Some field experience with battery impedance measurement as a useful maintenance tool.

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Summary

This paper reports on the initial findings of a coordinated program to assess the usefulness of battery impedance measurements as a maintenance tool. A newly developed impedance meter is being widely used to characterise the *on-line* cell and battery impedances of the range of lead-acid batteries used in the network. Early trends and some aspects associated with the use and interpretation of on-line impedance measurements are discussed. Encouraging results of the use of dynamic impedance measurement during discharge testing are also presented.

Introduction

In recent years there has been considerable activity and comment in the use impedance or conductance measurements in the assessment of the state-of-health of batteries.[1-7] The technique has been heralded as particularly useful with valve-regulated lead-acid (VRLA) which do not lend themselves to traditional battery maintenance practices. The interest in the measurement lies in the correlation of measured conductance with battery capacity, although the reported experience of the efficacy of the technique has been varied.[3-7] While the currently available single frequency impedance or conductance techniques may not provide unequivocal absolute capacity information, it is clear that the method is generally meritorious and provides additional, often valuable, information not otherwise conveyed by cell voltage or SG measurements. As such, the technique can be used as a maintenance tool.

Telstra has participated in the local development and manufacture of a low cost, hand-held, single frequency AC impedance meter (IMI) which is capable of ***on-line*** measurement of cell and battery impedance, as well as the battery interconnect conduction integrity. The IMI has been specifically developed as a battery maintenance tool and has been found to be useful with both vented and valve-regulated lead-acid batteries and vented nickel-cadmium batteries. After more than 18 months of controlled laboratory and limited field trials, the IMI has now been made available to specialist technical groups responsible for the maintenance of Telstra's batteries.

A program of controlled use of the IMI has been implemented to build a database of "real" impedance characteristics of the wide range of batteries used in the Telstra network. From the data base, the *on-line* impedance characteristics of operating cells and mono-blocks can be correlated with generic battery types and capacities. This project was established to allow Telstra to be in a better position to assess if the technique :-

- can identify risk cells on float
- can be used to track trends in battery aging
- can be used as a replacement for routine SG measurements,
- is successful at detecting high resistance joints and interconnections
- has a place as a routine battery and power system maintenance tool.

This paper reports on the results to date of this empirical approach to assess the practical use of single-frequency impedance as a battery maintenance tool.

Experimental

For telecommunications applications, the impedance technique as applied to batteries on-line on float is most relevant. The available literature about impedance testing of batteries on float is not unequivocal and is thus of limited value[1,4,7] It is assumed that cells of different sizes and manufacturers exhibit different impedances, while the impedance of cells of similar size and age should be similar. The state of charge of the cell at the time of the test may or may not be reflected in the impedance reading, although the internal resistance of cells with decreased capacity (sulfation) is expected to increase.[1,2,8]

Telstra has more than 25,000 battery banks in standby service, most of which are composed of a limited range of either vented (flooded) or VRLA cells in the standard 24 2V cell installations supporting 48V dc bus systems. This represents a sizeable population base on which to assess these assumptions.

A project to collect the *"as found"* individual cell and battery impedances of on-line battery installations has been initiated in the hope of capturing a "snap shot" of the impedance characteristics of the network's standby batteries. With such a large population base, the effect of random operating factors that might affect group or batch statistics are expected to be significantly reduced.

Measurements reported have all been taken with the Elcorp Pty Ltd IMI Model 810 Impedance Measuring Instrument (IMI). The IMI is a low-cost hand-held unit that reports the in-phase or real component of the ratio of the ac voltage response to a small, and known excitation ac current. The IMI uses an injection current of less than 1A peak-to-peak and has a resolution of better than 10 $\mu\Omega$. The IMI has a maximum input voltage 75 V_{dc} and thus is a milli/micro-ohm meter which allows in-situ measurement of telco battery banks.

Results and Discussion.

