BATTERY IMPEDANCE TESTING…
A PRACTICAL TECHNIQUE FOR BATTERY CONDITION ASSESSMENT AND CAPACITY MONITORING.

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ABSTRACT:

The management of the condition assessment of standby lead acid battery systems using impedance methods is now a highly regarded and mature technology delivering an accepted compliment to load discharge methods. Offering the significant attributes of being a non-invasive diagnostic method implemented at modest per-cell costs to in-service battery systems, impedance testing may be applied both to absolute or trended (CBM) condition assessment philosophies. Given the often sudden nature of battery failure mechanisms, the success of failure prediction is proportional to sampling intervals. Studies have expanded the scope of impedance technology to the determination of deterioration in battery capacity.

(1.0) INTRODUCTION:

Battery bank failure in emergency or standby power systems typically invokes consequences beyond all proportion to the value of the failed component. Losses of up to USD 2 million directly from battery failure-related causes have been documented in the literature [1].

Surprisingly, the concept of risk-assessed battery maintenance has only very recently been embraced in New Zealand and, even then, by only some of the power and communication industries. Many still continue to judge battery maintenance in terms of the ratio of maintenance cost vs. the investment in the battery system per se.

It is generally still the belief of the asset owner in New Zealand that the batteries will last a defined time in service (agreed on a sliding scale of warranty assurance with the battery supplier), and that this assurance permits an adequate security reserve to adopt a *minimal* maintenance regime and a timely calendar-based replacement schedule of the entire bank.

Whilst the latter maintenance concept offers a “first order” *degree* of reliability assurance, the experiences of the Industry (especially with valve regulated lead acid installations) in both New Zealand and internationally [2] document the flaws and severe cost implications in applying this maintenance assumption too literally, especially as regards the maintenance intervals adopted as the bank ages.

Experience [3] internationally suggests that batteries are the most unreliable component of emergency power systems: arguably, then, a more mature attitude to battery maintenance issues is merited, particularly in strategic installations.

Indeed, studies [8] presented at the 1995 Intelec Conference [11] confirmed that VRLA batteries appear to have a shorter-than-advertised life and that some manufacturers have shown a willingness to accept that observation.

By corollary, the realities of batteries subjected to such influences call for far more sophisticated condition monitoring processes than generally practiced if battery system reliabilities are to be assured.

(2.0) MECHANSIMS OF BATTERY DETERIORATION AND FALURE:

Prior to documenting the concepts and performance of battery impedance testing methods, it is important to understand the mechanisms of battery deterioration in order that the performance of this impedance technique in relation to detecting each failure method can be assessed.

Failure mechanisms in lead acid standby battery power systems are numerous and varied.

Failures in new batteries are rarer but still reported, attributable to reversed plates, plate separation, seal separation, and cracked cases [3].

Installation damage is another contribution [3] [4], arising from such factors as improperly torqued connections (damaging case or seal), reverse polarity, poor crimp joints, omission of non-oxidising grease from joints, failure to clean joints on lead terminations, and acid spills causing later corrosion. Deterioration prior to installation can occur through poor storage conditions [4] (including charge management to overcome self-discharge, and storage temperature), rough physical handling, and stratification of electrolyte before installation.

Failure Mechanism	Wet	VRLA
Jar Case Cracks	X	X
Specific Gravity Changes	X	X
Electrolyte Level/Dryout	X	X
Excessive Temperature	X	X
High Cycling Rates	X	X
Defective Post Seals	X	X
Strap Corrosion	X	X
Plate Sulfation	X	X
Plate Growth (Dendrite Shorts)	X	X
Plate Deterioration/Separator Problems	X	X
Post/Connection Hardware Problems	X	X

Table 1: Causes of Premature Failure in Lead Acid Batteries [3]

A host of internal and external influences on failure have been identified for batteries in service [3] (Table 1 and Appendix A [8]). Many of these contribute jointly to compound the complexity of reliable end of life prediction. As such, the combined effects of these physical and chemical influences on the battery integrity serve to undermine such simplistic concepts as a stated battery service life issued by a maker at the time of manufacture or installation.

Focussing on VRLA batteries, which are now (despite frequent misgivings in the Industry) the more common lead acid battery in service, there are several failure mechanisms that stand out. A major one is **loss of electrolyte [3]** [5] [6] [8]. This is caused, or exacerbated by:

a) Improper float charging:

This causes internal heat which will in turn create pressure build up. Once this pressure exceeds the battery's designed limits, the valve or vent opens until the pressure is relieved. The opening of the valve exposes the sealed cell to the atmosphere. Hydrogen is usually released and air is allowed to enter. Since this is done near the area of recombination, water is evacuated as well. Continuous operation under these conditions leads to gradual water loss and eventual capacity loss.[5]

b) Excessive ambient temperature operation:[5] [8]

c) Failure of the valve to close properly; [5]

d) Evaporation of the water through the 'jar' material: [7] [8]

Problems surrounding the internal design issues of positive plates of VRLA cells give rise to another common failure mechanism [8]. Positive plate growth is an inevitable consequence of the natural ageing and oxidation of grid materials but is traded in VRLA batteries against the requirement for tight compression of the glass mat construction against the positive plate. Whilst it is normal to design for a 5% plate growth by end of life, this is not always achieved in reality and leads to internal stresses giving rise to failures from plate buckling, container cracking, and post seal fractures.

