Battery Full Life Analysis with Portable Instruments and Computers

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Introduction

For many years, batteries have been examined, tested, measured and monitored. This paper presents a high level field examination overview, without load testing of 20 million VRLA cells over the period 2004 to 2014 for UPS Service applications. The author hopes that the information presented may be utilized in adjacent applications that place VRLA batteries in cabinets and enclosures, including Telecom, Utility and Industrial applications. In UPS Service applications, VRLA batteries within cabinets dominate the market share in the 225-600KVA power range. Many of these “medium sized UPS” systems include a permanent stationary battery monitoring and test system. However, many of these systems are inspected today periodically, in person, only with portable instruments. We have been fortunate to retain all in-person derived data since 2004. Recent advances in computer performance, big data analysis tools and laptop based SQL databases permits new capabilities and reporting. This “in the field” reporting allows field engineers to visualize the entire history of a battery string during any field inspection(s). This paper details the best practices, lessons learned and some performance data derived from in person inspections of 20 million VRLA cells. We will conclude with a short data analysis of batteries that have failed earlier in their lifecycle than expected (catches).

Portfolio Description

As reported previously our team (1) have been preserving on site performance details on many millions of stationary batteries installed for UPS (Uninterruptible Power System) duty across North America. Currently the active portfolio consists of more than 80,000 strings or 3.2 million active units. A subset of this includes those battery units (Jars) which are VRLA and in enclosures, typically with doors and ventilation louvers. This paper presents a field-derived analysis of the measured artifacts of performance of a subset of these units, but over the lifetime of site battery string replacements (3-5 years per string) the basis is approximately 20 million units. Data presented is limited to VRLA batteries, typically 12 Volt units in enclosures. In this UPS configuration, 40 battery units, each comprised of 6 cells are placed in a series configuration. For all that follows, we define this as a “battery string”. Many field configurations have multiple strings in parallel to increase capacity either in absolute available maximum current or to increase the runtime duration of the UPS when operating solely from battery energy. Our typical opportunities to test and inspect small capacity batteries as described above are approximately 12-15 times over their lifetime. The table below details the ratio and period of inspections within the population for this analysis.

Preventive Maintenance Test and Inspection Frequency	
30 Day	5.5%
90 Day	52%
180 Day	15%
360 Day	23%

Figure 1

There are various methods employed today to test and measure batteries within strings such as:

- Capacity Test (2)
- Induced Ripple Voltage (3)
- DC float current (4)
- AC impedance (5)
- AC conductance (5, 6)
- DC conductance (5,6)
- DC resistance (8)

We do not argue or defend the validity or justify the costs of these methods here. Within our existing customer base, all of the methods above have been or are employed. For performance comparison and this study, we have only reported and analyzed the following parameters from battery strings and those inspection types where this data is available, even if additional data is known.

- Environmental temperature
- Negative post temperature of each unit
- Voltage across the battery unit at full charge, in a float condition
- Portable Instrument based resistance measurement

The subset of our entire portfolio used in this study represents an active field portfolio of more than 3.2 million units, (identified as active portfolio) that have been inspected with portable instruments between February 2013 and February 2014. Tables and data utilizing 1 million samples (identified as medium sample). Some recent data have been included up to and including March 1, 2014.

As part of our own best practices, customers whose batteries are significantly above 77°F are advised during each inspection that the recommended temperature is above limits, and we implement remedies to bring every string into compliance with this maximum temperature.

Also, as part of our inspection and maintenance process for the UPS systems, we strive to float charge batteries at the manufacturers' recommended values, and again, when outside these values, we work closely with our customers to bring all strings back to within policy.

We enjoy the benefit of a well-trained and educated staff, which has resulted in 99.6% compliance based upon inspections. Having such a well-defined set of data collected for battery units has resulted in providing us the ability to track how any given unit performs over time. The primary indicator of battery state of health we have chosen to use is internal DC resistance (8).

