A GUIDELINE FOR THE INTERPRETATION OF BATTERY DIAGNOSTIC READINGS IN THE REAL WORLD

Bruce A. Cole – Director of Marketing
Robert J. Schmitt – Team Leader Telecom/Power Controls
GNB Technologies
Lombard, IL

Abstract

Over the past 15 years, the stationary battery market has seen a significant trend of deployment of products into applications that are remote and in many cases, harsh. Parallel to this trend has also been a sharp increase in the usage of Valve Regulated Lead Acid (VRLA) batteries and a desire on the part of the end user to reduce the overall maintenance costs of the system. In response to these factors, a market has emerged for the use of diagnostic tools that are intended to predict the integrity of the battery systems before network reliability is compromised. These diagnostic tools measure internal battery impedance, conductance or resistance (collectively referred to here as "ohmic") values and seek to make a judgement about the battery state of health. A major issue in the use of these tools however, has been the interpretation of data they generate and how to apply it to realistic expectations given the capability and limitations of the equipment. This paper will examine the topic in general terms by looking at data collected on new cells, cells artificially aged, and real world data, with the intent of providing a set of guidelines for making battery maintenance decisions. In addition, a more in-depth analysis will be provided to quantify trends with respect to types of failure mechanisms.

Introduction

The development of the VRLA battery system has proven to be useful for many stationary applications. It has resulted in an overall reduction in the amount of maintenance required and has allowed the deployment of batteries into situations where space and access are limited. In fact, in many of these situations the use of traditional flooded lead acid cells or batteries would not be possible.

However, with the advent of this technology there has been much debate about life expectations and the ability to assess the state of charge of battery systems without the need for a capacity test. Capacity testing of any battery, flooded or valve regulated, can be cumbersome, time consuming, and expensive. In some remote applications, the logistics of performing such testing can be challenging if not impossible.

In response to such market needs, a number of electrical test equipment suppliers have developed and marketed tools for examining the state of health of battery systems by measuring internal ohmic values. They have then correlated this data to the available capacity of the system. Correlation of these ohmic values to true battery capacity and health has been controversial. It has been the position of many that the only way to measure the true capacity of a lead acid battery is by performing a discharge test. However, there is also a growing consensus that diagnostic measuring devices can be used to trend the state of battery health and determine whether a system may be within a "failure zone". This failure zone can be defined as a significant shift in ohmic values that would correlate to 80% or less of the published rating.