Post seal failures can also permit air to enter the battery. Negative posts tend to "cold flow" [10] giving rise to the entry of oxygen resulting in a disruption of the recombination process [8], as well as deterioration of the inter-cell connections.

As a prominent failure mechanism of concern one would rate highly the internal deterioration [3] [4] [5] [6] of both strap-to-post connections, and of internal connections between cells in sealed multi-cell batteries. These are capable of resulting in complete open circuit or catastrophic failure with little warning [5]. **Indeed, it has been reported [6] that 80% of battery failures are conduction path related and usually present themselves during discharge.**

High cycling rates leading to premature end of life are common in PS applications [3].

(3.0) TESTING LEAD ACID BATTERIES:

Vented cell lead acid technology allows the testing of dc voltage, battery temperature, specific gravity, and, importantly considering the common failure modes, a visual inspection of the internal plates and connections.

Conversely, being opaque and sealed units, VRLA technology precludes all but external electrical testing and analysis of the temperature of the negative post. Whilst the latter helps in detecting early stages of thermal instability, this may be too little too late [6].

Mistakenly, the lack of accessibility of the VRLA battery to more traditional testing techniques, coupled with an intended marketing concept of the makers, has spawned the title “maintenance free”. Quite conversely, it is now accepted [3] [5] [6] [8] [9] that without regular and appropriate maintenance the life and capacity of VRLA batteries will be compromised.

Clearly, then, in the case of VRLA technology more advanced electrical testing methods and management methods are required to assess internal condition and predict end of life.

(3.1) LOAD CYCLE TESTING:

Load cycle testing is the discharge of a battery at a constant current or power to a specified terminal voltage, during which the voltages of each battery are monitored for accelerated voltage decay characteristics (correlating well with expected performance [9]).

Whilst generally recognised by battery makers as the best method to determine whether the battery continues to meet its published capacity rating [8] [9] [12], the technique is regarded more as a determination of the recent state of battery health [9]. It is not universally regarded as a determination of future reliability prediction [6] [9]. Comfort may be gained, however, from a verification of capacity that the *concern of failure is reduced* [12].

It is argued [6], and debated conversely [8], that the method can also exacerbate battery deterioration.

Accepted testing intervals are generally annually, reducing to semi-annually after degradation is observed [8] [13].

It is generally accepted [6] [12] that the method is expensive, logistically challenging for larger banks, and time consuming. These issues serve to preclude the more frequent use of the technique for condition monitoring.

(3.2) EXPLANATION OF THE CONCEPTS OF IMPEDANCE TESTING:

Internal battery impedance testing has been studied since the turn of the century. [4] Significant studies were performed in 1955 by A. Fleischer [14] on nickel cadmium batteries at audio frequencies.

Work done by Willihngenz and Rohner [15] first represented an equivalent circuit of a battery (Figure 1) which still remains essentially the accepted model today. It consists of a series connection of acid resistance (Ra) and metal plate resistance (Rm), a battery capacitance from plate effects (Rc), a series inductance (L) of the current carrying parts of the battery, and a non-linear resistance (R1) contributed by the contact resistance of plate to electrolyte [3], [4], [5], [10]. More detailed models [8] [16] [18] [19] relating to *fully charged* VRLA batteries portray Rm as a series string comprising of the resistances of terminals + straps and posts + inter-cell welds (Figure 2).

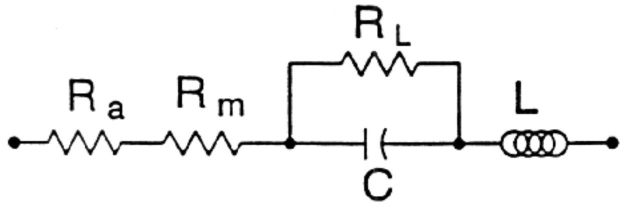


Figure 1: Battery Equivalent Circuit [4]

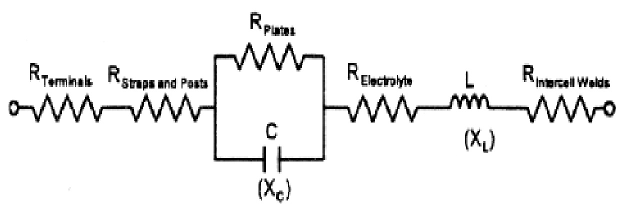


Figure 2: VRLA Battery Model {8]

Cell inductance is normally very small, ranging from 0.05 to 0.15 Microhenries for typical cell sizes [8]. The capacitance tends to be substantially larger, and figures published range from 1.3 to 1.7 Farads per 100 AH of capacity [5] to 1.5 to 2.0 Farads [8].

