BATTERY CHARGING IN FLOAT VS. CYCLING ENVIRONMENTS

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ABSTRACT

In lead-acid battery systems, cycling systems are often managed using float management strategies. There are many differences in battery management strategies for a float environment and battery management strategies for a cycling environment. To complicate matters further, in many cycling environments, such as off-grid domestic power systems, there is usually not an available charging source capable of efficiently equalizing a lead-acid battery let alone bring it to a full state of charge. Typically, rules for battery management which have worked quite well in a floating environment have been routinely applied to cycling batteries without full appreciation of what the cycling battery really needs to reach a full state of charge and to maintain a high state of health. For example, charge target voltages for batteries that are regularly deep cycled in off-grid power sources are the same as voltages applied to stand-by systems following a discharge event. In other charging operations equalization charge requirements are frequently ignored or incorrectly applied in cycled systems which frequently leads to premature capacity loss. The cause of this serious problem: the application of float battery management strategies to cycling battery systems. This paper describes the outcomes to be expected when managing cycling batteries with float strategies and discusses the techniques and benefits for the use of cycling battery management strategies.

INTRODUCTION

Proper battery charging strategy is critical to the realization of full expected life from batteries used in all applications from infrequently discharged float UPS systems to frequently cycled traction applications and off-grid power systems. Float systems rarely go through a deep discharge without immediately being fully recharged. In addition, the discharge rate for a float application is usually well defined for each application. On the other hand, cycling systems are frequently deep discharged and then often recharged to an arbitrary state-of-charge (SOC) in the range of 90-95% nameplate rating before being discharged again. Additionally, the discharge rate often varies from extremely high currents to extremely low currents during each discharge cycle.

Historically, both float and cycling batteries have been charged using the same charge profile as shown in Figure 1. A voltage is applied at ① that results in a constant current that is maintained until the voltage of the battery reaches the set voltage at ②. The voltage at point ② is then maintained by tapering the current until the battery reaches some arbitrary state of charge at point ③, or is fully charged as event ④ is reached. In this paper, the pitfalls associated with charging cycling batteries using this standard float charge strategy is discussed and a method of charging batteries in a cycling environment is presented. During the last two years, a battery test program has been underway at Sandia National Laboratories using the proposed charge strategy for batteries in a cycling application. Some results from that program and conclusions are discussed in this paper.

FLOAT SYSTEMS

Float systems are designed to maintain a battery at a full state of charge until it is needed, usually as an emergency backup to keep critical loads on-line when main power is lost. Typically the battery is floated at a voltage designed to overcome standing losses due to local actions within each cell of the battery. Float voltages are usually set at the manufacturer's suggest voltage using temperature compensation to maintain the correct voltage at temperatures other than the standard 25 °C (77 °F). In general, the battery is infrequently discharged and is routinely maintained at a full SOC by the charging system. If the float voltage is of high quality and is maintained at the proper temperature compensated setting and the battery room is kept at a temperature near 25 °C (77 °F) and the battery is not discharged more frequently than it was designed for, most batteries will meet or exceed nameplate life expectancy.

Float Charging Strategies

Following activation of a battery to support a power loss event, the battery is immediately restored to a full state of charge as soon as possible in preparation for the next event that requires backup power. Batteries in float applications are discharged only occasionally and the time that the battery rests on float at ④ in Figure 1 allows all of the cells in the battery to reach the same relative SOC which is critical to maintaining the battery at a high state-of-health (SOH). In addition, most battery manufacturers do not recommend periodic equalization charging of their valve regulated lead-acid (VRLA) products in float applications because of the self-equalization that occurs routinely during float charge. However, equalization charges are necessary for flooded batteries that do not have active electrolyte agitation in order to overcome battery stratification actions.

CYCLING SYSTEMS

Cycle applications contrast heavily with float applications. The typical operating environment is often hostile and not conducive to maintaining the battery system at a high SOH. In addition, the application of a float recharge strategy as shown in Figure 1, is also detrimental to battery SOH as, after each discharge, the battery is frequently not recharged to 100% SOC with the appropriate overcharge required to overcome internal charge inefficiencies at top of charge. Consequently, batteries that are not charged properly rarely, if ever, meet expected nameplate cycle life.

