Batteries Die in Thirds

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Abstract

With over 19 years of continuous monitoring of stationary batteries, archival of over 1.5 billion points of data and chronology of over two million batteries, we are finding some common history.

As batteries age to the point of replacement, individually, and collectively in strings and multiple string systems, we find distinctive fingerprints indicating end of life conditions in thirds (life divided into thirds.) Distinctive characteristics are visible during a battery system life, in each third of total life.

"Life is divided into three terms - that which was, which is, and which will be. Let us learn from the past to profit by the present, and from the present to live better in the future." - William Wordsworth

Discussion

Aging, individual and collective traits cannot be simulated and seen conclusively in the laboratory setting using accelerated life testing. This is due to the extended time required, quantity of data required, plus other restraints of simulation versus real historical data. This can only be reliably observed in real life usage conditions over time.

As batteries age, there are changes over time in the internal ohmic value. As stated in various IEEE battery standards, Manufacturer specifications, etc., significant (30% - 50% and greater) changes in Ohmic value indicate aging, and loss of capacity. While not definitive, this level of change from a baseline can be an indication that capacity has decreased from when the battery or unit was new. These aging changes are caused by time, electrical and chemical variances, and/or mechanical anomalies in the battery unit. Many other measurement parameter changes, in turn, will cause ohmic value changes as a result. As the ohmic value changes, a decrease in capacity occurs. This correlation to capacity indicates aging plus individual anomalies, and has been proven by lifetime data and other studies referenced by this paper.

Continuous monitoring, archiving, trending, and prognostics of battery ohmic values, plus other battery measurement parameters are necessary and essential in predicting end of life conditions. This is true for individual batteries, as well as the complete battery system. Measuring and archiving these values over time, plus prognostics and curve prediction of other measurement parameters that affect these ohmic values allow for predictive analysis.

Introduction

Because the battery asset must be ready to perform instantly at any time, its state of health, and ability to support associated emergency power systems should be continuously monitored, and evaluated regarding its ability to perform promptly and reliably. It must also be determined whether it has the capacity to provide adequate power to the critical loads which are normally powered by the associated UPS, the utility company, or other forms of electrical power.

The above is true for all standby lead acid battery technologies. Standby technologies include Vented (flooded or wet batteries), Nickel Cadmium, or VRLA (Valve Regulated Lead Acid) batteries. All stationary battery systems used in this manner usually consist of one of these available battery technologies, but the commonly used, and most difficult to analyze VRLA types will be concentrated on in this paper.

Aging

All batteries have a finite lifetime, during which they are able to provide reliable and adequate power as defined by their manufacturers' specifications. Depending on the battery type, quality of product, influence of supported peripheral power systems, load cycling events, and many other factors, various batteries have real lifetimes ranging from a few months or less, to several years or so. Typical manufacturers may provide some form of warranty from a year or two, up to several years or longer.

Manufacturer warranties usually refer to the user maintaining and operating the battery asset within Manufacturer's specifications of specific models and technologies. This can be in addition to maintenance standards defined by the manufacturer, or IEEE Standards (Recommended Practices.)

The accepted key measurement of remaining battery life is the percentage of original design capacity determined by discharge. A battery unit is considered to be at end of its life when it cannot produce more than 80% of its original capacity design specifications. At that point, it is highly recommended to replace the battery as history has shown that battery capacity drops off exponentially after this point.

When a battery unit is new, and is at close to 100% of design capacity, it exhibits a specific range of initial "ohmic value." This is used as a beginning baseline measurement. This value can be obtained by making a precise measurement with one of many instruments or stationary battery monitors designed for this purpose. The "ohmic value" is also known by terms of internal "resistance," "impedance," "conductance," "admittance," "response," or other similar terms or names. Ohmic values can also be obtained by impedance or conductance spectroscopy, or other methods used for measuring these values. Ohmic value ranges for specific battery units vary based upon the measuring instrument or system method of obtaining this value, types of batteries, and their capacities. While variances occur, ohmic trends over time are far more important than specific values when determining age and performance criteria.

A simplified definition of "ohmic value" follows:

"The internal ohmic value of a cell/unit is derived from the response to changes in voltage or current stimulus under various conditions." (IEEE 1491-2012 Section 6.13.1)

Basic calculations are obtained by Ohm's law, (E=IR).

