Verifying the Health of Backup or Emergency Power Supply Batteries

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Executive summary

Emergency power systems rely on batteries to deliver power at the right moment, in order to start a generator or to run a UPS in the event of an outage. Neglected batteries, however, are the most common reason for backup power failure. This paper discusses how automated testing systems provide precise functional assessments of battery health, and how such systems prevent unnecessary failures.

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Introduction

The lead acid battery: even the most advanced power backup systems rely on this relatively low-tech device to help deliver power after a grid failure, either to start the generator or to run the UPS. Even though lead acid batteries are limited by low energy-to-weight and energy-to-volume ratios (they are big and heavy), they are also capable of high-surge currents, making them ideal for electric starter motors in automobiles and generators. However, an improperly managed and below capacity battery can render an emergency backup system inoperative.

In healthcare settings, battery management systems help protect investment in emergency power backup solutions, improve the reliability and efficiency of these solutions, increase safety for patients and staff, and promote a more 'green' environment by reducing energy waste. Ultimately, ensuring the health of a lead-acid battery for generator startup goes a long way towards ensuring the reliability of the entire backup solution. Batteries are perishable items with relatively short shelf lives.

The basic premise behind lead-acid battery technology has changed little since the nineteenth century. Multiple cells, insulated from each other by separators and comprised of two lead plates – one positive plate covered with lead dioxide paste and one negative of sponge lead – are immersed in sulfuric acid and water (electrolyte). Each cell's resulting voltage combines via series connections to produce the battery's total voltage. In the case of a twelve-volt battery, for example, six single cells combine to produce a fully charged voltage of 12.6 volts. Plate surface areas and electrolyte capacity determine battery ampacity; that is, the upper limit of electrical current a battery can generate before its abrupt or progressive weakening. The thickness of the lead plates and the grid design of the cells determine the battery's discharge rates. Modern battery design also adds new chemicals, such as nickel cadmium, and more efficient grid designs that increase battery longevity and reliability.

> **SOH**
>
> **State of health (SOH)** describes the condition of a battery, or battery cell, compared to its ideal conditions. SOH is measured in percent (100% = the battery's conditions match the battery's specifications). Battery SOH should be at or near 100% at time of manufacture.

Operating conditions and environments make it difficult to benchmark standard thresholds, and functional assessments are often imprecise. Fortunately automated systems exist today that are designed for emergency generators or UPS systems battery health testing (battery monitoring specifically in the case of UPS testing). These solutions can combine cranking voltage measurements, operating environment temperatures, and battery age to help provide an inexpensive but accurate measure of battery health. Such systems help extend battery replacement lifecycles and reduce operating costs while also providing accurate records and reports for archival purposes.

Why manage batteries?

Batteries are electrochemical energy reactions, and as with all such reactions they begin to expire the moment dioxide paste is factory-applied to their lead grids. In fact, unlike most other components within a mechanical system, there is usually no outward indication of battery failure (except in the most extreme cases such as thermal runaway). The addition of electrolyte only accelerates deterioration. The chemical discharge/recharge cycle is never-ending until all lead and electrolyte have been consumed. Unlike other components within an emergency power backup system, or a modern energy management system, batteries will experience significant degradation over time. Once a battery can only produce 80% of its rated capacity, it is considered "dead" and should be replaced.

Within a UPS system a battery breakdown is as critical as any grid malfunction. Management and monitoring systems can detect cell faults and validate satisfactory operating conditions of network batteries.

Replacing a battery before its end of service creates more risk for battery faults and unnecessary costs, as each new battery carries with it new risks of either manufacturing errors or preventable issues. For the system to be reliable, batteries must be monitored and managed.

Using standards to define battery health

A common problem is how to describe battery health in a standard way, such as State of Health (SOH).

Unfortunately SOH is not governed by a standard. Instead it is specified by test equipment manufacturers or by users.

Battery management systems help you apply a consistent set of rules for accurate SOH measurement.

Expected vs. actual performance

As is the case with many products, the real performance experience may fall short of the stated manufacturer specifications. For example, the advertised battery life of today's smartphones does not always align with users' experience, and may need recharging more frequently than expected. This has everything to do with how the product is used, how often it is used, its operating conditions, firmware, operating system, and software memory demands, as well as any unforeseen design imperfections that may have occurred in the factory.

