OHMIC MEASUREMENTS: THE HISTORY AND THE FACTS

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INTRODUCTION

Internal battery ohmic measurements have been a hot topic amongst battery users and battery manufacturers for the last ten or twelve years. Everyone seems to agree that measuring the internal parameters of a cell can be very useful in determining a battery's state of health. These measurements, which have in recent years been accepted by the IEEE battery working group as well as most battery manufacturers, are still not well understood.

What has not been properly documented and explained is the difference in the various measurement methods used and the fact that it is the internal resistance of a cell that is the important parameter in determining a cell's state of health. Most AC impedance or conductance devices, whether they are monitors or portable instruments, do not measure the true resistance of a cell and do not provide reliable state of health information.

Very little has been published on the internal parameters of a cell in the last 50 years. This paper will review the most significant tests and experiments performed and explain how these results reach the same conclusions drawn by the author of this paper.

DIFFERENCE BETWEEN AC MEASUREMENTS AND DC RESISTANCE

Let's look at the basic electrical battery model shown in Figure 2 to point out the differences. The DC resistance of the circuit ignores the internal capacitor and is, therefore, equal to $R_1 + R_2$. An AC measurement cannot ignore the capacitor, which acts as a parallel ohmic path to R_2. Because the capacitor is in parallel with R_2, it will mask the problems that occur in the R_2 part of the path, and it will even distort what happens in the R_1 part of the path. At real high test frequencies, the capacitor becomes a short circuit, and the AC measuring instrument will not detect any changes in R_2 no matter how great. AC instruments are basically limited, as an effective state of health indicator, to small ampere-hour 12 volt modules that have high internal resistances and low capacitance values. The effect of the capacitor depends on frequency and the size of the capacitor. The size of the capacitor in turn depends on the ampere-hour size of the cell.

WHY DC RESISTANCE MEASUREMENTS ARE MORE ACCURATE

As a battery deteriorates and loses its capacity, the internal resistance of the battery increases. The increase in resistance can be used to determine end of useful life. Albércorp experiences show that if a cell's resistance increases by more than 25% above its baseline value (known good resistance of new 100% capacity cell), the cell will no longer be able to deliver 80% or more of the rated capacity. The battery manufacturers want some extra margins for warranty purposes, and they recognize a 40% to 50% increase.

The resistance of the cell includes all the components in the conduction path through which a discharge current has to flow to deliver energy to an external load. Figure 1 shows all these major components.

R_{Post} R_{Strap} R_{Grid} $R_{Grid->Paste}$ R_{Paste} $R_{Separator}$ $R_{Electrolyte}$

Figure 1

Note that some of the resistors are metallic in nature, and some are part of the chemical path. The loss of capacity that results from an increase in resistance depends on whether the cell is suffering from a metallic or chemical problem.

The cell's electrical makeup also includes a huge capacitor, which is shown in the simplified electrical model in Figure 2. The typical value of the capacitor is 1.5 farads per 100 ampere-hour of cell capacity. Various authors and electrochemists have discussed different cell models showing the placement of the capacitor, but there doesn't seem to be agreement on any one model presented.
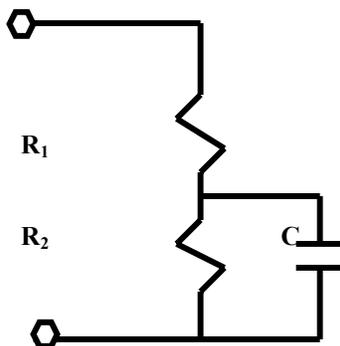
Figure 2. Simplified Battery Equivalent Circuit

Figure 2, which is a generally accepted model, has grouped the various internal resistors into two general resistors labeled R1 and R2, and it shows the internal capacitor in parallel with R2. An application note about impedance and conductance testing written by Johnson Controls a few years ago assigns 40% of the total cell resistance to R2. The author will use a value of 45%, since this is more consistent with results calculated from field testing.

