Technical Notes

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Battery Testing for Off-grid Solar Products

This Technical Note discusses battery testing of off-grid solar products seeking to meet Lighting Global's Quality Standards. It gives an overview of battery failure issues and provides justification for the tests chosen by Lighting Global to evaluate battery performance and durability.

This article builds on previous Technical Notes available at www.lightingglobal.org

Introduction

The lifetime performance of off-grid solar products is highly dependent the cycle life of the battery. The daily charge/discharge of the system battery will eventually degrade it to a point where the product no longer functions at an acceptable level, and nothing short of replacing the battery will restore the product to normal operation. Other system components (e.g. switches and connectors) also experience cycle life failures, but the number of cycles in these cases is often many times the expected number of cycles for a battery. This leaves the battery in the unique position of being a critical system component with a relatively short predicted lifetime. No other system component is so important and so limited in performance.

Several different aspects of the battery performance and control in an off-grid product can be tested for quality. These include (but are not limited to) battery capacity, storage durability, charge/discharge regulation, and cycle life. Battery tests can range considerably in complexity, with some tests requiring long periods of time and relatively expensive equipment. Because of the many variables involved in the real world performance of battery-powered systems, battery testing in the lab may or may not be predictive of battery performance in the field.

Lighting Global has developed a battery testing policy that balances the need to test battery quality with the need to achieve reasonable laboratory testing costs and time frames. Battery capacity is tested to verify truth in advertising. Charge/discharge regulation is tested to ensure that improper voltage levels do not prematurely damage the battery cells. Storage durability is tested in an attempt to ensure that the battery is sufficiently robust to endure extended periods in the supply chain and rugged use by end consumers. Battery cycle life, however, is not tested as this would be extremely difficult within the context of the Lighting Global program and would lead to long wait times and very high laboratory testing costs.

Battery failure

Anecdotal evidence from manufactures, distributors, customers, and program stakeholders suggests that battery failures are one of the leading causes of off-grid solar product failures. This makes intuitive sense given the battery's central role in product performance and also the well-established electrical requirements for charging and discharging different battery chemistries. All of the different types of batteries used in off-grid products have constraints on charging rates and cut-off voltages, and failure to properly follow these constraints can result in damage to the cell. Temperature issues are also important during both the storage and use of a battery. Extreme temperatures can lead to battery degradation and early failure.

Battery failure is typically characterized in terms of capacity loss. The point at which a battery 'fails' is subjective and depends on the application and service needs of the device. For some applications, a capacity loss of 20% (80% remaining capacity) is enough to trigger replacement. In pico-powered and solar home systems (SHS), a battery with 80% capacity may still provide enough useful service to be considered 'good'.

It is necessary, of course, to establish a baseline capacity that is used as the starting point for the capacity loss measurement. For battery testing purposes, this is the initial measured capacity of the specific battery being tested. From a manufacturing or product performance perspective, battery failure must be measured in relation to a nominal value as measuring individual battery capacities for a large volume of units would be impractical or impossible to effectively implement.

Lithium battery failure mechanisms

Lithium batteries lose capacity due to chemical changes in both the anode and/or the cathode that impede the transport of lithium ions during charge and discharge cycles. Thin films (called solid electrolyte interfaces (SEI)) trap lithium ions and prevent necessary chemical interactions on the anode. The SEI formation grows over time as a result of normal battery cycling. The cathode can similarly form an oxide layer, trapping lithium and reducing ion transport to the cathode. This is called electrolyte oxidation and occurs quickly if the battery is held at elevated temperatures and high voltages.

Both processes are irreversible and occur at rates that depend on the specific charge/discharge conditions and temperatures seen by the battery. Altering these conditions will alter the rate of change in the available capacity of the battery.

Lead-acid battery failure mechanisms[1]

Several different mechanisms can cause lead-acid battery failure. These occur at different rates and according to the specific use conditions experienced by the battery. These processes can be interdependent, where one failure mechanism accelerates another and helps establish negative feedback conditions.

For example, anodic corrosion of the positive battery plate increases the battery resistance. Portions of the plate will then not receive a complete charge, which in turn helps the formation of sulfate crystals. These block chemical reactions at that plate location.

This is known as sulfation and is another cause of capacity loss and eventual failure. During discharge, lead in the positive and negative battery plates converts to lead sulfate. Charging the battery reverses the chemical processes and returns the plates to lead (negative plate) and lead dioxide (positive plate). Over time, some of the lead sulfate crystalizes and is no longer available as an active material in the battery. Leaving a battery in a discharged state for more than 2 weeks, especially at elevated temperatures, accelerates this process and should be avoided.

