Eliminating Battery Failure – Two New Leading Indicators of Battery Health – A Case Study

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Abstract – **In the backup power industry, reliable power is a must. A large and growing installed base of lead acid batteries supply mission critical power to hospitals, banks, mobile telecommunication sites, receiving and transmission utility sites, and countless other industrial and commercial installations. Despite the importance of these mission-critical, backup power systems remaining healthy, in most cases customer testing of their systems does not accurately show battery health. This is mainly due to the fact that only the electrical properties of the battery have been measured using conventional battery test equipment. Consequently, sites are not adequately protected, preventative maintenance costs remain high, and batteries are replaced frequently.**

The World Energy Labs' Interrogator™ ElectroChemical battery analyzer is the only battery testing solution available today for the Energy Storage and Power Conversion industries with the ability to accurately measure both the electrical and chemical state of a battery.

Two chemical processes, dryout (loss of water from a valve-regulated lead acid cell) and sulfation (a build up over time of lead sulfate on the plates) are two leading causes of battery failure in backup power systems.

Proprietary CEL-Scan™ algorithms allow the Interrogator™ to test both the Electrical and Chemical (ElectroChemical) parameters within lead acid batteries. The Interrogator™ has proven to be capable of detecting significant degradation within cells before the more usual ohmic measurements show any variation from their baseline values.

The results of the CEL-Scan™ algorithms for Dryout and Sulfation show remarkably good correlation with actual discharge or load test results, in some cases eliminating the need to perform load testing, which is time-consuming and unsafe. Failing batteries can be caught earlier and serviced; prolonging life, reducing maintenance and replacement costs, and reducing the amount of hazardous materials going into recycling plants. Although the algorithms have been developed for the stationary battery market, their fields of application is actually wider and are now finding use in motive power and other areas.

I. INTRODUCTION

The World Energy Labs Interrogator is a compact, microprocessor-based instrument that uses impedance spectroscopy to characterize batteries and other low impedance devices. To date, our primary focus has been on lead acid batteries – particularly those designed for standby power. In this arena, we have generated algorithms that relate impedance changes to specific failure modes such as sulfation and dryout. This capability is a radical advance over prior technology and understandably, we have encountered a certain amount of skepticism in the market place. The main purpose of this paper is to provide evidence to back up our claims by drawing on a few casestudies.

A. Pattern Recognition

To gain a qualitative idea of how electronic measurements can provide chemical information let us examine the following charts. Fig. 1 shows a typical "Nyquist plot" for a lead acid battery.

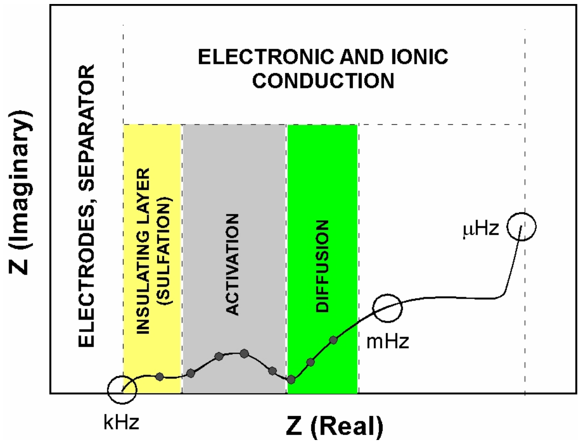

Figure 1: Typical Nyquist plot for a lead-acid battery

The plot in Fig. 1 is generated by passing a series of AC (sine wave) signals through a battery and graphing the response in the complex plane. The vertical axis represents the imaginary component of the impedance and the horizontal axis represents the real component of the impedance. Each point in the plane corresponds to a single frequency. From the shape of the resulting curve, experienced scientists can deduce a great deal of information about the condition of the battery. At the highest frequencies, the impedance is controlled by electron movements in metallic components and resistive films. As the frequency is lowered, a sequence of other processes becomes important, including (from high to low frequency), ionic migration, the electrostatic charging of electric double layers, and charge transfer reactions at electrode surfaces. At the lowest frequencies,

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diffusion processes in liquid and solid phases tend to dominate. In this region of the curve the frequency is in the millihertz range, that is one 1000th of a cycle per second. Obtaining data in this range is impractical in field applications because it would require many minutes per data point. Fortunately, the most useful diagnostic information tends to occupy the middle range of frequencies. However, it should be clear from the intricate shape of the Nyquist plot that reliance on a single frequency point cannot possibly provide information about all the processes that affect the health of a battery.

