Some aspects of battery impedance characteristics

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Abstract

Impedance and conductance techniques have been advocated in the determination of the condition of lead-acid batteries in service. The usefulness of these "ohmic" techniques lies in an understanding of the bounds and domain of the measurement. This paper reports the frequency response and battery impedance behaviour generally observed for a range of commercially available batteries. The generic behaviour of batteries typically used in telecommunications networks is demonstrated. The effect of temperature and residual capacity on the impedance spectra are also reported.

Introduction

In recent years there has been considerable activity and debate regarding the use of internal "resistance" characteristics as a battery condition measurement [1-9]. The interest reflects the desire for simple electronic means to replace discharge testing as a practical determination of residual battery capacity, particularly given the increased usage of valve-regulated lead-acid (VRLA) batteries. The available techniques, which include AC impedance and conductance methods and momentary "DC" loading, all involve controlled current or voltage perturbations to determine a representation of the internal "ohmic" condition of the battery.

Internal battery "resistance" has been proposed as a means to track battery life, [1,4,6] but greater interest lies in reported claims of specific correlation between cell impedance or conductance with battery capacity [2,3,5]. More recent reports indicate that the currently available single-frequency "internal ohmic determination" techniques can not, in general, provide unequivocal absolute battery capacity information [6,7]. However, the techniques have been shown to have some merit as a comparative tool, and thus are useful in detecting early trends in rogue cells and components with poor conduction integrity. In this sense, battery impedance, conductance or resistance measurements are now currently best viewed as an aid in assessment of battery "state-of-health" [7,8,9].

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Telstra is cautiously incorporating simple impedance measurements into various battery and power system maintenance routines [9].

Advocacy of merit of any one determination method over the other is both of interest and a source of confusion to the end-user. For AC techniques, the selection of measurement frequency appears empirical in origin, drawn from very limited determinations of the frequency response of specific types of batteries. Furthermore, the published literature on fundamental impedance characteristics of lead-acid batteries is not unequivocal [10-13]. Electrochemical impedance spectroscopy has been used in studies of electrode and plate behaviour during charging and discharging, but there has been only limited application to the near-equilibrium condition for lead-acid batteries on float duty. The *ohmic* response of the battery depends on the measurement frequency and the "state" of the battery and has been reported to be affected, to varying degrees, by many fundamental cell characteristics, including cell design [3,12], temperature [12,14], and capacity [3,14].

An understanding of the behaviour of lead-acid batteries on float is of paramount importance for stand-by applications. The frequency response of lead-acid batteries is important in determining the relative merits of various AC perturbation techniques currently used to probe the "state-of-health" of lead-acid batteries on standby duty. This Paper reports on the frequency response and the general impedance behaviour of a range of different types of lead-acid cells.

Experimental

The AC impedance behaviour of lead-acid batteries reported in this work was measured over eight decades of frequency (10^{-3} - 10^{5} Hz) by two-electrode potentiostatic techniques similar to those previously described [3,10-13]. A known and controlled, small AC voltage amplitude is applied to the steady-state battery condition, and the resultant AC current measured. The complex impedance behaviour of the battery is then determined directly from the in-phase and quadrature phase components of the applied AC perturbation voltage and the measured current. The equipment used in this work is shown in *Figure 1*. The battery under study was connected to a standard commercial potentiostat *(E&EG PAR Model 273)*, and a lock-in amplifier *(Hewlett-Packard Model 5208)*, both of which are connected to a controlling computer *(IBM-compatible PC)*.

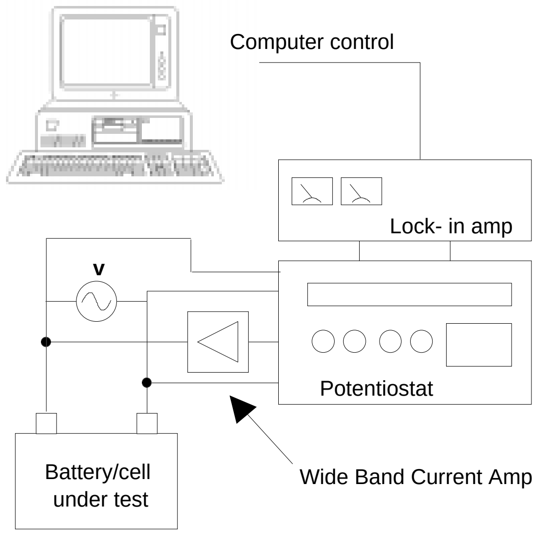

Figure 1: Experimental set-up used to study and measure the AC impedance behaviour of lead-acid batteries.

A specifically designed wide-band current amplifier was used to overcome current limitations of the potentiostat. Commercially available control and measurement software *(E&EG PAR Electrochem Impedance Software Vr 2.92)* was used. Single sine-wave excitation was used over the frequency range of approximately 10 Hz - 100 kHz. For the frequency range of approximately 5 mHz - 100 Hz, the frequency response was determined by multi-sine (white noise) excitation followed by Fourier Transform (FT) analysis. Voltage amplitudes in the range 1-5 mV were typically used, depending on the size of the battery. Using this equipment, impedance spectra could be recorded for both steady-state open circuit and float conditions. Lower limit of reproducible impedance determination in the potentiostatic mode on a test resistance was approximately ± 50 μΩ. Galvanostatic determination of impedance behaviour at fixed frequencies using a modified commerical battery impedance meter [9] was used to better than 10 μΩ resolution.