The internal resistance varies from less than 1 milliohm for a large cell to greater than 2 milliohm as the cell size drops below 100 AH [8] [15].

Studies with these models served to indicate that the response of the elements of the model to the passage of AC current within the battery offered a powerful diagnostic process. They also served to indicate [3] [5] [8] [19] that in lead acid batteries the resistance portion is the dominant factor, whilst the reactive portion is largely capacative if the frequency is kept in the order of mains fundamental frequencies (ie: below 100 Hz) where cell resonance occurs. Results taken at differing frequencies in the 50-220 Hz range will differ in absolute impedance values but no significance has been attributed to the phenomenon from a diagnostic point of view [3]. On very large batteries, the capacitance is large so that the capacitive reactance becomes far less dominant and the impedance and resistive values converge.

Frequencies approaching 1000 Hz start to generate a significant influence from the lead inductance. Conversely, DC methods of internal ohmic measurement have not been progressed further because of their effect on charge condition [3].

Work published in 1987 [20] [23] served to consolidate the earlier studies and confirmed the correlation of battery deterioration with a rise in internal impedance when using an ac current stimulus. The discoveries were that the relative internal impedance of a cell increases due mainly to losses of active material as its capacity decreases. Further, the concept was also established of a generic life curve of impedance vs. age and the construction of actual curves for in service batteries to assist in predicting end of life and associated capacity reduction with age (Figure 3a) [6] [8]. An example of a more generic impedance life cycle curve is reproduced in Figure 3b [22], indicating also the advent of premature battery failure mechanisms.

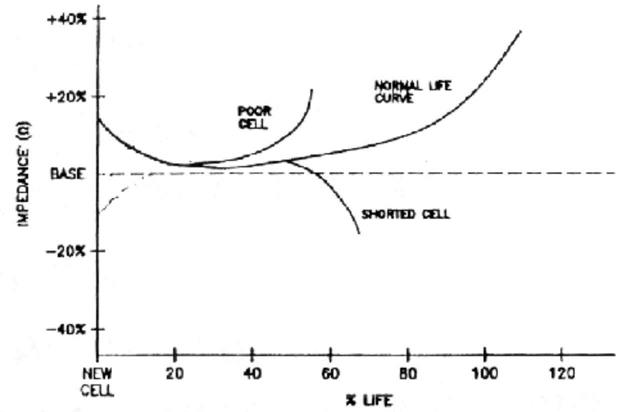


Figure 3b: Generic Impedance Life Cycle Curve [22]

Shortly afterward, extensive field testing served to introduce and validate the concept of <u>battery peer comparison</u>. It was announced in 1992 [6] that the all cells in a bank of similar age and discharge history should exhibit cell impedances within 10% of one another and, as a general rule, form a compact grouping of impedance values below 5% of the mean. Conversely, a disparity of more than 20% from the cells in a given string correlated with a health problem for such cells [6]. Other tests [4] [9] have served to reinforce that concept (in comparison to an extrapolated baseline average for a new cell) but slight disparity exists in both directions, some [5] advocating a 15% level and others 30%, with others of influence being in agreement with the 20% figure [13].

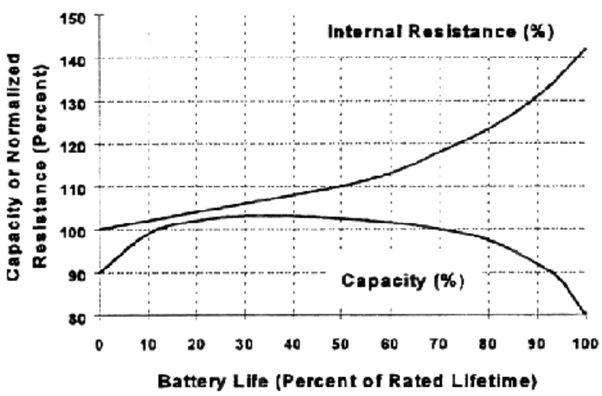


Figure 3a: Lead Acid Internal Impedance and Capacity as a Function of Age [8]

(4.0) DIAGNOSING BATTERY CONDITION USING IMPEDANCE METHODS AND FACTORS INFLUENCING CELL IMPEDANCE :

Researchers now generally concur as to the parameters governing the interaction of the various contributing mechanisms to overall cell impedance as the cell ages.

Changes in the metallic resistance path do not usually occur during charge / discharge [8] but significant resistance changes due to deterioration from corrosion, internal weld breakdown, and poor contract between conductive materials have been already noted earlier. Impedance methods readily detect such occurrences. Deterioration

usually *increases* these individual resistance components but rarer failures from shorted parts can result in a decrease in total reading (Figure 3b).

