AC impedance spectra of field-aged VRLA batteries

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Abstract

This Paper reports on studies into the AC impedance spectra and behaviour of field-aged VRLA batteries. The AC impedance spectra of "normal" and "abnormal" field-aged batteries are presented. Preliminary results indicating how the variation of the battery impedance with frequency might be used to identify aging characteristics are also shown.

Introduction

Amid varying claims of efficacy, single frequency AC impedance or conductance measurements are now generally considered meritorious as a comparative diagnostic tool in the maintenance of VRLA batteries [1-5]. For telecommunications applications, the usefulness of the technique in the ***on-line*** measurement of VRLA batteries on float is most relevant. Telstra Corporation has incorporated on-line single frequency impedance measurements into battery and power system maintenance routines to assist in detecting early trends in rogue cells and components with poor conduction integrity. A program to benchmark the impedance of Telstra's existing, in-service lead-acid batteries has resulted in a look-up table to enable field staff to identify "abnormal" cell and battery impedances [5]. More recently, the Telstra Research Laboratories (TRL) have developed a low cost monitoring system which continuously and automatically trends individual cell and battery impedance behaviour while on float service over the life of the battery [6]. Abnormal battery impedance and voltage conditions are therefore captured during unattended events.

While single-frequency impedance or conductance measurements may not convey unequivocal absolute capacity information, there is much interest in further extending the technique as a diagnostic maintenance tool. TRL has an on-going program to better understand the implications of "abnormal" impedance of in-service cells. This Paper reports on laboratory studies into the AC impedance spectra and behaviour of service-aged VRLA batteries which were initially determined as "abnormal" by single-frequency impedance measurements during routine maintenance. The AC impedance frequency characteristics of failed batteries have been compared with those of similarly aged batteries which still exhibit rated performance. Preliminary results which demonstrate how the AC impedance measurements may be used to identify basic differences between capacity depleted cells and aged cells are presented.

Experimental

The routine discharge testing of standby batteries in Telstra is now not common, and is usually only carried out to verify design reserve at sites where battery or power system standby integrity is suspect, or when poor battery performance must be recorded to instigate warranty claims. However, on-line battery impedance readings are now routinely used to identify possible rogue VRLA cells or monoblocks. Telstra Corporation uses the hand-held Elcorp IMI801 Impedance Measuring Instrument. The IMI801 determines the single-frequency battery impedance at approximately 400 Hz and is capable of measurement to a resolution of better than 10 $\mu\Omega$ in common-mode voltages up to 75 V_{DC}.

A small number of 12V, 40 Ah VRLA monoblock batteries in float service and of varying service life were found to exhibit high single-frequency impedance during routine maintenance. Each battery string was subsequently subjected to a standardised constant current discharge test at the nominal C_3 rate (10A). Single frequency impedance measurements (using the IMI801) were manually recorded at 10-15 minute intervals during the discharge. To observe the total

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battery string performance as might occur in a power outage, the bank discharge was allowed to proceed for the full three hour designed reserve time. This was a modification of standard battery maintenance procedures where test discharges are normally terminated when any cell or monoblock falls below 1.80 V/cell. After the test discharge, each bank was placed back on-line and constant-voltage recharged at the system float voltage.

The batteries were all in a Telstra 48V stand-by power system comprising 6 banks of 4 series-connected monoblock batteries. The batteries had been floated at 2.23V/cell (53.52V) without temperature compensation in an uncontrolled operating environment where the ambient temperature was known to sometimes be as high as 35°C. The service age of the monoblocks ranged between 1 year and 5 years and can be correlated with successive site power system upgrades. At the time of the field-based discharge tests, Bank 1&2 had been in service for 5 years, Banks 3&4 for 3 years, and Banks 5&6 can be considered new with less than 1 year of service life on float. The C_3 rated capacity and the expected on-line single-frequency impedance of the 12V monoblock is 30 Ah and 3.5-5.5 mΩ respectively.