The ideal operating environment for cycling applications is to operate the battery at 25 °C (77 °F), never discharge the battery below 50% SOC at all discharge rates, restore the battery to 100% SOC (including appropriate overcharge) after each and every discharge operation, and equalize the battery as recommended by the battery manufacturer. When one considers the typical operating environment for cycling batteries, for example traction applications and off grid renewable generation systems such as photovoltaic and wind generation systems, rarely can the ideal operating environment be attained. Usually the environment is highly abusive and the batteries seldom meet full life expectations.

Charging Strategies

Perhaps we cannot control all the life threatening environmental and operational abuses that cycling batteries encounter, but we can control one abuse that leads to the early demise of cycling batteries, failure to restore the battery to a full SOC at reasonable intervals. Additionally, cycling batteries need to be frequently equalized, a procedure that is both time consuming and considered abusive by some battery engineers, especially for a VRLA battery. In some applications such as off-grid photovoltaic systems, there is not enough energy or time available to effectively equalize a battery. However, there is a solution that has been shown to overcome the damage caused by both chronic undercharging and lack of equalization.

Figure 2 shows a charging profile for VRLA technologies that has resulted in increased performance for batteries in a cycling environment. It is sometimes referred to as Constant Current – Constant Voltage – Constant Current – Constant Voltage (CICVCICV) charging. Assuming the battery is at some unknown state of charge, the charge procedure begins by applying a temperature compensated voltage at ① that results in the desired current for the initial charge. When the battery voltage reaches the desired regulation voltage at ②, charging current is tapered to maintain the regulation voltage until the current drops to a desired value at ③. At that point, the current is held at that constant predefined level while the voltage is allowed to rise to a new regulation voltage. When the voltage reaches the new set point level at ④, it is held there and the current is tapered until the end of charge is reached at ⑤. The vertical dashed lines at ③, ④, and ⑤ and the targeted currents and voltages are arbitrarily selected so that the appropriate amount of overcharge, determined by ampere counting, is reached when event ⑤ occurs. It is important that temperature compensation be applied to the charging voltage throughout the charge period. At first glance, one would think that thermal runaway is immanent. Not so. During the test program later discussed in this paper, there was never any evidence of thermal instability at any point in the charge profile.

A CYCLING OPERATING ENVIRONMENT

Figure 3 is an operational profile that could easily be applied to an off-grid hybrid power system using a generator and a battery to support a variety of loads that would result in extremely inefficient generator operation during low load periods. The approach is to operate the generator at 80-100% capacity when it is needed and to use the battery to support the loads that would result in operating a lightly loaded generator at 10-20% capacity. A light operational load is detrimental to the health of the generator. The operational profile works like this. Assuming that the battery is at 100% SOC, 50% of the charge is delivered from the battery to the load using ampere hour counting to accurately measure the discharge of the battery. When the battery reaches 50% SOC, the generator is brought on-line to support the load and restore the battery to 80% SOC, again using ampere hour counting to return the proper number of ampere hours to the battery. Note that the charger will use all available generator power that is not going to support the load to charge the battery keeping the generator above its 80% capacity point, its most efficient operating regime. When the battery reaches 80% SOC, the generator is shut down and the battery is brought on-line to support the load. The system continues to operate between 50% and 80% state of charge for a predetermined period that depends on actual time or on the droop in voltage when the battery reaches the 50% SOC point. Although the battery is nearly 100% efficient in charge acceptance in this operational range, a decreasing voltage at each succeeding 50% SOC point is an indication that the battery is dropping below the 50% SOC point and needs to be restored to a full SOC to maintain battery state-of-health.

When the control system makes the decision to fully charge the battery, the battery is discharged to 1.75 Vpc to measure the accuracy of the ampere hour counting activity for future reference. The battery is then brought to a 100% SOC using the CICVCICV charge profile in Figure 2. For the purpose of the testing program discussed later in this paper, the battery was then discharged 1.75 Vpc to determine the actual capacity of the battery. In a true operational environment, following the 100% recharge of battery, the battery would then be returned to cycling service to begin a new complete capacity cycle. The results of operating in this intermediate state-of-charge regime is discussed in the next section.