Stand Alone Methodologies

From 2004 until early 2013 our primary methodology could best be described as "find the outlier" battery preventive maintenance. One method to determine variances within a series string of battery units is to establish and strive for fixed operational and uniform values of temperature and voltage within a cabinet. For example, a typical 350 Watts Per Cell 12 Volt Unit with available *manufacturer's data* would exhibit the following subset of operationally required values.

Minimum Critical	Minimum Monitor	Nominal Float	Maximum Monitor	Maximum Critical	Ideal Temperature	Manf Resistance
13.20VDC	13.30 VDC	13.70 VDC	13.90 VDC	14.00 VDC	77 F	2630 µOhms

Figure 2

Field tables with more than 2000 entries have been created and are utilized by field engineers during inspections to determine if the operational state and environment of the battery is appropriate and correct and if not correct to remedy those conditions as much as possible. Consider for a moment a methodology whereby each preventive maintenance visit must stand on its own, as if the field engineer had never tested or measured the batteries previously. The technician would measure values above and then compare the 40 battery units as a family and analyze the results, closely following IEEE 1188 (7), excluding baseline. One way to do this would be to take each value and determine if it is within the bounds above, and then compare the observed resistance with the provided manufacturer's resistance. Our staff have observed that the Ohmic value from a single lot (n=1000) of units exhibited variances of +/- 30% from the manufacturer's average value. Others have published that a change of 125% should bring attention to a unit for further examination (3). The figure 3 below represents measured data from a very uniform three string startup with 40 units each of the same model, date code, manufacturer and ship date. The initial variance is 91% to 108% on internal resistance to mean or nearly half the way to our "monitor and observe" policy limits in place for field engineers. Due to these variances we discovered a significant percentage of our new units were found potentially "bad" during their initial startup when utilizing manufacturer data. Very soon afterwards this method was abandoned. However, observations and resistance values were preserved in all tests for future use.