Only Banks 5&6 achieved rated performance and the other four banks (*i.e.* 16 monoblocks) were withdrawn from service and sent to TRL for further investigation. The AC impedance spectrum of the integral monoblock battery was determined over a frequency range from approximately 5 mHz to 100 kHz using modified AC potentiostatic methods. The laboratory techniques used by TRL to characterise the AC impedance spectrum of a lead-acid battery have previously been described [7]. All AC impedance spectra reported in this paper were obtained at laboratory room temperature (21°C ±1°C). Controlled charge and discharge conditioning of the monoblocks were performed on an automated battery test facility [8]. A calibrated IMI801 was used for single frequency impedance determinations.

Results and Discussion.

The general characteristics of the frequency response of the impedance of lead-acid batteries have been previously described [7]. Modelling the battery impedance characteristics is outside the scope of this paper. The AC impedance response between 10 mHz and 10 kHz is presented in Bode magnitude and phase format.

Field-based results.

A summary of the condition of the site battery before and after the test discharge is given in *Table 1*. The ampere-hour capacity of each bank to 43.2V end-of-discharge voltage is also listed. A bank or monoblock was considered to have achieved rated capacity if, at the end of the 3 hour discharge, the respective terminal voltage was higher than 43.2V or 10.8V.

As can be seen from *Table 1*, only Banks 5 & 6 demonstrated available capacity above 30 Ah. All monoblocks in these two banks demonstrated rated capacity, and after 3 hours discharge, all monoblocks had an impedance had no higher than about 14 mΩ. The delivered capacity to 43.2V varied significantly for Banks 1-4, although many of the monoblocks within these banks achieved rated capacity. After 3 hours, some monoblock voltages were alarmingly low, implying excessive capacity depletion and a number of monoblocks had an impedance higher than 20 mΩ. Banks 1-4 all had *one* monoblock which exhibited an on-line impedance prior to discharge well above the expected range, and three of these actually exceeded the 20 mΩ maximum

Bank #	Mono	on-line, float prior to DCH		after 3 hr DCH of bank	
age Cap. to 43.2V	block #	V_{bat} volts	Z_{bat} mΩ	V_{bat} volts	Z_{bat} mΩ
#1 5 YO 5.0 Ah	1	12.92	> 20	7.48	13.9
	2	13.57.	5.4	10.97	>20
	3	13.51	5.6	10.83	>20
	4	13.48	4.7	11.34	10.9
#2 5YO 22.5 Ah	1	11.26	15.0	9.03	>20
	2	14.11	4.9	11.15	14.0
	3	14.33	4.7	11.28	11.0
	4	13.81	4.4	10.57	19.0
#3 3YO 15.5 Ah	1	13.41	>20	7.23	19.7
	2	13.47	4.4	11.24	13.0
	3	13.41	4.6	11.20	13.7
	4	13.47	7.5	11.25	14.4
#4 3YO 16.0 Ah	1	13.55	4.4	10.66	>20
	2	13.10	>20	7.6	12.8
	3	13.48	5.2	11.21	12.6
	4	13.41	7.4	4.95	>20
#5 1 YO 31.5 Ah	1	13.15	3.6	10.93	14.5
	2	13.47	3.6	11.39	7.3
	3	13.10	3.5	11.11	12..0
	4	13.81	3.5	11.42	8.1
#6 1 YO 31.6 Ah	1	13.1	3.5	11.42	8.5
	2	13.71	3.6	11.38	8.8
	3	13.56	3.7	10.92	14.1
	4	13.17	3.6	11.13	10.8

Table 1: Field measurements of the 6 parallel 48V AGM VRLA battery banks before and after discharge.

measurement capability of the IMI801. These are the monoblocks referred to as “abnormal” monoblocks. It is a curious note that all of the “abnormal” monoblocks finished with an impedance less than 20 mΩ, implying a *reduction* in impedance during discharge.

The voltage and impedance behaviour *during* discharge for two of the “normal” monoblocks are shown in *Figure 1a*. As expected, the monoblock terminal voltages were very similar and slowly decreased throughout the discharge. The monoblock impedances displayed a wider variation but exhibited a unilateral non-linear (exponential) increase during the discharge. This behaviour was typical for all the monoblocks exhibiting “normal” on-line impedance and achieving rated capacity. This is consistent with previously reported generic behaviour (*Figure 1b)* for “healthy” AGM VRLA cells and monoblocks [5].

