An Improved Battery Characterization Method Using a Two-Pulse Load Test

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Abstract—It is very important to have the ability to determine the available capacity, the state of charge (SoC), and the state of health (SoH) of a battery; this ensures that the battery has the available power for the system requirements. A battery is aged by charging and discharging cycles; this process degrades the chemical composition of the battery. An undercharged battery has sulphation and stratification effects that shorten the lifetime of the battery. Overcharging causes gassing and water loss. This paper describes a novel two-pulse test to determine the AHC, SoC, and SoH of a valve regulated lead acid (VRLA) and a lithium ion battery. These parameters are related to the voltage drop after each pulse of current discharge. The first pulse stabilizes the battery relative to its previous history, and the second pulse establishes the parameters. The new approach is fully validated by experiment.

Index Terms—AHC capacity, lead-acid battery, lithium ion battery, state of charge (SoC), state of health (SoH).

I. INTRODUCTION

IN EVERY application where batteries are deployed, the state of the battery is critical to ensure that the required power is available; for example, in consumer electronics, electric vehicles, and standby capability in emergency backup systems. The charge/discharge cycle has a profound effect on the life of the battery. The life of the battery is dependent on the aging effects of its chemical composition. Overcharging the battery causes gassing and water loss. Undercharging or overdischarging causes sulphation, which reduces the active area of the plates and can cause plate buckling. In the past, battery capacity determination required a full discharge test [3]; this had the disadvantages of taking a long time and subjected the battery to overdischarging. A one-pulse method [4] measured the voltage under a given current load and compared the voltage measured with predetermined lookup tables to determine the AHC of a battery. The problem with this approach is that the previous history of the battery will affect the accuracy; also, the current load must be preset and large in relation to the battery capacity.

The relationship between SoC and SoH needs clarification. A fully charged battery has 100% SoH and 100% SoC. As the battery is discharged, SoC describes the percentage of remaining capacity. The SoH describes the full charge that the battery can hold; therefore, 50% SoC represents less remaining charge in an aged battery. In an aged battery, some active material is electrically isolated and electrical resistances are increased. A
number of existing methods exist to measure the SoH and SoC of a battery, which are summarized in the following sections.

A. Coulomb Counting (SoC)

The capacity of a battery is the product of the current and the duration of the discharge. The SoC is determined from the previous capacity history and the capacity charged or discharged, as shown in (2). The SoC is easily measured by coulomb counting (Ah balance). Coulomb counting requires an initial value of SoC and the instrumentation needs to be calibrated regularly.

B. Full Discharge Test (SoH)

The full discharge test involves applying a full load discharge to the battery and measuring the charge delivered. The delivered charge is, then, compared with the charge from a full discharge test when the battery was new. The IEEE standard [3] recommends a full discharge test for accuracy. The disadvantages of this approach include the length of time required to perform the full discharge and the requirement for the battery to be offline, which follows that the battery must be recharged after the test. Repeated discharging of the battery shortens its life.

C. Internal Resistance Test (SoC and SoH)

The internal resistance test involves applying a brief load to the battery and measuring the changes in voltage and current to determine the internal resistance of the battery. The internal resistance will increase with age due to the chemical degradation of the active material. The internal resistance increases as the SoC decreases. The disadvantage of this approach is that the parameters are dependent on the SoC and temperature. The test is indicative only.

D. Impedance Method (SoC and SoH)

The impedance method involves applying an ac current or voltage signal across the terminals of the battery and measuring its voltage or current response. The impedance increases as the SoH deteriorates [5]. A rule of thumb with the impedance method is that if the impedance increases by 30% from its original impedance (for a new fully charged battery), the battery should be replaced. The advantage of this method lies in its ability to be implemented online without interfering with the battery system. The main disadvantage of the impedance method is that the parameters are dependent on the SoC and temperature and not proportional to the available capacity of the battery. This test is indicative only.

The two-pulse method overcomes the disadvantages described before and will be described in the next section.

II. Two-Pulse Method

The three parameters of interest to determine the state of the battery are AHC, SoC, and SoH. These parameters may be found using the two-pulse current method. The measurements involved are illustrated in Fig. 1. The test consists of three modes. We begin with a battery of unknown history. In mode 1, the battery must be in open circuit. The minimum duration of the open circuit will depend on the typical load profile of the battery and the pulse current. For testing purposes, we use a minimum period of 1 min to stabilize the battery, the minimum duration is described in detail in Section II-D. In mode 2, a known pulse of load current is applied to the battery for 10 s. The current pulse may be as short as 3 s, but the authors found that the 10 s pulse gave consistent results. The voltage drop $\Delta V_1$ over the course of the first pulse is recorded. After the pulse is removed, the voltage recovers for a further 10 s to $V_{MAX}$ at the start of the second pulse. In mode 3, a second pulse identical to the first pulse is applied and $\Delta V_2$ is recorded. The voltage drop $\Delta V_1$ from the first pulse suffers from the same drawbacks as that of the pulse method in [4], as described in Section I, due to unknown history of the battery prior to mode 1. We, now, have three measurements $I$, $V_{MAX}$, and $\Delta V_2$, and these give us the battery state as follows.

