Experimental Study of Battery Parameters and Their Variations During Cycle Aging and State of Charge of a Sealed Lead Acid Battery

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Abstract

Sealed lead acid batteries are widely used for backup power in telecom centers, data centers and for energy storage systems for microgrids. Yet determining the condition of a lead acid battery is still a challenge. We have set out to study how a 12V 200Ah sealed lead acid battery performs when cycle aged. This paper describes the experiments to measure and characterize the battery parameters of a sealed lead acid battery - current, voltage, battery capacity, and DC internal resistance for a fresh battery and two batteries that have undergone deep discharge cycling for 70 cycles and 180 cycles. The results show a steady change in the internal resistance of the battery with cycle aging. Variations of the load voltage as a function of state-of-charge and battery capacity after 70 cycles and 180 cycles are also presented.

Keywords

Sealed lead acid battery; battery characterization; battery parameters; battery aging; State of Charge; State of Health

Introduction

The use of lead acid batteries (LABs) is still very wide in different applications such as microgrids, frequency regulation, electric vehicles, uninterruptible power supplies, among others. Although this battery technology has a low energy density and shorter cycle life compared to other technologies (Nickel-Cadmium, Nickel-Metal Hydride, and Lithium-ion) [1], it has several advantages in terms of cost, ease of use, maintenance, reliability, high rate discharge, safety, among others [2]. In addition, a LAB becomes attractive compared to other technologies because over 90% of its parts can be recycled [3], [4]. LAB technologies include flooded lead-acid batteries, valve-regulated lead acid battery (VRLA), tubular and bipolar batteries [5]. The composition, geometry and internal chemical reactions of a LAB are well known because it typically consists of positive electrodes (porous PbO_2), negative electrodes (porous Pb), plastic separators, and corrosive sulfuric acid as electrolyte [6], [7].

Accurately and precisely measuring parameters of a LAB during cycling is fundamental to determining aging effects, as well as State of Health (SoH), battery degradation, and State of Charge (SoC) of a LAB. At each cycle, the LAB gradually decreases in capacity, increases internal resistance, decreases load efficiency, and increases self-discharge [8]. Merrouche et. al. [9] obtained the SoH of a LAB within the context of a PV application through voltage, current and temperature measurements in experimental charge/ discharge tests. Marchildon et al. [10] presented a procedure based on applying two discharge current pulses on a 185Ah-LAB to determine its SoC and SoH. In addition, Fru et al. [11] indicated that LAB batteries with a high SoH have higher energy recovery abilities and relatively small open circuit voltage (OCV) variations. However, when the SoH of a battery is reduced, it has larger OCV variations and lower energy recovery ability.

Some internal processes during LAB cycling: The charging and discharging processes of a LAB cause deterioration of the battery properties. LABs are charged through procedures such as constant current, constant voltage, combined constant current constant voltage [3]. These processes produce a decrease in the battery capacity, an increase in the internal resistance, a reduction in the charging efficiency, and even an increase in the self-discharge [8]. It should be noted that the loss of capacity due to cycling is known as aging, where its main processes on the battery are anodic corrosion, and degradation of active mass, among others [12]. Anodic corrosion is a progressive process that leads to the failure of a LAB, mainly in applications such as vehicles and backup power [13]. DoD during cycling accelerates positive active mass degradation [14]. When exposed to high temperatures added to the heat generation of its cells during cycling, a LAB can considerably affect its performance and cycle life [15]. In addition, other processes that accelerate the degradation of a LAB are over-charging, over-discharging, and storing batteries for long periods in a discharged state [16].

Battery parameters reflect the changes in the battery states and their performance arising from their SoC and with their cycle age. In this paper, we present battery parameters measured during cycle aging of a 12V, 200Ah sealed lead acid battery over 70 and 180 cycles and the corresponding assessed SoH degradation.

Methodology

Battery parameter values are sensitive to the procedures used to obtain the required SoC and cycle-age of the battery. Further, the variations of these parameters, with the SoC and cycle-age of the battery, are exceedingly small as a result of the improved battery designs. Therefore, the following battery characterization procedures (for 12V, 200Ah Sealed Lead Acid Battery), have been carefully specified and adopted for the parameter measurements described in this section. The next procedures are based on the observations and their analysis, of test measurements, during charging and discharging for battery characterization.

Experimental Setup: The following equipment has been used for conducting the experiments / measurements for battery characterization:

1. DC Power Supply – Chroma, Model 62012P-40-120
2. DC electronic load – Chroma, 63205A-150-500
3. 6 Digit Multimeter – Agilent, 34401, 6 ½ Digit Multimeter
4. Charge-discharge software

The setup is shown in Figure 1.