The reason for the loss of capacity is:

1. Any increase in resistance of the metallic path causes a large drop in the cell's terminal voltage when the battery is placed under load. That means the operating end voltage is reached before the end of the rated time. Under a worst-case scenario, the internal resistor will overheat and fuse open during a discharge.

2. A resistance increase in the chemical path, such as the electrolyte or paste, means the fuel supply of the cell has been affected, and it will not be able to store the rated amount of energy. Dryout in VRLA cells is a good example of a chemical path problem.

What makes AC based ohmic measurement ineffective is the fact that the internal capacitance of the cell is in parallel with a significant portion of the conduction path and, therefore, tends to mask the resistance increases that take place in that part of the path. Experiments performed by both a battery user[2] and a battery company[4], using AC instruments discussed below, have shown that impedance and conductance measurements do not correlate well with cell capacity, and they proved that the higher the frequency of the test signal, the worse the correlation got. The following mathematical analysis will explain why this is true.

COMPARISON OF CELL RESISTANCE VERSUS IMPEDANCE

As a cell deteriorates, it can be detected by monitoring the total cell resistance. AC impedance or AC conductance measurements will not track the cell resistance changes correctly unless they are performed at very low frequencies that approach DC.

Example: Let us look at a commonly used battery and evaluate what happens as this type battery ages/deteriorates. A known good cell in the 800 to 1200 ampere-hour range has an internal resistance of approximately 200 microhms. (This comes from actual resistance measurements.) The resistance of a given size cell depends on whether it was designed for telecom or UPS applications. This size cell also has a capacitance value of approximately 15 farads.

Assigning these realistic values to the cell model shown in Figure 2 will allow us to calculate the AC impedance and/or AC conductance readings of this cell. We can increase the value of either resistor (simulating internal cell problems) to show how this impacts the AC readings. We can also use different measurement frequencies to show these measurements become totally ineffective and misleading at the higher test frequencies.

$R_{Tot} = R_1 + R_2 = 110\ \mu\Omega + 90\ \mu\Omega = 200\ \mu\Omega$

$X_C = 1/2\pi fc = 1/2\ (3.14)(f)(15)$

$Z_{Tot} = R_1 + \dfrac{(R_2)\ (jX_C)}{R_2 + jX_C}$

$R_1 = 110\ \mu\Omega$

$R_2 = 90\ \mu\Omega$

$C = 15\ F$

- Known good cell has a resistance of 200 $\mu\Omega$
- Impedance calculated using formula above
- Frequencies used are typical of today's instruments and monitors

Typical 1000 A*Hr Cell
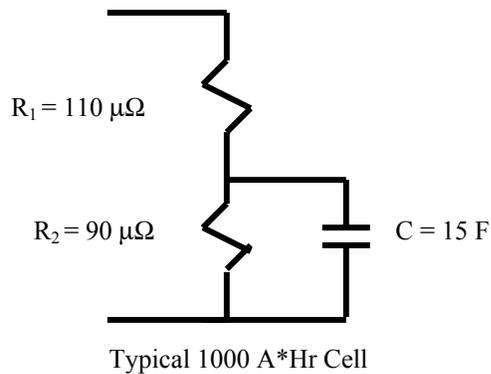
This example will illustrate what happens to the impedance readings as the 200 $\mu\Omega$ cell above deteriorates to the point where it is a failing cell. As stated earlier, a 25% increase (50 $\mu\Omega$) in the internal resistance means the cell has failed, but we will also look at what happens with a 50% increase, since this is what the manufacturers tell customers to use.

Table 1 below shows what happens to impedance when a cell fails as a result of either R_1 or R_2 increasing. First, R_2 is increased to where the total resistance reaches the failure level, and then the same analysis is repeated by increasing R_1. The test frequencies used match the frequencies of typical instruments and monitors on the market.