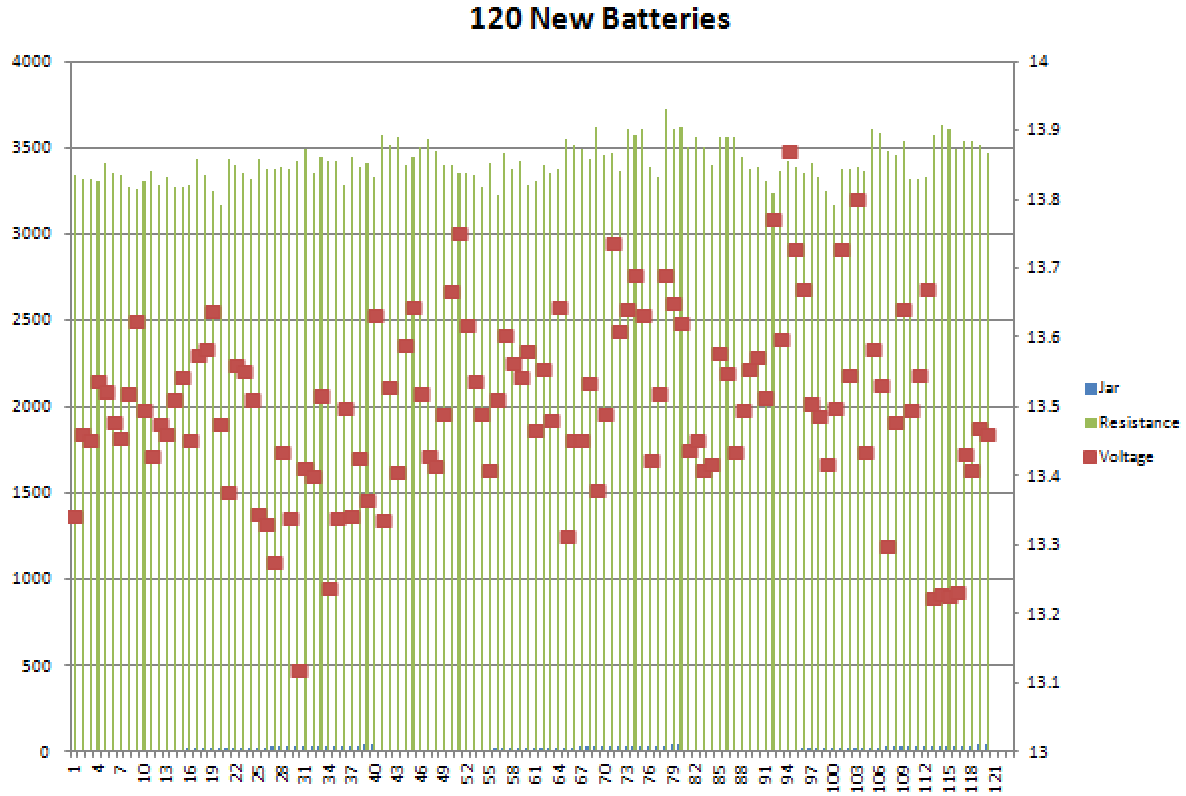

Figure 3

Another method within standalone methodologies would be to retrieve all 40 values, then determine their deviation statistically, by the variance from their average. This is particularly useful and can capture single units that are failing prematurely. This methodology has been found inadequate if within a battery string the set of individual units ages very uniformly, as there would never be an outlier. Comparing the average Ohmic value of all units in a string against the individual values is supported by a standalone methodology, but we were curious what occurred for a given string as the batteries aged. Were we able to determine and locate outliers just as effectively? Examining approximately 100,000 units detailed a "smoothing" effect whereby the values tend to wash out outliers. Figure 4 below details 40 resistances taken early in a string's life.