In a similar way, there can be a performance gap between the functional potential of lead-acid batteries – the stated design expectations of the manufacturer based on optimum operating conditions – and their actual performance in the field. One sealed battery study of nearly 25,000 cells clearly indicated the majority of these cells would not be capable of delivering their stated performance potential.[1] After only two years, batteries in this study could no longer be considered reliable. **Figure 1** illustrates battery performance rates over time

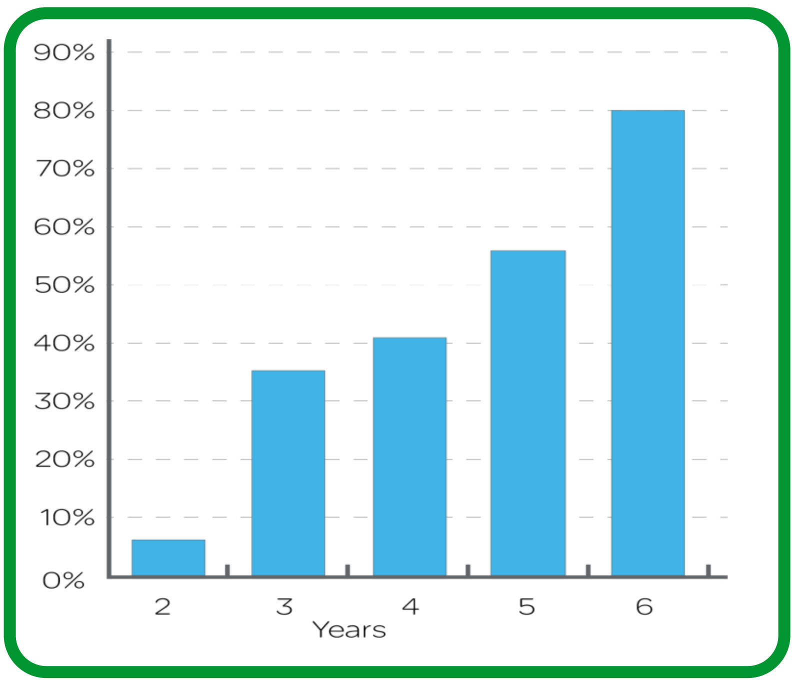


Figure 1
VRLA (valve-regulated lead-acid battery) failures by year (Source: D.O. Feder, PhD Electrochemical Energy Systems, Inc.)

[1] Feder, D.O., "Performance Measurement and Reliability of VRLA Batteries", *Proceedings of INTELEC,* 1995.

Battery failure modes

While each cell of every battery has its own unique rate of deterioration, a variety of factors contribute to actual rates of decline and length of battery service life (see **Figure 2)**. Preventable issues and manufacturing errors combine for a total of 69% of battery failures[2].

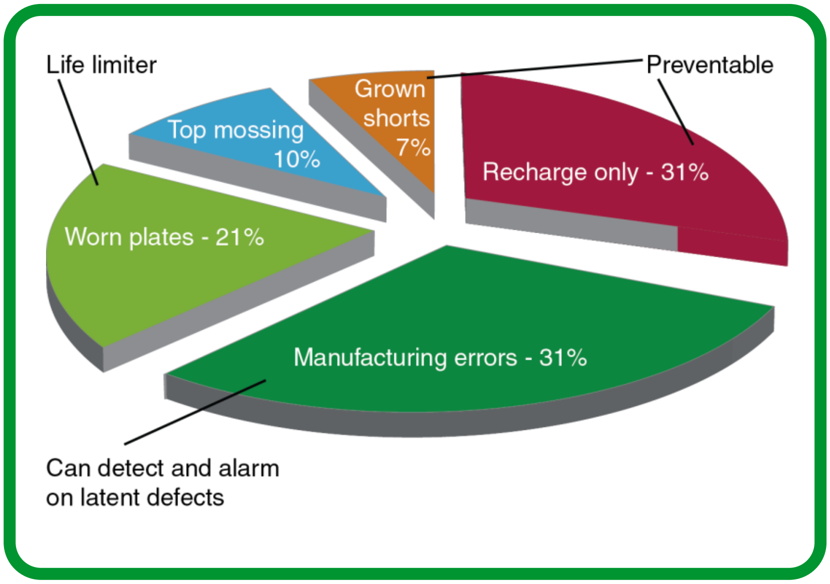


Figure 2
Failure modes of lead acid batteries (source: BCI, 107th convention).