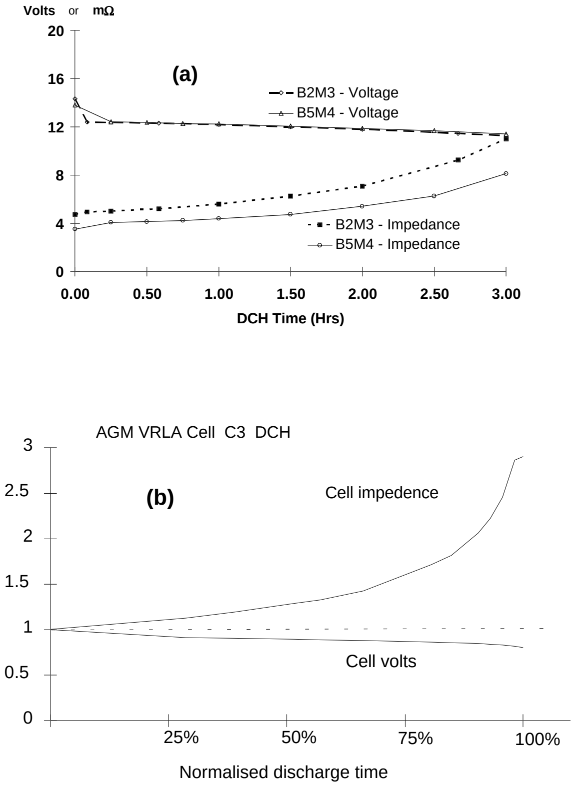

Figure 1: Discharge behaviour for (a) “normal” field-aged monoblocks, and (b) previously reported “generic” behaviour for “healthy” AGM VRLA cells

It is of interest to note that the on-line single frequency impedance prior to discharge generally increases with the service age of the battery. This supports claims that impedance and conductance readings may be useful in tracking ageing [2,4]. Further, for those monoblocks with terminal voltages greater than about 10.8V, the ratio of the monoblock impedance at the end of the bank discharge to the on-line impedance prior to discharge monoblocks tends to be higher for the older batteries. This is the first time this has been observed for field batteries. Correlation of these two aspects - that is, the on-line impedance and the change in impedance for a given capacity discharge - with service age would provide an obvious improvement in the diagnostic use of single frequency impedance measurements.

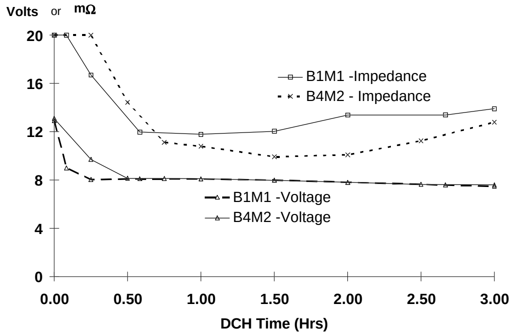

Figure 2: Discharge profiles for two of the “abnormal” monoblocks

In *Figure 2*, the impedance and voltage profiles measured during discharge for two of the “abnormal” monoblocks are plotted. The impedance profile is remarkably different to the expected behaviour of “healthy” batteries shown in *Figure 1b*. For both of these “abnormal” monoblocks, the impedance significantly decreases then increases during the discharge. Both monoblocks also exhibit a significant decrease in terminal voltage relatively early in the discharge, and then maintain a low terminal voltage throughout the rest of the discharge. In fact, on the basis of monoblock performance, the test discharge would have normally been terminated within the first 15 minutes (10.8 V/monoblock). Neither the voltage nor impedance profiles are consistent with typical capacity depletion.