As a battery unit ages, there are changes over time in the internal ohmic value. As researched and stated in various IEEE standards, ohmic value changes greater than 50% of <u>individual</u> cells or units warrant investigation. While not definitive, this level of change from a baseline figure can be an indication that the battery unit capacity has decreased below 80% of when the battery was new and met design specifications.

Common Aging Factors

Some common aging factors, elements or measurement parameters causing ohmic change to occur are listed below:

Temperatures

Battery manufacturer specifications for optimum Lead Acid technology battery temperature is typically 25C or 77F. Out of range (especially warmer) temperatures over time affect aging rates. Temperature affects ohmic value.

Discharges

Battery discharges, light and heavy, can have an effect on battery life. Discharge events affect ohmic value.

Decreasing electrolyte volume

All VRLA batteries contain a valve which allows gas to escape from the battery cells when pressure increases above normal atmosphere pressures. This can be caused by higher temperature as a result of discharges, ripple voltage and currents, excessive charging voltage and currents, and a myriad of other temperature and pressure related events including high ambient temperatures. As the gas escapes, the remaining electrolyte (acid) in the battery is reduced, causing an inefficiency of the recombination process, thus changing ohmic value and decreasing life and capacity. This is normal with all VRLA batteries. As an additional point, vented (flooded) batteries can have their electrolyte replenished by the addition of water. Normally, VRLA cannot, except in special cases using special procedures.

Unit replacement percentage within the battery system

This affects string aging. There is no established standard for this important percentage. It can range from 10 - 25% or higher. This percentage varies within this typical range depending on the maintenance organization, battery manufacturers, and risk tolerance of users.

Individual battery interaction (“King of the Hill” Effect)

Replacement battery units affect string health and aging characteristics. Unequal charging occurs between older and newer replaced battery units. Older and newer battery units each require different charging currents, thus affecting each other when a single charger is used. As an example, a new battery unit does not require the same level of charging current (less), than an older battery unit (more) from a common charger in a single string. This illustrates the “King of the Hill” battery unit interaction effect. This writer has coined that term over years of observing this interactive behavior.

“King of the Hill” is a child’s game where the strongest child reaches the top of the hill first and defends the position while the others try to take their place. The strongest and smartest child is the “King of the Hill.”

Harmonics and other factors

Effects of connected and supported peripheral power systems affect aging rates, i.e.: chargers, rectifiers, inverters, load levels plus source and load harmonics, etc.

Battery System or String Aging Characteristics

Below is a 15 year graph showing aging fingerprints collected from a single system or string. Data for this graph is collected by a monitor using impedance as the ohmic value.

The system is a 150 kVA UPS system with one string of 40 ea. 6 cell VRLA battery units. Each battery unit was monitored, collecting voltage and ohmic data, once a week, on each unit. This was archived to the database from which the graph data was obtained and generated.

Each battery unit in this system represented in the graph is shown collectively and all are overlaid together.

During the 15 years shown, note that there were four complete battery string replacements. Time to replacement varied from over 4 years to less than 2 years.

The performance and profile of each battery unit and its associated measurement parameters during any time period in the system was retrieved and analyzed for further detail.

Within the battery string, individual battery unit replacement data was retrieved and observed for further analysis. Note the top half of the graphs denotes voltage, and the bottom half denotes ohmic value in "milli-ohms." Note that the voltage graph does not reflect aging characteristics.