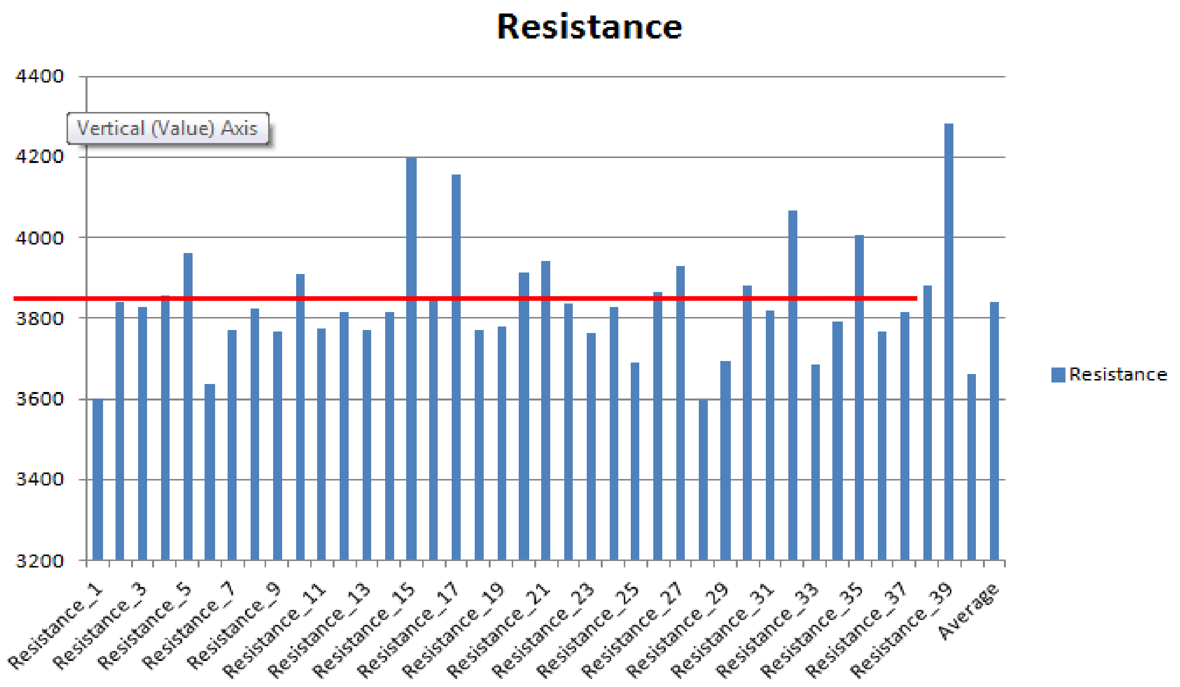

Figure 4

Clearly, units 15, 17 and 39 are outliers. The mean resistance from this string is 3840 µOhms, the peak resistance is 112% of the mean. Due to inbound manufacturing variances as described above it is not practical to declare if these values are excessive or not. The figure below depicts the string resistance values 3 years later, when resistances have climbed approximately 50%. Notice that now the outliers are no longer visible in the data, if an average resistance is utilized. We have observed this pattern moderation across many strings, whereby a mid-life string has few outliers, during the middle, reliable portion of the "bathtub curve". Once failures begin to occur, the outliers re-appear within the data abruptly as the resistance; voltages and temperatures begin to change rapidly.

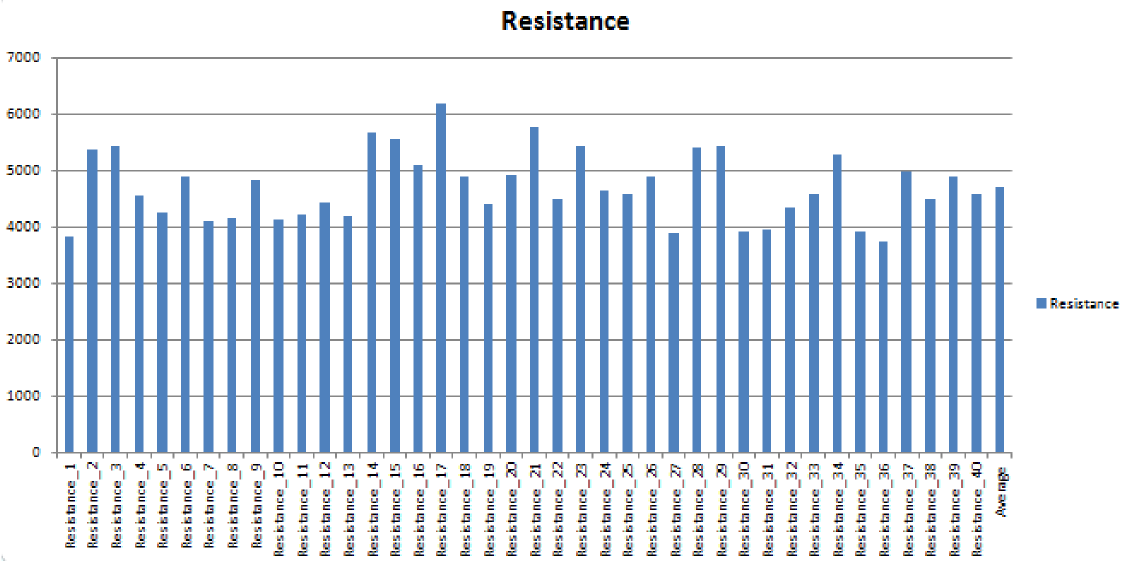

Figure 5

During a typical single inspection these differences would include low or high voltage across its terminals, higher temperature than nearby units and perhaps physical differences, like bulges, evidence of post leaks or discoloration. Correcting the environment and insuring that each battery is performing uniformly has proved to be completely acceptable for many years.

Baseline Methodology

Another methodology we have employed is to create a best effort baseline temperature, voltage and internal resistance set of data *for each unit* that persists as its “signature properties” for the unit’s entire lifetime. Practically, this requires a historical record be kept of each and every touch of the battery at each point in its lifetime and then comparing those values directly with previous values for that unit. Our most important discovery was that each unit should be tracked individually. The recordkeeping effort for this approach is arduous, but can be managed with modern, database equipped laptops and field engineers equipped with identical instruments calibrated regularly. If multiple technicians or vendors are responsible for periodic inspection and portable instrument testing, each technician must be provided each unit’s baseline and signature values.