Nickel-metal hydride battery failure mechanisms

The main failure mechanism in nickel-metal hydride batteries is a gradual increase in internal resistance and decrease in power capacity due to drying of the separator. This occurs through two main mechanisms: redistribution of the electrolyte due to swelling of the electrodes, and loss of electrolyte through oxidation of the separator and electrode materials. Further damage can be caused by extended storage in a deeply discharged state, which results in breakdown of the positive electrode and oxidation of the metal hydride active material; in some cases this degradation can be reversed through low-rate cycling.

In batteries with multiple series cells, the cell with the lowest capacity can be overdischarged to the point of polarity reversal. This can result in gas production, venting, and damage. Adequate deep discharge protection can help prevent polarity reversal.

[1] Ruetschi, P. "Aging mechanisms and service life of lead-acid batteries" Journal pf Power Sources 127 (2004) 33-44

Lighting Global Battery Testing

The procedures included in the Quality Test Method (QTM) of IEC Technical Specification 62257-9-5 involve several test requirements aimed at evaluating batteries in off-grid solar products. These are focused on verifying truth-in-advertising claims and identifying system design problems that are known to lead to early product failures. The tests can be performed in a reasonable time frame and do not require high cost equipment purchases.

All QTM tests use strict sampling requirements that ensure that samples are drawn from warehouse production stock. The overall sample sizes are small (four or six units depending on the system), but the selection process prevents cherry picking that might otherwise use 'good' batteries that are not representative of the normal production units.

Battery capacity

Battery capacity tests provide a check for advertising claims. These capacity tests establish an initial battery capacity for each battery unit and require only a few days to prepare the test units and perform the tests. They include five charge/discharge cycles to prepare the battery.

Battery protection

Proper charge/discharge regulation with a charge controller is known to be critical to the cycle life of a battery. Any battery, regardless of material and construction quality, will be damaged by improperly regulating the voltage levels and currents seen during service. Damage can occur at any stage during the battery's lifetime, and products without adequate regulation stand a high chance of early failure.

QTM testing includes several overvoltage and undervoltage tests. These tests can be performed in a few days and help ensure that a product's battery will not be damaged by improperly controlled charge/discharge cycles during normal operation.

Battery durability

Batteries are often stored in hot locations ranging from shipping containers to warehouses while they make their way from the factory to the consumer. This can degrade the battery materials and reduce battery capacity before the product reaches its final destination and is placed in service. Moreover, once they are in service, batteries are often subjected to rigorous use patterns. Lighting Global identified these problems and developed a battery storage test method[2] to evaluate the ability of a product's battery to resist damage from storage and use. This battery durability test measures the battery capacity loss after a battery is stored for 15-30 days (depending on battery chemistry) in a discharged state at elevated temperature.

As of mid-2016 Lighting Global has tested batteries for over 40 pico-solar systems using these procedures and identified failures in five. The majority of the systems used lithium batteries, but only one of these (a lithium-ion battery) did not pass. Three out of four sealed lead-acid (SLA) batteries failed the durability test, indicating that these batteries are more sensitive to failure during storage and use.

The battery durability test helps to identify low quality batteries quickly without the need for additional

[2] The storage test was derived from the following documents: PVRS 5A, VW 75073, AS 4086, (Flooded lead-acid); PVRS 5A, DIN EN 43539-5, (Sealed lead-acid); DIN EN 43539-15, IEC 61951-2, (NiMH); IEC 61960 (Lithium-ion). Researchers from the Fraunhofer Institute for Solar Energy Systems were involved in developing the methods.

laboratory equipment. While not substituting directly for a cycle life test, it does hold the battery at a low voltage in an elevated temperature environment. This condition accelerates known failure mechanisms that occur over time in normal service and is considered by Lighting Global to be the best proxy for extended cycle life testing.

Battery Cycle Testing

Battery cycle life is typically described in terms of the number of cycles a battery achieves before its capacity drops to a predetermined value and is considered a failed battery. This dynamic, however, is dependent on a number of factors including charge rate, discharge rate, depth of discharge, temperature, and time between cycles. When discussing battery cycle life and performing cycle life tests, standard charge/discharge rates (based on the nominal battery capacity) are used, the depth of discharge is constant, and the battery cycles are performed on a regular interval at a standard controlled temperature.

Requirements for batteries in off-grid PV applications are given by IEC 61427-1:2013, *Secondary cells and batteries for renewable energy storage - General requirements and methods of test - Part 1: Photovoltaic off-grid application.* This standard includes two cycle life tests: a “generic cycling endurance test” (subclause 8.2) and a “cycling endurance test in photovoltaic applications (extreme conditions)” (subclause 8.4). The former simply references the cycling endurance test methods in the applicable standards for each battery chemistry (for example, IEC 61056-1 for portable valve-regulated lead acid batteries and IEC 61960 for portable lithium batteries).