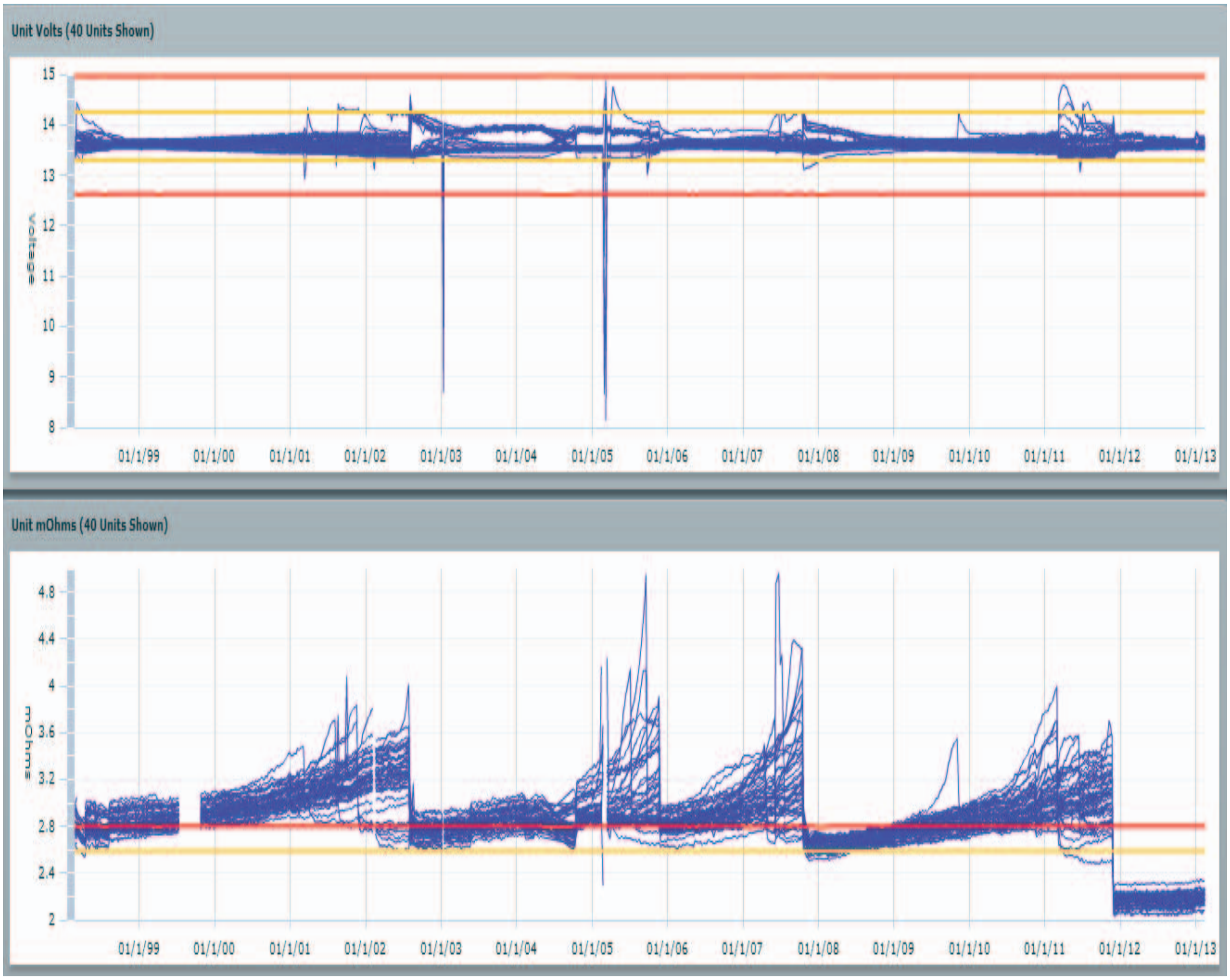


Figure 1 - Five lifetime graph

Below is another graph showing 7 years composed of two string lifetimes of 40 ea. 12V VRLA units. The data shown is one string of 3 parallel strings installed on a 375 kVA UPS. Data on this graph is taken from a different monitor that measures DC Resistance, once per day during the 7 year duration. Note that the resistance rise is similar to the impedance rise shown on the five lifetime graph above. In the two lifetime graph, the battery system exhibits more stable rise as a system due to the particular battery model being shown.