Test Freq.	Cell Failure	$R_{Tot} = R_1 + R_2$ ($\mu\Omega$)	% change R_{Tot} from baseline	X_C ($\mu\Omega$)	Z_{Tot} ($\mu\Omega$)	% change Z_{Tot} from baseline
60	None	200	0	177	185	0
60	$R_2 > 140$	250	25%	177	208	12%
60	$R_1 > 160$	250	25%	177	234	26.5%
60	$R_2 > 190$	300	50%	177	220	19%
200	None	200	0	53	139	0
200	$R_2 > 140$	250	25%	53	135	-2.2%
200	$R_1 > 160$	250	25%	53	187	35%
200	$R_2 > 190$	300	50%	53	133	-4%

Table 1.

This analysis comes up with the following very interesting answers:

1. When a cell's total resistance increases as a result of the resistance R_2 in parallel with the internal capacitor, the impedance value only indicates a very small change and will, therefore, fail to alert the user to a failing cell. A 60Hz instrument shows only a 12% increase in impedance instead of reporting a 25% increase. Note that this instrument slightly overstates the problem if the failure is in the R_1 part of the path.

2. It is also obvious that the problem of using AC test methods gets much worse as the test current frequency is increased. A 200Hz device actually shows the cell gets better when the R_2 part of the path causes the cell to fail. This same device will also declare good cells bad by overstating the problem when it occurs in the R_1 part of the path. Instead of reporting a 25% failure, it shows the impedance having increased by 35%.

3. Another important observation is that, as the R_2 path continues to fail, pushing the total cell resistance more than 25% above baseline, the impedance reading distorts the actual ohmic results even further. The conclusion to be drawn from this is: By the time a failing cell reaches the impedance warranty level of 50%, it is pretty much a dead cell.

4. A number of monitors and battery users developing their own test methods use the existing ripple current flowing through a battery to calculate the internal impedance. This is not a good idea, since the ripple current in a UPS system has a frequency of 360Hz. Table 1 does not even bother showing this frequency, because the results of using it are even worse than the 200Hz device.

HISTORY

The following ohmic measuring experiments are offered as proof that, "It is the internal resistance of a cell that counts when it comes to measuring a cell's state of health."

1. In 1959, E. Willihnganz and Peter Rohner[1], both C&D battery company employees, investigated the internal parameters of a cell and published a paper titled: "Battery Impedance: Farads, Milliohms, Microhenrys." The basis for their investigations was not to study ohmic measurements as a state of health indicator, but, rather, to measure the magnitude of the internal parameters.

    The Willihnganz/Rohner measurements showed a battery has a huge capacitance (approximately 1.5 farads per 100 ampere-hour), and they showed the internal resistance of a cell decreases as the ampere-hour size of the cell increases.

    Since the test equipment used in 1959 was limited in capability, the authors used a signal injection, variable frequency measurement technique. The experiment clearly showed the internal ohmic value of a cell yields different values for different test frequencies. The fact that the ohmic value changes with frequencies proves that AC based measuring techniques do not measure the true resistance of a cell.

2. In 1986, New York Telephone Company engineer Sheldon DeBardelaben[2] published a paper called "Determining the End of Battery Life." The paper discusses the results of experiments designed to show internal ohmic measurements could be used to determine a battery's state of health. It is this author's belief that Mr. DeBardelaben should be credited as the original discoverer of this concept.

    Mr. DeBardelaben designed his own AC injection test instrument, measured ohmic values at both 5Hz and 45Hz, and compared results with actual capacity tests performed on two large flooded strings. While the correlation (ohmic vs. capacity) testing was based on a fairly small sample, DeBardelaben goes to great length to point out that the results were much better for the low frequency testing. His argument is that the internal resistance is the predominant indicator of cell capacity. He uses the same general battery model as shown in Figure 2 to explain why the capacitor obscures the true cell resistance value, and points out that this is even more pronounced at higher frequencies.

3. In 1994, Misra, Noveske Holden and Mraz[3], all from C&D, published their findings from experiments designed to determine if AC conductance and AC impedance instruments could be used to determine the reliability of VRLA battery systems. The results of their testing, based on a significant number of cells, show very poor correlation between conductance and impedance readings versus cell capacity. The conclusions diplomatically state these readings cannot be relied on to determine state of health or capacity, but can be used to find gross defects.