Operating temperature

Operating temperature has the most impact on premature battery failure. Higher temperatures within the battery cells cause its chemical reactions to speed up. This increases current draw, water loss, and the interior rate of corrosion on the positive grid material. The *Arrhenius equation*, developed in the late 19th century, describes the relationship between temperature and chemical activity. Higher temperature equals higher activity. **Figure 3** illustrates how every 10°C temperature increase doubles battery reaction rates, basically halving its functional life.

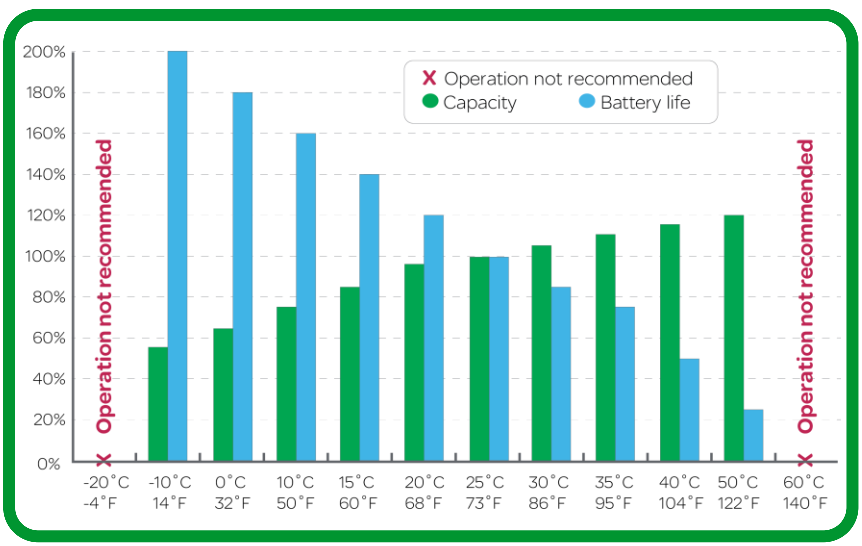


Figure 3
Battery capacity and life compared with temperature.

[2] Battery Council International, "Failiure modes of batteries removed from service", *Report of the BCI Technical Subcommittee on battery failure modes*, 2010.

Grid corrosion

Grid corrosion can lead to short circuits within the battery due to the compact design of modern batteries. Because normal chemical reactions within the battery cause corrosion (shedding lead from the plates) within the grid; these reactions can be decelerated but not stopped. Typically a battery that fails because of grid corrosion has been in service longer than its expected lifespan. Controlling complete discharge, suitable operating temperatures, and controlling overcharge are good ways to slow the corrosion progression.

"In healthcare settings, battery management systems help protect investment in emergency power backup solutions".

Sulfation

Sulfation occurs when a battery does not receive a complete charge. Lead dioxide disintegrates on the negative electrode, reducing active surface area and causing capacity loss. It also reduces the batteries consequent ability to receive a charge, causing a longer charging cycle as the resulting sulfation increases internal resistance. This chronically undercharged condition is common in lead-acid batteries that are used only periodically in load hungry applications (i.e. numerous starts and stops).

Short circuit (due to paste degradation)

Paste on the positive electrode becomes porous, causing a loss of contact between the positive material and the grid. During discharge, a battery's plates grow larger as they absorb sulfate from the acid, and in turn grow smaller as they relinquish sulfate from the charging cycle. Little by little, from each cycle, the plates shed paste. It is important that there is room underneath the plates to catch this shed material. If (or when) this shed material makes contact with the plates, the cell will short-circuit.

Dry-out (water loss)

Overcharging increases the acid concentration in the electrolyte, which increases self-discharge and sulfation rates. As the battery gases, it loses water, leading to eventual dry-out, capacity loss, and ultimately separator (insulator) breakdown. In today's sealed batteries, water loss leads to dry-out and decline in capacity. Proper care and charging to avoid dry-out is important.