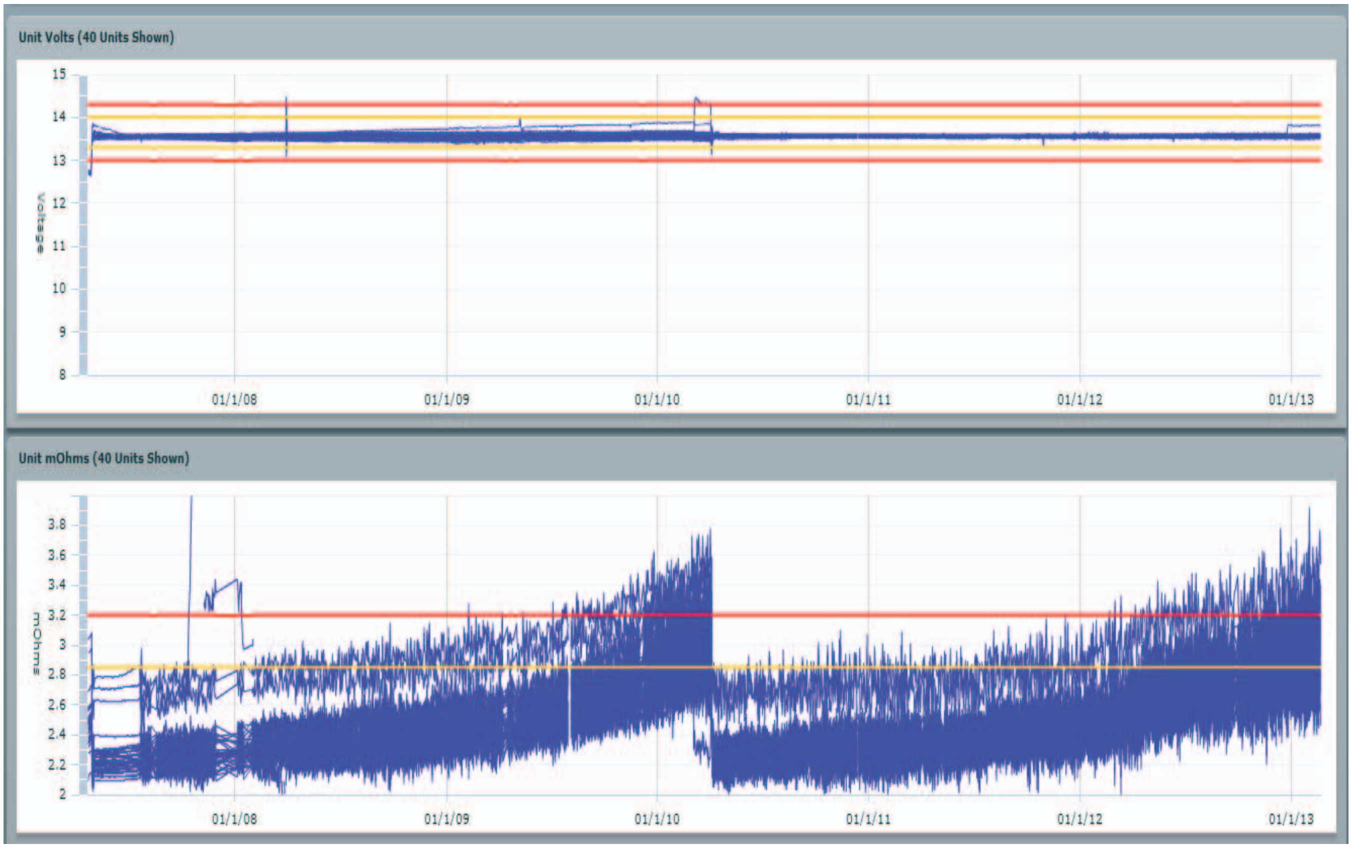


Figure 2 - Two lifetime graph

It can be seen from the two lifetime aging graph above that different methods used to obtain ohmic values show similarities with each other when observing aging trends for prediction, analysis, and prognostic methods.

What does “Thirds” mean?

By close examination of each battery string lifetime in the above graphs, it can be seen that there is a distinct change in ohmic rise that can be divided into thirds. This is more evident in the five lifetime graph. When the battery string is replaced, the first third of its lifetime’s ohmic value remains relatively constant with some ohmic rise, regardless of the total lifetime length, which is different for all lifetimes shown. In the second third of life, it is noted that ohmic value rise continues to accelerate during this middle third but individual battery units exhibit somewhat uniform rise.

During the last third of life, rapid ohmic rise occurs on individual units which necessitate individual battery replacement within the string. As these individual units are replaced, interaction begins between newly replaced units and older more stable units. This interaction phenomenon is due to required charging current draw changes between newer and older units. This begins to accelerate ohmic value changes and other instabilities observed at this last third point in battery life within the string. While observing the graphs above (particularly the 2 lifetime graph) it can be seen that more uniform battery unit ohmic rise does not further exacerbate acceleration of ohmic change. Stability and uniform aging characteristics are more evident in that graph.

When ohmic value rises on more individual units during its life, the acceleration of the total string or system is more pronounced. This needs to be taken into account during the analysis and prediction of end of life conditions. It can be seen that predicting where the aging curve is going is a complex process and requires close examination of conditions within the battery system composed of its individual battery units.

Regardless of the length of life for whatever reason, all strings or systems tend to exhibit these same characteristics.