Dryout of electrolyte material can cause a significant (positive) change in internal impedance [4]. Water loss also increases the acid concentration of the cell which leads to more rapid sulphation of the negative terminal, serving to increase resistance Ra (Fig.1). Loss of active material in contact with the electrolyte increases the electrolyte contact resistance (RL of Fig 1), also increasing internal impedance (all after [5] [8] [24]).

The measured internal impedance is most greatly affected by the cell's state of charge and temperature [4] [8]…

(4.1) EFFECT OF CELL TEMPERATURE ON IMPEDANCE:

Studies [4] confirm that cell impedance drops with increasing temperature. The correlation shows similarities for differing battery types but precise characteristics are determined by battery design and thus are unique to each make and model.

Accordingly, readings taken of cell impedance, when collected for trending purposes, should be correlated to a temperature determined from the negative post of at least one battery in the bank. Battery characteristics should be obtained from the maker to normalise results in such occurrences.

Simple impedance comparisons between cells in a bank can be undertaken without concern to temperature effects *provided all cells in the bank are at the same temperature.*

(4.2) EFFECT OF CELL CHARGE ON IMPEDANCE:

The combined resistance of the plates, separators, and electrolyte is refereed to collectively as the *electrochemical resistance.* Unlike the metallic resistance of a cell, the electrochemical resistance does change curing the discharge and recharge cycle. For example, the discharge cycle causes the electrochemical resistance to rise via two mechanisms, one being the drop in specific gravity (decreasing the conductivity), the other being the discharge process changes the active material on the plates from $PbO2$ to the more resistive $PbSO4$ [8].

Research [4] [6] indicates that cell impedance indeed rises markedly with discharge level and in an essentially linear relationship. The same research also indicated that the impedance profile of the bank prior to discharge was reflected unaltered throughout a progressive discharge from 100% to 0%. Thus an impedance test of a battery bank conducted at any discharge level will still permit a valid means of defective cell determination, by comparative methods.

Should a trendable impedance result be sought for a battery bank, all cells should be determined to be at float charge prior to testing.

(4.3) PREDICTION CERTAINTIES USING IMPEDANCE METHODS:

Gabriel [25] summarises his many years of experience impedance testing on VRLA batteries as affording about an 80% success rate in both the prediction and detection of battery problems. The 20% uncertainty level is attributed to a range of physical and chemical properties inherent in VRLA batteries which tend to deliver erratic outcomes, generally of a catastrophic nature and of very sudden occurrence.

Perhaps the most dramatic of these is illustrated in the case of lateral corrosion fractures of internal connection paths [5]. As opposed to cross-sectional corrosion which exhibits an earlier onset of increasing impedance, lateral fractures across the connection are masked by parallel conduction paths until a full fracture occurs. An example of this is depicted in Figure 4 [5], clearly showing a mere three week warning period before compete fracture from negative bus strap corrosion.

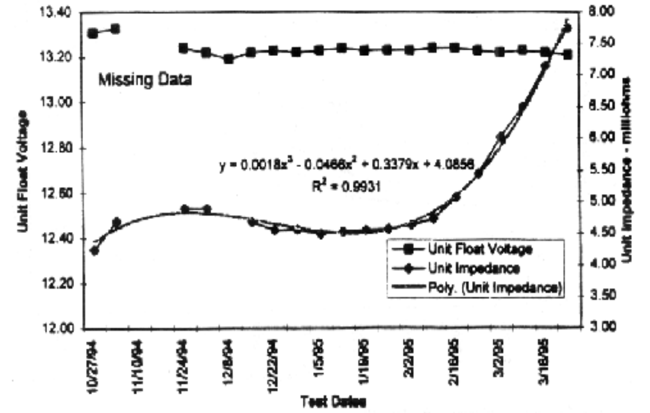


Figure 4: Effect of Catastrophic Internal Bus Corrosion on Impedance [5]

By the very nature of the failure mechanisms, the inability of the impedance technique to predict the event early in the piece is fully defensible. Interestingly, no other technique has been revealed as offering a remotely comparable success rate (see Section 4.4).

As depicted above, one can indeed use the impedance methods to capture the unfolding scenario in a timely manner and raise an alarm. Clearly, this outcome demands a more frequent sampling rate than normally practicable unless by permanently-installed impedance monitoring systems (see below).

(4.4) COMPARISON TO OTHER METHODS:

With VRLA batteries, there are two main alternative methods to impedance testing for condition assessment: cell voltage measurement and load discharge.

Monitoring of cell voltages does not indicate internal problems until significant damage or deterioration has occurred [8]. Experience by the author (Figure 5) confirms that, even in the case of battery float voltage measurements to a resolution of 10 mV, a shorted cell (detected by impedance methods) in a 12 V VRLA battery did not show any appreciable difference in float voltage across the battery.