Figure 4
Battery array that has experienced thermal runaway.

Thermal runaway

Thermal runaway occurs when the temperature inside the battery is high enough that it is unable to be dissipated from the battery casing, causing a temperature increase around the exterior of the battery. This, in turn, increases the temperature within the battery ultimately leading to case meltdown and exposed battery grid (see **Figure 4**).

Top mossing

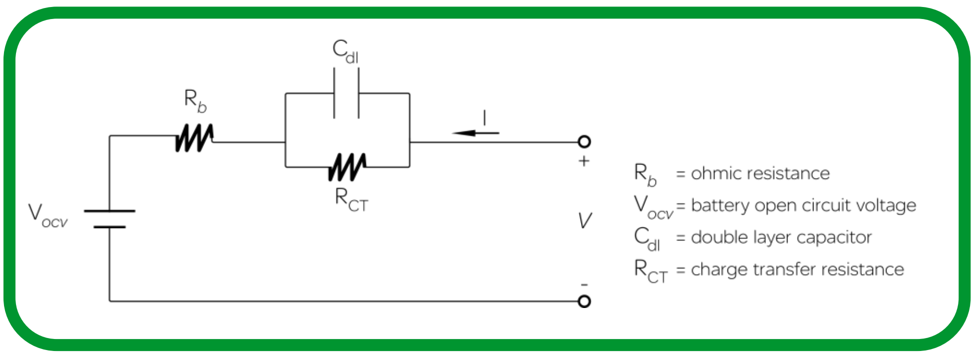
Top mossing is a result of inaccuracy or carelessness during the manufacturing process. Separators and plates are poorly aligned, causing plate areas to become exposed. This exposure allows a crystalline ‘moss’ to form, leading to self-discharge (or ‘soft short’).

Battery testing theory

A battery test provides specific answers to important questions, not just about the battery but also about its individual cells (i.e., how much charge is left; the deterioration in performance since the last test; and estimates on its remaining life). Several different testing methods are used to manage and report on battery health – discharge, which reduces battery life; impedance, where electronic noise can affect accuracy; and current, which is reliable and accurate, but which does not consider major battery life factors such as temperature and state of charge.

Perhaps the most common approach to battery operation is the Thévenin model (see **Figure 5**), which holds that combinations of batteries and resistances with two terminals can be replaced by a single voltage source and a single series resistor. Impedance or resistance can be measured and from that measurement, infer battery health. However, since many circuit values are linear over a certain range, Thévenin is only valid within these ranges[3]. Resistance measurements are important, to be sure, but combining these with other relevant data points within software designed with specific SOH algorithms provides a more precise and comprehensive battery diagnosis.

Figure 5
Thévenin's battery model (source: Grube, 2008).



Battery cranking voltage as battery health indicator

Figure 6 illustrates the results of a battery undergoing an accelerated 14-week aging test cycle. The cranking voltage signal failed to crank the DC starter at week 14. Notice that minimum voltages (V1) for week 9, just a little more than a month before cranking failure, and week 13, just a mere week before failure, are very similar. The challenge here is to standardize the V1 threshold in order to differentiate between the still-useful battery and one at the end of its life. Too low of a setting would either cause false alarms or would provide no alarm of imminent failure. Voltage is a useful measure, but combining it with other notable, measureable data points offers a more accurate and robust reporting mechanism. A test that combines such data points is possible using battery cranking voltage.[4]

[3] Thevenin's Theorem is a way to reduce a network to its circuit equivalent, comprised of a single voltage source, series resistance, and series load. It can only determine what happens to a single resistor in a network: the load *(source: ‘All About Circuits’, chapter 10)*

[4] Grube, Ryan J. “Automotive battery state-of-health monitoring methods”, *Masters Thesis, Wright State University*, 2008.

