DYNAMIC PROPERTIES OF THE LEAD ACID BATTERY

Zbigniew Noworolski, Ulo Reskov
Polytronics Engineering
Toronto, Canada

Upon development of the Valve Regulated Lead Acid (VRLA) battery (and the ensuing problems associated with their maintenance) an urgent need has developed for techniques and instruments capable of assessing their state of health.

The fact that VRLA batteries are sealed to the external environment, means that the only measurable parameters, which are test accessible, are electrical in nature. It is not surprising then, that the measurement of the internal ohmic value of the cell, and its relation to battery health and/or state of charge has been frequently published. Although there are numerous techniques, which may be employed when determining this value, none of them can claim a 100% correlation between the measured parameters and the actual capacity of the cell.

The authors of this article believe that static measurements of a single electrical parameter provide insufficient data to characterize battery quality and/or the state of health to a sufficiently meaningful degree of accuracy. To illustrate this point of view let's consider that some measurements of a car are taken to determine the quality and level of its performance. One researcher measures the cars physical dimensions with great accuracy. Then another does a speed assessment, and other researchers measure the fuel consumption, noise level and so on. Each researcher may be able to claim some degree of correlation between his measurements and total car quality, but it is obvious that regardless of the accuracy of their measuring tools and techniques, only by combining the results can the cars performance be assessed with a low probability of error.

The same analogy holds true for batteries. Voltage alone (especially floating voltage [1]) is a poor indicator of the state of health of the cell, as voltage is influenced by many externalities that have little to do with cell quality (charger performance, recent battery states: discharge, charge). However, in the past voltage readings of the cell combined with specific gravity measurements and a visual inspection, were sufficient for determining the state of health of floated cells. The latter two parameters are inaccessible when testing VRLA batteries, and for estimating purposes have been replaced by ohmic value measurements.

Although several instruments (for ohmic measurements) now available can impress the user with their measurement accuracy, there are justifiable doubts [3,5] as to the nature and relevance of the relation between these measurements and battery health and/or state of charge. The fact, that different instruments use different frequencies (seldom published) to measure the ohmic value of the battery, makes those instruments comparative tools only.

The ohmic value of the cell varies with changes in the floating voltage. Since float voltage is not steady over time [9], the measurements of ohmic cell values can vary above the stated instrument accuracy due to float changes alone[2,3,4]. However the published accuracy of the measured parameter can give a false impression of the reliability and accuracy of the device and the method on which it operates.

The battery is not a linear device. The ratio of the voltage to current is not constant as for a resistor. This ratio will vary with the voltage at the time of measurement. See the figure 1 below.

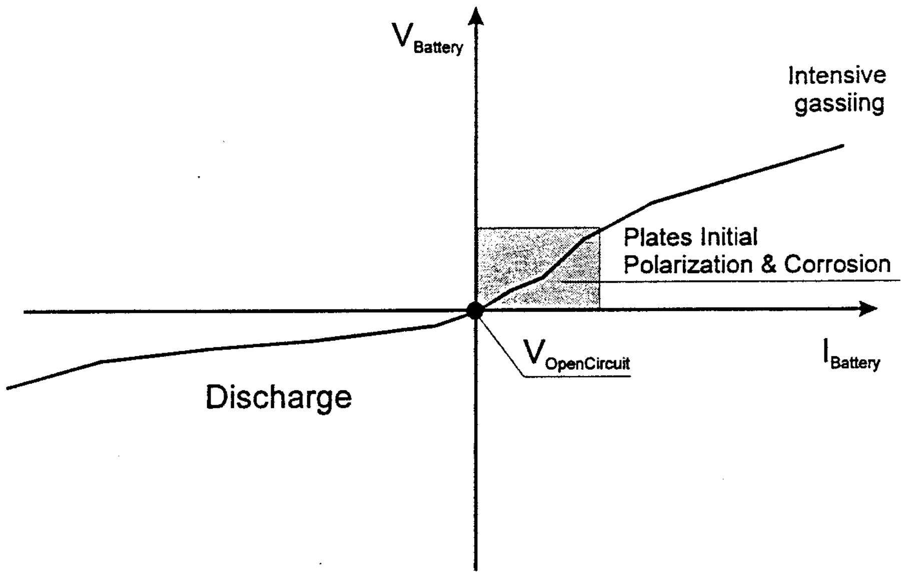

Fig. 1

Increasing the voltage above the open circuitry potential will result in an increase in float current in accordance with Tafel curves[1]. In the vicinity of the open circuitry voltage, the current rise (due to the polarization of the positive and negative plates) is not linear.
Reduction of the voltage down to open circuit voltage will cause the current to diminish. Further reduction of the cell voltage will result in rapid rise of the current in the negative direction (discharge).

It is clear that the resistance of the cell represented by plotting the tangents of the curve is nonlinear and is dependant on the voltage level at the time of measurement (for the comparison a straight line represents ordinary resistor response). It is also clear that measurements of the ohmic value of the cell, without simultaneous readings of cell voltage, will lead to a questioning of the reliability and purpose of the reading.

