THE VIRTUES OF IMPEDANCE TESTING OF BATTERIES

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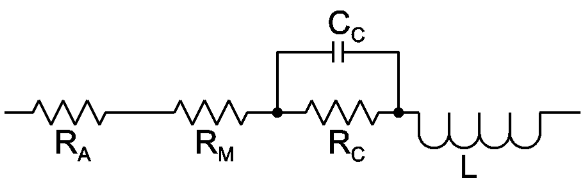
I. Electrical Definition of Impedance.

Impedance is comprised of the vectors of dc Resistance and Reactance (Capacitive and Inductive). Ohm's law says that $E = I * Z$ and $Z = \sqrt{(R^2 + i^2)}$ where R is the real component, resistance, and i is the imaginary component, reactance, which is frequency dependent. So if frequency is constant, (the BITEs use 60 Hz) then reactance does not change due to frequency. However, both real and imaginary components can change due to valid changes in the condition of the battery. Theoretically speaking, measuring batteries at various frequencies will present a better picture of the condition of the battery, but no one yet has determined the practicality of measuring batteries at various frequencies.

With that said, there are several equivalent circuits of a battery with the seemingly predominant circuit having been discussed by Willihnganz and Rohner[i] which is shown here.



In this Equivalent circuit, R_A is the resistance of the acid; R_M is the metallic resistance including grids, top lead, posts; C_C is the capacitance of the cell; R_C is the Charge transfer resistance and L is the inductance. At a fully charged specific gravity of 1.215 and 2.25 Vdc, when the cell is discharged to 1.75V, its specific gravity is approximately 1.17 which is similar to the "tropical specific gravity". The resistance changes by only a very small amount and so is not significant in the overall impedance of a cell. The metallic resistance is significant by virtue of the insignificance of the acid resistance. The Charge transfer resistance must change with state-of-charge lest the cell won't function as it does in practice. If the Charge transfer resistance is too low, it acts like a short circuit and the capacitor will not be functional. If it is too high then the battery will never recharge. Inductance will change with cell size but will change very little within a given cell type. The internal impedance of the cell will vary mainly due to changes in metallic resistance, capacitance and to a lesser extent by charge transfer resistance and not so much by inductance. It is evident from the mathematical equations,

$X_C = 1/(2\Pi fC)$ and $X_L = 2\Pi fL$, where f is frequency, C is capacitance and L is inductance,

of capacitive reactance and inductive reactance that different values for impedance will be obtained at different frequencies. Impedance at a constant frequency can not vary due to changing frequency. The term, $2\Pi f$, becomes a constant and thus the reactance only varies due to real changes in capacitance and inductance. Measuring impedance at the same frequency over time shows that impedance does, in fact, find weak cells caused by real changes in cell condition.

II. Four-wire Kelvin Measurements and CTs.

Now that frequency has been determined not to be a factor, let's focus on the measurement and the calculation of impedance. In order to obtain the most valid data, a four-wire, Kelvin-style lead set is used with a CT to measure the current simultaneously to the voltage drop. Without the CT, it is difficult to accurately measure current especially in smaller strings such as 4*12Vdc-48Vdc systems with parallel strings. Current losses through parallel paths are not measured. It is relatively easy to measure voltage drop and assume current is constant (or known) and solve for resistance, impedance or conductance. But the most accurate method measures both voltage and current and accurately solves for impedance following Ohm's Law.

III. Measuring Methods.

Currently, there are two primary ways of stimulating a battery to take internal ohmic measurements: cause a signal to be generated in the battery by “pulse” discharging the battery or by applying an AC current signal. In instruments that remove energy from the battery, it is incumbent upon the charger to correct for the discharge the test instrument has caused.

Impedance, using the frequency generated by electric company (60 Hz or 50 Hz, depending upon geographic location), employs the latter, i.e., apply an ac current signal to the string. The instrument calculates cell impedance by measuring the ac rms voltage drop due to a measured ac rms current signal without consideration of its components, resistance and reactance. The current signal is predominantly from the instrument’s transmitter but ripple current from the charger can add current to the battery system; the extent of that ripple current is dependent upon the level of filtration. In telecom power systems, the ripple is negligible while in other systems it has been measured as high as 70 A rms. An additional factor is the overall impedance of the string which will reduce the current in the string.