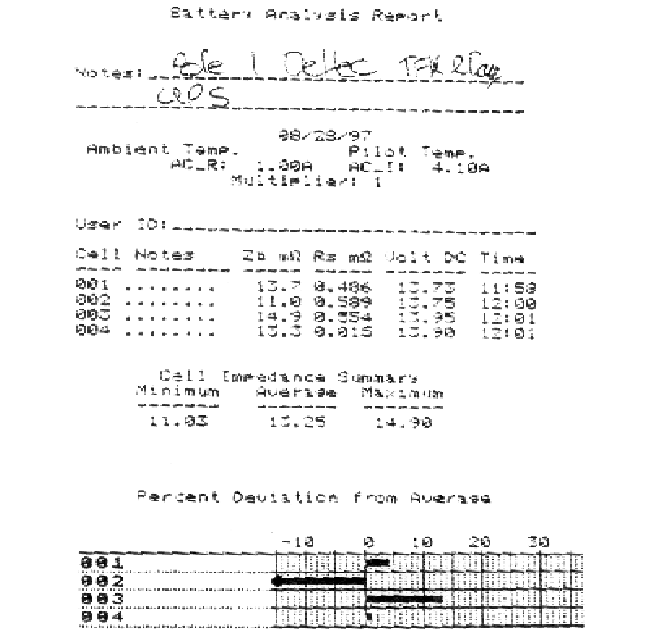
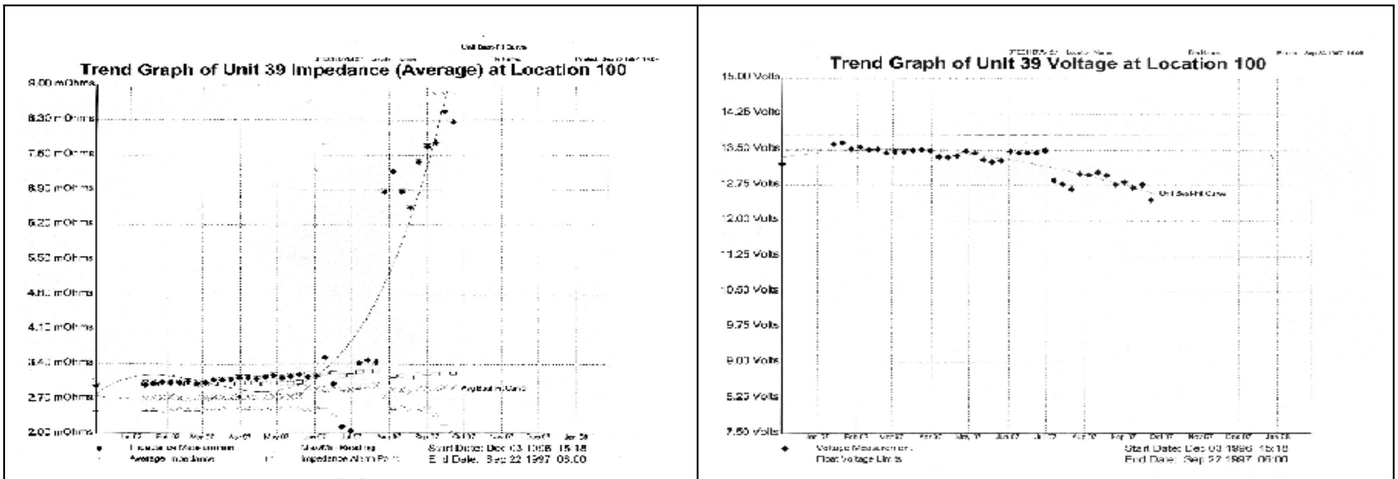


Figure 5: Impedance Test on a Bank of 12 V VRLA Batteries, Showing Shorted Cell on Battery 2 and no Appreciable Change in Battery Float Voltage.

Figure 6 [26] illustrates the performance of a 12 volt VRLA battery in the event of a catastrophic open circuit of similar cause to that of Figure 4 above: Figure 6a depicts the impedance profile over a 10 month interval, contrasted in Figure 6b against the comparable battery float voltage performance for the same battery and time interval. **Clearly, impedance is by far the more sensitive indicator of deterioration, increasing by some 300% over the baseline value, by comparison to a drop in battery voltage of nominally only 10% over baseline!! One cannot fail to conclude that, whereas system 'noise' in normal float voltage variations could serve potentially to mask the float voltage indicator of massive deterioration, the effect on impedance is such that any alarm settings invoked for trends above nominated deviations from baseline data could be unambiguously detected. Note also that a clear upward impedance trend was evident prior to the event, giving warning of advanced deterioration: nonetheless, the sudden end of the battery life was, although unexpected, detected at the onset of the event (and in time to react) via (on-line) impedance methods.**



(a) (b)

Figure 6: Contrast of Effects on Cell Impedance (a) and Cell Voltage (b) with Catastrophic Cell Failure [26]

Load discharge methods have been discussed earlier and the conclusion drawn that the method is ideal as a capacity assessment tool but impractical for frequent assessments. It is not regarded as a predictive technique, wherein impedance testing offers a significant advantage.

