cells, and one cell's deterioration in a six-cell unit.

RECHARGING VRLA CELLS

While the level of charge is not necessarily a measure of health, it certainly is a measure of how ready the battery is to supply the amount of energy expected of it. With this said, the change of cell impedance with cell charge is interesting.

Two NP38-12 batteries were allowed to become discharged to the point where their impedance was maximum. Because these are VRLA cells, bubble formation is minimal, and therefore relatively accurate impedance measurements can be made while the batteries are charging.
Figure 2 shows each unit's impedance as energy is returned. Note that the two curves are different for any same value of returned charge. Since the two units were being charged in series, an attempt was made to bring Unit #1 to a lower final impedance value by separately charging it over a longer period of time. The result was unsuccessful and the final values remain essentially as shown on Figure 2.

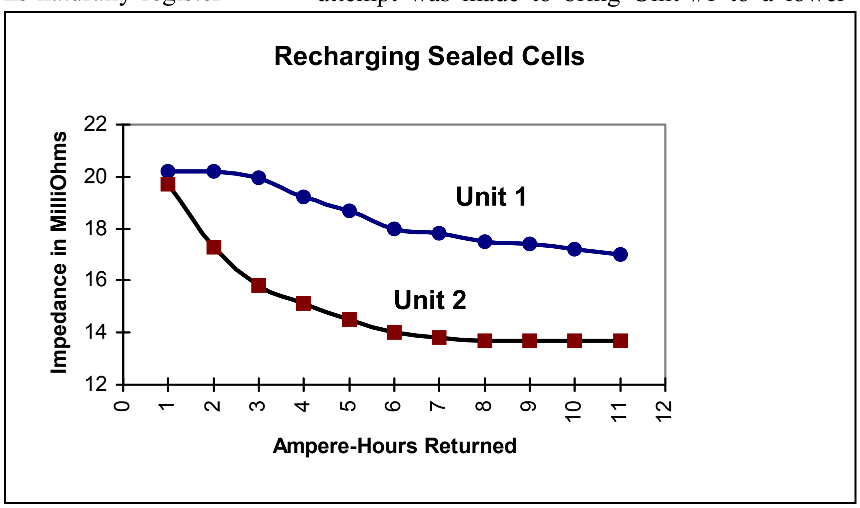


Figure 2 Recharging Sealed (VRLA) Cells

We conclude that Unit #1 is seriously degraded (it was part of a string discarded after years of service). In addition to the impedance evidence, we have observed that Unit #1 voltage drops much more rapidly than Unit #2 during use in sales demonstrations. While this condition provides interesting observations during demonstrations, Unit #1 could no longer be used in a battery backup system because it will not carry its fair share of the load.

EFFECT OF CELL TEMPERATURE ON IMPEDANCE

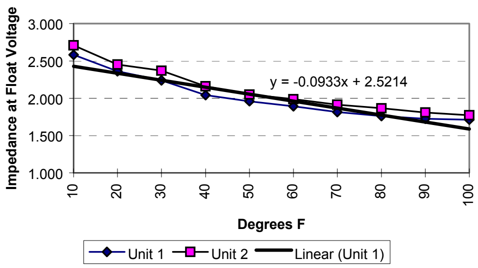


Figure 3 Effect of Temperature on Impedance

If an absolute value for impedance is desired, it is necessary to correct for temperature of the electrolyte. To avoid this, the impedance in a string of cells can be averaged and a comparison made of any one cell against the group average. This approach is valid if the assumption that all cells increase and decrease in temperature together is valid. Under these conditions, impedance values corrected for temperature are unnecessary; only relative values are important.

If a temperature correction is required, Figure 3 illustrates a pair of VRLA units studied in a thermal chamber. The temperature was varied between 10 and 100° F (-12 - 38°C) with sufficient time for stabilization. As the temperature approached the lower temperatures, the impedance change was more pronounced while the warmer temperatures provided a slower rate of change. The linear portion of the curves falls within the normal environmentally controlled temperature range and a trend line is supplied for Unit 1 values. The resulting equation can be used for temperature corrections if required. It is cautionary to note that this curve is for an absorbed glass mat VRLA module and temperature-impedance response will differ for gelled electrolyte product.