As a note, a distinct difference is observed between the systems and batteries shown in Figures 1 and 2. Differences in monitoring technology measurements, battery manufacturers, other variables, and different UPS model operation can make the acceleration rates, and outliers more pronounced. The key observation is the uniformity and granularity of the two different systems and the outliers can skew the acceleration, but the rate of acceleration is basically the same.

Predictive analytics, and prognostics, of acceleration curves can be used to help determine lifetimes. There are no battery systems that exhibit identical characteristics.

UPS Filter Capacitor Aging and Observation

By close analysis of the above equipment specific aging graph (Five Lifetime Graph), it can be seen that the first three lifetimes subsequently became shorter, as compared to the 4th lifetime. Referring to aging factors which affect ohmic value shown above, harmonics is an important parameter. Harmonics cause ripple current and voltage, which in turn cause heating within the battery system. This, in turn, will cause ohmic values to rise or change more rapidly as it takes a toll on battery life. In this particular case shown in the referenced graph, UPS filter capacitors were replaced at the end of the third life. The result can be seen by the longer 4th string life.

Ohmic value vs. Capacity, and Load Testing

Controversy exists regarding the correlation of battery capacity to ohmic values. It is accepted that measurement of ohmic values has some relationship to battery capacity, but testing of battery discharge capacity against a known load is the traditional method used to determine battery performance.

Load testing is an indication of battery capacity and performance, but it is only valid at a given moment in time and does not predict future performance unless it is archived and the results trended over time. Ohmic value trends give a clue to future performance. Most UPS users do not load test beyond acceptance load testing at beginning of battery system life. Expense and risks associated with load testing tend to cause users to rely more on battery monitoring and periodic maintenance.

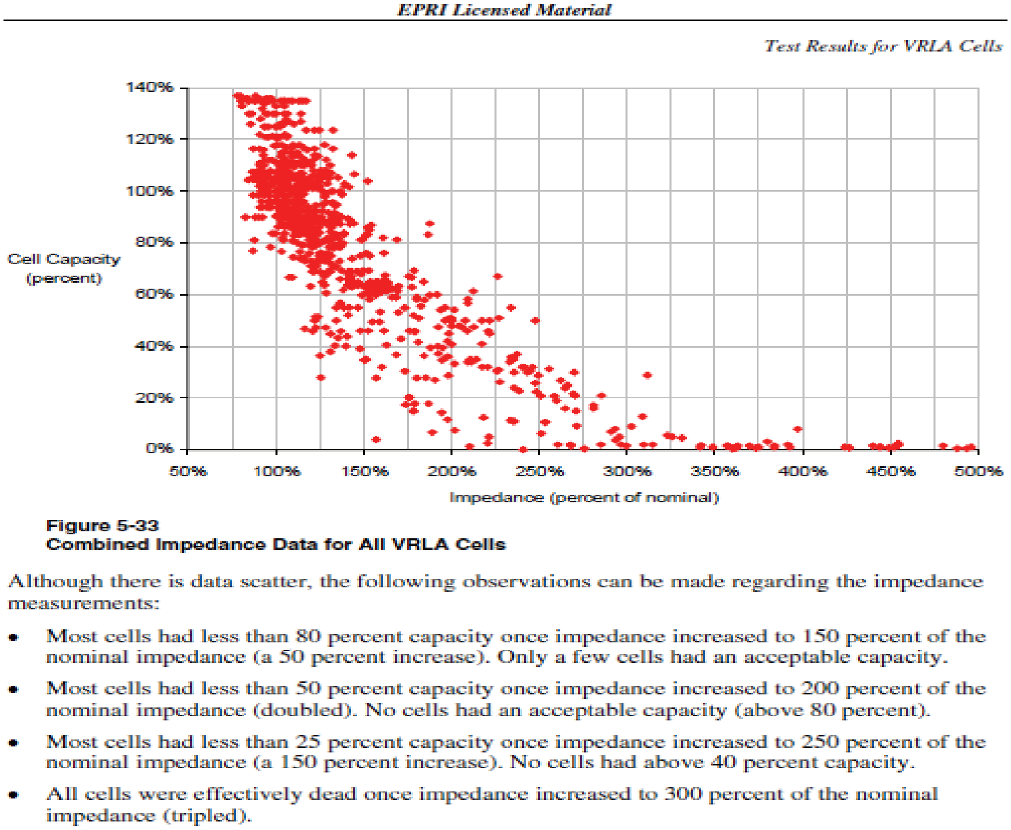
All aging mechanisms and battery measurement parameters including temperature, ripple, float voltage levels, discharges, and load levels affect ohmic values over time. These all should be monitored, trended, and archived over time. Ohmic values and related battery measurement parameters must be analyzed for reliable capacity and performance data, and prediction of present and future performance. It follows that all these mechanisms and parameter measurements affect ohmic value and aging rates.