THE SANDIA NATIONAL LABORATORIES TEST PROJECT

The Need

In early 1998, the Energy Storage Systems Department at Sandia National Laboratories initiated a research program to determine an optimal strategy for the management of cycling batteries in off-grid hybrid power systems like the ones typically used in remote off-grid applications. Because of the low charge acceptance efficiencies of batteries at near top-of-charge, off-grid hybrid systems were typically being operated at low generator efficiencies to fully restore the battery to 100% SOC after each discharge cycle using the charge profile shown in Figure 1. As users became more sensitive to the inefficient operation of their generators, they modified their operations to shorten generator run times and, as a result, batteries were not being restored to a full SOC and were not regularly equalized. Although this operational strategy modification appeared to save money in the near term, the ultimate result was that the batteries were severely abused and many had to be replaced long before they reached their normal end of life.

Test Project Development

An early hypothesis was proposed that suggested that a VRLA battery could be operated at an intermediate state of charge (ISOC) for an extended period of time without permanent damage if the battery was periodically restored to 100% SOC and equalized. It was also determined that the battery should never be allowed to drop below 50% SOC during routine cycling operations. This restriction is primarily based on manufacturers severely shortened life expectancy for cycling operations that take the battery below 50% SOC. Because of the susceptibility of flooded lead-acid batteries to sulfation and stratification during cycling operations without immediate full recharge, they were not considered viable candidates for the ISOC operational environment and were not included in the study.

In mid 1998, several battery manufacturers were contacted and asked if they would be interested in providing VRLA gel or absorbed glass mat (AGM) batteries that would be tested in the operational environment shown in Figure 3. Group 31 batteries were requested in order to have a direct comparison among the various batteries being tested. Each battery type was tested as single modules and as a five module string. Because of the abusive nature of the test program and the potential to cast a dark shadow on a particular battery model, the manufacturers were assured that they would have the ultimate right to control the release of results for their battery test. However, Sandia reserved the right to release test results based on VRLA technology while maintaining the anonymity of the manufacturer. The test program ended in January, 2000. Initial results for one of the batteries tested are presented here.

The Test Project Results

The Sandia ISOC test program began in late 1998 using batteries provided by 3 manufacturers. There were 2 gel and one AGM VRLA technologies tested. Every battery tested exceeded life expectancy as recorded in the manufacturers specification sheet for the battery. Because of the nature of the cycling environment, as shown in Figure 3, it was determined that cycle count is not a reasonable quantity on which to evaluate battery performance. Each battery was life rated by determining the number of ampere hours that would be delivered in the operation of the battery at the five hour rate for the number of 100% cycles publicized in the manufacturers specification. Implementation of this approach means that a battery rated at 90 ampere hours, at the 5 hour rate, rated to deliver 300, 100% DOD cycles, would have an output of 27,000 ampere hours over its expected lifetime. This approach to determining battery performance in the cycling environment represents an innovative, logical approach to measuring the energy delivery from a battery independent of the actual depth of charge/discharge for operations between 0 and 100% SOC. A consensus was reached among the experimentalists and the manufacturers that this is indeed the best way to evaluate battery performance in a random DOD cycling environment.

Table 1 shows the results of the AGM tested in the Sandia ISOC Test Project. Batteries 824 and 825 are single 12 V modules; battery 826 is a string of five 12 V modules. Both the single modules and the string were operated in the regime defined in Figure 3. Following each CCC, the battery was charged using the charge strategy indicated in Figure 2. Based on a special request from the manufacturer, normal equalization of this particular battery was not performed during the test program. The data speaks for itself. Each battery exceeded its life expectancy, both in equivalent 100% DOD cycles and in accumulative ampere hours removed. Of particular note is the ambiguity in the number of "cycles completed". It begs the questions: What is a cycle? Are they operational cycles, equivalent 100% DOD cycles, or perhaps Complete Capacity Cycles? The ambiguity is removed when the performance measure is defined to be the total ampere hours removed during a battery's lifetime.

Figure 4 indicates the way a battery ages in a cycling environment. This capacity degradation curve is true for all the batteries tested in the Sandia ISOC test program. Of particular interest is the general slope of the % Nameplate Capacity lines for each battery. As a rule of thumb, a battery is defined to be at end of life, requiring replacement when its capacity falls below 80% of nameplate rating. Using that metric, the battery should have been taken out of service at CCC #21, even when it was still effectively meeting its performance requirement. This EOL criteria is a flaw in battery state of health evaluation initiated by bringing a "float system mentality" to the cycling operational environment. The battery capacity is indeed falling but the battery is still able to meet all functional requirements well below its 80% capacity limit. The real measure of battery performance should be based on the battery meeting operational requirements with replacement targeted at a time after the full complement of ampere hours have been removed from the battery. When it can no longer meet operational requirements, then it needs to be replaced. If an application is critical and cannot wait for the time that the batter fails on-line, there are ways to more accurately predict the point in the future when the battery will fail to meet its performance criteria. But that is a paper it itself.