This effort to capture the impedance characteristics of Telstra's standby batteries is in its infancy and only initial data is available. No correlation was found between the *on-line* cell impedances and the cell float voltages. Float voltage distributions are therefore not reported. Most of the readings were taken on batteries housed in temperature controlled conditions between 20-22°C. The effect of the temperature range on the impedances reading is considered negligible.[4]

On-line cell impedances

Fig. 1 illustrates the typical range of *on-line* impedance readings for commonly found 2V cells within the network. Table 1 shows the average impedances for some types of cells obtained from a more significant population base. The larger number of older, flooded cells in the data set reflects the ratio of flooded to VRLA cells in the network. Most are flat-plate, pure lead-positive cells built to Australian Standard AS1981 (now AS4029.3). The relatively small standard deviation in the average impedance of the flooded cells is not surprising given the required performance standards of AS1981.

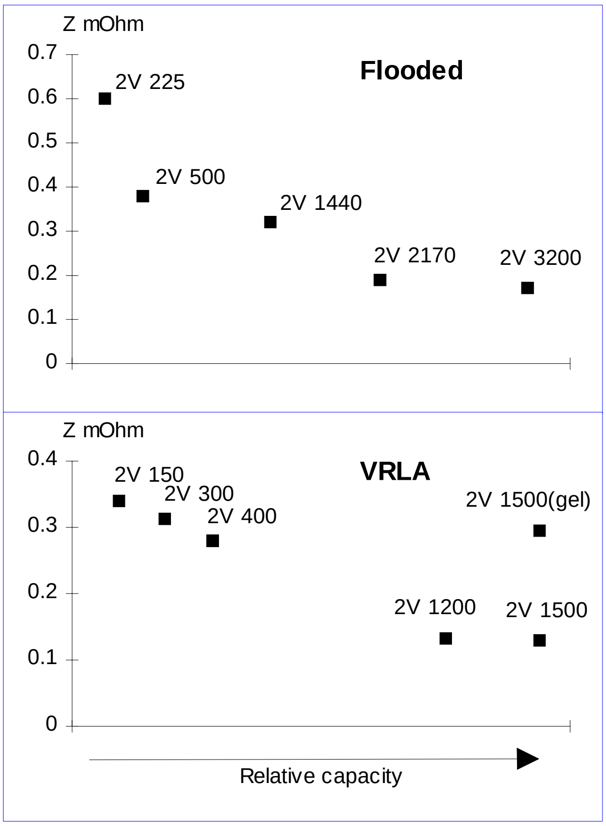

Fig. 1 General range of the *on-line* impedances for common 2V lead-acid cells in the network.

Wide scale adoption of VRLA technology into the network is a relatively late occurrence in Telstra, and VRLA batteries in the network older than about 6 years are rare. There is a plethora of different capacities, size, type and manufacturer and a comparatively larger variation in cell characteristics is not unexpected. The VRLA cells used in the network are predominantly absorbed glass mat (AGM). Only one type of gel VRLA is used in significant numbers.

For both flooded, and AGM VRLA cells, there is a non-linear trend of decreased *on-line* impedance with increased capacity. Generally, the impedance of AGM VRLA is lower than that for a similar capacity flooded cell. The noticeably higher impedance of the gelled VRLA cell compared to AGM VRLA is not unexpected. However, there is very little difference in the *on-line* impedance of large flooded and AGM VRLA cells. In fact, the impedances found for flooded 2170 and 3200 Ah cells is consistent with the 170 mΩ resistance previously reported for the in-circuit measurement of 2V 7000 Ah cells.[1] This similarity suggests a capacity-independent minimum cell impedance.

Nominal C_{10} capacity (@ 25°C)	Age range (years)	Average Impedance		
		mΩ	± s.d.	Np
Flooded				
3200 (2V)	1-11	0.170	0.003	96
2170 (2V)	1-12	0.196	0.005	648
500 (2V)	1-12	0.362	0.010	552
VRLA				
40 (12V)	1	3.67	0.071	48
150 (2V)	1-3	0.341	0.030	72
300 (2V)	3-5	0.314	0.048	64
400 (2V)	0-1	0.342	0.043	48
1500 (2V)	1-3	0.580	0.063	144

Table 1 Average *on-line* impedances of cells on float. Np is the sample size for the particular cell type.