A significant effort is required with all baseline methodologies to pick the correct and best baseline value that is available at the first and subsequent visits. Potentially in conflict with IEEE 1188 (7), as described above, our opportunity to measure and establish a baseline could range from 30 days to 360 days after initial startup. Therefore, creating an initial baseline is mandatory and then opportunistically updating it during inspections is required. The figure below represents the real resistance returned from a monthly resistance test of a typical battery string. This is graphically depicted in figure 6. We have observed that a mathematical saddle is evident, this saddle being the optimum choice of a resistance baseline for each unit. Notice also that the units ultimately converge and become more uniform in voltage, temperature and resistance.

The complexity required to equip each field engineer with the best baseline is daunting if handled on paper, in spreadsheets and to some extent even with field databases. An architecture that helps simplify this process is to utilize automation and a system whereby each inspection is perpetually synchronized before and after each visit, with the most recent inspection determining if the current inspection contains either a minimum or saddle. If this is true the current inspection establishes a new, optimum baseline, and then publishing for all subsequent visits to leverage. Additionally, a manual process will be required to override any automation if the technician has evidence to overrule, or some independent source provides an optimum baseline has been recorded.

Elevating Field Engineers

Once the complexity of maintaining baselines is automated the representative data and visualization of the past portable instrument data become paramount. For example, if a 40 unit battery cabinet is inspected quarterly, near the end of its 4 year life more than 2,000 values are required to represent it temperatures, voltages and resistances. We have utilized several representations that enable engineers to quickly understand and visualize this signature of a battery string. The figure below represents one, very early (in a strings lifetime) inspection. This representation is not a trend graph, but a fingerprint of the resistances of this string on the day the tests were performed. If this was the earliest inspection known, as described above this is the best baseline resistance value for each unit at that moment in the string's lifecycle. A subsequent visit may comply with IEEE 1188 (7), but this is the best available at this point in time. Consider the image as a fingerprint that is unique to these 40 units.

