Electrical Theory as it Pertains to Internal Ohmic Testing of Stationary Batteries

In the world of stationary batteries, there is a tremendous amount of pressure to reduce operating and maintenance costs associated with batteries. The same is true for many other installed assets. Furthermore, there have been many papers and presentations about the best method to test batteries at the lowest possible cost while extracting the most performance and verifying that performance.

Since the beginning of battery-testing time, there have been two important changes in testing. One is the realization that there is no correlation between voltage/specific gravity and battery capacity and the other is the introduction of internal ohmic testing methods, namely impedance, dc resistance and conductance. Internal ohmic testing is both efficient and extremely cost-effective. Other tools and measurements are necessary, indeed, yet are not as important when determining the state-of-health of installed batteries. These other tools include dc voltage, float current and yes, discharge testing. However, it is only internal ohmic testing that can reliably fill the gap between discharge tests. In fact, internal ohmic testing can extend the time between discharge tests from an annual event to a triennial event, thus saving much time and money without sacrificing backup time.

A review of IEEE 450 and IEEE 1188 over the ages will reveal the changing landscape in the required testing of stationary batteries. Included in IEEE 450 is a discussion of the three major techniques of internal ohmic testing. The main body of this paper deals with the apparent and real differences among the three internal ohmic techniques.

An enormous study was commissioned by EPRI, the Electric Power Research Institute, in Palo Alto, California. The study had three objectives:

- To determine the extent to which internal ohmic measurements can identify low capacity or degraded cells
- To evaluate the correlation between battery capacity and internal ohmic measurements
- To provide guidelines to assist users with the implementation of internal ohmic measurements in a battery maintenance program

The study encompassed somewhere around 34,000 cells over a period of about four years. One conclusion drawn from this study was “Internal ohmic measurements [sic, impedance, dc resistance and conductance] proved an effective indicator of the general health of a station battery and its individual cells. These measurements reliably predicted degraded battery cells. With few exceptions, cells with a poor internal ohmic value also had a low capacity when checked by a discharge capacity test. Furthermore, a high degree of correlation was demonstrated between the three types of internal ohmic measurements (conductance, impedance and resistance): all three test technologies were effective. The results of this project readily demonstrate that internal ohmic measurements can be a valuable part of a battery maintenance program.”

Armed with this information a prospective purchaser of an internal ohmic instrument should understand the similarities and differences among the three major manufacturers of the instrumentation as well as having full understanding of battery construction, battery failure modes, and testing parameters and methods (beyond just internal ohmic tests).
Starting with battery construction, there are several main components to a battery. First there is the jar, which holds everything in place, and a cover. There are the plates which include the grid and active material, separators to keep one plate from shorting to an adjacent opposite polarity plate, acid, top lead which connects all of the positive and negative plates to their respective posts and finally positive and negative posts. Each of these has electrical characteristics and hence, reacts differently to the three different signals applied by the three different internal ohmic techniques. The EPRI study concludes that all are correlated to each other and are capable of finding low capacity cells.

Electrical Theory

In 1959, Willinhganz suggested an electrical schematic for a battery. It is shown in Figure 1.

![Figure 1](image_url)

In this diagram, Rs is the resistance of the series circuit of post, top lead grid, and active material (acid in a lead-acid cell). The capacitor, Cdl, is the double layer capacitance. The resistor, Rct, is the resistance of the charge transfer and lastly, W is the Warburg impedance. As expected, charge is accumulated (stored) in a battery much like a capacitor but with much greater efficacy. What is not shown in this diagram is the inductance associated with the large top lead conductors. The higher the battery capacity, the more current the top lead must carry. There is a limit as to how small this top lead can be on smaller batteries while still mechanically supporting the grids. Presumably, in smaller batteries inductance becomes a larger component in the electrical schematic. Normally, the inductance will remain constant except when the top lead corrodes leading to a catastrophic failure of the battery during a discharge.

The series resistance varies due to corrosion of lead, the change in specific gravity of the acid, loss of active material, top lead corrosion, etc. As the battery discharges, the specific gravity decreases by about 0.15 and the active material becomes sulfated. The decrease in specific gravity has essentially no effect on the impedance of the cell, since it is still an electrolytic solution of sulfuric acid. As the active material becomes sulfated, the increase in impedance is marked. The sulfated active material has a much higher electrical resistance in absolute terms and especially in comparison to the lead oxide and lead metal of the positive and negative plates, respectively.

The double layer capacitance (ignored by dc resistance testing instrumentation) decreases as the cell ages. It also decreases due to excessive cycling which causes shedding of the active material which is not necessarily seen by standard dc resistance techniques. Shedding is visible by visual inspections as a layer of yellowish white dust on the bottom of the container. Shedding, a form of loss of active material, does not cause an increase in dc resistance. However, sulfation and mechanical separation of active material from the grid (another form of loss of active material) do cause an increase in all internal ohmic values.