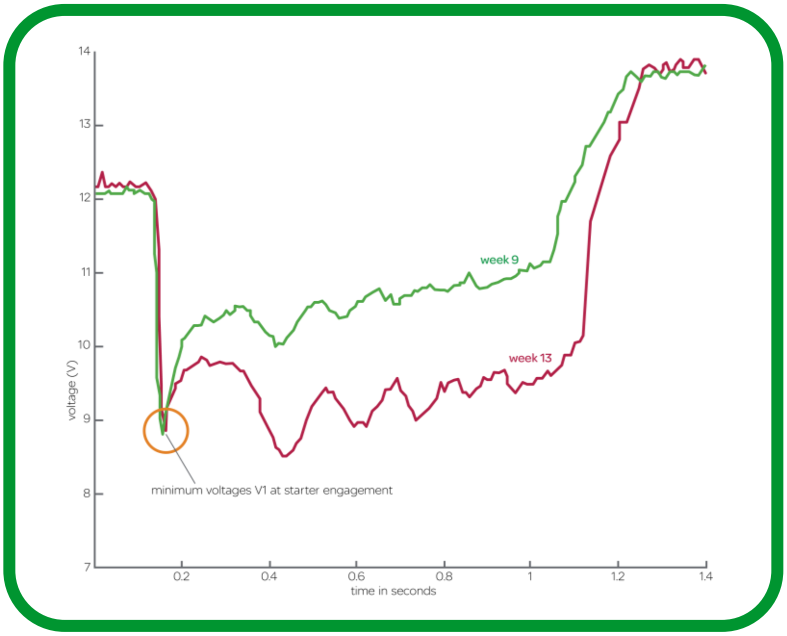


Figure 6
Battery cranking voltage signals (source: Grube 2008).

The starter motor on an engine is a high-torque, high-efficiency DC motor designed to operate at overload. Modern sealed batteries, in fact, are especially well-suited to handle this overload, as they can deliver high power over short bursts (such as when a starter motor is engaged). A typical voltage waveform will indicate a successful engine start. In **Figures 7 A, B** the relationship between voltage and current is illustrated. In fact it could be said that voltage accurately implies current. The plot of **Figure 8** indicates that the relationship between current and voltage is actually linear. Thus we can use voltage to analyze and predict current.

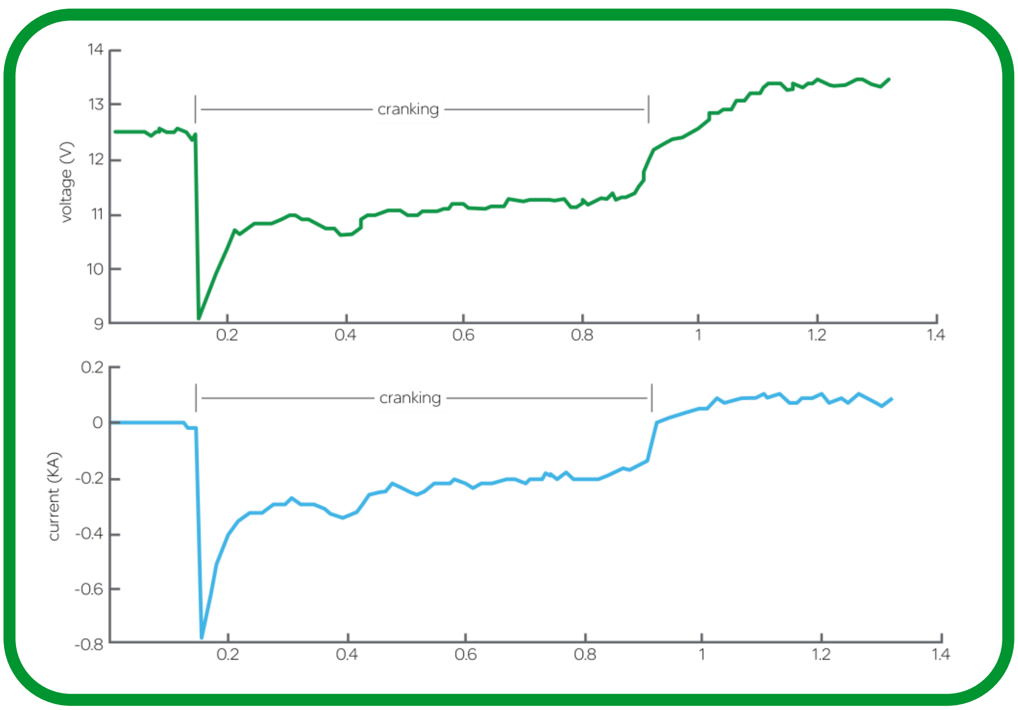


Figure 7 A, B
Voltage and current battery signals during engine cranking (source: Grube, 2008).