Fig. 2 plots the average cell impedance of two flooded capacities as a function of the years of service covered in the sample population. On a population basis, the data does not exhibit a general trend to higher impedances with age. However, the correlation of higher cell impedances with age,[2,4] may be a batch rather than population characteristic. Alternatively, the age range may be insufficient and none of the batteries in the population are near end of service life.

Fig. 3 shows the relative scatter of the average impedances of same-aged cells for both an "old" and "new" flooded battery as a function of cell position. Fig. 4 plots a similar response for two age different VRLA batteries.

Fig. 2 Plot of on-line cell impedance as a function of years in service for two flooded cell capacities.

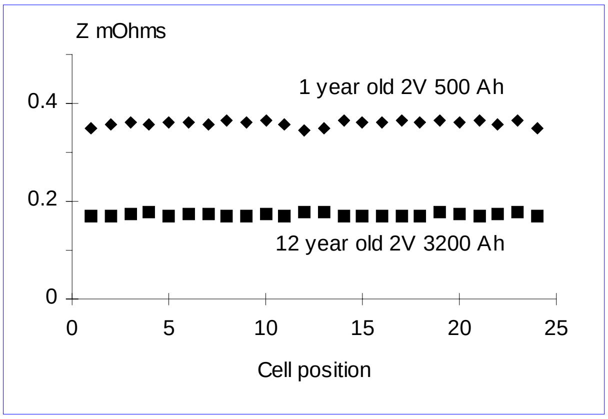

Fig. 3 Distribution of *on-line* cell impedances for "old" and "new" flooded cells plotted as a function of position within the battery bank

Clearly, the VRLA impedance variation is larger than that for flooded cells, which mirrors the common observation that VRLA cells exhibit greater spread in float voltages that flooded cells.

The usefulness of *on-line* impedance measurement of cells is limited unless the technique can be used reliability to discern the difference between natural scatter and real, significant changes in cell impedances.

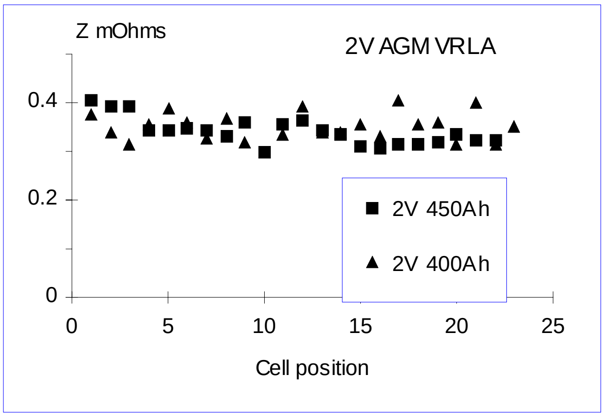

Fig. 4 Distribution of *on-line* cell impedances for two different AGM VRLA batteries plotted as a function of position within the battery bank

On the basis of Fig. 3, even relatively small 5%-10% changes in cell impedances should be readily identified. For VRLA batteries , only considerably higher levels of change in cell impedances may be detectable. Fig. 5 shows the distribution of *on-line* cell impedances for a batch of the same type of 2V 300 Ah VRLA cells of the same age and service history. This type of cell is known to suffer product quality problems leading to early failure.