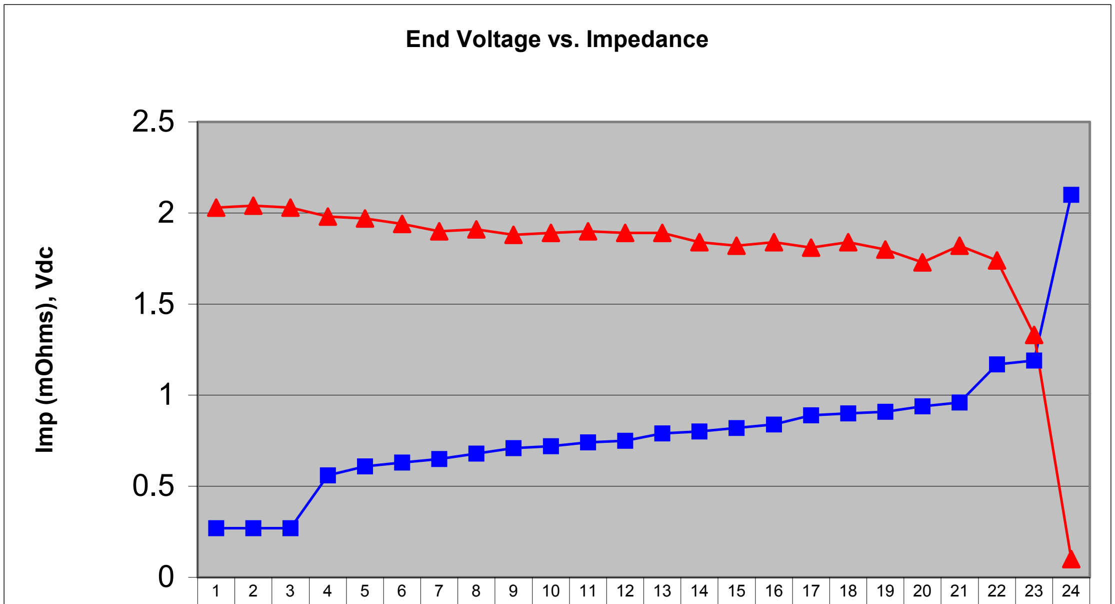
IV. Simplicity/ Complexity of Taking Measurements.

Impedance measurements are easily taken. There is a lead set which adds a little complexity to the instrument but the instrument weight is extremely low. The transmitter which applies the current is heavy to account for the transformer and the blocking capacitors but it merely sits on the floor while the measuring head weighs a diminutive 1-1/2 pounds. Simply apply current to the entire string (or half string) and record each cell and its intercell connector in memory by walking down the string. Simultaneous impedance and dc voltage measurements are taken. No need for two passes. The intercell connector measurements are directly measured so it is not possible to get any negative resistance values. In essence, the user is taking voltage readings, ac voltage and dc voltage simultaneously.

An additional feature of impedance is the ability to measure the ripple current manifested in the string by the charger. As chargers age, the ripple current output trends slightly upward. However, if a diode blows, the ripple current may double or treble leading to heating and shortened battery life if left undetected.

V. Impedance versus Load testing and its Correlation to Capacity.

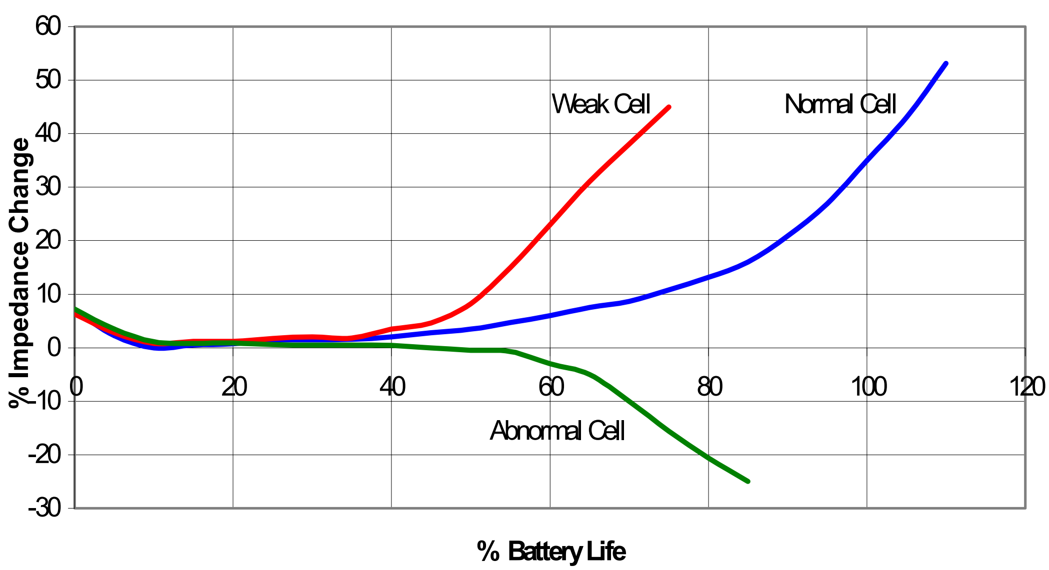
Everyone knows the limitations and costs of load-testing; dragging in a second battery, connecting it, making connections to all cells to monitor voltage, waiting eight hours or so, off-peak hours, recharging the battery (2-3 days), removal of the second battery and coming back in another three days as a double check. Furthermore, in a Pb-Ca battery, it removes one of its 3-50 cycles. There is no predictive nature to load testing due to its infrequency. It has limited value in that it generally will indicate that if an outage had occurred whether the battery would have supported the load or not. It is agreed that internal ohmic tests do not eliminate the need for load tests but it is generally agreed that impedance *et seq.* can increase the interval of load tests. Not only is risk not increased by reducing the amount of load test, risk is actually decreased since impedance can find weak cells more quickly than load tests. The graph of End Voltage vs. Impedance below shows the correlation between capacity and impedance. Although it is not perfect, it is obvious that Cell Nos. 17, 7 and 19 are weak based on impedance while a load test verified these results. The age-old question of how many cells does one replace at what age of a battery remains to be answered. It is eventually a decision of the owner of batteries to decide the level of risk it will tolerate.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Cell No.	11	15	16	3	18	22	13	24	10	14	23	20	5	9	6	4	21	8	1	12	2	17	7	19
Z	0.27	0.27	0.27	0.56	0.61	0.63	0.65	0.68	0.71	0.72	0.74	0.75	0.79	0.8	0.82	0.84	0.89	0.9	0.91	0.94	0.96	1.17	1.19	2.1
Vdc	2.03	2.04	2.03	1.98	1.97	1.94	1.9	1.91	1.88	1.89	1.9	1.89	1.89	1.84	1.82	1.84	1.81	1.84	1.8	1.73	1.82	1.74	1.33	0.1