(5.0) PRACTICAL IMPEDANCE TESTING HARDWARE AND METHODOLOGIES:

(5.1) PORTABLE TESTERS:

In 1987 a patent [20] was awarded to the Commonwealth Edison Company in Chicago for impedance testing apparatus and their research into its application.

AVO International's Biddle division, working under licence to Commonwealth Edison, began manufacture of the "BITE" product range in the early 1990's and published their supporting field experiences successively from 1992 [6] [10] [21] [22] et al. AVO chose to follow the Commonwealth Edison approach of current injection at mains frequency (depicted in Figure 7) at a level of two to three times the level of ripple current [6], measuring the RMS voltage developed across the cell and straps, then converting this to an impedance value. Excellent field performance is reported.

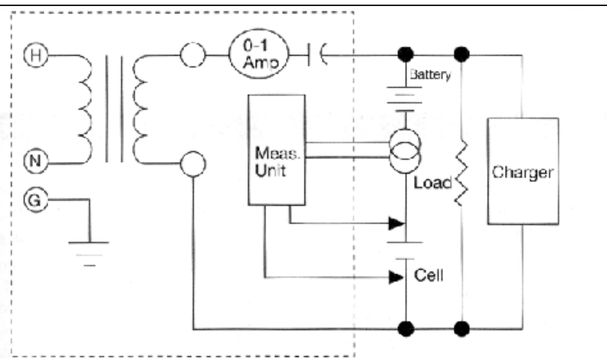


Figure 7: Schematic of AVO's Impedance Testers

Subsequently, AVO have refined their technology into a 'second generation' range of practical, portable equipment. Three models are offered (Figure 8), giving the user a choice of capability from 250 AH cells (testing current 1 A nominally), to 2500 AH (testing current nominally 7.8 A at 50 Hz). Each model segregates strap resistance results and cell impedance results, reads directly in milliohms, and provides real-time logging of this data.

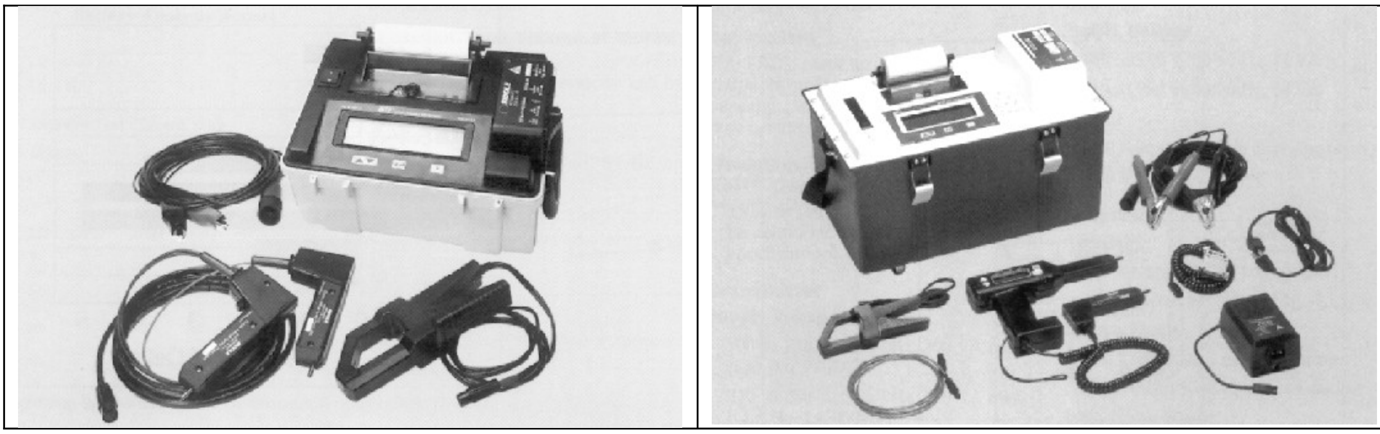


Figure 8a: 250 AH AVO Impedance Tester	Figure 8b: 2500 AH AVO Impedance Tester

To simplify on-site condition assessment and to permit attention to any condition issues whilst on site, the sets feature a direct printout capability for results. These printouts (Figure 9) are in the form of collated impedance statistics for all cells in the battery bank, *normalised to the mean impedance value for the bank.* In addition, the on-site report includes a calculation of the bank mean and deviations, as well as a full collation of all strap values at a glance.

Data acquired is readily exported into spreadsheets for trending and overlay work. Suitable software to facilitate this and permit end-of-life determination has been commissioned by AVO for release soon [1].