It can also be seen why, for rated performance and warranted life, battery manufacturers want their products to reside in a place where the temperature remains within a small range around 25 degrees C. As a rule of thumb, battery life is cut in half for every 10 degree rise above 25 degrees C since the activity of the electrolyte increases (indicated by the decrease in impedance). In the other direction, the battery becomes increasingly incapable of discharging its energy to an external load due to its own impedance increase. Charging current, especially under float conditions, must be compensated as well to avoid over-charging at elevated temperatures or under-charging at low temperatures.

TESTS ON A DAMAGED 3-CELL BATTERY

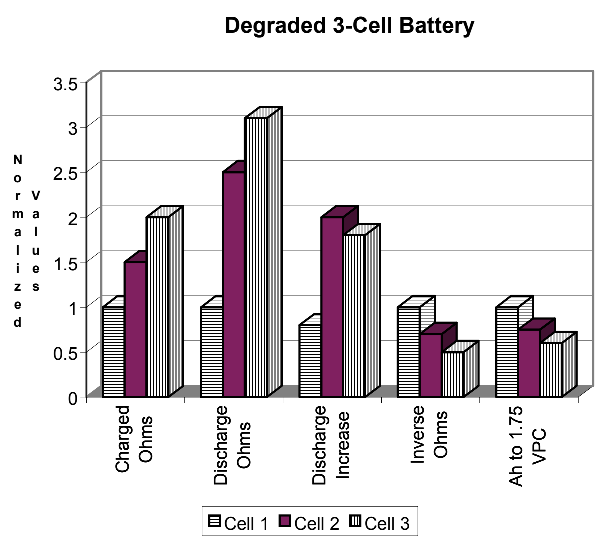


Figure 4 Degraded 3-Cell Flooded Battery

An obviously damaged 6-volt flooded battery of the automotive type was tested to demonstrate the relationship between impedance and health, including available capacity. We suspect that the battery, while in a discharged state, was allowed to freeze. The case around Cell #1 appeared normal while the case and sealant around the other two cells was severely distorted. Electrolyte level was just below the tops of the plates in all the cells.

First, water was added to bring the electrolyte to the full level. Then the battery was charged, first slowly, then at a recommended rate for its size. Finally, it was allowed to float at 6.75 volts for several weeks. Cell voltages and specific gravity equalized of their own accord.

The test program was begun by making impedance measurements with an impedance monitor. The relative values are shown in Figure 4 by the bars labeled "Charged Ohms". Next, load was applied at about an 8-hour discharge rate. The ampere hour delivery to 1.75 volts for each cell is shown by the set of bars labeled "Ah to 1.75 VPC". The adjacent set of bars labeled "Inverse Ohms" facilitates comparison of impedance with capacity. Finally, the impedance was measured again and shown as "Discharge Ohms".

Manufacturer's impedance data on this battery was not available. We suspect that Cell #1 was in relatively good condition, as its impedance and delivery were reasonable for the dimensions of the cell. In addition, from full to end-of-charge, its impedance increased about 80%, which experience says is within the normal range. Therefore, the other two cells are compared against Cell #1 as the "standard".

Note the relative impedance of Cells #2 & 3 both before and after discharge. Not only do "bad" cells exhibit higher fully charged impedance values but the increase with decreasing charge is also greater - in this case, 2.5 to 3 times greater (labeled "Discharge Increase" on the graph).

Note also that, under this relatively benign discharge load, the delivered capacity was commensurate with the reciprocal of fully charged impedance. It is suspected that internal cell interconnections may have been damaged by the same conditions that distorted the case, and that therefore under very high discharge currents Cells #2 & 3 would have reached 1.75 VPC relatively more quickly. The delivery of charge above 1.75 VPC would then have been even less than demonstrated in the subject test.