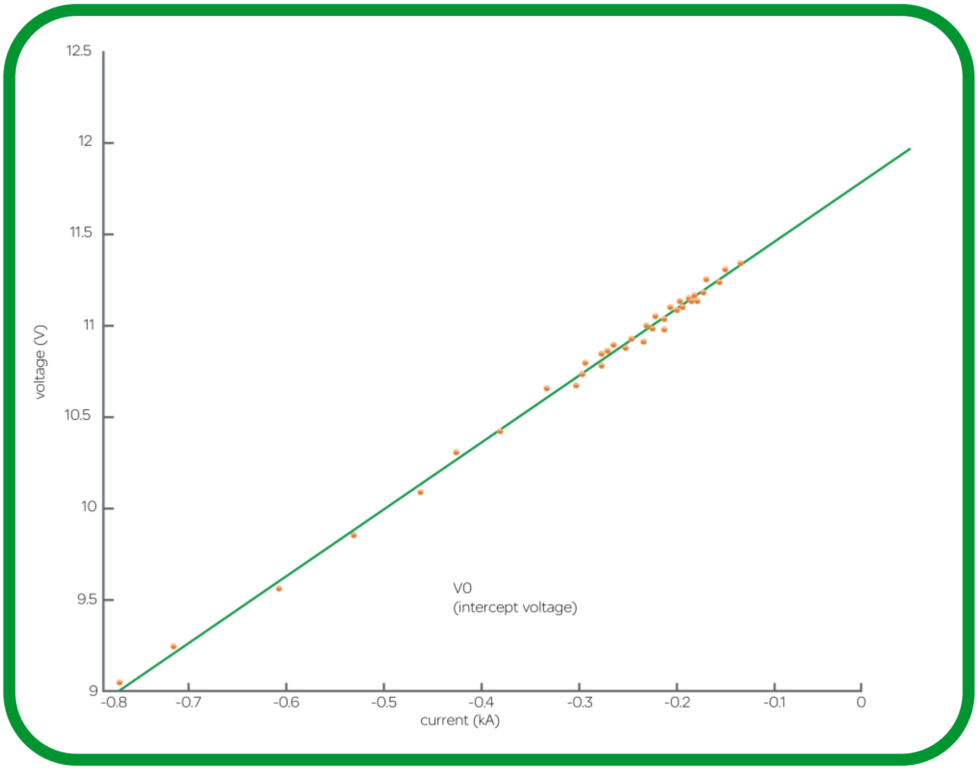


Figure 8

Plot of cranking voltage vs. current (source: Grube, 2008).Note the nearly perfect linear relationship between V and C.

Using battery cranking voltage to gauge the health of a battery also has its advantages. It is an accurate and efficient depiction of the battery dynamics that occur within the cells, during engine cranking as well as startups. Such an approach does not require the addition of costly sensors. These readings can also be compared with previous tests to compare the degradation of the battery(ies).

There are two steps to this methodology:

1. Cranking power capability of the battery is determined by comparing the battery voltage at the instant the starter engages (i.e., V1) with the minimum voltage during the ensuing engine cranking.
2. The state of battery charge (SOC) is created by combining in an algorithm the cranking power capabilities of the battery with other relevant data points like battery operating temperature, number of discharges, and battery age, thereby inferring a reliable battery statement of health (SOH).