Step 1) The equilibrium $V_{EMF}$ voltage is deduced from $V_{MAX}$ and manufacturers’ data.

Step 2) The SoC of the battery is deduced from $V_{EMF}$ and manufacturers data.

Step 3) The $C_{IR}$ is deduced from $\Delta V_2$.

Step 4) The AHC is derived from (1).

Step 5) The SoH of the battery is given by (3).

These steps are graphically summarized in Fig. 2. The basis of Steps 1, 2, and 3 will now be described in detail.

A. State of Charge

$V_{MAX}$ was measured at the end of mode 2 in the two-pulse test for a series of valve regulated lead acid (VRLA) batteries ranging from 4 to 100 Ah, and the results are plotted in Fig. 3 against the SoC. Each battery capacity was tested for several batteries over different current pulses. The SoC was measured independently by Coulomb counting, as described in Section I-A. $V_{EMF}$ is the electromotive force of the battery, and it is the open circuit voltage after the battery has been in equilibrium for 24 h. The manufacturer supplies the equilibrium...
Fig. 2. Steps of the two-pulse current method.

Fig. 3. $V_{\text{MAX}}$ of different AHC batteries with 20-A pulse.

voltage $V_{\text{EMF}}$ as a function of SoC in the form

$$V_{\text{EMF}} = \alpha \text{SOC} + \text{EMF}_{\text{MIN}}$$  \hspace{1cm} (4)

where the slope inclination ($\alpha$) and $\text{EMF}_{\text{MIN}}$ are found from manufacturers’ data sheets. Typically, $\text{EMF}_{\text{MIN}}$ is 11.4 V and $\alpha$ is 0.018 V and SoC is expressed in percent. $V_{\text{EMF}}$ is plotted in Fig. 3 above 20% SoC. $V_{\text{EMF}}$ is related to $V_{\text{MAX}}$ by a constant offset of 0.24 V ($\beta$) $\pm$ 0.06 V for VRLA batteries. Thus, we may write

$$V_{\text{EMF}} = V_{\text{MAX}} + \beta.$$  \hspace{1cm} (5)

Knowledge of $V_{\text{MAX}}$ and $\beta$ allows us to find SoC from (4) as

$$\text{SOC} = \frac{V_{\text{MAX}} + \beta - \text{EMF}_{\text{MIN}}}{\alpha}.$$  \hspace{1cm} (6)

The values of $\alpha$ and $\beta$ will depend on battery type, but the general relationship holds.

B. Ampere Hour Capacity and State of Health

At the end of mode 3, $\Delta V_2$ was measured for four different load currents 5, 10, 15, and 20 A on a range of batteries of known AHC. The results are plotted in Fig. 4, where Fig. 4(a) shows the current rate and Fig. 4(b) presents the same data in terms of the different battery capacities. Evidently, there is a linear relationship between $\Delta V_2$ and $C_R$.

$$C_R = \delta \Delta V_2 + \gamma$$  \hspace{1cm} (7)

where $\delta = 1.868$ and $\gamma = -0.2505$ by least squares analysis. The coefficients $\delta$ and $\gamma$ are consistent for VRLA batteries, but will depend on battery type where the general relationship holds.

The estimate of $C_R$ is accurate to within 7%–12% of the best fit in the least squares line in Fig. 4. Narrowing the test to a single family of battery would improve the accuracy further.

Finally, the remaining capacity of the battery under test is

$$AHC = \frac{I}{C_R}$$  \hspace{1cm} (8)

and the SoH is

$$\text{SOH} = \frac{AHC_{\text{Aged}}}{AHC_{\text{Nom}}}.$$  \hspace{1cm} (9)
C. Electrical Circuit Model

There are many electrical circuit models available to describe the electrochemical processes and dynamics of a battery [6]–[9]. The simplified lumped parameter model shown in Fig. 5 adequately describes the waveform in Fig. 1.

$R_\Omega$ is the internal ohmic resistance of the battery, which contributes to the voltage drop in $\Delta V_2$. The internal resistance increases with age. The $R_{ct}, C_{ct}$ combination describes the charge transfer and diffusion process between the electrode and electrolyte. The recovery time after the first pulse is related to $R_{ct}, C_{ct}$, and the previous history determines the polarity and magnitude of the voltage across $C_{ct}$. This time constant is a function of SoC, SoH, and temperature, and indirectly leads to the determination of SoC and SoH through $\Delta V_2$ and $V_{MAX}$.