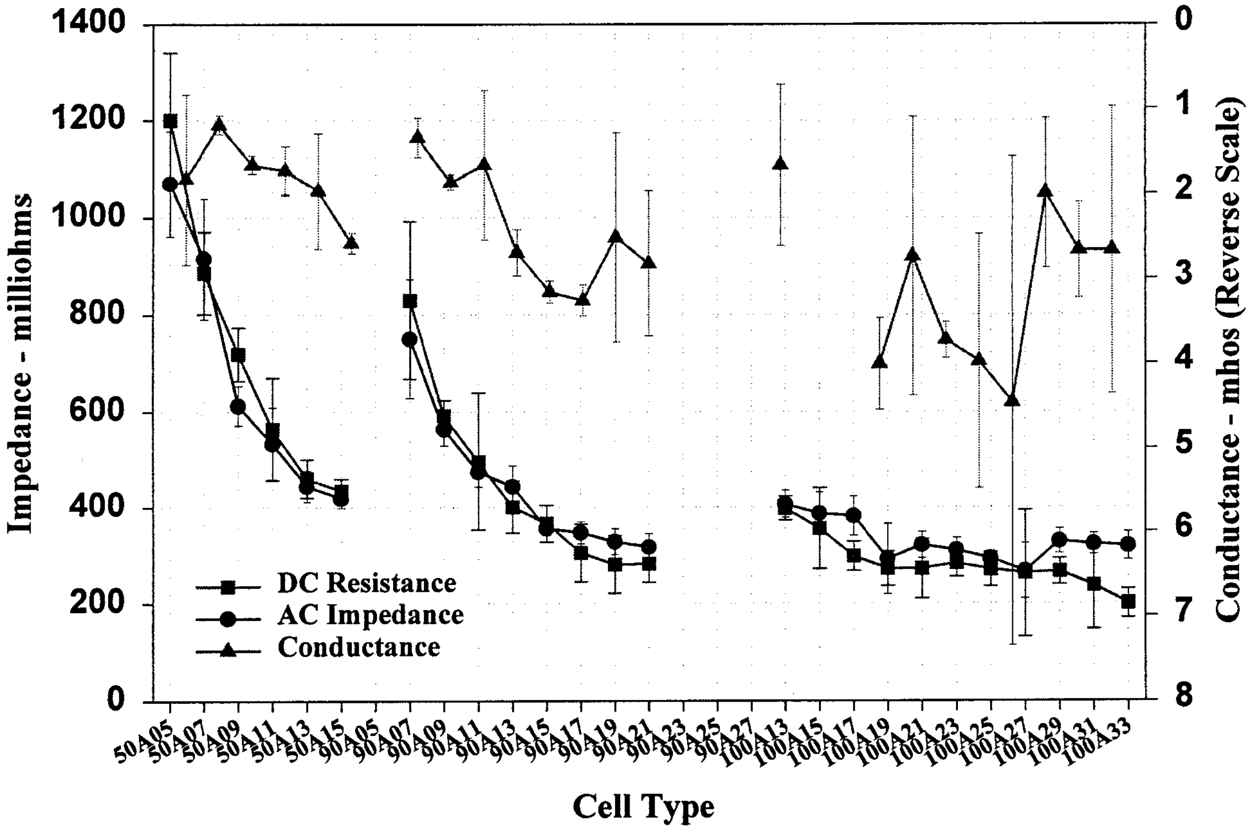
It is the purpose of this paper to look at data collected over several years with the intent of understanding what types of failure mechanisms may be detected with such measuring devices and what are realistic and meaningful shifts in the actual values.

Baseline Values

A piece of information often requested by battery users from manufacturers is the "baseline" value of all battery or cell types produced. It is perceived that this data can then be used to help determine battery state of health by comparing measured field values to the provided baseline numbers. A predetermined ohmic value shift, the theory goes, would imply low capacity.

There are a number of inherent difficulties with this approach. A few of these are; type of technology (impedance, dc resistance, and conductance), meter manufacturer, repeatable placement of measurement probes, and actual spread in the true baseline readings. In order to evaluate these variables, GNB began a collection of baseline readings on the Absolyte IIP product range. The study consisted of equipment made by three different manufacturers that employed three differing ohmic technologies (impedance, dc resistance, and conductance). Over 500 cells were measured with each device at the GNB factory in Kankakee, IL. Each cell measured had passed an in plant capacity test and was representative of typical fully charged cells that would be received by an end user. A test engineer took and recorded all measurements. See Figure 1 below for a summary of the data.

Figure 1: Preliminary Baseline Ohmic Measurements



As can be seen there is a reasonable trend in the data with the impedance and resistance declining (and conductance increasing) as the cell sizes, and thus ampere-hour increase. Shown on the chart are error bars that depict the variability in readings among a data set. An analysis of the data yielded a 3 σ deviation (from the mean) of 10%, 16%, and 25% on cells for impedance, resistance, and conductance measurements respectively. The authors acknowledge that over the initial 6 to 12 months in operation, the ohmic variation may decrease as the cells reach full states of charge and optimal levels of gas recombination.

The conclusion from this data is that when setting standards for concern regarding a battery's state of health, there can easily be a 10-25% range of variation on healthy, new, cells at full capacity.