C. Failure Modes

In our work to date, we have focused primarily on two particular failure modes that are important for standby power batteries. The first failure mode, known as dryout, involves loss of water from VRLA (Valve Regulated Lead Acid) batteries. When properly managed, VRLA batteries retain adequate water throughout their design lives. However, when subjected to prolonged over-charging or overheating, water loss from VRLA cells can reach the point where the separator loses conductivity. It is most likely to occur in conjunction with thermal runaway since there is a feedback effect whereby each increment of water loss raises the ohmic heating and further accelerates water loss. Dryout of an AGM separator causes it to shrink away from the electrodes, ultimately producing a large increase in internal resistance and a sudden loss in capacity. Water loss from a gel cell can eventually cause disintegration of the separator and a catastrophic drop in capacity. The early stages of dryout can go undetected even by capacity measurements because the effect on capacity is small until very late in the process

The second failure mode that we have examined is the phenomenon of sulfation. The discharge process in a lead-acid cell deposits lead sulfate throughout the active material of each electrode. In normal operation, the lead sulfate forms as small crystals that readily re-dissolve during the charging process, allowing the active materials to revert to their original form. However, if the usage profile is not carefully controlled, the lead sulfate crystals can gradually grow in size, becoming progressively more difficult to convert back to active material. In the early stages, while recharge is still possible (albeit with much effort) the condition is known “soft sulfation”. Eventually, however, the crystals grow so large that recharge is impossible.

At this point, the condition is known as “hard” sulfation. Fortunately, the sulfation readings registered on the Interrogator^{TM} are equally sensitive to both soft and hard sulfation, allowing detection of sulfation before it becomes irreversible.

We have devoted less effort to grid corrosion because a battery that reaches the end of life solely by this failure mode has generally exceeded its design life. The process of grid corrosion involves the gradual conversion of the positive current collector (a lead alloy) into positive active material (lead dioxide). At first, the process can actually increase the cell capacity. A closely related failure mode is grid growth. Because lead dioxide takes up more space than the original lead, the conversion leads to a physical expansion of the grid. Extra space is normally designed into the cell to accommodate the expansion. However, eventually the growth can result in short-circuits as it pushes together the interconnect bars at the top of the cell

D. Cell Aging

Fig. 2 divides the life of a battery into three zones.

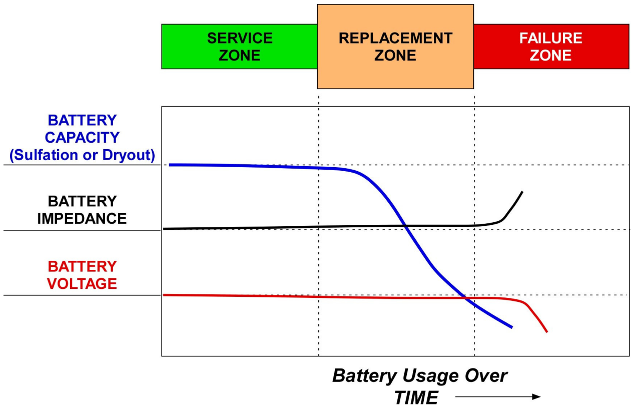

Figure 2: Aging zones of a battery

The initial zone shows very little change in capacity or single-point electrical characteristics. It is important to test the battery at this stage, not only to catch possible infant mortality failures, but also to look for premature signs of aging that might signify improper battery management. In the middle zone, chemical changes become important and discharge tests reveal an accelerating roll off in capacity. Unlike single-point electrical characteristics, the Interrogator^{TM} gives early warning of potential problems in this zone and allows the operator to apply corrective measures. In the final aging zone, cell capacity declines erratically and failure can be too sudden to be predicted by routine electrical measurements.

To show how much the impedance pattern of a battery can change over time, Fig. 3 compares the Nyquist plot of a battery before and after an aging treatment of 450 cycles. Just as the human eye can readily discern the changes, the Interrogator^{TM} algorithms apply digital pattern recognition to diagnose and quantify the failure processes.

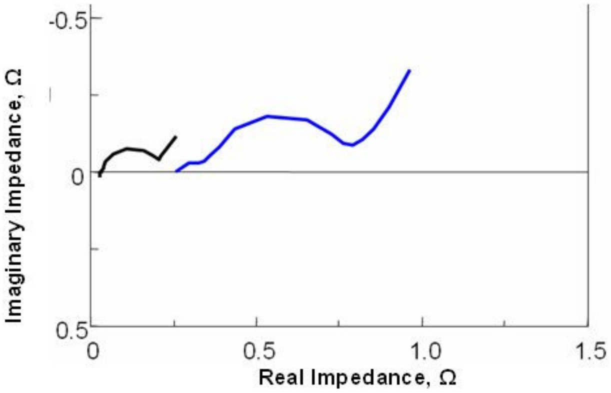

Figure 3: Nyquist plots for a lead acid battery before (black) and after (blue) 450 aging cycles

II. CASE STUDIES

Examples outlined below are offered as validation for the ability of the Interrogator to measure capacity losses due to dryout and sulfation in lead acid batteries

A. *Laboratory Tests*

Sulfation tests were performed on new GNB Absolyte IIP 104 Ah VRLA cells and Enersys Powersafe 3CC-3 50 Ah VLA Type Batteries. A baseline C/3 capacity was established at the beginning of life (BOL) and sulfation was artificially induced at reduced float voltage and elevated temperature. Figures 4 and 5 compare the C/3 capacity losses after aging with those predicted from impedance data.