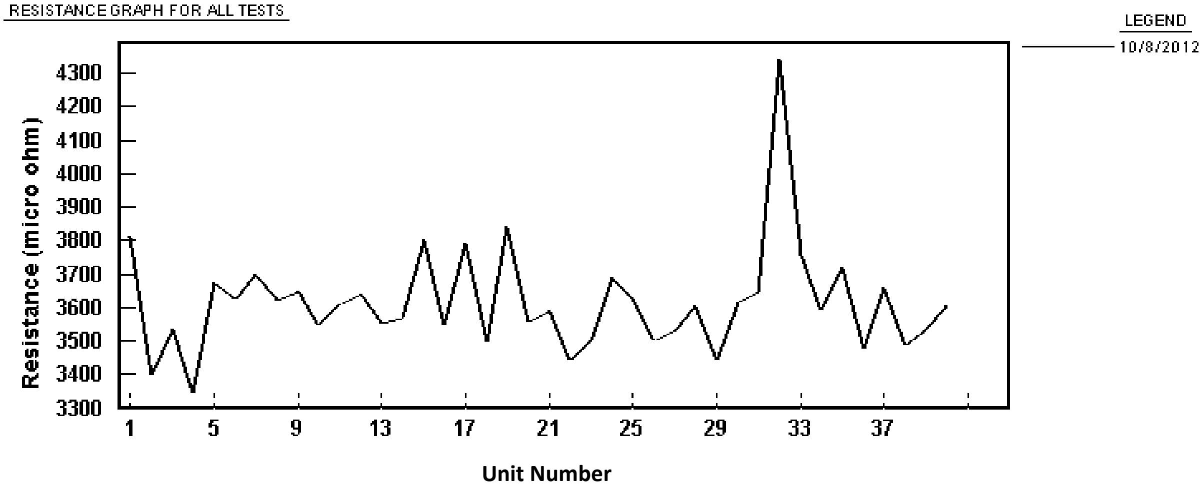

Figure 6

Now, fast forward 48 months, with five portable instrument tests completed. From the image below the string fingerprint has been uniform, consistent and stable over time except for unit number 7. Also, notice that unit 32 begins its life with a relative higher resistance than the other units. Unit 7's average resistance has risen to 4356 µOhms or 124% of the baseline. Furthermore, unit 7's resistance has been climbing since the original inspection in 2012. If using a standalone mean-based methodology, the average resistance change across this string over the optimum baseline is less than 5%. Ideally and without cost and time consideration, this unit or string could be removed from service, charged independently and tested via a capacity test. However, this is not possible, as the cost and risk impact of that testing outweighs the cost of just replacing the entire string. We chose to take a wait and observe posture until the resistance climbs to 125%-150% of the original baseline. However, for every subsequent visit, unit 7 will stand out as an anomaly and field engineers will be watching it closely for physical, particularly for leaking posts, bulging or relief valve stress. The key values of voltage, temperature and internal resistance (4) will be tracked graphically until string replacement is planned. Finally, notice that unit 32 has risen along with the other units, but is not changing appreciably, although anomalous. Unit 7 is the rogue in this inspection.

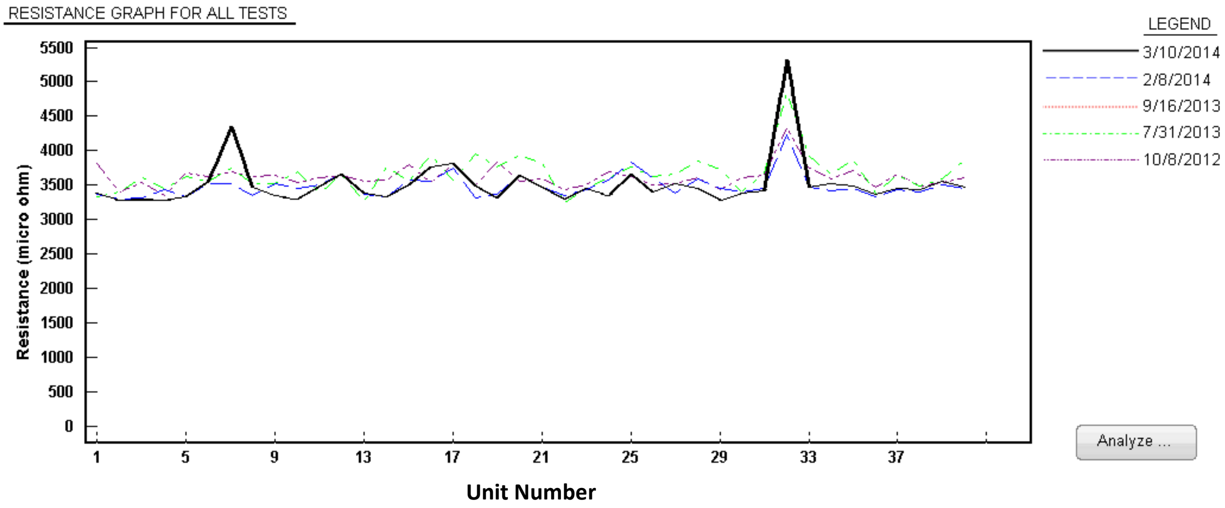

Figure 7

Lessons Learned

Enjoying the benefits of a large installed base permits the investment in software development and hardware integration whereby incremental improvements can be proposed, justified and implemented continuously. Although it is logical and technically accurate to capacity test suspected or aged battery strings, our challenge remains to convince our customer base that this expense worthwhile, particularly for aged strings.

Without waxing philosophical, business leaders require adequate facts, details and alternatives in order to make a reasonable replace, repair or continue preventive maintenance decision. The best compromise we have found for those business leaders are to provide indicators of the likely state of health of the battery string as economically as possible.

While stationary, permanently installed instruments with continuous testing and monitoring are the best methods to track the degradation of VRLA batteries, in some cases that cost is not justified for smaller, cabinet based VRLA battery types for various reasons. When this is the case an opportunistic approach as described above, which equips every visiting engineer with a comprehensive historical data set on every visit has been found to be a reasonable compromise. This methodology is not without its risks. More frequent inspections, as frequent as every 30 days increases availability (and of course, cost). Therefore, customers determine their risk exposure and plan maintenance on condition, replacement on time, paradigm that insures relatively high availability.