In the absence of any other evidence, it is reasonable to conclude that both these monoblocks have sustained one or more shorted cells during discharge. The monoblock impedance behaviour can be reconciled with the failure of one or more cells by shorting. A shorting condition is not at first evident in the open circuit and on-float terminal voltage of each monoblock, and the on-line high impedance does clearly indicate some change in the conduction path. On-load, the rate of decrease in impedance lags the drop in terminal voltage and this is consistent with “growth” of the plate shorting conditions as the discharge progresses. Towards the end of the discharge, plate capacity loss results in an increase in the impedance similar to that observed with the "normal" monoblocks. It is not possible to determine from these results whether the initial monoblock high impedance is due to some precursor to the shorting conditions, or arises from an unrelated passivating condition. It is significant however, that the impedance for any of these monoblocks does not go lower than about 10-12 mΩ, indicating a residual high ohmic resistance in the conduction path.

Cell failures from through-separator plates shorts are not new, but have not before been noticed with this type of premier VRLA battery. There are ramifications for maintenance activities. High on-line impedance found during routine maintenance may not only indicate potential aging and concomitant capacity loss, but also may point to the potential for shorted cells during discharge. Shorted cells on discharge may cause excessive heating on discharge which may lead to battery fires. This therefore may represent a more urgent condition than the potential decrease loss of reverse capacity. Nevertheless, there appears to be considerable advantage in monitoring the changes in single-frequency impedance during discharge events.

Laboratory investigations

The impedance spectrum shown in *Figure 3* is representative of the impedance characteristics of all the "normal" monoblocks. The "as received" spectrum refers the impedance characteristics of the monoblock following the constant voltage (float) system recharge at site after the test discharge. The "discharged" state plots the impedance characteristics of the monoblock after a subsequent C_3 discharge to 10.8V/monoblock in the laboratory. All the "normal" monoblocks exhibited a discharge capacity in the laboratory similar to that measured in the field. The "recharged" conditions shows the impedance response of the monoblocks each after a separate C_{10} constant current recharge (*i.e.* at at 3.7A) to 14.40 V/monoblock (2.40V/cell) followed by a constant voltage charge at 14.10 V/monoblock (2.35V/cell) for 16 hours. In this time, about 105-110% of the discharge capacity was returned to the battery. Comparison of the impedance spectra after recharge with the "as received" spectra indicated that the monoblocks were fully charged after the field test discharge. Differences in the magnitude of the impedance are consistent with previously reported correlations between the impedance spectrum and capacity [7].

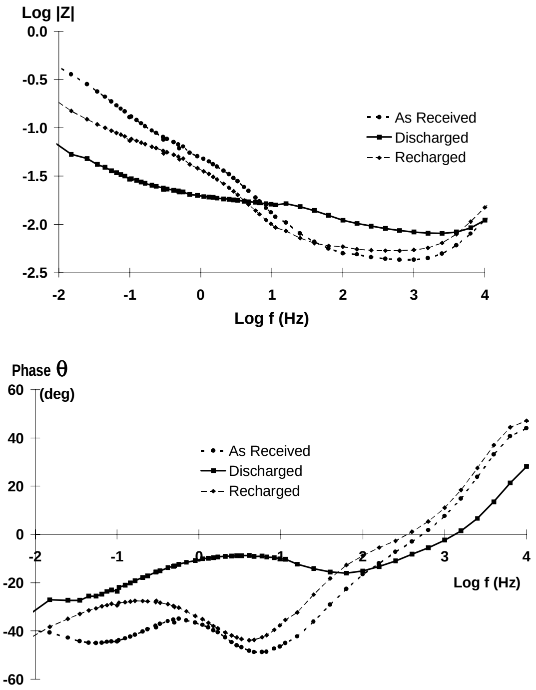

Figure 3: AC impedance spectra for a typical "normal" monoblock: (a) Bode magnitude and (b) phase.