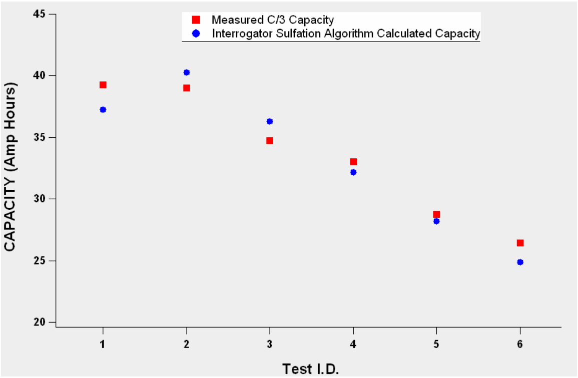

Figure 4: Sulfation induced capacity loss for Enersys Powersafe 3CC-3 50 Ah VLA type battery.

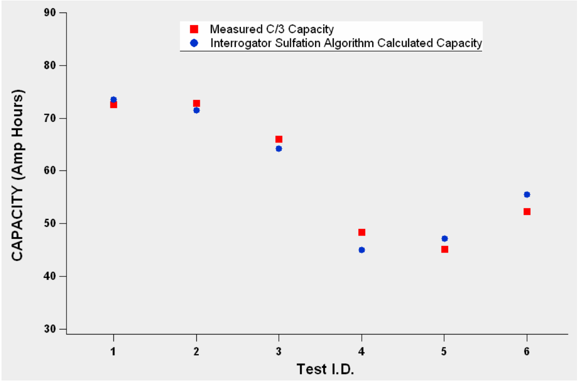

Figure 5: Sulfation induced capacity loss for GNB Absolyte IIP 104Ah cells.

Dryout tests were performed on a series of new GNB Absolyte IIP 104 Ah VRLA cells. A baseline C/3 capacity was established at the beginning of life (BOL) and dryout was artificially induced with a flow of nitrogen. Fig.6 compares the C/3 capacity losses after aging with those predicted from impedance data.

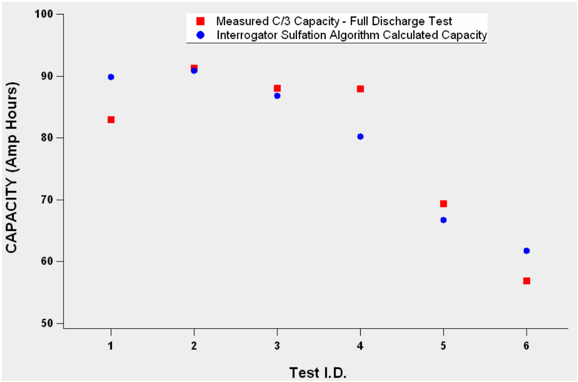

Figure 6: Dryout-induced capacity loss for GNB Absolyte IIP 104Ah cells.

B. *Automotive Battery Tests*

Comparative tests performed by an automotive company on a series of field-aged 90Ah batteries appear in Fig. 7.

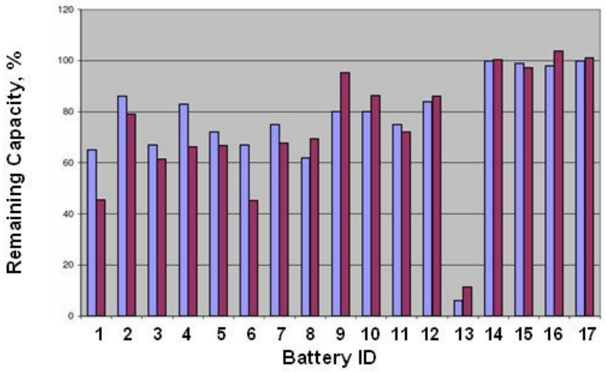

Figure 7: Percentage capacity losses estimated from Interrogator ™ sulfation readings (blue) and discharge measurements (red) on used automotive batteries.

Most of their results showed excellent agreement between Interrogator ™ estimates of sulfation losses and capacity losses measured in discharge tests. The agreement is surprisingly good, considering that the algorithms were developed for standby-power type batteries.

C. *Standby Power Tests*

Comparisons performed on standby power batteries generally yield even better agreement. For example, results reported by a global telecommunications company showed agreements within 4% or better between Interrogator ™ predictions and discharge measurements. For a global power company, the agreement was within 7%.

III. CONCLUSION

Accurate impedance measurements, intelligently applied, can be invaluable in the timely diagnosis of lead acid battery health. By placing this capability in the hands of the standby power operator, the Interrogator ™ can drastically shift the risk/benefit equation in the user's favor.