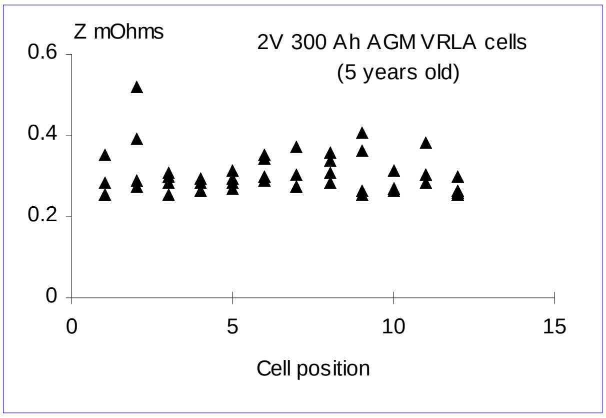

Fig. 5 Distribution of *on-line* cell impedances for a batch of the same type of VRLA cells that were known to have product quality problems.

The distribution of cell impedances is larger than those observed in Fig. 4. Clearly, there is one cell with a notably higher cell impedance. The cell voltage was also high, but not uniquely. Negative group bar corrosion is suspected, and this cell has been withdrawn from service for further analysis.

Total Battery Impedance

Total battery impedances are not presented because the different interconnection schemes used in the battery installations prejudice direct comparison of total bank impedances. Analysis of the total battery impedance data to take account of the effect of different components of the conduction path has not yet been completed. Nevertheless, the IMI is now routinely used to detect abnormal cell interconnections.

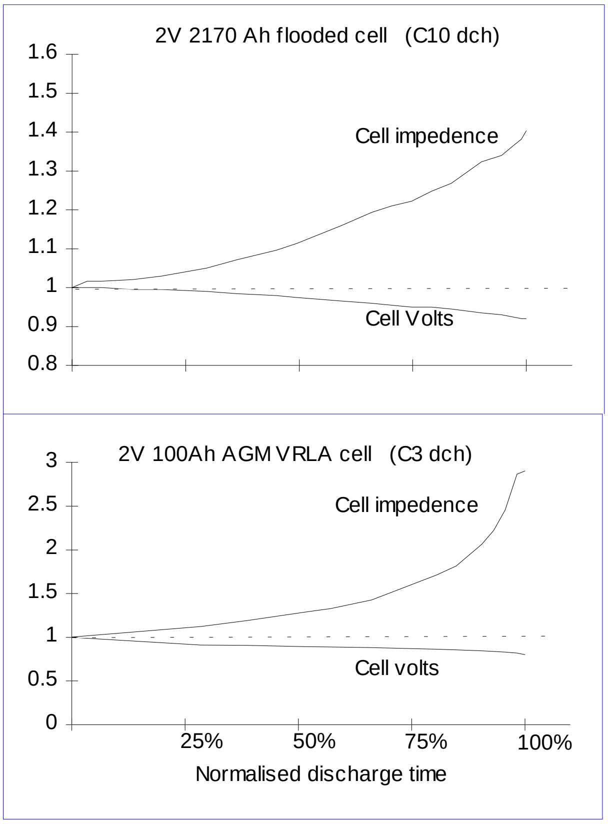

Fig. 6 Comparison of the change in normalised cell voltage and *on-line* cell impedance as a function of discharge time.

"Dynamic" Impedance

The use of *on-line* impedance measurements *during* battery discharging appears to be valuable in identifying capacity-limiting cells. Fig. 6 plots the normalised cell impedance and voltage characteristic as a function of normalised discharge time for both a flooded and VRLA battery. Both cells achieved rated capacity. As can be seen, the relative rate of increase in cell impedance of a cell discharging at constant current is significantly greater than the rate of decrease in the cell voltage. The non-linear behaviour of the *on-line* cell impedance during discharge is consistent with measured impedances of cells at varius discharge states[1,4] and that predicted by a battery model.[9]

This phenomenon is particularly noticeable with VRLA cells, and allows the scope for *dynamic* impedance testing to be introduced as part of the discharge testing regime.