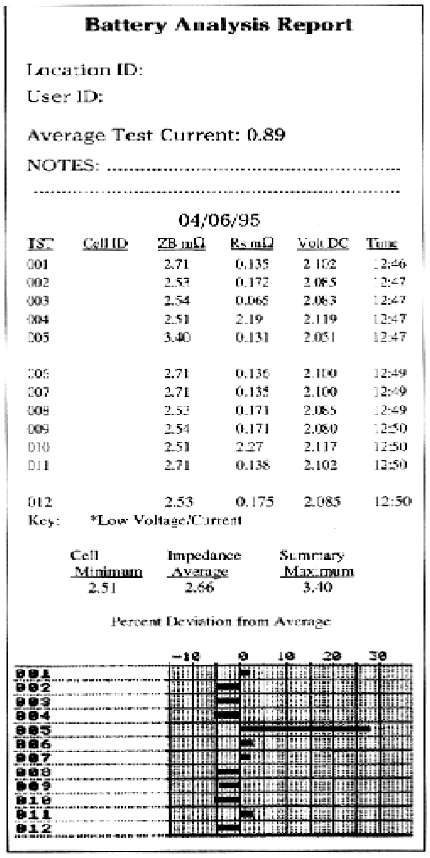
Results are acquired with batteries on-line and set up is achieved in minutes. Test time per cell or strap is under 10 seconds per reading, permitting a total 110 volt bank test inside 30 minutes including setup and pickup.

Site testing with portable equipment is recommended variously as semi-annually [4] [6] to quarterly [8] [13]. New batteries have been identified [4] [6] as being inspected at quarterly intervals. *In reality, inspection intervals should be adjusted (in a more conservative direction, as practicalbe) to the observed bank condition, the criticality of the site, and the age of the bank.*

(5.2) "ON-LINE" (PERMANENTLY_INSTALLED) TESTERS:

Aside from the portable and very cost-effective impedance testing technology offered, critical sites may be monitored by permanently-installed impedance-based systems dedicated to a given bank. The BTECH company [3] offer a series of such devices using a 220 Hz-based impedance system operating on a patented AC "current drain" impedance system, as opposed to the AC current injection method in the AVO / Commonwealth Edison patent.

Sampling times for measurements of cell / interconnection impedances and cell voltages are selectable but typically 1 / week, a rate judged to be adequate for detecting all failure modes in a timely manner. Room ambient temperature, pilot battery case temperature, the differential between the two, and total battery bank voltage is checked on a one minute basis. Alarm levels are pre-settable and modem access is included to read stored trend data as required. BTECH units also monitor the presence of mains voltage on the charger and total bank float voltage.



Battery Analysis Report

Location ID:

User ID:

Average Test Current: 0.89

NOTES: ....

04/06/95

IST	Cell ID	ZB mΩ	Rs mΩ	Volt DC	Time
001		2.71	0.135	2.102	12:46
002		2.53	0.172	2.085	12:47
003		2.54	0.065	2.063	12:47
004		2.51	2.19	2.119	12:47
005		3.40	0.131	2.051	12:47
006		2.71	0.136	2.100	12:49
007		2.71	0.135	2.100	12:49
008		2.53	0.171	2.085	12:49
009		2.54	0.171	2.080	12:50
010		2.51	2.27	2.117	12:50
011		2.71	0.138	2.102	12:50
012		2.53	0.175	2.085	12:50

Key: *Low Voltage/Current

Cell Minimum	Impedance Average	Summary Maximum
2.51	2.66	3.40

Percent Deviation from Average

Figure 9: Sample of AVO BITE report.

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Figure 10a: BTECH On-Line Battery Monitor

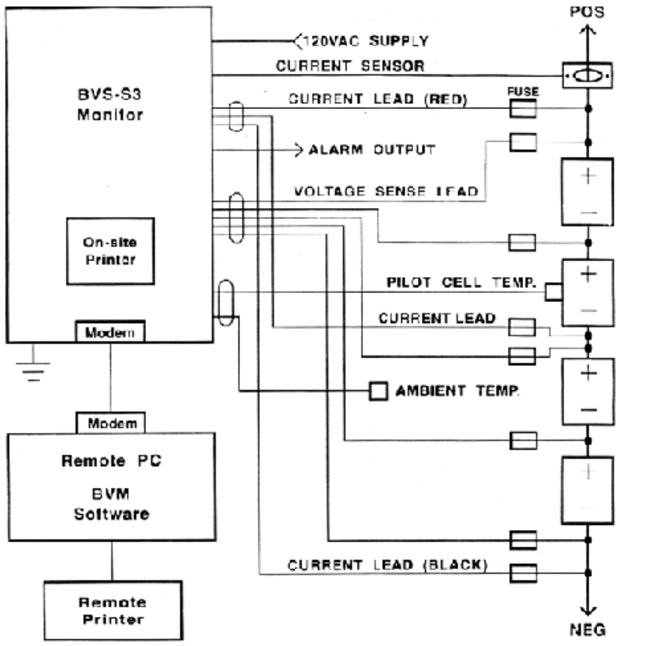

Figure 10b: BTECH Connection Schematic

drain" impedance system, as opposed to the AC current injection method in the AVO / Commonwealth Edison patent.