CONCLUSIONS

VRLA Batteries can operate, without permanent damage, at intermediate states of charge for reasonably long periods of time, if they are periodically and carefully brought to a full state of charge using a CICVCICV charge strategy in a controlled operational environment. State of health of batteries in a cycling operational environment must not be evaluated by absolute battery capacity as is done for float applications. As long as the battery can meet its cycling application operational requirements, absolute capacity is not a meaningful measure of battery EOL. Management of battery SOC is possible only through the implementation of ampere hour counting, especially in the ISOC operational environment. No other method is effective in measuring the transfer of charge into and out of a battery. Cycle count is ambiguous for measuring the aging process for a cycling battery. The only way to determine the operational age of a cycling battery, within some reasonable error band, is through an ampere hour counting process.

Cycling battery system management is indeed different from float battery system management.

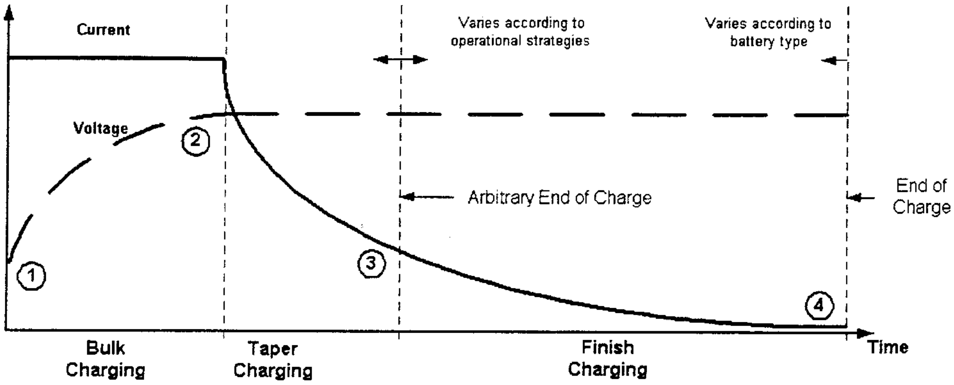

Figure 1. Typical Charge Profile for Lead-Acid Batteries

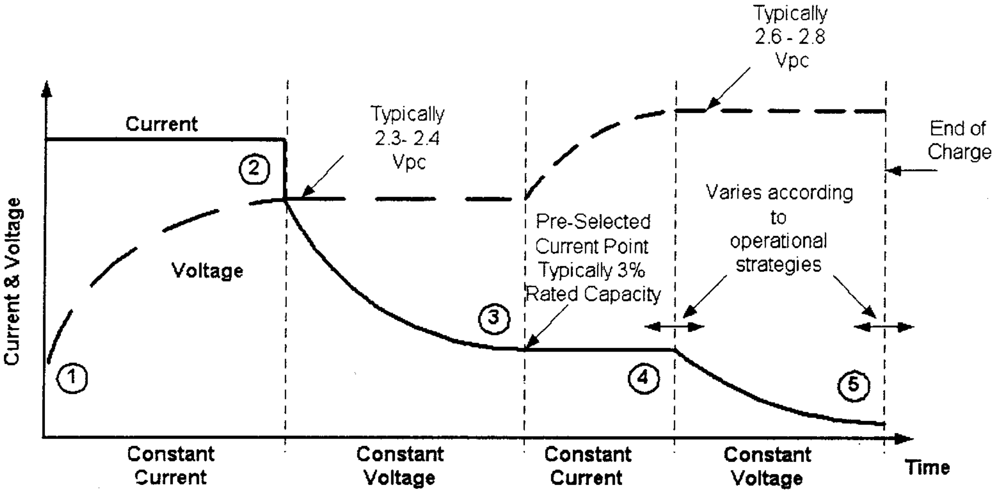

Figure 2. Constant Current – Constant Voltage – Constant Current – Constant Voltage (CICVCICV) Charge Profile