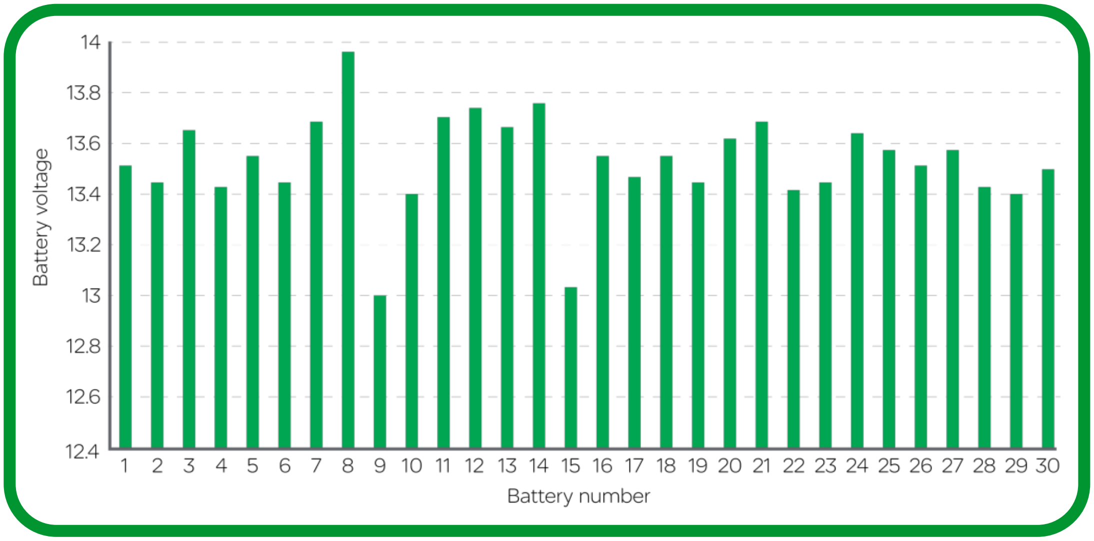
Once the automated comparison of starter engagement voltage surge with engine cranking voltage occurs, and is combined with measurements of voltage dips and recovery times (Coupe de Fouet effect), SOC, and temperature readings, a cost-effective and accurate report on the battery condition can be generated. Data can also be compared with results of previous tests to indicate the rate of battery degradation. This method can be used to offer a very effective alert of imminent battery end-of-life and avoid costly and reputation-damaging losses owing to battery failure.

Battery management and test methods

Since no industry standards exist for battery management, several different testing methods are in use in the industry. Each manufacturer utilizes a unique approach to defining and measuring battery health – from simple conductance testing to multiple parameter averages, and each designs unique testing equipment to supply the results. This lack of standards can present a challenge, especially when testing combines equipment from different manufacturers.

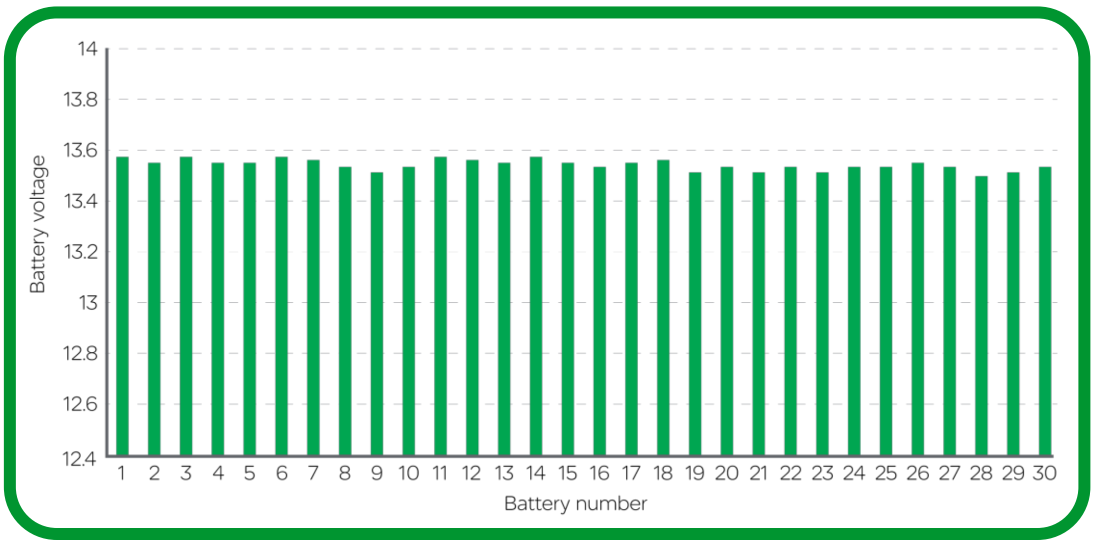
One of the issues with conventional battery charging is that these systems charge an entire string of cells or batteries. Often referred to as 'float charge', this method of charging can result in some cells or batteries receiving too great a charge while other batteries in the string are undercharged (see **Figure 9**).