These standards establish the cycle test conditions used to evaluate battery cycle life. Batteries are subjected to 50 cycles between approximately 10% and 30% state of charge, followed by 100 cycles between approximately 75% and 100% state of charge. Cycling continues until the battery capacity decreases to 80% of its initial value. This means that proper cycle life testing for batteries requires lengthy (and varying) periods of time, estimated at 6-24 months, with higher quality batteries requiring lengthier testing. In addition, the testing equipment is expensive and the testing environment must be carefully controlled for temperature. When sample sizes and multiple products are considered, the prospect of conducting battery cycle life testing for off-grid solar products in a reasonable time frame becomes extremely challenging and very expensive. Lighting Global estimates that the inclusion of battery cycling tests, even when limited to a predetermined duration[3], would substantially increase testing costs. This includes a *minimum* estimate of $3K USD equipment expenses and 11 hours of personnel time *per product* in addition to the necessary dedicated lab space in a climate controlled environment. The equipment and lab space is dedicated for the duration of the test period, so a lab would either be constrained in terms of capacity or would need to make a substantial investment in order to test multiple products at the same time.

Lab Testing vs. Real World Performance

In real world service, batteries may experience conditions that differ from those of a laboratory test environment. Temperature fluctuations, charge/ discharge rates, and depth of discharge during each cycle can vary according to the specific consumer and the geographic location. Aging of the battery materials, generally limited to one cycle per day in a real world environment, will typically be greater than aging in a standard test environment where charge cycles

[3] Cycle tests could be performed, for example, for 6 months whereupon a pass/fail assessment could be made based on capacity loss. This would not, however, verify truth-in-advertising claims for cycle counts longer than 6 months.

immediately follow discharge cycles. Natural aging plays an important part in the deterioration of battery components, and test methods designed to accelerate and simulate aging may not accurately simulate real world performance.

Products in the pico-solar and solar home system markets have a wide range of performance characteristics, including very different battery sizing and power usage ranges. Some products will see daily deep discharges at high currents (relative to the battery capacity) while others may experience much lower discharge rates. This variation is implicit in the number of different applications for solar products.

Cycle testing provides one approach for identifying low quality batteries, thereby preventing those batteries from reaching the market and leading to early product failure and consumer disappointment. It would not, however, guarantee that the number of cycles measured during laboratory testing for a battery would match the number of cycles in real world conditions. Moreover, the existing battery durability test specified in QTM testing provides a useful alternative method for identifying low quality batteries. The high added cost and duration of cycle testing must be justified within the context of the overall QTM program before such testing could be adopted.

Lighting Global Product Testing Philosophy

The Lighting Global program developed the test methods that were later adopted and published as IEC/TS 62257-9-5 with a goal of making standardized testing methods available to the off-grid solar product market. These products incorporate photovoltaics, batteries, electronics, and (increasingly) many different types of appliances, including advanced solid-state lighting (LEDs), motor driven appliances (e.g. fans) and a growing list of consumer electronics (TV's, radios, etc.). They also serve an extremely cost-sensitive market and so must remain low testing costs. These competing dynamics (technical complexity vs. low cost) also exist within Lighting Global's product testing philosophy, which believes that proper product evaluation must incorporate rigorous testing through the use of reasonably low-cost instruments. Performance tests must be economically practical and achievable within a reasonable time frame.

Lighting Global continues to investigate ways to improve the QTM program and increase the value of product testing to the off-grid solar product market. This includes discussions with government officials, manufacturers, distributors, and other stakeholders regarding the evolution of the off-grid solar sector and the changing performance requirements of a growing consumer base. Experience with off-grid products and product failures help inform what changes are made to the test methods in the future, and Lighting Global will continue its efforts to best serve the needs of multiple stakeholders within the off-grid solar product market.

Conclusion

The QTM procedures in IEC 62257-9-5, which are used to evaluate the quality of off-grid solar products, include several tests that assess battery performance. These tests were chosen to meet specific program testing goals and can be performed in a reasonable timeframe with low cost equipment. The battery capacity test is used to verify truth in advertising. The battery protection test ensures that a product has adequate charge/discharge regulation to prevent premature battery damage and early product failure (regardless of the initial quality of the battery). The battery durability test was adopted after experience showed that products were failing because (hot) storage conditions and rugged use patterns were adversely affecting system batteries.

These tests evaluate critical aspects of battery quality and performance, and, while they are not comprehensive in terms of testing battery lifetime, they do provide a valuable assessment of battery quality within a reasonable amount of time and testing expense.

Lighting Global does not require battery cycle life testing for off-grid solar products. After much consideration, this testing was considered too expensive and time consuming to include in the Quality Test Method.