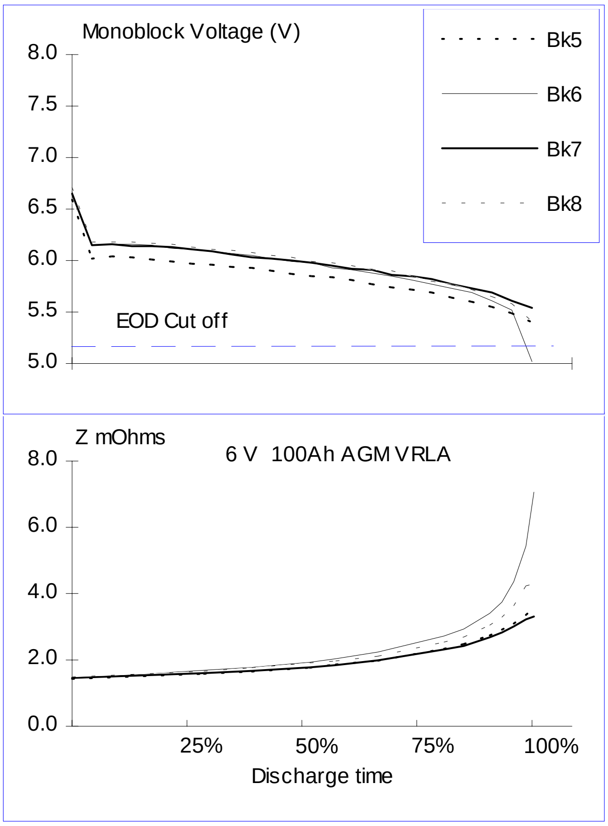

Fig. 7 Cell voltage and impedance behaviour of the 4 weakest 6V 80 Ah monoblocks in a discharge test of a 48V string.

A typical example, given in Fig. 7, was obtained from a 48V battery comprising 8, 6V 80Ah VRLA monoblocks during a standard 3 hour constant current discharge. Fig. 7 plots the cell voltage and impedance behaviour of the 4 weakest monoblocks towards the end-of-discharge. Note that the weakest cell, identified ultimately by the cell voltage, can be uniquely identified much earlier in the discharge from the impedance readings. Fig. 8 plots the trend of the rate of change in cell impedance (dz/dt) determined at 4 points during the discharge. Clearly, the rate of change of the weakest monoblock (Bk6) is consistently and discernibly higher than that for the other monoblocks. Similarly, Bk8 is identified as having the next lower capacity which is not immediately evident from the voltage characteristic. Similar behaviour has been measured during the discharge of vented lead-acid batteries. In all banks, the *on-line* dynamic cell impedance can be used to uniquely identify the weakest cell early during the discharge. The use of the change in impedance characteristics during discharge to derive cell capacity by computational methods has recently been proposed.[9] Characterisation of the dz/dt curve may provide a means to reliably predict remaining capacity during discharge.

While the sample test population base is small and it may yet be too early to claim universal behaviour, the results encourage the use of *on-line* dynamic impedance measurement as an informative measurement to accompany discharge logging.

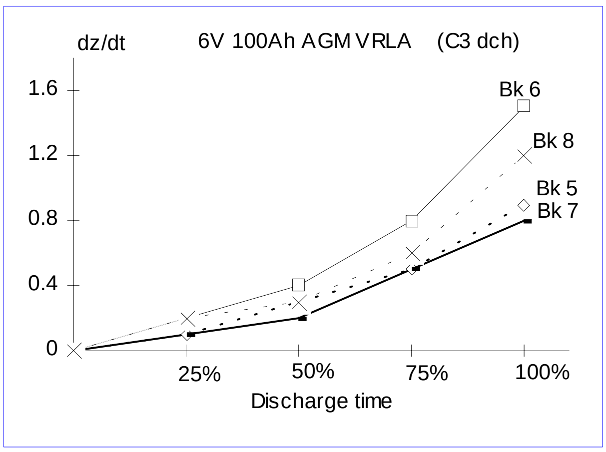

Fig 8 Plot of normalised rates of change of the impedance and voltage the 4 weakest (lowest capacity) 6V monoblocks in a 48V string as a function of discharge time.