Ohmic values of the cell are easily measured. But measurements of the ohmic value alone without disclosing the frequency can be misleading, especially when the tested cell is in the floating condition . For instance, impedance is by definition frequency dependent and to gain sufficient information for its determination requires a wide range of the frequency spectrum to be observed [2]. Specifying the impedance without disclosing the frequency is relevant in one instance only: at a frequency equal to zero. (DC measurement or in the another words internal RESISTANCE).

Many publications discussing the measurement results of impedance and conductance tests and their relation to battery health report different levels of correlation between these parameters. However, in all of them the reader will find mention of a strong correlation between conductance and impedance.

Physically and mathematically this is possible only when the conductance is reciprocal of the inductance, which occurs only when the frequency is equal zero. In the other words when the theoretical imaginary part of the measurement of the battery 's ohmic parameters is much less relevant than the real one.

The situation will become more complex if the measurements are taken with an AC stimulant (either current or voltage). A meaningful discussion of the response of the battery to the AC stimulant will be aided by using an electrical model of the battery.

Numerous models of the battery have been presented over the years [2,4,6,11]. Here the authors choose to use a model proposed by Weiss[6]. He tested the model during float, charge and discharge of the 100Ah battery and found a good relationship between the predicted and the measured state of charge of the battery.

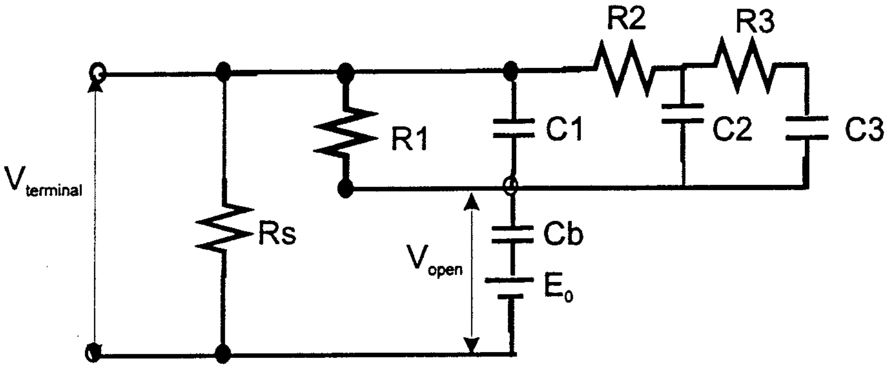

Figure 2. Battery Equivalent Circuitry

Rs - self discharge resistance
R_1, R_2 and R_3 - overcharge resistance
C_1, C_2 and C_3 - overcharge capacitance
Vopen - constant voltage source (equivalent to the open-cell voltage)
Vterminal - measurable terminal voltage
Cb - electromechanical capacitance
E_0 - open potential of fully discharged cell

His general model, in fact, constitutes a compilation of three different models. Each having the same configuration with different component values depending on whether the cell is in a float, charge or discharge condition. Even with these three conditions described the model still fails to account for the *'coup de fouet'* phenomena[1]. Since this phenomena depends on various factors such as crystallization speed, properties of the electrolyte, mobility of the H_2SO_4 ions, porosity of the grids etc., the authors believe that including the observation of such a process will in fact increase reliability of the measurement of the battery for the purposes of predicting battery quality and state of charge. It is simply one more piece of information which will be available for battery evaluation.

[1] When the initial voltage drop that occurs at the beginning of a battery discharge is followed by a slight increase in voltage this increase is known as the '*coup de fouet*' phenomenon.

For modeling purposes of this paper, a small change in the Weiss model will accommodate physical changes in the battery during the beginning of discharge.

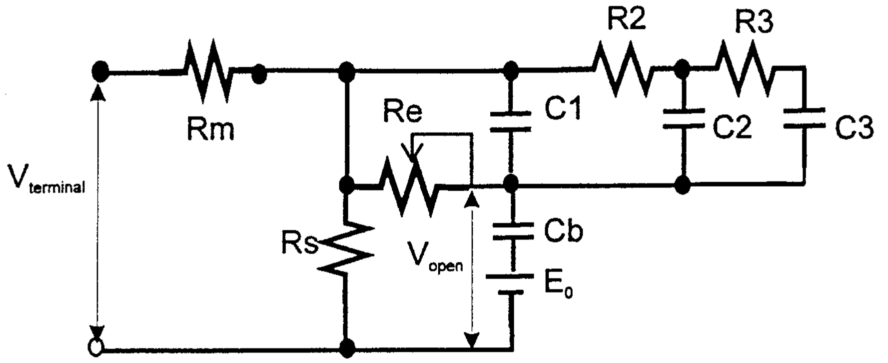

Fig. 3
Modified battery model

Rm - mechanical path resistance
Re - electrochemical resistance (variable) represents the '*coup de fouet*'
Rs - self discharge resistance
R_2 and R_3 - overcharge resistance
C_1, C_2 and C_3 - overcharge capacitance
Vopen - constant voltage source (equivalent to the open-cell voltage)
Vterminal - measurable terminal voltage
Cb - electromechanical capacitance
E_0 - open potential of fully discharged cell

Battery internal resistance (electrochemical resistance) is higher (lower concentration of the reaction components, slower crystallization process) during the initial stage of the discharge. The model will account for this if Re or its part is replaced with time dependent resistance. This model may be expressed as a set of differential equations. At the present time the authors are experimenting with the SPICE program for such an application and are in the process of formulating a relation between the '*coup de fouet*' and battery condition.