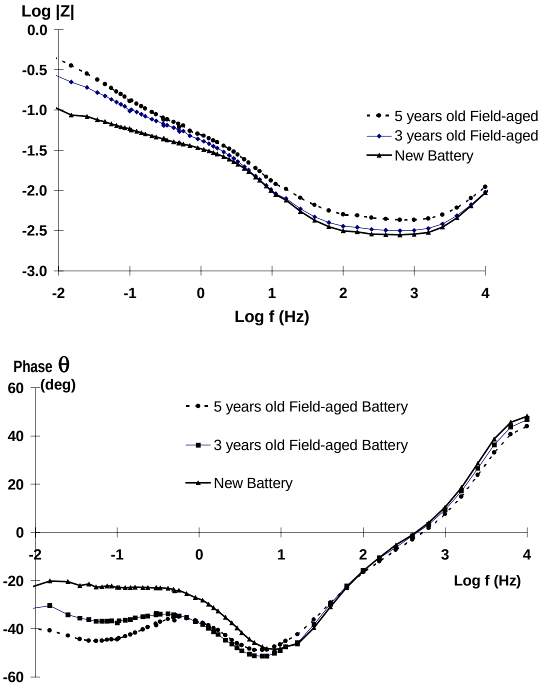

Figure 4: Comparison of impedance spectra between aged monoblocks; (a) Bode magnitude and (b) phase.

Figure 4 provides a comparison of the impedance spectra for representative a 3-year and a 5-year service-aged monoblock with the benchmark spectrum of a new monoblock. There appears to be discernible differences in the frequency response as a function of battery age. The magnitude impedance plot clearly shows increasing impedance with age which is consistent with observations with single frequency impedance and conductance measurements. The phase plot shows a “hump” around 1 Hz for the aged monoblocks which is not evident for the new battery.

However, the differences are small, and must be viewed with caution. The capacity condition of the field batteries is a result of series-connected float charging, and therefore not directly comparable to the capacity of the laboratory charged new monoblock. That is, from the test discharges, the field batteries displayed variations in available capacity. The AC impedance spectrum of any one service-aged monoblock must reflect both the impedance characteristics due to corrosion, corrosion-caused capacity depletion, and dryout (*i.e.* aging) *and* the impedance characteristics due to variations in the state of charge of the monoblock. There appears to be little practical difference between the impedance spectra of “normal” monoblocks of different ages which could not be explained as arising from variations in capacity alone. For other types of VRLA batteries, both the phase and magnitude of the impedance characteristic have been observed to change with capacity and state of charge [7] However, in a recent experiment using 6V AGM VRLA monoblocks, it has been shown that only the magnitude of the impedance changes with accelerated aging, with little or no observable change in phase [9]. This is only a preliminary observation and must be confirmed a wider range of batteries, but does suggest an opportunity to separate age and state of charge impedance behaviour for in-service batteries. This is provides strong grounds to pursue AC impedance techniques as probes of the health and integrity of VRLA monoblocks.

Representative AC impedance spectra of the “abnormal” monoblocks are shown in *Figure 5*. The “abnormal” monoblocks were discharged similarly to the “normal” monoblocks, although the discharge capacity in the former case was only about 1-5 Ah (due to the 10.8V end-of-discharge voltage). The discharge behaviour observed in the field (*i.e. Figure 2*) was confirmed. Under the same recharge conditions used for the “normal” monoblocks, only about 3-8 Ah could be returned into the “abnormal” monoblocks. This implies that the “abnormal” monoblocks did not have any appreciable charge acceptance or, alternatively the monoblocks already had a high state of charge Notably, the phase spectrum in the discharged state is considerably different from the “as received” state, while there is very little difference in the phase behaviour between the “as received” monoblock and the “recharge” state. Both the magnitude and phase spectra of the recharged state for the “abnormal” monoblocks” are very similar to that observed for the “normal” monoblocks.