DESCRIPTION OF VRLA

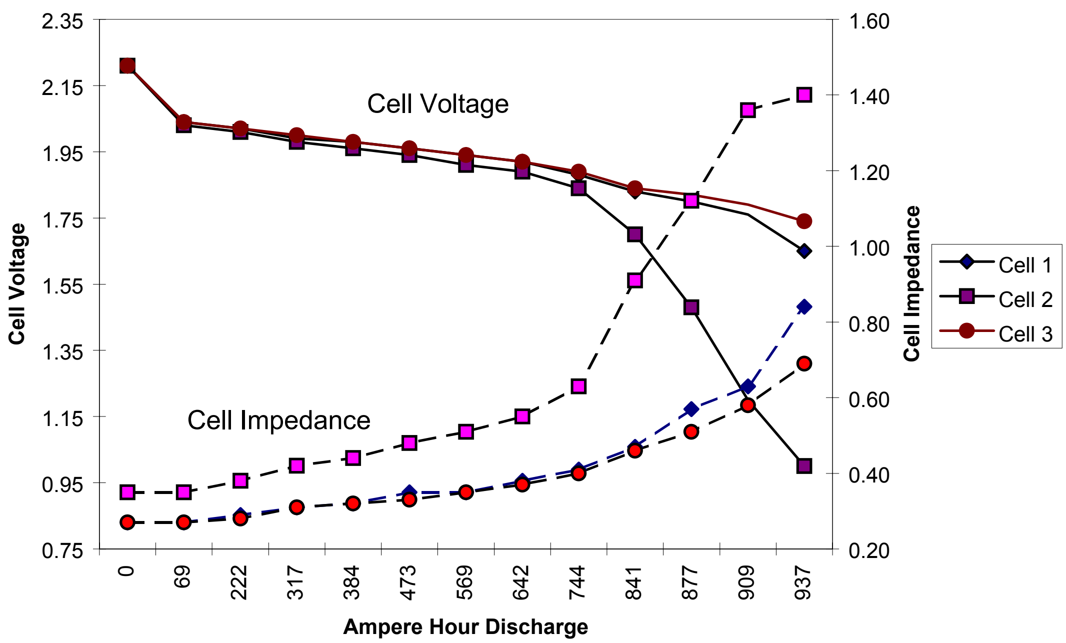


Figure 5 VRLA Discharge Test Units 1-3

DISCHARGE TEST

The purpose of this test was to observe the correlation of impedance under stabilized float charge conditions with a cell's capability in a battery string to contribute its fair share of voltage while delivering its charge. Prior to a discharge test, this six-cell VRLA unit was float-