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A typical BTECH system is illustrated in Figure 10a and a connection diagram in Figure 10b.

(6.0) RELEVANT TESTING STANDARDS AND DOCUMENTED PROCESSES:

The portent by the early 1990's of a reliable and non-invasive diagnostic method for VRLA batteries using the above concepts was received with excitement internationally and the preparation of testing standards integrating such concepts was to follow.

IEEE-1188 1996 [13] is regarded as a primary VRLA battery maintenance document integrating impedance technology. Further guidelines for impedance testing under this standard are shortly to be published.

Other documented processes employing impedance technology have been published [4] [8] [9].

(7.0) APPLYING THE TECHNOLOGY TO BATTERY CAPACITY DETERMINATION:

Clearly, the definitive method for determining actual battery capacity remains the load discharge method [9] et al.

Gabriel [12] outlined in 1992 a linear correlation between battery impedance and load capacity, lower impedances relating to higher capacities. Moreover, he outlined a process for determining overall battery bank capacity by way of a simple "two cell capacity test" method. This required a load discharge test to be performed only on the cells in the bank having the highest and lowest impedance, respectively; the average capacity indicated that of the bank average. Assumptions were made that the cells were of the same type and age, that all impedances were within 20% of each other, and that all cells were fully charged.

The method was also considered suitable for banks with no test history.

Interestingly, Gabriel also went on to suggest that no change in all battery impedances in the bank since the previous test would indicate that bank capacity remained the same and that load capacity testing could be dispensed with on that occasion. Further, he also commented on strap management as well, advocating that any change in strap values from the previous impedance test should be attended to.

Earlier work by Markle [4] had also proffered the suggestion in less detailed form that impedance monitoring offered the scope to "reduce or eliminate" load testing.

Whilst some controversy has been reported [8] as to the precise relationship between internal impedance of a bank and actual capacity, Davis [9] produced further evidence in 1997 of the inverse linear correlation between impedance and capacity.

Clearly, the processes outlined by Gabriel above appear sound and permit a determination of change in battery capacity to be determined by battery impedance methods. As such, a major cost saving in conducting unnecessary load discharge testing is offered by the findings.

(8.0) CONCLUSION:

VRLA batteries offer a complex management issue, exacerbated by documented shortcomings over published lifetimes. Failure modes are complex and dynamic, generally well understood in concept, but very hard to quantify on a generalised basis.

Load discharge methods perform verification tests as to cell capacity and retrospective condition assessment but are neither a practical or cost-effective method of predictive cell condition monitoring.

A requirement exists for a low-cost and practical means of condition assessment of cells and prediction of end of life. Impedance technology offers that solution at an impressive level of effectiveness.

Hardware exists for impedance monitoring via portable field testing or dedicated installations.

Whilst a quantitative relationship between impedance and load capacity is not yet determined, the technique is suited to trending capacity deterioration of batteries and, as such, provides a cost-effective means of managing the implementation of load discharge methods.

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APPENDIX A: DEGRADATION MECHANISMS FOR LEAD ACID BATTERIES (after [8])

Mechanism	Effect on Battery	Effect on Operation
Electrical		
Overcharging	Excessive temperature Accelerated corrosion Excessive gas generation Shedding of active material	See thermal mechanisms Reduced capacity Battery dryout Reduced capacity or battery failure
Undercharging	Buckling of plates Battery discharge Plate sulfation	Reduced capacity or battery failure
Overdischarge	Hydration	Battery failure
Excessive ripple	Excessive temperature Accelerated corrosion (VRLA batteries)	See thermal mechanisms Reduced capacity
Mechanical		
Handling	Cracked cases Broken connectors or terminals	Electrolyte leakage
Seismic bracing	Cracked cases	Electrolyte leakage
Positive plate growth	Cracked cases Poor contact between lead grid and active material	Electrolyte leakage Reduced capacity
Excessive cycling	Accelerated corrosion Shedding of active material	Reduced capacity Reduced capacity
Thermal		
Overcharging	Accelerated corrosion	Reduced capacity
Elevated ambient temperature	Accelerated corrosion Degradation of positive plates Deterioration of separators Embrittlement of positive terminals	See positive plate growth Reduced capacity Battery failure Battery failure
Ripple (internal heating)	Same as above	Same as above
Environmental		
Impurities in the electrolyte	Shedding of active material Corrosion of positive grid Hydrolysis	Reduced capacity Reduced capacity Reduced capacity
Dirt and moisture on cases	Low resistance between terminals Low resistance to ground Oxidation or corrosion of terminals	Discharge of cell Ground faults or shorts Battery failure
Gases	Oxidation or corrosion of terminals	Reduced capacity
Seismic event	Broken positive plates, straps, or terminals Cracked cases Broken posts or connectors	Reduced capacity and battery failure Electrolyte leakage Battery failure