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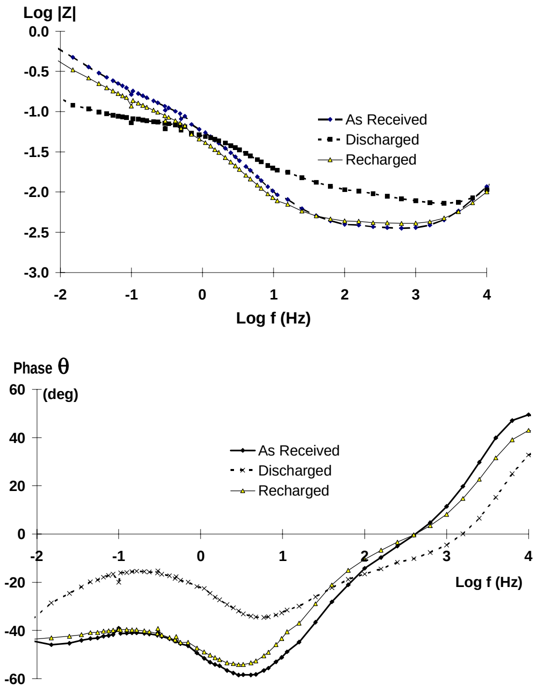

Figure 5: Typical AC impedance spectra for the “abnormal” monoblocks; (a) Bode magnitude and (b) phase.

After recharge (to 2.40V/cell), the single-frequency impedance of the “abnormal” monoblocks” was monitored during another C_3 discharge. *Figure 6* shows the voltage and impedance profile during this discharge. Remarkably, the behaviour demonstrated in *Figure 2* was no longer evident, and the “abnormal” monoblocks now exhibited voltage and impedance characteristics during discharge which were very similar to the ”normal” monoblocks. Furthermore, the discharge capacity (to 10.8V/monoblock) of the “abnormal” monoblocks all increased substantially to about 2/3 of the original rated capacity (*i.e.* about 20 Ah). A subsequent charge/discharge cycle confirmed that the originally observed “abnormal” voltage-impedance behaviour had disappeared. However, the increase in discharge capacity could not be further increased with cycling, suggesting permanent capacity loss.

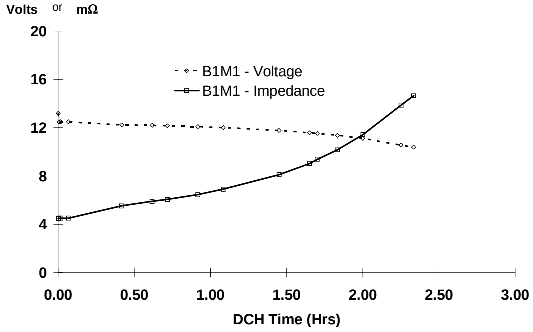

Figure 6: Discharge profile of "abnormal" monoblocks after recharge at 2.40 V/cell

The apparent recovery of the "abnormal" monoblocks is interesting. It appears that a specific "high" voltage charge was required (*i.e.* 2.40 V/cell) to remove the original "high" impedance and "abnormal" discharge behaviour. The period at 2.40 V/cell was sufficient to remove the precursor shorting conditions, and in doing so, also return the impedance to a level consistent with a "healthy" battery. Thus, high impedance characteristics might be removed with a period of high voltage charging, although this is unlikely to occur in the field where the monoblocks would only ever see the float voltage (2.23V/cell, in this case). The monoblocks have been placed back on float conditions and the AC impedance characteristics periodically measured to study whether the high impedance or shorting conditions return.

The origin of the high impedance (or passivation) is subject to speculation. It does appear remarkably coincidental that *one* monoblock in each of the older banks on float developed similar failure symptoms. The apparent permanent capacity loss of the "abnormal" monoblocks does suggest an inability of these monoblocks to float adequately in series-connected strings at 48V. The float performance of VRLA battery strings is critical for standby applications, and to date only float voltages have been used to assess float conformance within a battery string. Single frequency impedance measurements may therefore have merit as a new tool to identify circumstances where the cells or monoblocks in a battery are not floating equally.

Conclusions

The impedance behaviour of service-aged VRLA monoblocks has been described and it has been shown that single-frequency impedance may be used to identify batteries with the potential to enter shorted conditions on discharge. The AC impedance spectra can be used to identify basic differences between capacity depleted cells and aged cells. Differences in impedance behaviour may be correlated with service age, although at this stage it is difficult to distinguish impedance changes originating from solely from aging and impedance behaviour resulting from capacity variations arising from the float service of the batteries.

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