Figure 9
Results of a typical float-charged battery string.



In a more efficient charging system, each individual cell gets charged according to the needs of that particular cell (see **Figure 10**).

Figure 10
Same string after individual battery charging.



Because of the inherent issues that arise with even the most ordinary use of batteries, a battery management system that combines battery monitoring and testing with individual battery charging would be an excellent way of supporting the critical power component in healthcare settings, as these sites must be able to rely on an uninterrupted and reliable supply of power. There are a variety of operational approaches in use today; some are capable of individual battery cell monitoring and charging. These systems optimize the charge state of an entire string without raising individual cells to unfavourable voltage levels. But while it is an ideal approach, one drawback is that such a system can be rather complex and expensive to implement.

A more cost-effective approach is to capture the voltage signature of the battery during times of high current draw. In the case of a genset, this would occur during engine start. For UPSs, it would occur at the instant utility power is lost and the switchgear makes the changeover to UPS battery power (*Coup de Fouet* or *Whiplash* effect). [5]

Since voltage is proportional to current (as described previously), this approach allows for an accurate indication of battery health by capturing the voltage signature of the battery during those times of high current draw. Combining this with ambient temperature allows for a good indication of the SOH. While this does not provide information about individual cells, it does give a warning signal if the health of the battery string is below acceptable thresholds. This applies to both nickel-cadmium and lead-acid cells (flooded or VRLA applications) in their diverse cell numbers and voltages.

In addition, alarms can be configured to respond to direct measurements (individual battery voltage, string voltage, or ambient temperature) or aggregate measurements (SOC, cell temperatures, and cell resistance). Collected data (including logging intervals and event timestamps) can include individual cell and string voltages, DC current flow, ambient temperatures, lowest measured voltage, deterioration rates, and even flags for under-performing battery units.

Benefits

Automated battery health reports provide robust charts with reference signatures that overlay the test signature, indicating cumulative voltage differences, thresholds, and issues with battery health. Very often such systems can be incorporated into modern energy management systems that are already in use within healthcare facilities.

[5] Ribeiro, Anderson Luiz et al. “Shutdown of DCS due to the Coup de Fouet effect of lead acid batteries”, *International Stationary Battery Conference*, 2010.

Conclusion

In healthcare environments, reliable, accurate battery health measurements are crucial for any equipment related to the continuity of electrical supply and related patient safety. Because expected design life does not always align with actual life in the field, automated battery management solutions that offer battery testing and reporting are key.

One of the most cost effective approaches are found in energy management or monitoring systems that include automated reports to capture voltage signatures during time of very high current draw (such as during engine start or UPS utility supply loss) to determine the batteries' SOH. These automated reporting systems can help provide practical guidance regarding how to assess and validate battery SOH, as well as provide data to predict potential instabilities and feed strategies to help prevent such volatility.

Analysis of battery SOH should be an expected part of any effective healthcare or critical power facility design, and also part of an effective healthcare center energy management plan.

For further reading

- Battery Technology for Data Centers and Network Rooms: Site Planning (White paper 32)
- Battery Technology for Data Centers and Network Rooms: Battery Options (White paper 30)
- Battery Technology for Data Centers and Network Rooms: VRLA Reliability and Safety (White paper 39)
- Data Center VRLA Battery End-of-Life Recycling Procedures (White paper 36)

About the authors

Markus Hirschbold (PEng, PMP, CEM) has worked for Schneider Electric for more than two decades. He began his career in R&D working on the designs for many of the power monitoring devices still available on the market today. He has also worked as an applications engineer, project manager, and eventually program manager of a team responsible for deploying and commissioning energy management systems worldwide. He has been Segment Director for Healthcare since 2009, responsible the creation of electrical distribution and energy management solutions for healthcare facilities. He holds in excess of 30 patents related to Schneider Electric hardware and software.

Chuck Hoeppner (BA, BKin) is a Senior Communications and Content Manager for Schneider Electric. He has worked for the company since 2001 and has held a variety of marketing-related positions. He is a University of British Columbia alumnus and has worked extensively in the technology sector in the fields of education and training, thought leadership development, and marketing communications.