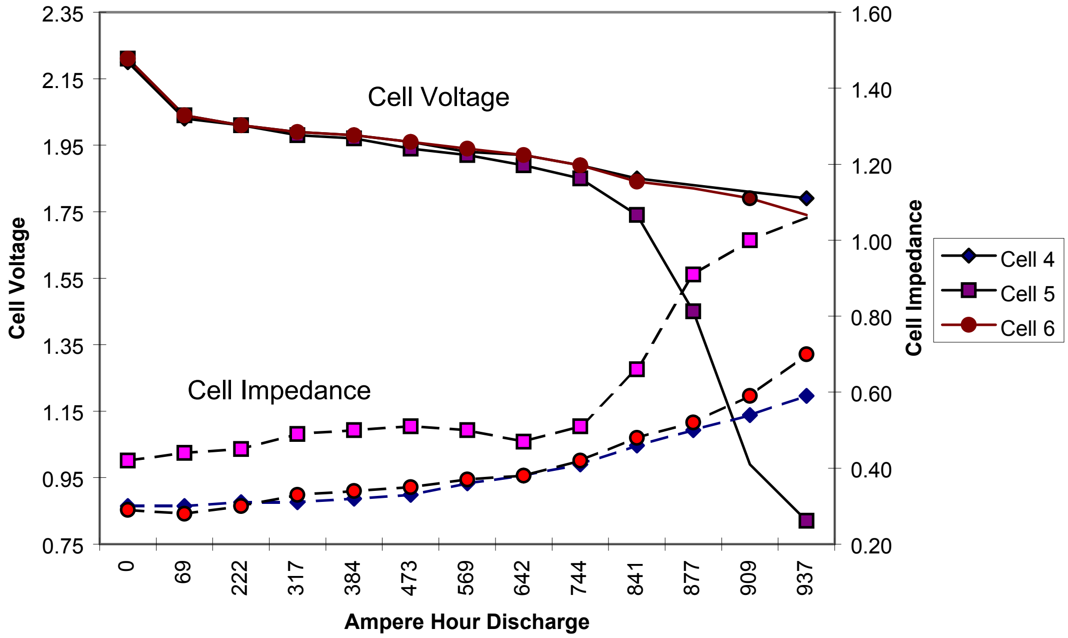


Figure 6 VRLA Discharge Test Units 4-6

stabilized. While in this condition, connections to the impedance monitor were made such that each of the cell's impedance could be measured separately from the impedance of the interconnecting bars and their interfaces with the cell posts.

Cells #2 and 5 (refer to Figures 5 & 6) revealed themselves initially by demonstrating impedance values more than 15% above the other four cells. Note that the voltage of all the cells, both initially and for about 40% of the test duration, remained within a small band. After that point, cells 2 & 5 were progressively less able to sustain their terminal voltage under load until, all cells reached the usual "end-of-charge" voltage of 1.75 volts. Note also that the "weak" cells exhibited a much greater impedance at 1.75 VPC than the "good" cells. While the performance of cells #2 and 5 could only be described as "weak", the attached UPS would have been unable to sustain load for the prescribed maximum duty cycle. A typical user could elect to delay replacing these two cells for, perhaps, another few months. The impedance increase predicted that significant degradation was in process before the situation reached the critical point.

LOAD TEST OF A SIX-CELL VRLA UNIT

A load test was performed on a 12 volt VRLA module. This unit was marked for testing because its impedance in a battery string was 36% higher than the string average. Just prior to discharging at an 8-hour rate, this unit was floating within the manufacturer's specification.

Figure 7 shows the loss of voltage contribution by one cell about one quarter of the way through the discharge. The other cells continued to deliver normally until they had supplied about 40 Ah. Thereafter, they too began a more rapid decline. It should be noted that this was not a constant current test, and that the current was always less than the 8-hour specified current. Therefore, the results make the battery appear to be better than it actually was. Had the UPS to which it was connected required a complete charge to be delivered in, say, 15 minutes, the "bad" cell probably would have reversed polarity

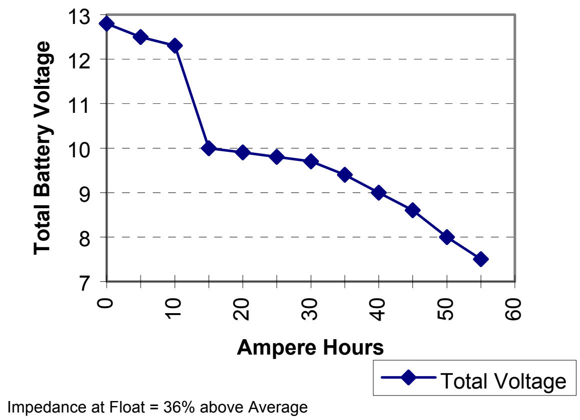


Figure 7 Load test of 6-Cell Battery

and become an energy sink instead of an energy contributor.

THE BATTERY VALIDATION SYSTEM MONITOR

BTECH Inc., an engineering and manufacturing company formed from ex-Singer Company engineers, developed a battery monitor to validate emergency backup battery systems. The challenge was to alert key personnel on developing problems in sufficient time to allow corrective action to be taken. The Battery Validation System monitor (BVS) uses predictive cell impedance technology. Measured data is automatically evaluated, trended, and compared to preset limits. Trending allows the user to extrapolate critical values and flag developing problems before they cause critical shutdowns. The BVS monitor thus "predicts" that a specific problem will occur in the future. It identifies the problem area as well as the specific cell involved. Assuming the user initiates corrective action when first alerted by the BVS of an impending problem, the battery system will always remain in good working shape. Those whose responsibility it is to keep uninterruptable power supply (UPS) equipment powered during power-out emergencies, can be assured that the battery will perform as designed. It is a well understood fact that the frequency of power disruptions is increasing. Many of these disruptions, although short in duration, result in significant loss to those who rely on continuous uninterrupted power.