Impedance as a function of State of Charge

In relating battery state of health to internal ohmic measurements, it is fundamental to ask how the predictive variable changes with respect to state of charge. In other words, if a healthy, new battery was discharged, what is the relationship between its ohmic values and depth of discharge?

A study was run on a 12 volt Absolyte IIP (90A11/440 Ah) battery where the cells were discharged at the 8 hour to 1.75 vpc rate. During the discharge the ac impedance of the cells was measured at 20-30 minute intervals to determine how the values changed as a function of the level of discharge. In Table 1 below, the summarized results are presented. As can be seen, after 103% of the total Ah capacity was removed the average impedance of the string increased 122%. However, at the point where 50% of the total ampere-hour capacity was removed, the average impedance had increased only 7%! This value actually falls within the total variability on new healthy cells. It is not until the cells have had 75% of the total ampere-hours removed that the impedance shifts by as much as 25%. In fact it takes over 90% of the ampere-hours to be removed for the impedance to increase 50%.

Table 1: Impedance vs. State of Charge

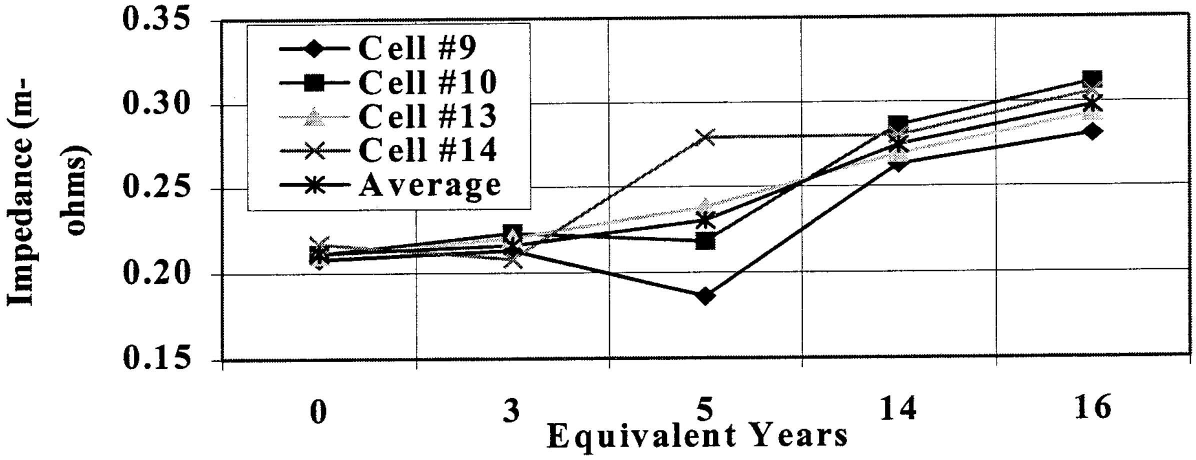
Ampere-Hours Removed	% Depth of Discharge	Average Impedance (mΩ)	% Impedance Increase
0	0	0.443	0
108	25	0.443	0
216	50	0.474	7
324	75	0.556	25
392	91	0.662	50
432	100	0.784	77
445	103	0.983	122

These results draw into doubt the ability of these devices to accurately predict loss of capacity due only to discharge of the active materials. This is supported by the knowledge that the resistivity of the electrolyte is much more significant than that of the active material and will have a larger impact on the overall cell resistance value. This is coupled with the fact that the resistivity of the electrolyte reaches a minimum at approximately 1.235 specific gravity. The Absolyte IIP cell has a full charge specific gravity of 1.310 and a discharged specific gravity of 1.100. This means that at the end of discharge, the resistivity of the electrolyte is approximately 25% higher than when the cell is fully charged.