It is very important for UPS service batteries that the float voltages are kept at the appropriate levels for each and every unit. A battery that is beginning to fail causes an imbalance that adversely affects the life of the other units in the string.

We have found that battery baselines vary far too much to utilize manufacturer published resistance values. Our process of installing the battery string, observing the resistance as the string “field forms” and becomes acclimated to its role within the string and then establishing a system baseline for that particular installation is the most practical methodology. These data are required to produce repeatable, verifiable telemetry comparisons, very similar to stationary based systems, only utilizing far less frequent acquisition of new data. We then calculate a percentage resistance rise over initial baseline as our key metric of battery health through automation. The graphical rendering of a string’s performance over the entire lifetime on a single page since “zero day” for engineers and analysts on a string basis allows experts to quickly determine if further actions are required.

This graphical representation provides a backup confirmation to maintain a high confidence in the remote or human derived, in person “telemetry” system. New batteries, forming batteries, damaged wires and updated instruments are portrayed graphically and help provide guidance and insight to our staff for the entire life of the battery string. These representations also quickly identify our own mistakes.

Results

Utilizing a historical based visualization system has saved time, but more importantly empowers field engineers so that they can technically and visually defend their intuitive recommendations concerning unit and string replacement. Batteries that are failing are quickly identified and removed from service. Rarely, a customer permits us the luxury of capacity testing a string when high resistance is observed. During a recent examination we compared 120 units, all identical as above and noted three outliers within resistance which correlated to lower unit voltage at the end of a 20 minute discharge test.

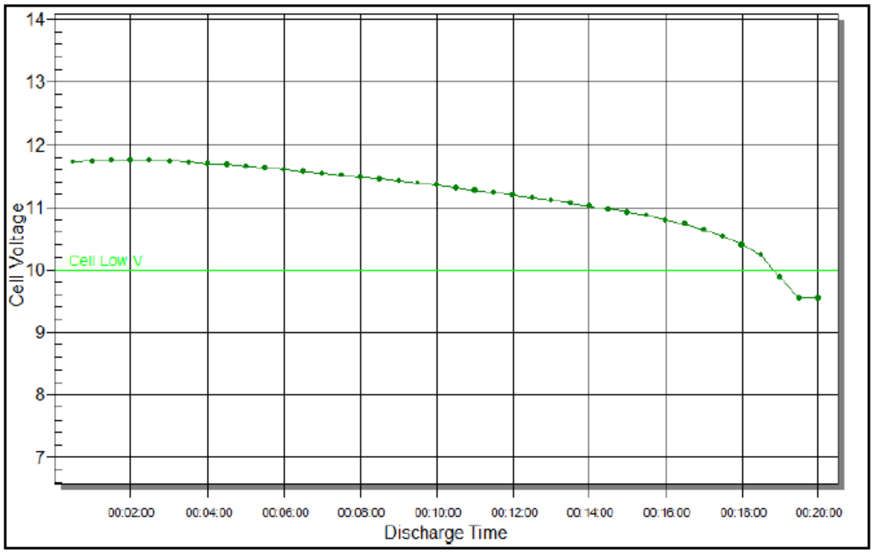

Figure 8

We have found that battery baselines vary far too much to utilize published resistance values. Our process of installing the battery string, observing the resistance as the battery "forms" and establishing a system baseline for that particular installation, battery type and instrument are necessary to producing repeatable, verifiable telemetry comparisons. We then calculate a percentage resistance rise over initial baseline as our key metric of battery health through automation. The graphical rendering of a string's performance over the entire lifetime on a single page since "zero day" for engineers and analysts on a string basis allows experts to quickly determine if further actions are required.

Conclusion

Knowing how an entire portfolio of batteries performs in a real world application has enabled a very high demonstrated level of availability (10). This is best accomplished with in-person physical inspections, stationary instruments producing very repeatable results and an analysis system supported by skilled engineers working collaboratively. The end resultant benefit has ultimately resulted in longer battery utilization and real dollar savings in operational uptime for critical facilities operators.

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