VI. Impedance as an Indicator of Battery Aging.

In the long run, a cell will generally follow one of the curves below[ii]. If it is a normal cell where the proper maintenance is performed including temperature regulation, then the blue curve will dominate. A weak cell is one that fails early in life while an abnormal cell failed due to a short circuit thereby reducing impedance and eventually will be evident using simple float voltage. But notice that trending is a primary method to long term analysis of battery condition. Baseline values are sometimes difficult to acquire because notice at the beginning stages of a cell's life, its impedance decreases. This phenomenon occurs due to the finishing of the formation process *in situ* rather than in the factory. IEEE[iii] defines that all cells must deliver 90% of rated capacity upon delivery unless otherwise specified to account for this.



VII. Battery Failure Modes and Impedance.

The failure modes and short-term losses of capacity of batteries comprise a long list but a battery is a complex electrochemical device. Some failure modes are preventable while others can merely be ameliorated through constant care and maintenance. An unscientific observation: that a battery's life can not be lengthened but its shortening may be avoidable. The failure modes are separated into two groups: flooded and sealed lead-acid. The following table indicates the most prevalent modes and is not intended to be all-encompassing.

Flooded Lead Acid	VRLA
Positive Grid Corrosion	Positive Grid Corrosion
Post Seal Leaks	Post Seal Leaks
Shedding	Dry-out (Loss-of-Compression)
Sulphation	Sulphation
Hard Shorts	Hard and Soft (dendritic) Shorts
Slivering	Thermal Runaway

Impedance can find most but not all of these failure modes and short-term losses in capacity. Referring to the Equivalent circuit above, positive grid corrosion is RM and will increase impedance as the positives corrode. Shedding will be seen through impedance on two fronts: 1) loss of active material and 2) upon incipient shorting across the plates. Incipient shorting may or may not be found by voltage alone. Hard shorts behave similarly to shedding except that it typically occurs in the first year of a cell's life. Dry-out (loss-of-compression) is found early in the drying (loss) process for two reasons: 1) increased impedance through the cell (R_A and R_M) and 2) loss of capacity, C_C. Hard and soft shorts, especially in the early stages, can be found with impedance before they are evident from float voltage. Sulphation is evident in the R_M value. Thermal runaway is due to other factors, namely, dry-out (loss-of-compression) but is also evident by measuring float current as well as impedance. Post-seal leaks are visible but only if a visual inspection is performed.

VIII. Future Technology.

Promising investigation[iv] into multiple frequency testing of battery impedance has been underway for sometime now. This methodology requires a relatively accurate model of a cell and should be able to indicate what areas of the battery construction and chemical processes are varying over time. By knowing these parameters it is expected to learn what processes are showing signs of natural aging, defect, overstress or damage. By detecting these conditions early or as they start, one may be able to eliminate some of these situations, thereby lengthening (or, at least, not shortening) the life of a battery system and possibly predicting when replacement will be needed and aid budgetary planning. Such an advanced system would also relieve the strain in the relationship of the battery user versus battery manufacturer. With such test equipment in use, each could be fairly confident that battery system is being maintained in a proper healthy state and with shared information, battery technology will improve due to new insights into the changing characteristics of batteries under long term use.

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[i] Willihnganz and Rohner, "Battery Impedance: Farads, Millohms, Microhenrys", AIEE Chemical Industry Committee, Paper #59-823, 1959.
[ii] Markle, Gary, "AC Impedance Testing for Valve-Regulated Cells", 1994
[iii] IEEE, "IEEE-485 Recommended Practice for Sizing Lead-acid Batteries for Stationary Applications", ©1995.
[iv] Scott, Nigel D., "A Single Integrated Circuit Approach to Real Capacity Estimation and Life Management of VRLA Batteries", Proc. Intelec 2001, Edinburgh, Scotland.