Battery Parameters: The battery parameters selected for measurement are given below:

1. OCV at full charge
2. Battery capacity at three selected levels of its cycle-age.
3. Voltage under load, V_L @ 10-hour rate and its variation with the Depth of Discharge (DoD) up to 80% and the value, V_{Lmin} at this level, for each of the three stages of battery life (cycles) – 0, 70, and 180 cycles.
4. Stabilized battery voltage, $V_{under\ load.stable}$ and its variation with DoD up to 80% during battery discharge @ 10-hour rate.
5. Battery internal DC resistance, R_{int} of fully charged battery of the three selected cycle-age levels of 0, 70, and 180 cycles of the battery.

Characterization Procedures: Characterization procedure to extract battery parameters used the following steps:

1. Fully charge the battery: Charge the battery at constant voltage (CV) - 14.8V, 80A maximum, till the charge current reduces to 1.0 amp. Float charge the battery at 14.0 V, till charge current reduces to 0.2A or charge current begins to rise. The lead resistance for these CV and float charges is to be around 5 mΩ. Stabilize the

Figure 1. Experimental setup for battery auto cycling and battery characterization.

battery for at least 1 hr. Measure the battery capacity at a C/10 constant current (CC) rate. After a rest period of 15-18 hours of fully charging the battery, start CC discharge of a fully charged battery, at 10 hrs. rate (=20A), till battery terminal voltage, V_L reduces to the End of Discharge Voltage (EODV) (=10.8 V @ 10 hr. rate – as per manufacturer's datasheet). Note the time taken in hours "h".
   - Find the actual battery capacity C_n (=20*h). 10% DoD = C_n/10.
   - Note the minimum battery load voltage @80% DoD, $V_{Lmin.}$
   - Restore battery charge to at least 20% SoC level
2. Plot discharge characteristics - V_L vs DoD @ 10 hr. rate: CC discharge the fully charged battery at C/10 rate for 8 hrs to obtain this plot. Note the value of load voltage, V_L after 8 hrs (for ~80% DoD), and record this value, as V_{Lmin} @C/10.
3. Conduct a Step-Discharge as per procedure below:
   - Discharge the fully charged battery at 10 hr. constant current rate, C/10 (=20A) in steps of 1 hour, for 8 hrs.
   - Measure the battery voltage under load, V_L at the end of each hour and switch off the CC load. Stabilize the battery for 1 hour and measure this corresponding stabilized battery voltage, $V_{under\ load.stable}$
   - Obtain "V_L vs $V_{under\ load.stable}$ @ C/10" plot.

Experimental Results

Present experiments are being conducted for cycle-aging of the batteries – 24 hours a day, 7 days a week, and battery characterization to generate a battery database for five, 12V, 200 Ah, sealed lead acid batteries that have undergone five stages of their lives. We have made the above measurements for one new battery and for two others, which have undergone 70 and 180 cycles of aging. The results of these measurements are presented next.

1. V_L vs %DoD @ 10-hour discharge rate up to the end of discharge voltage, EODV of the battery.
   This experiment provides: Open circuit voltage (fully charged battery) OCV, V_L vs %DoD plot, battery capacity and V_{Lmin} for the battery, at a particular age level. A plot of V_L vs. %DoD for a new battery is shown in Figure 2

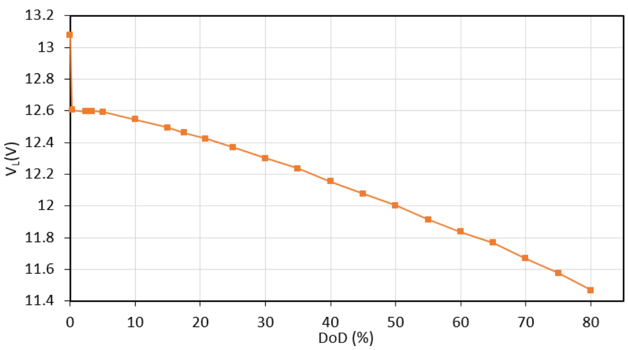

Figure 2. V_L vs %DoD @ 10-hr rate up to EODV=10.8V; V_L (min) = 11.375V; Ah max = 192.953 at EODV=10.8V

2. Step Discharge @ 10-hour CC discharge rate (up to EODV) for a new battery, which provides stabilized battery voltage corresponding to different battery load voltages during the discharge is shown in Figure 3.

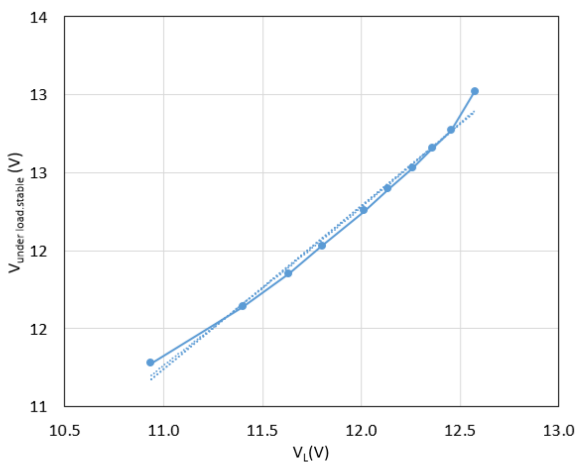

Figure 3. $V_{under\ load.stable}$ vs V_L for a NEW battery @ 10-hour step discharge rate up to EODV=10.8V; V_L = battery voltage during discharge.