Large sums of money are spent annually to inspect and test batteries and their connections. It is in this scenario that BTECH's patented BVS monitor comes to the rescue. With it, the user can be assured that the battery is always available to deliver. No longer does the user need to rely on human intervention to determine the condition of the battery. Like a robot, the BVS automatically and on a pre-determined schedule validates the battery system. Major operational losses can thus be prevented. Since it is automatic, the chance for human error is omitted. The Battery Validation System monitor is designed as an on- line monitor, permanently connected to the battery string. Round the clock protection is thus possible. Since it is on-line, it can detect power outages or "events" of less than one second. During these outages, the BVS tracks the voltage decay of the entire battery string and that of each individual cell while under load. The measured voltage decay data is automatically polled, stored in memory and sent to a remote PC for analysis and graphing.

For alarm purposes, measured values can be preset and tailored to suit the profile of each battery system. Once set, the BVS is password-protected to prevent accidental changes in the alarm levels. The BVS will alarm whenever any of the preset values are exceeded. For example, if the impedance level of any individual cell and interconnection exceeds the default limit (set in terms of percent above the others, usually 15%), the impedance alarm will light. Similarly, if any cell voltage exceeds or drops below the default window set for cell voltage, the BVS will go into alarm, etc. The BVS will alarm on any measurements which fall outside of acceptable preset values. The BVS monitor interrogates the battery string once every minute. At the one minute interval, total battery voltage, room ambient temperature and pilot battery case temperature is checked. Cell voltages and cell/interconnection impedance are measured on a predetermined cycle, usually once a week. More frequent measurements are not necessary. Since the BVS will always alarm on cataclysmic changes such as thermal runaway temperatures, power outages, and high or low system voltages, it is not necessary to continually look at impedance values. Impedance values usually do not change rapidly. Apart from impedance fluctuations caused by factors already mentioned, the average increases are a result of a gradual deterioration and occur over time. Consequently, once a week readings are sufficient to detect developing cell and connection problems. In the event of an alarm, dry contact switches are available which permit remote annunciation. The BVS Observer® software which is available with the BVM 2.0 for Windows® reports alarm conditions to the designated PC and initiates autopolling during power outage situations. The cause for the alarm can be determined from the BVS' LED display, and/or from the on-site printer, or alternately from a remote PC. In summary, the BVS includes the following features:

- Continuous on-line monitoring of total battery voltage, local ambient and battery case temperature.
- Monitoring, at intervals or on demand, terminal voltage of each cell or unit, impedance of each cell or unit including cell interconnects, to assure system capacity to deliver specified power.
- Alarm on any of the above when limits are exceeded.
- Battery and cell voltage decay data collection during power outages.
- Monitoring capacity to 256 cells and 750 volts.
- Remote interrogation capability via modem interface to PC computer
- "Event" recording capability.