The cell terminal voltage of the battery represented by the model above is expressed by equation (1):

$$\text{Vterminal} = \text{Vopen} + \text{Vover} = (t) + (t) \qquad (1)$$

where:

- operating cell over-potential (positive during float and charge, negative during discharge)
- voltage sourced by cell electrochemical processes.

As stated above, any measurement (impedance or resistance) taken when the cell is in floating condition, depends on the float voltage of the cell and is actually measuring the combined effect of C_1, C_2, C_3, R_1, R_2, R_3 and Rm + Re, which is not considered to be the cell's internal resistance. If many cells are connected serially the float voltages will vary not only from cell to cell but also with respect to time

(ratio of RC component to the float current and self-discharging current). In order to measure cell internal resistance, the cell must be brought to the level (i.e. the charge of C_1, C_2 and C_3 has to be removed).
To accomplish this a controlled discharge current was applied to the cell for a fixed length of time and thereafter the cell was allowed to recover. A fast data sampler was used to collect the discharge and recovery data from which R_1 C_1 and R_2 C_2 discharge/ recovery curves were calculated. Finally the simplified set of differential equations were solved to derive the open circuitry voltage (virtual open circuitry voltage).

Once the open circuit voltages were known, the discharge current was applied until such voltages were reached . Thereafter a series of test pulses of variable lengths were applied to the cell. From the test data values can be obtained for each individual component of the cell model .

Due the fact that the measurements are always taken at the open circuitry voltage, it is highly probable that repetition of the test will yield the same results within a tight margin of error, regardless of the initial float voltage level.

Short discharges in the order of few seconds, do not change value significantly. Therefore the measurements can be taken repeatedly for greater accuracy. In time, the numerous measurements can be collected and trend analysis performed to determine the level of degradation of the cell. Degradation will incorporate changes in various components like Rmt, Re initial, Cn Rn.

Conclusion

Based on the examination of numerous publications and current research, it becomes evident that the measurement of one electrical parameter of a cell is usually not sufficient to assess the cells ability to deliver the power. Voltage alone does not give a sufficient level of confidence, nor does the ohmic value. Combining these measurements is far more useful than when each is taken separately but is still somewhat inadequate for determining cell health. The ohmic readings will vary depending on the frequency applied, the voltage may vary with time and alone has weak correlance to the battery health. Although such variations are generally unwelcome they could be used in an advantageous manner by modern electronics. They can be captured and analyzed using the set of equations derived from the cell model.

The Voltage and ohmic values are not the exclusively measurable parameters of modern electronics. Introduction of a time domain to the popular voltage, or ohmic value measurements, permits measurement of impedance at ALL frequencies. It also allows for the elimination of errors associated with float voltages influences. Finally, solving the set of equations for individual components of the model described in this paper, makes it possible to estimate the quality and deliverable capacity of the cell separately.

References.

[1] Feder, D. O. (1994) . The Never Ending Pursuit of Float Voltage Uniformity in stationary Reserve Battery Plants. Proceedings of INTELEC94 Conference, pp.609-617

[2] M. Hughes, The Residual Capacity Estimation of Fully Sealed 25 Ah Lead/Acid Cells, Journal of Power Sources, 17 (1986), pp. 305-329

[3] Robinson, "A Reliable Method for Determining Battery Health?", Proceedings of INTELEC 96 Conference, pp. 654-661

[4] T.Ogata, Method of Estimating Deterioration of Lead-Acid Batteries ..., Electronics and Communications in Japan, Part 1, Vol. 77, N0. 10,'1994

[5] W. Cantor, Monitoring Lead-Acid Batteries In UPS Systems, Electronic Design, January, 1998

[6] R. Weiss, Battery State of Charge Determination ...,Electrochemical Science and Technology, September, 1982

[7] J.Zhang, Using High Speed Pulse as an Analysis Tool,12th Annual Battery Conference on Applications and Advances, California State University, January, 1998

[8] C. M. Schell, A Miniaturized Tester For Detecting Weak Individual Cells in Ni/Cd Batteries, 94TH0617-1,IEEE, 1994

[9] K.Floyd, et al, Assessment Of The Lead Acid Battery State of Charge by Monitoring Float Charging Current, Proceedings INTELEC 1994 pp602-608

[10] U.Teutch, A Mathematical Model for Float Operation of Valve-Regulated Lead-Acid Batteries, TELESCON Proceedings, 1994, pp89-96

[11] S.Waaben, Battery Model Using ADVICE Computer Simulation of PIN Diodes and RLC Circuit Topology, IEEE,1983.

[12] N.A. Hampson, The electrochemistry of the lead acid battery