Work by Telstra has seen the development of a very low cost and functional Battery Monitoring System (BMS) with integrated impedance measurement suitable for widespread implementation throughout Telstra. The BMS is currently undergoing commercialisation.

Some Practical Aspects and considerations

Operator perceptions

It is important to consider the use of the impedance measurement in the context of some practical considerations. The use of the IMI by maintenance staff has highlighted a number of perceptions about battery impedance readings. First, and foremost, is the common expectation that the technique will convey absolute capacity or state of charge information. No impedance or conductance technique yet gives reliable absolute capacity information and any value in the method is as a comparative and indicative tool.

Reproducibility & Measurement Methodology

The IMI is inherently very accurate and gives high degree of reproducibility for repeated measurement by the same operator. However, as a milli/micro-ohm meter, the physical location of measurement points may affect repeated readings. Comparison of readings from different operators must be accompanied with comparable points of measurement. In some battery installations, it is possible to perform, separately, post-to-post and post-to-interconnect impedance measurements. In others, particularly with some VRLA monoblock batteries, easy post access is not possible, so the cell impedance measurement includes the impedance of the cell-interconnect junctions. These issues in the use of the IMI merely demand repeatable measurement methodology. Participants in the program to construct the database are requested to note measurement points and encouraged to use them when taking readings in the future.

Interpretation of readings

The effective impedance of any element in a closed circuit obtained by injecting current across the element will be less than the actual open-circuit impedance of the element. The degree of inaccuracy will depend on the circuit parallel to the measurement circuit. Thus, the in-circuit impedance measurement obtained by injecting current across any of the battery banks will underestimate the "true" bank impedance by a degree which depends on the rest of the bus system. Similarly, the accuracy of the in circuit impedance or resistance of a cell or monoblock in a series-connected battery string depend on the length of the series connections and the effect of parallel banks and equipment. Therefore, similar conduction path components of battery installations may exhibit different impedances. For cell impedances this should not be immediately interpreted as a battery problem. Consideration of the in-circuit measurement has been previously noted.[1] However, the results illustrated in Figs 3-5 do not indicate any significant effect of cell position within the string. That is, the error caused by in-circuit measurement is either effectively constant, or lower than the "natural" distribution of impedances. Therefore, comparisons of the impedances of cells within a single bank are directly comparable. The situation can be simply avoided by isolating (if possible) the bank under measure, but the aim here is for a complete in-situ, on-line measurement. Other measurement tools which are available to provide more accurate *on-line* impedances are less convenient to use than the IMI. That said, the impedance values found in this work are comparable to reported values of cells of similar capacity determined by other techniques.[3,6,7]

For a comparative technique, the absolute value is not as relevant as relative change. Provided the wiring topology does not change between measurements, the absolute inaccuracy for a repeated measurement should remain the same. Changes in readings over time can be attributed to changes in the impedance of the component cells or interconnection circuit. Thus, issues of absolute accuracy and meaning do not need to cloud the benefit of comparative information.

It is of interest to model the total dc system. The measurement of impedances of all the component elements at a number of selected installations of different connection topology will allow full description and allow more relevant comparison of battery impedance data.

Conclusion

The *on-line* impedance characteristics of a large number of cells in the network has been undertaken to determine the range of cell impedances to be expected for a particular type of battery. This empirical approach has not sought to correlate cell impedances with capacity, but rather to determine to what general level the technique can function as a routine battery maintenance tool. There is potential for the use of *on-line* cell impedance measurement during discharge testing.

This program is in its infancy but already the technique has proved valuable in assessing the conduction path integrity. There are practical grounds to advocate impedance testing as an element of battery monitoring systems.

Acknowledgment

The Author would like to acknowledge the contribution in this work provided by Mr. L. Barling and Mr. J. Clarke. The permission of the Director of Research, Telstra Research Laboratories, to publish this work is also acknowledged.

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