Below is a scatter diagram taken from the Electric Power Research Institute battery capacity vs. ohmic value study done in 2002. In this particular diagram, impedance is used for the ohmic value. The study correlated to other ohmic values employing DC resistance, and conductance. These methods were available using the instrument technology at the time (late 1990's) the study was performed and documented.

Please note that the graph and its summary is stating that a 50% increase in ohmic value correlates to 80% capacity. This is shown with individual batteries in a battery string at the point in time when the impedance tests were performed. Similar correlated results were obtained and proven in the same EPRI report using other ohmic value measurement methods including Conductance and DC Resistance.

In this same 2002 EPRI report, technology at that time is discussed in the context of historical trending of ohmic values. This discussion is shown below.

At the present, historical trending and archiving of data is in wide use, and is today's current technology. At the time of the EPRI study, there were no extensive trending studies and widespread use of today's monitoring systems and analysis, but its importance was acknowledged at the time. The EPRI report summary regarding trending and insight is shown below the scatter diagram (Figure 3) and its conclusions as (Figure 4):



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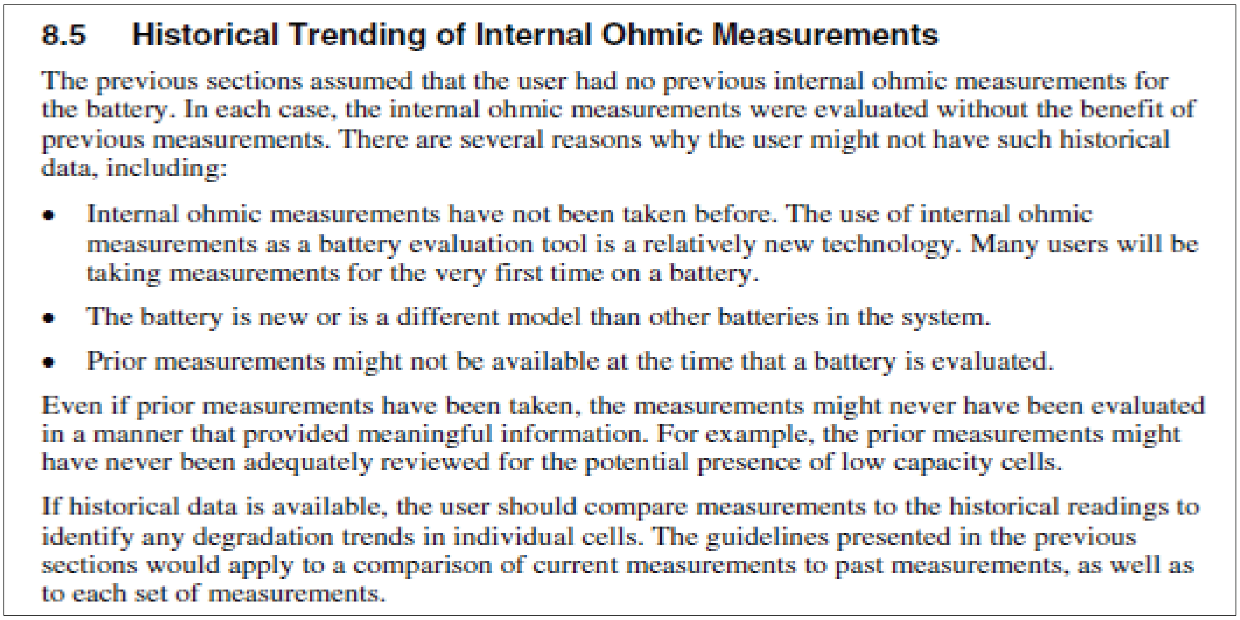
Test Results for VRLA Cells

Figure 5-33
Combined Impedance Data for All VRLA Cells

Although there is data scatter, the following observations can be made regarding the impedance measurements:

- Most cells had less than 80 percent capacity once impedance increased to 150 percent of the nominal impedance (a 50 percent increase). Only a few cells had an acceptable capacity.
- Most cells had less than 50 percent capacity once impedance increased to 200 percent of the nominal impedance (doubled). No cells had an acceptable capacity (above 80 percent).
- Most cells had less than 25 percent capacity once impedance increased to 250 percent of the nominal impedance (a 150 percent increase). No cells had above 40 percent capacity.
- All cells were effectively dead once impedance increased to 300 percent of the nominal impedance (tripled).