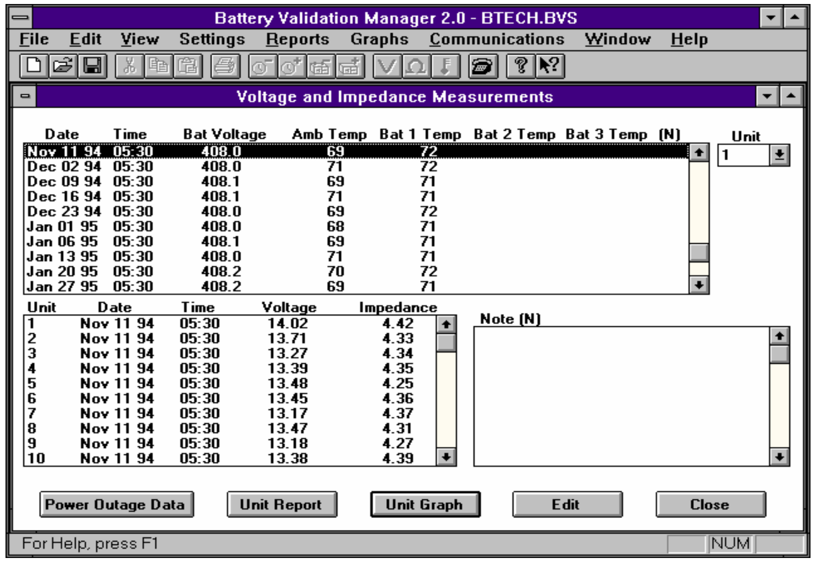
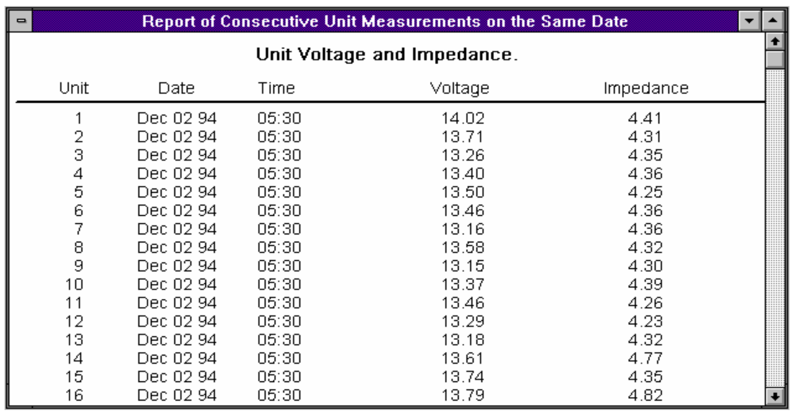


Figure 8 BTECH BVM "Results Screen"



Report of Consecutive Unit Measurements on the Same Date

Unit Voltage and Impedance.

Unit	Date	Time	Voltage	Impedance
1	Dec 02 94	05:30	14.02	4.41
2	Dec 02 94	05:30	13.71	4.31
3	Dec 02 94	05:30	13.26	4.35
4	Dec 02 94	05:30	13.40	4.36
5	Dec 02 94	05:30	13.50	4.25
6	Dec 02 94	05:30	13.46	4.36
7	Dec 02 94	05:30	13.16	4.36
8	Dec 02 94	05:30	13.58	4.32
9	Dec 02 94	05:30	13.15	4.30
10	Dec 02 94	05:30	13.37	4.39
11	Dec 02 94	05:30	13.46	4.26
12	Dec 02 94	05:30	13.29	4.23
13	Dec 02 94	05:30	13.18	4.32
14	Dec 02 94	05:30	13.61	4.77
15	Dec 02 94	05:30	13.74	4.35
16	Dec 02 94	05:30	13.79	4.82