3. DC Internal Resistance, R_{int} (DC Load-interruption Method (Load to No-load approach):

R_{int} of a fully charged battery was measured during the CC C/10 step discharge. The stabilized no load voltage, $V_{under\ load.stable}$, after 1 hour of load switch-off also asymptotically reached the measurable OCV of the battery at its fully charged level. This method was further validated by the voltage relaxation technique [17].

Variation of R_{int} with SoC @ C/10 current, for a new battery, 70 cycle age battery, and 180-cycle-age battery are shown in Figure 4.

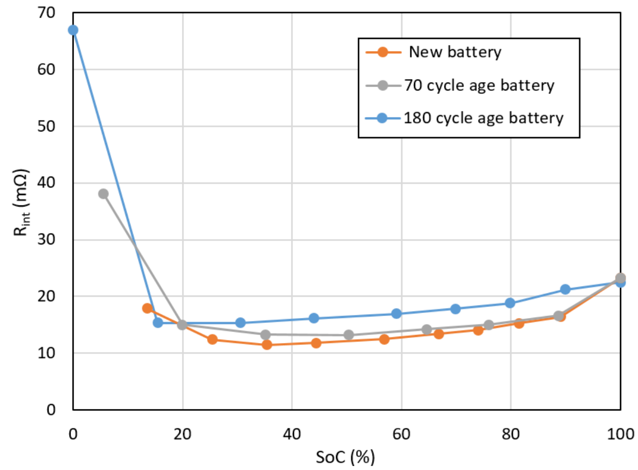

Figure 4. R_{int} vs. %SoC @ 10-hour step discharge rate for new battery, 70 cycle age battery, and 180-cycle-age battery.

Studies with the new, 70 and 180 cycle-age batteries indicate that there is not much difference in their OCV levels at full charge. However, their capacities seriously decrease and R_{int} deterioration below 20% SoC level is much steeper, with higher cycle-ages. For example:

- R_{int} variation with SoC for the 70 -cycles old battery, indicates a steep rise from 15 mΩ to more than 38 mΩ, at below 20% SoC levels to EODV levels.
- R_{int} variation with SoC for the 180-cycles old batteries, indicates a very steep rise from 15 mΩ to 70 mΩ, at below 20% SoC levels to EODV levels.

The measured capacity data, during the continuous and step discharge experiments with 0, 70 and 180 cycle age batteries, have been identified and are given below:

- New battery: continuous discharge: 192.952Ah
- New battery: step discharge: Not available.
- 70 cycle age battery: continuous discharge: 130 Ah
- 70 cycle age battery: step discharge: 124.3333Ah
- 180 cycle battery: continuous discharge: 62.32Ah
- 180 cycle battery: step discharge: 99.31Ah

Discussion

A few salient takeaways during the experiments are given below:

- A very linear reduction in V_L with time has been observed during a constant current discharge, with time till V_{Lmin}.
- Experiment-runs for C/10 continuous- and step- discharge (CC at 10 hrs. rate) indicate that higher Ah capacity maybe expected to be delivered during intermittent discharge as compared to continuous discharge use of the battery.
- While the fresh battery exhibited close to the rated capacity, the battery capacity dropped to almost 2/3 of its original capacity after 70 cycles and to almost 1/3 of its capacity after 180 cycles, when continuously discharged. The battery capacity dropped by about 35% after 70

cycles and to about half its capacity after 180 cycles when tested through intermittent discharge testing.

- Rint of a battery is almost constant in the active region (90-20%SoC) of the battery. It suddenly increases by around 30% for close to EODV levels. It increases by about 10% at lower SoC and is has been found to a little (~12%) higher at full charge. This resistance increases, as the cycle age of the batteries increases (Figure 4).

Conclusions

This paper shows the experimental results of cycling tests on LABs. Here, we have set out to study how the performance of a 12V 200Ah sealed lead acid battery performs when cycle aged. The measurements for ~~and~~ characterization of the LABs were performed by obtaining their parameters, such as current, voltage, battery capacity, and DC internal resistance, for a fresh battery and two batteries that have undergone deep discharge cycling for 70 cycles and 180 cycles. These are the initial results of a deeper study of this technology of an energy storage system.

The battery parameter measurements and generation of the battery data base has been motivated by the potential of the diagnostic information, to not only provide the charge condition of the battery but also its relative ability to perform as per design of the battery. These parameters provide experimentally validated battery characteristics.

So far three batteries have been measured - a fresh one, one that has undergone 70 cycles and one that has been cycled 180 times. Given that the data sheet for these batteries indicate a 400-cycle capability for these batteries under the cycling conditions being used, we plan to make additional measurements at 270 cycles and 360 cycles. This data will be incorporated into a look up table for estimating the SoH of a battery. This should provide an easy way through some simple measurements to estimate the battery's performance.

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