    Some of the many tests performed were to compare different instruments to each other and against a pseudo resistance test referred to as a relaxation technique measurement. Basically, the resistance was calculated from subjecting a cell to a discharge and then measuring the change in voltage from beginning of test until right after the coup de fouet, and then dividing it by the discharge current.

    Several different tests were performed with varying degrees of correlation results, but the one test that compared three different commercially available AC injection instruments with the resistance test proved once again that the closer an instrument comes to measuring pure resistance, the better the results. The following table shows the result of one of the tests performed on a small sample of 100 ampere-hour cells.

INSTRUMENT	TEST FREQUENCY	% CORRELATION WITH RESPECT TO CAPACITY
DC Resistance	-------	92%
Conductance	20 Hz	59%
Impedance	60 Hz	45%
Impedance (Hewlett Packard)	1000 Hz	28%

Table 2.

HOW ARE RESISTANCE MEASUREMENTS MADE?

This paper will not present proprietary circuit details of the implementation, but will explain how the true resistance of a cell can be captured using dynamic measuring techniques.

When a cell is placed under load for a short duration, its terminal voltage will depress while the load is on and then recover after the load is removed. Figure 3 shows the voltage of a cell initially floating and then subjected to a three second load of approximately 72 amps.
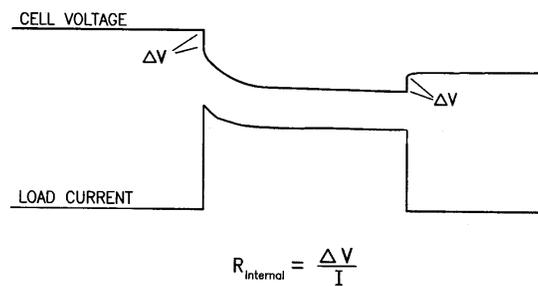
$$R_{internal} = \frac{\Delta V}{I}$$

FIGURE 3.

The instantaneous voltage drop at time zero and the voltage recovery when the load is removed shows the voltage drop across the internal resistance. The resistance can be calculated by capturing the voltage change and measuring the value of the test current. The exponential decay of the voltage from time zero until load is removed is a result of the internal capacitor discharging.

How do we know the resistance from these dynamic measurements is accurate? The results from these measurements have been verified against the resistance values calculated from short circuit current testing performed by both C&D and Albércorp in front of nuclear power plant engineering witnesses.

OTHER FACTORS THAT AFFECT OHMIC TEST ACCURACY

Noise
All stationary batteries are normally connected to a charger, which is also in parallel with the critical load. This means the test device, instrument or battery monitor must be capable of operating in this real world environment. This environment is typically a very harsh, electrically noisy environment. Figure 4a shows what the typical cell voltage looks like in a UPS application. Figure 4b zooms in on the ripple present all the time.
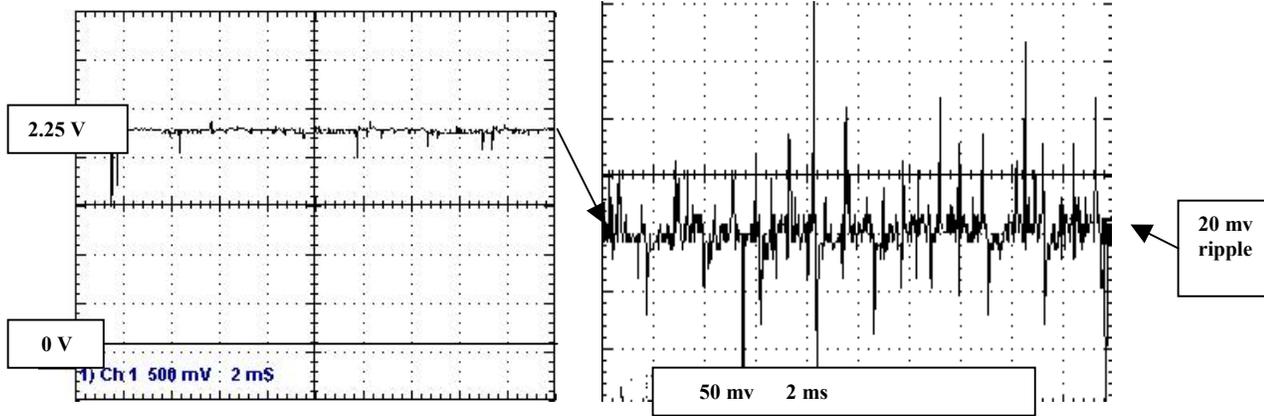
Typical 2 V cell