D. Reliability and Accuracy

The history of the battery prior to the application of the first pulse has a significant and variable effect on the voltage change ($\Delta V$) as a result of the pulse. Fortunately, the second pulse shows consistent voltage drops. This is best illustrated by an example. Three 5 A pulses were applied to a 12 V 17.2 Ah VRLA battery with a SoC > 80%, in a sequence similar to that shown in Fig. 1. The battery was tested under known previous histories listed in Table I ranging from 10 A discharge to 1 A charging over time periods ranging from 10 s to 1 min. The battery was then, left in open circuit for up to 2 min, and the pulse test was applied. The voltage drop ($\Delta V$) after each pulse is recorded in Fig. 6. The response to the first pulse varies from 0.25 to 0.51 V, whereas the response to the second and third pulses vary between 0.31–0.34 V. This confirms that the second pulse gives consistent results, and that the third and subsequent pulses are not required.

The test shows that the rest period in mode 1 may be as short as 5 s, but it depends on the relative size of the pulse current compared to the rated load current of the battery. In a typical application, 1 min is adequate where the load is below a $C_R$ of $2 \text{ h}^{-1}$.

E. Aging Effects

Fig. 7 shows the voltage drop of a battery when new and aged under a set pulse discharge of 10 A. As the battery ages, $\Delta V$ becomes greater. The available capacity decreases in relation to the decrease in the SoH. With less available capacity, the current load has a greater effect on the battery, and therefore, the $\Delta V$ increases. In effect, it is the same current load on a smaller capacity.

There are two distinct regions in Fig. 7, a linear region and a hyperbolic region as illustrated. The two-pulse method is accurate in the linear region. For a new battery under a 10-A pulse discharge, the linear region is above 40% SoC, and for an aged battery, it exists above 70% SoC. Based on the data in Fig. 4, the maximum discharge current should be limited to a $C_R$ of $1.2 \text{ h}^{-1}$.
The two-pulse method was verified on aged 12 V YUASA VRLA batteries. A full discharge test was carried out on the batteries with the requirements outlined in the YUASA data sheet. The two-pulse method was applied to the batteries above 80% SoC. Table II shows the results of the both methods. The batteries had different original battery capacities, battery 1 (10 Ah), batteries 2–5 (17.2 Ah), battery 6 (38 Ah) and battery 7 (100 Ah). Evidently, the error is greatest at SoH below 60%, as expected because the onset of the hyperbolic region takes place at a higher SoC in an aged battery. In practice, a battery below 80% SoH would be replaced.

### III. EXPERIMENTAL SETUP

The data in Figs. 3, 4, 6, and 7 were obtained from tests carried out on different batteries at 25 °C. The test setup is shown in Fig. 8; it consists of a power supply and electronic load with associated meters. These instruments are connected in a LabVIEW environment to control the battery charge and discharge processes. The battery under test is placed in a temperature-controlled chamber. The AHC of the battery is measured in a full discharge test at constant current, and the discharge is measured by Coulomb counting. The LabVIEW controls the two-pulse test and automates data collection.

The data in Fig. 7 were obtained by thermally aging the batteries. The reaction rate in a battery doubles for every 10 °C rise in temperature [10]. By cycling the battery through a charge/discharge sequence at 70 °C accelerates the aging process with a consequential drop in the SoH.

The two-pulse method must be implemented at a specified temperature. The temperature dependence of the reaction rate means that the voltage drop $\Delta V$ is temperature dependent, and so is the AHC. It is relatively straightforward to repeat the tests described in this paper at other temperature values, and find the parameters of interest.

### IV. CONCLUSION

A two-pulse method has been described to establish the main parameters of a battery, i.e., AHC, SoC, and SoH. The two-pulse test overcomes the disadvantages of other tests; it is very short as compared to a full discharge test, and it is more accurate and reliable than a one-pulse test. The paper concentrates on VRLA batteries, but the method may be modified and applied to other battery types (see Appendix). It has been shown that the test can be applied to a very wide range of battery sizes.

### APPENDIX

The two-pulse method was implemented for lithium ion batteries, and it was established that the principle of the two-pulse test is equally applicable. The coefficients in Figs. 3 and 4 are different, but the method is the same. Lithium ion batteries have a different voltage per cell (3.6 V) in comparison to VRLA batteries (2.25–2.3 V per cell).

Unlike the VRLA battery, the lithium ion battery does not have a linear relationship between the EMF voltage and SoC. The EMF voltage relationship with SoC was determined from applying a pulse load on the battery, then, allowing the battery to reach equilibrium [11]. The pulse load discharges the battery in steps of 5% of its SoC, and the battery is, then, placed in open circuit for 1 h to determine the EMF voltage; this is repeated for the entire SoC range. A correlation is, then, established between the $V_{\text{EMF}}$ and SoC. Fig. 9 shows $V_{\text{EMF}}$ for a 7.2 V 1.3 Ah lithium ion battery under a pulse discharge. The process is similar to the VRLA battery for predicting $V_{\text{EMF}}$ in (5). The $V_{\text{EMF}}$ curve in Fig. 9 can be analyzed under least square regression.

Fig. 10 shows the $C_R$ vs $\Delta V_2$ over different current pulse loads for the 7.2 V lithium ion battery. The linear relationship between $C_R$ and $\Delta V_2$ may be described by (7), but with different values of $\delta$ and $\gamma$. 
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REFERENCES

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