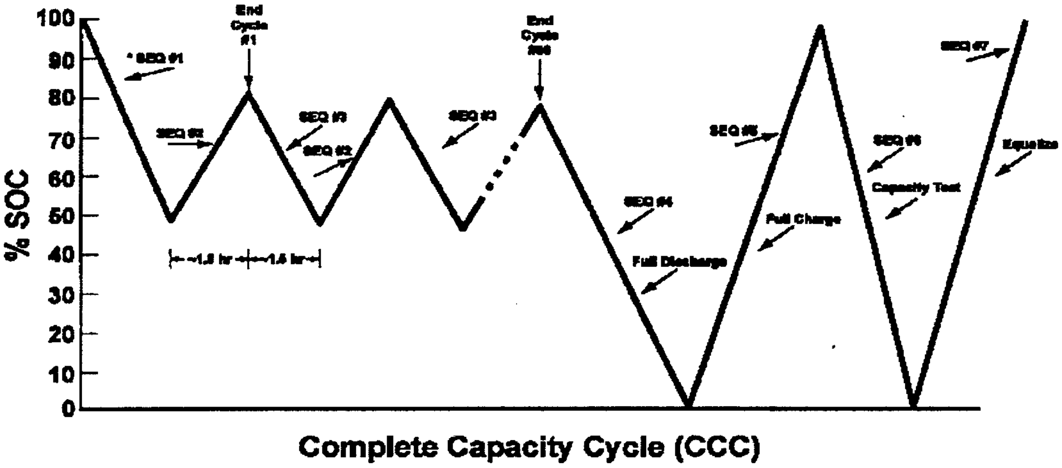

Figure 3. Operational Profile for CCC Test Program

Table 1. ISOC Test Results for VRLA AGM Battery

Battery	824	825	826
Nameplate Capacity Ah	67	67	67
Actual Initial Capacity Ah	66	68	64
End of Test Capacity Ah	51	53	42
End of Test % Rated Capacity	75.9%	78.9%	63.0%
ISOC Cycle Sets	27	27	27
Cycles Completed	1,653	1,684	1,686
Equivalent 100% Cycles Completed	528	532	536
Equivalent 30% Cycles Completed	1,759	1,772	1,788
Total Amp Hrs Removed	35,349	35,622	35,939
Rated Ah to End-of-Life	26,800	26,800	26,800
% Rated Life	132%	133%	134%

Note: Mfg. Rates this battery for 400 100% cycles

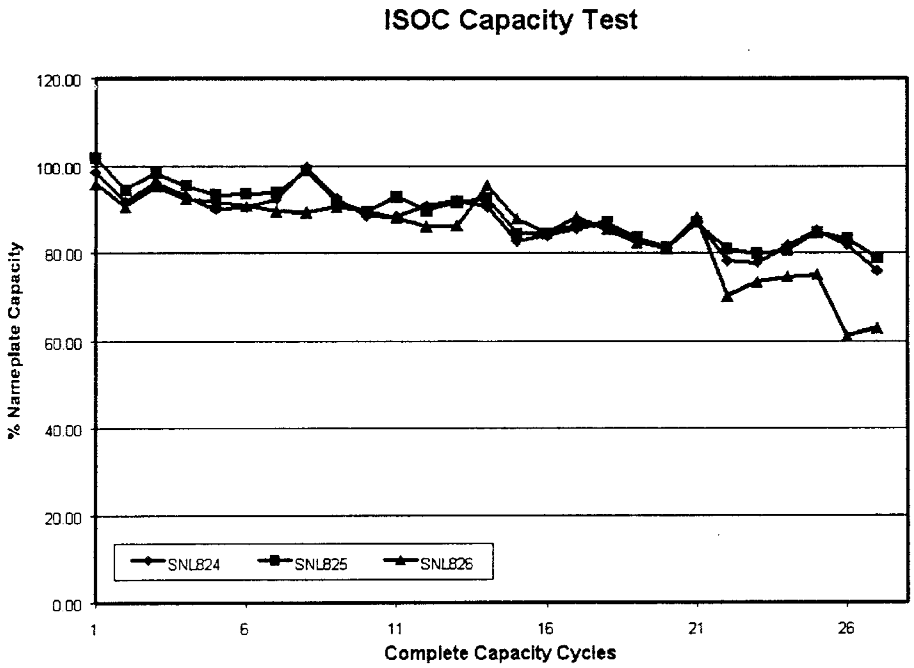

Figure 4. Capacity Loss Over Life of AGM VRLA Battery ISOC Cycling