Figure 4a

Ripple on 2 V cell

Figure 4b

The huge amount of ripple current present will interfere with the AC test measurements, and it is not uncommon to see 25 amp rms ripple current flowing through a 300 KVA rated UPS battery. The amount of ripple current present depends on how much load is applied to the UPS. An AC test device will typically show different readings for the same model battery when the readings from two differently loaded UPS systems are compared.

DC readings, if performed properly, can virtually ignore the ripple and will, therefore, produce the same reading regardless of whether the battery is loaded or not.

It should also be noted that DC instrument are more accurate than AC instruments; just check the AC and DC accuracy specification on any of the popular digital voltmeters on the market.

Test Current
Another very important factor is the amplitude of the test current used. In the noisy environments in which ohmic measurements have to be performed, it is imperative that a high test current be used. This is true for both AC and DC test measurements. It is important to have as high a signal to noise ratio as possible. A lot of the test devices being used today use a test current as low as one amp.

One way to illustrate the importance of high test currents is to look at the resolution required. From our previous example, the known good resistance value was 200μΩ, and a failing cell was 250μΩ. That is only a 50μΩ difference. Detecting a 50μΩ difference using a one amp test current means the instrument would have to be capable of measuring 50 microvolts reliably in a noisy environment. That is a practical impossibility; just look for an AC voltmeter with those specs.

Also remember (Table 1) that if a cell's resistance changes by 50μΩ, the impedance for a 60Hz instrument only changes 23μΩ, making it even more difficult to get reliable, repeatable readings. A 200Hz device would never even detect a problem existed.

Resolution
Many of the typical monitors and AC instruments on the market advertise a ±100μΩ resolution. If we apply that to our typical cell of 200μΩ, then, by definition, these instruments could read either 100μΩ, 200μΩ or 300μΩ, a totally unacceptable performance, since it would provide a battery user with very misleading information.

SUMMARY

The battery industry as a whole, including the IEEE standards committee and battery manufacturers, has erroneously lumped all ohmic measurements together in terms of their effectiveness in measuring a cell's state of health. Hopefully, this technical analysis will help clarify for everyone concerned that it is the change or increase in the cell's resistance that confirms the cell is deteriorating. Using AC type measurements will not provide the early warning required to maintain a reliable battery system.

AC state of health measurement accuracies improve as cell ampere-hours decrease. That is because the capacitor value is not as great and, therefore, does not distort the results as badly. AC measurement accuracies also improve as the measurement frequency decreases, again because the capacitor is not as significant at the lower frequencies. The limitations of the AC measurements, i.e., the frequency used and the size of the cells being tested, must be taken into consideration before employing these devices.

Independent testing and mathematical analysis both confirm the parameter of importance is the cell resistance.

REFERENCES

(1) E. Willihnganz and P. Rohner, "Battery Impedance: Farads, Milliohms, Microhenrys," AIEE, 1959.

(2) S. DeBardelaben, "Determining the End of Battery Life," Intelec 1986, Toronto, Canada.

(3) Misra, Noveske, and Holden, C&D Charter Power System, "The Use of AC Impedance/Conductance and DC Resistance for Determining the Reliability of VRLA Battery Systems."

(4) Johnson Controls, "Impedance and Conductance Testing," Application Note Form 41-7271, Aug. 1994.