Figure 3 – Combined Impedance Data for All VRLA Cells and Information



8.5 Historical Trending of Internal Ohmic Measurements

The previous sections assumed that the user had no previous internal ohmic measurements for the battery. In each case, the internal ohmic measurements were evaluated without the benefit of previous measurements. There are several reasons why the user might not have such historical data, including:

- Internal ohmic measurements have not been taken before. The use of internal ohmic measurements as a battery evaluation tool is a relatively new technology. Many users will be taking measurements for the very first time on a battery.
- The battery is new or is a different model than other batteries in the system.
- Prior measurements might not be available at the time that a battery is evaluated.

Even if prior measurements have been taken, the measurements might never have been evaluated in a manner that provided meaningful information. For example, the prior measurements might have never been adequately reviewed for the potential presence of low capacity cells.

If historical data is available, the user should compare measurements to the historical readings to identify any degradation trends in individual cells. The guidelines presented in the previous sections would apply to a comparison of current measurements to past measurements, as well as to each set of measurements.

Figure 4 – Historical Trending of Internal Ohmic Measurements Information

Lifetime Projection Prognostics

Continuous monitoring, record keeping and archival of battery ohmic values, plus other influencing battery parameters are essential to predicting end of life conditions. This is true for individual battery units as well as the complete battery system. Archiving these values over time allows for predictive analysis. Again, this includes other parameters that affect these ohmic values, and helps to maintain battery unit and system state of health.

Continuous monitoring, archiving and analysis builds up a database that can be analyzed during the life of the battery asset. Actions can be taken in real time to maintain state of health as the battery system ages by identifying individual battery units in need of maintenance or replacement. In addition, actions can be taken to predict not only individual battery unit replacements, but also when the battery system /string(s) have fallen below safe capacity to perform (<80%).

This can include archived and trended Load Test data if available.

In addition, permanent records of archived data from previous systems can be studied and further analyzed. Conclusions from this past data can be further analyzed and compared to current data.

Conclusions

The examples above, and the narrative presented in this paper are very similar to all standby based or stationary battery systems. While voltage and other trends are important for verification purposes, as well as temperature, interaction between individual batteries, and peripheral power equipment issues (harmonics, etc.), it is found that ohmic value is the most significant factor for observing aging behavior.

While testing load capacity is a more precise method of identifying specific low capacity battery units, and string performance, it is only valid at the time that it was performed. Capacity test results (if they are frequently conducted and documented) can be trended over time to show aging effects. Continuous and frequent monitoring of ohmic values, and other key measurement parameters affecting ohmic value, can be archived in the historical record allowing for more detailed analysis and prediction purposes. It is important that both methods are linked together to ensure the integrity of the battery system.

Based on the observation of the examples here, and the continued observation of all Lead Acid battery types, it becomes apparent that this behavior and its resulting fingerprint and characteristics can be modeled.

From these models utilizing continuous and historical monitoring data, mathematical methods can be used to observe and predict the aging process. Several reference papers shown below refer to Bayesian theories, various filtering techniques, regression analysis, and many other mathematical models. These techniques are an enhanced verification technique for observations and prognostic health management in order to properly manage the battery asset. These methods are in ever increasing use for predictive analytics and prognostics.

With the ever growing database over time, more modeling and predictive analytics can be performed. Prognostic methods are used to monitor and track "degradation paths" in one or more battery parameters that are correlated to remaining life. Deviations between the observed and expected parameters are evaluated to determine when a monitored unit is degrading excessively. Remaining life is predicted by classifying the unit's degradation path in reference to degradation path models calibrated with run-to-failure data for units experiencing a similar mode of failure.

In addition, once these additional methods are employed, the next step can be used for other battery technologies, chemistries, and applications. Other applications would include vehicular and airframe, grid energy storage, and energy generation. Other battery chemistries and technologies have been shown to exhibit similar characteristics to the VRLA and VLA technology presented in this paper.

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