Impedance as a function of accelerated float life

Accelerated life testing at elevated temperatures has become a widely accepted practice among manufacturers and users in evaluating battery design life. Typically cells are float charged at their normally recommended voltage at a temperature between 40°C and 80°C (60°C is most common) and for test segments of 15 to 60 days. At the end of these segments, the cells are capacity tested until the point where the capacity drops below 80% of the nominally rated value. These tests are useful for evaluating the major components of the battery such as the positive grid, strap connections, and plastic components. Accelerated life testing can be effective for evaluating design criteria such as the corrosion and growth rates of the positive grids. It is often these corrosion rates which are key in determining the design life of the positive grids and thus the battery.

Currently, a life test is being run at GNB on the new Absolyte XL 2000 design. There are four 2000 ampere hour cells on test at 65°C. Figure 2 below shows the ac impedance as a function of equivalent years on float. The test is currently at slightly greater than 16 years (equivalent) and the impedance has increased on average by 26.7%. Although the cells are still on test and capacities are still slightly greater than 100% there is certainly some degree of grid corrosion and growth occurring. The increase in impedance is fairly linear as shown and we could project that by the 20-year equivalent point (end of design life) the average impedance will have risen by 50%. It is fair to say that based on previous experience with this type of testing, the rise in impedance can be primarily attributed to positive grid corrosion.



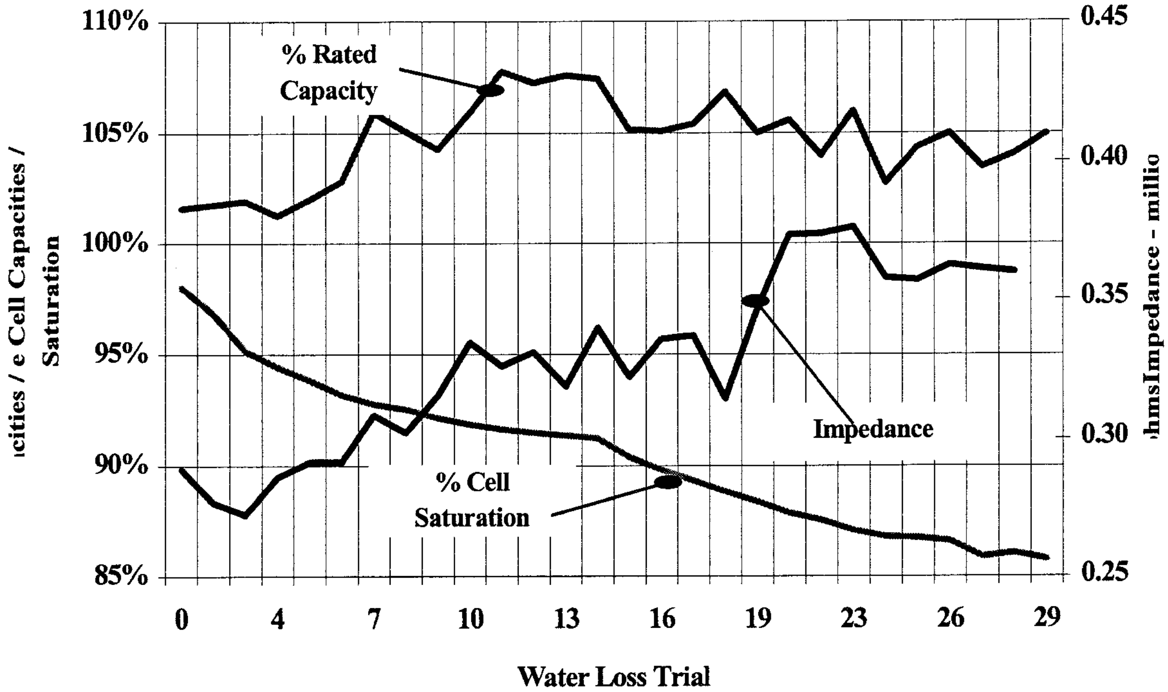
Impedance as a Function of Cell Dryout

Given that VRLA batteries do not have any excess electrolyte and watering the cells is not a normal maintenance practice there is some perception that the cells can fail due to excess water loss or dryout. A study was conducted at GNB, with the results first presented at the Intelec '97 conference, which looked at the effects of forced dryout on both the capacity of cells and the impedance.