The charge transfer resistance varies with many of the same phenomena as the double layer capacitance. As the battery ages, it loses capacity to the point that at 80 percent of its original capacity it will need to be replaced per IEEE Recommended Practices. Since Rct is similar to Cdl, dc resistance may not measure this form of loss of capacity.

Finally, the Warburg impedance becomes a factor at frequencies less than 0.1 Hz. It is a term for describing diffusion of the electrolyte from one plate to another. For internal ohmic values, it does not have any significance.

Impedance is the vector of dc resistance and capacitive reactance; therefore, impedance includes the dc resistance component. It goes further than dc resistance testing because it does include the capacitance which does vary with both state-of-charge and state-of-health.

In addition to Willinhganz’s cell, a battery model was created for the purposes of determining from manufacturers’ data sheets how a particular battery would behave in certain applications, but the focus was on high rate discharges common in EV, HEV, and UPS applications. The modeling utilized PSpice and a module called Analog Behavior Modeling (ABM). ABM included modeling the capacity of the battery as it changes during the discharge process. Since it is known that battery discharge curves are very similar to battery capacity aging curves, capacity does vary much with percent of discharge and with battery age. According to the paper, the modeling demonstrates “that this model provides a reasonable representation of the battery terminal voltage for different discharge conditions.” In other words, their success was due in part by utilizing the real understanding that battery capacity does vary with both terminal voltage (during a discharge) and during the battery’s life cycle and aging process (over time).
The discussion thus far has been addressing vented lead-acid batteries. With respect to sealed lead-acid batteries, one of the major failure modes of them is dry-out or loss of compression. A review of the literature shows that there is some debate as to whether the actual cause of this failure mode is due to overcharging and hence driving off gases or whether it is caused by a mechanical change in the absorbed glass matte separator. The effect is the same regardless of the causative factor – the capacity is reduced. All internal ohmic techniques can find this failure mode.

Another failure in VRLA batteries is negative lug rot which is corrosion of the top lead of the negative polarity. Lead is not soluble in sulfuric acid and it is soluble in water. In VRLA batteries, oxygen and hydrogen gases recombine to form water. If that water accumulates in the headspace of the cell, the negative top lead is exposed to water and corrodes. As the top lead corrodes, there is less mass of the current conducting material. During an outage, the negative top lead can melt open causing an open in the battery string. Since inductance is affected, this failure mode can be found far earlier in the degradation process by ac test methods than by dc test methods. Only after considerable corrosion has occurred when the metallic resistance is affected can this failure mode be detected by dc resistance methods.

\[ Z = \sqrt{(R^2 + X_c^2)} \]

\[ Z, \text{ impedance} \]

\[ X_c, \text{ capacitive reactance} \]

\[ R, \text{ resistance} \]

The above failure modes are basically electrochemically based. There are external factors which can cause other issues for battery life. Some of them are ripple current, heat, and cycling among others. Ripple current is an output of the charger. Battery chargers are designed to convert ac into dc and no charger is 100 percent efficient at that conversion. Telco rectifiers have filters to remove ripple current. Some utility chargers do have some output filtration but that is not the norm. UPS systems are notorious for high levels of ripple current.

Ripple current in and of itself does no harm to the battery. Battery manufacturers have limited the ripple current to about 5A rms for every 100Ah of battery capacity. When ripple current is higher than that five percent, the excess current heats the battery and shorts battery life. A battery temperature that is elevated by 10°C will yield about half of the battery's design life. Increase the temperature by another 10°C and its life will halve again. Some chargers will have an indicator of excess ripple current (or voltage). Most do not. There are clamp meters which will measure the ac ripple current on a battery. There is also at least one impedance instrument that measures ripple in conjunction with other battery parameters. Ripple current should be measured quarterly to ensure that it is not above the threshold.

Float current, if abnormal, indicates impending thermal runaway in sealed batteries. Vented batteries can not go into thermal runaway due to the large acid volumes. There are dc clamp meters which will measure float current and once again, there is at least one impedance instrument which incorporates float current measurement in the instrument. Float current can be different based on type and alloy of the battery. The range of expected float current values is from 40mA per 100Ah for sealed batteries and only 10mA per 100Ah for flooded lead-acid batteries.

In conclusion, battery testing can be time-consuming and expensive. There are methods to reduce costs while not sacrificing battery reliability. Internal ohmic testing is one of the best methods to reduce the time to measure and gather data. Studies have proven the worth of internal ohmic testing in finding weak, low capacity cells. Trending of all battery data has proven to be invaluable in determining when to replace a battery string in a planned budgetary manner rather than emergency situations. Emergency situations are costly from an outage perspective, i.e. the load is not supported, and from an asset replacement perspective. There are differences in the feature sets of internal ohmic test instrumentation. One thing is clear, however, and that is one technique is not measurably superior to another based on many studies, one of the most important of which has been cited here along with other supporting papers. If one manufacturer’s instrument’s data are not measurably superior to the others, then the differences lay in the customer-oriented features and other needed parameters measured by the instrumentation.

References


A Discussion about Water Loss, Compression and the VRLA Cell, Cole, B. et al.


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