Figure 9 BTECH BVM Tabular Report

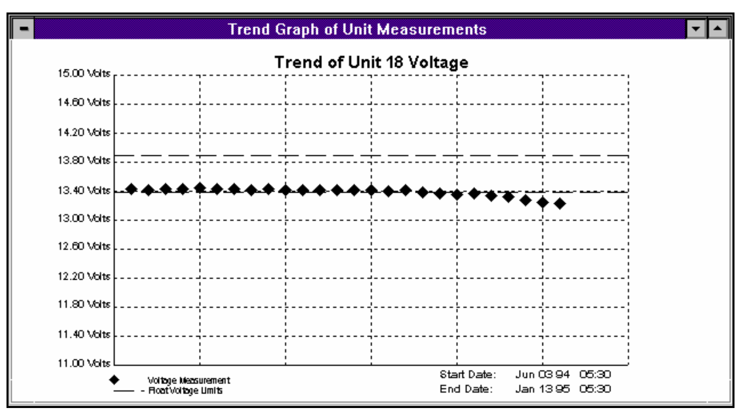


Figure 10 BTECH BVM Voltage Trend

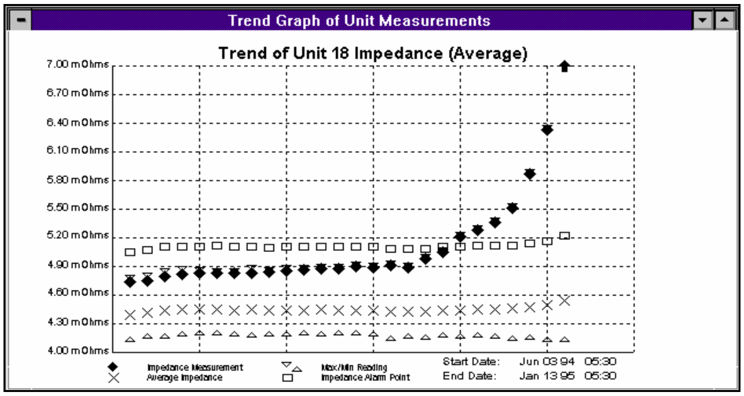


Figure 11 BTECH BVM Impedance Trend

The "Result Screen" shown as Figure 8, provides a listing of all battery data captured, which the user can select for further analysis. Selected data can be presented in report format or observed as interactive graphs. Figures 10,11 and 12 are a representative sample of the graphs available with the BVM 2.0 software for typical data collected from a UPS battery system.

Summary

In summary, in an environment where the frequency of power disruptions are increasing, the need for a reliable backup battery system is important. As an alternative to periodic "load testing" of cells, impedance measurements can become a valuable tool to determine the "health" of a battery system's cell, as well as the external interconnections between cells. Test data presented demonstrates the viability of the impedance method. Absolute values are not as important as relative values. Trending information allows the maintenance provider to compare one cell verses another through a common system history. Since cell impedance values do not change rapidly, unless discharging, measured data will show a deterioration trend which will permit the user to determine developing problems before they cause his critical backup system to fail.. □

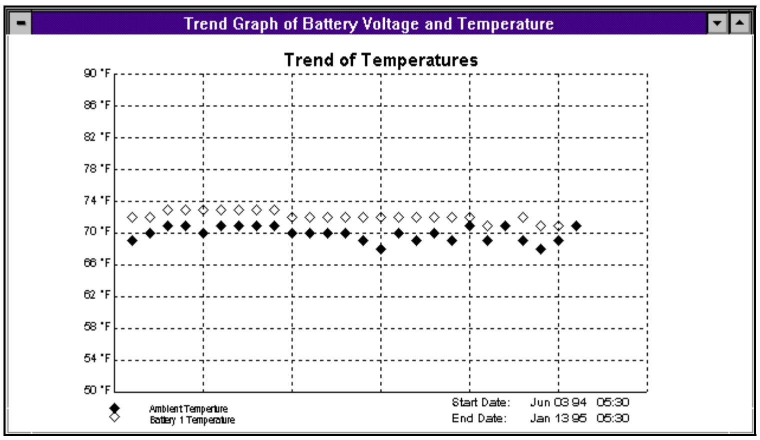


Figure 12 BTECH BVM Temperature Trend

Measurement Information

Battery String and Unit Measurement Averages

Battery Voltage
Battery Voltage: 408
Battery within limits.

Unit Voltage

Average Unit Voltage:	13.64	
Maximum Unit Voltage:	14.03	Unit: 1
Minimum Unit Voltage:	13.20	Unit: 9
Number within Voltage Limits:	15	(50%)
Number above Upper Voltage Limit:	8	(26%)
Number below Lower Voltage Limit:	7	(23%)

Unit Impedance

System Average Impedance:	4.44	
Maximum Impedance:	4.87	Unit: 18
Minimum Impedance:	4.21	Unit: 30

String 1 Average:	4.44	Suggested Startup		
String 1a Average:	4.36		Multiplier:	102
String 1b Average:	4.51		Multiplier:	98
String 1 Max Impedance:	4.87	Unit: 18		
String 1 Min Impedance:	4.21	Unit: 30		

Figure 13 BTECH BVM Measurement Information