A string of Absolyte IIP cells was repeatedly cycled and overcharged. After each cycle, the cell weight (water) loss, the 8-hour capacity and the ac impedance were measured and recorded. From the weight loss values, the calculated cell saturation was determined. The cell saturation is defined as, the amount of electrolyte present in the void space of the cell relative, to the total void space.

As we can see below in the Figure 3, the cell saturation over 24 cycles was driven down to approximately 87%. At this point in the test, due to highly efficient gas recombination, it became extremely difficult to force additional water loss. The cell capacities were unaffected while the ac impedance of the cells increased on the order of 23%. So under the conditions of this test, even though the cell capacities had not dropped to a failure range, a 23% increase in the average ac impedance could be directly attributed to saturation loss or dryout.

Figure 3 - Average Cell Capacities, Saturations and Impedances as a Function of Water Loss Trial



Impedance as a Function of Loss of Compression

Over the previous 6 years GNB has reported several times on a phenomena which relates loss of battery capacity to a compression loss in the glass mat separator. The glass mat separator holds a majority of the electrolyte in an absorbed glass mat design and serves a critical role in the performance and life of the battery. This separator allows oxygen to diffuse from the positive to the negative plate to create the gas recombination reaction within the cell and serves as the acid reservoir which is necessary for the discharging and charging reactions. It is vital that the separator maintains intimate contact with both the positive and negative plates. If gaps are created between the separator and the plates, areas of the active material will become electrically isolated and discharged resulting in reduced capacity, and increased internal resistance.

Shown in Table 2 below is a set of typical Absolyte II 975 ampere-hour cells that had suffered from a loss in separator compression. The cells were roughly five years old at the time of evaluation. In this analysis the cell compression and ionic contact was re-established through the addition of a small quantity of water. After the water addition the impedance of the cells on average decreased by 55% or in other words over the course of the life of the cells the impedance had increased by 125%. The maximum value in the string decreased by 77% or had been inflated by 345%. This is 4.5 times the average increase seen in a fully discharged cell. This is a very significant number and could most likely only be attributed to some loss of electrical continuity within the cell. In this case it is due to the loss of separator compression.

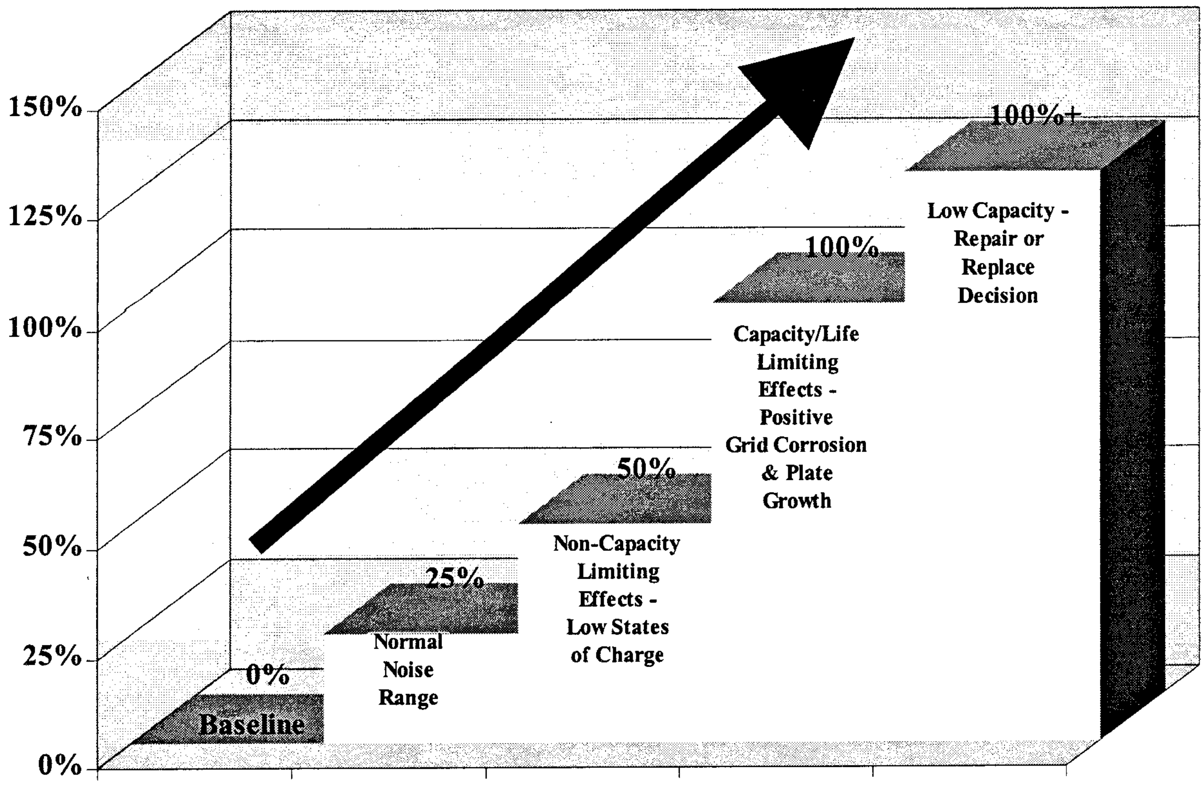
Table 2: Impedance Before and After Water Addition

Cell Number	Impedance Before Water Addition	Impedance After Water Addition & 30 Days Float
1	0.538	0.339
2	0.634	0.359
3	0.624	0.354
4	0.551	0.354
5	0.790	0.383
6	0.888	0.387
7	1.095	0.355
8	0.866	0.343
9	0.681	0.340
10	0.623	0.316
11	0.820	0.328
12	1.175	0.348
13	0.882	0.360
14	0.460	0.349
15	0.652	0.375
16	0.745	0.345
17	0.537	0.345
18	1.868	0.419
19	0.627	0.346
20	0.891	0.348
21	0.541	0.330
22	0.967	0.315
23	0.623	0.327
24	0.863	0.335
Max	**1.868**	**0.419**
Min	**0.460**	**0.315**
Average	**0.789**	**0.350**
Standard Deviation	**0.295**	**0.023**

Conclusions & Guidelines for using impedance as a diagnostic tool

A general summary of the information developed in this study is depicted in Figure 4 below. This diagram categorizes shifts in impedance values and correlates those shifts to the characteristics of the batteries being measured.

Figure 4 - Ohmic Value Changes and Ramifications



From this diagram and other information presented we can draw the following conclusions:

1) Impedance and dc resistance baseline values are fairly similar and track each other over the range of the Absolyte IIP product line.
2) There can be a normal 10-25% variation in baseline readings on new product leaving the factory. This is true regardless of meter type or manufacturer.
3) Capacity loss due solely due to discharged active materials cannot be detected above 30% state of charge. Thus, failure mechanisms such as negative plate self-discharge will be difficult to detect using impedance devices.
4) End of life impedance shifts, caused by positive grid corrosion, are on the order of 50% to 100%.
5) Maximum shifts in impedance values due to cell dryout are on the order of 25%. This value however is not significant enough to indicate a loss in cell capacity falling in the failure zone.
6) Loss of separator compression is characterized by dramatic shifts in the impedance beyond 100% and in some cases over 300%. These are only recoverable by re-establishing plate to separator contact.
7) Impedance shifts in the range of 50% to 100% on average are reasonable in the expectation that the battery may have a loss in capacity below 80% and require further investigation.