For batteries subjected to changed equilibrium conditions, spectra were measured after 2-4 hours rest times as per previously reported wait times [12,13]. Generally, the reported spectra were measured at room temperature (21°C ±1°C). Temperature effects of the impedance behaviour were studied using computer controlled environment chambers with temperature control to better than 0.1°C. Controlled discharge and charge were performed on an automated battery test facility [15].

Results and Discussion

Electrochemical interpretation and modelling of the impedance behaviour is outside the scope of this paper. Spectra are presented in Bode plot format.

A wide range of batteries of different battery technologies and capacities have been studied in the work. As expected, the absolute value of the impedance depends on both the battery technology and the capacity. *Figure 2* illustrates the general frequency response of battery impedance for three different types of battery technologies.

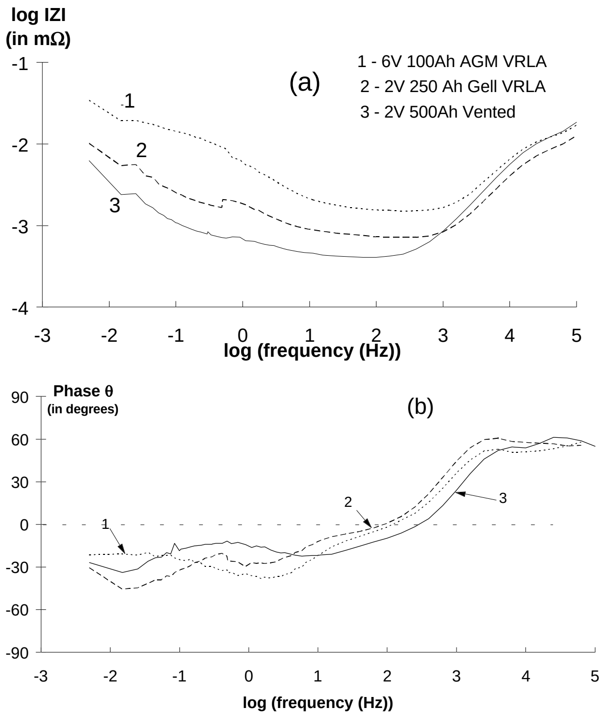

Figure 2: Bode magnitude (a) and phase (b) plots of the typical open-circuit impedance spectra for three different types of nominally charged lead-acid batteries.

The frequency response of the impedance behaviour is clearly generic for the three basic types of battery technology. The magnitude plot can be characterised as a "skewed parabola" with the impedance increasing for higher and low frequencies and a relatively broad minimum occuring across the mid-frequency region. From the phasing information, lead acid batteries are predominantly inductive for higher frequencies ($f > \approx 1$ kHz, $\theta > \approx +10°$), generally increasingly capacitive for lower frequencies (f <≈ 10 Hz, $\theta < \approx -10°$) and mainly resistive over mid-frequencies (≈ 10 Hz < $f < \approx$ 1kHz, $\theta \approx 0$). The impedance response in the capacitive reactance region was found to be relatively sensitive to battery condition and experimental techniques, and reproducibility is not as high as for either the resistive or inductive regions. The reproducibility of repeated experiments on the same battery was typically 2%-5%.

The inductive reactance is similar in both impedance magntitude and phase behaviour for all three batteries, and thus supports previously reported assumptions that this results primarly from the metallic lead componentry of the conduction path [2,4,6]. The general behaviour is consistent with previously noted impedance characteristics of some types of lead-acid batteries [2,6], although "generic" similarity over a wide range of frequency has not hitherto been reported.

For all batteries studied, the minimum impedance occurs in the resistive region. The impedance determined when the phase angle, θ, is zero, is termed the *ohmic* resistance, and is denoted $|Z|_{\theta=0}$. *Table 1* compares the ohmic resistance for a number of different types of batteries used in the Telstra network. The ohmic resistance is similar for batteries of similar capacity and constructin technology, although there is some frequency dependence. The phase information suggests that frequency of the ohmic resistance is lowered as the nominal capacity of the battery increases. This is an important observation in that there does not appear to be one unique measurement frequency optimised for all types of lead-acid batteries. In practical terms this means that some single frequency impedance and conductance meters may be more suitable for use with a particular type of lead-acid battery.

Battery type		|Z| @ selected frequencies, (Hz) (mΩ)			$\|Z\|_{\theta=0}$ (mΩ)	f @ $\|Z\|_{\theta=0}$ (Hz)
		10	100	1 k		
AGM	6V, 6 Ah	32.3	16.4	13.6	13.4	1580
AGM	6V, 10 Ah	17.1	8.3	6.9	7.0	800
AGM	2V, 25 Ah	2.9	1.8	3.4	1.8	100
AGM	6V, 100 Ah	2.1	1.6	1.7	1.5	210
AGM	6V, 105 Ah	2.5	1.8	3.4	1.8	100
AGM	6V, 110 Ah	2.8	1.7	1.8	1.6	300
AGM	2V, 250 Ah	2.6	1.7	2.7	1.7	100
AGM	2V, 400 Ah					
Gell	6V, 8 Ah					
Gell	2V, 250 Ah	1.0	0.7	1.0	0.7	100
Vented	6V, 50 Ah	3.6	2.8	3.1	2.8	160
Vented	2V, 225 Ah	0.9	0.7	0.9	0.7	100
Vented	2V, 560 Ah	0.6	0.5	0.8	0.4	400

Table 1 : Some characteristic values obtained from the battery impedance spectra.

Effect of the charged condition

The state of charge of the battery is observed to affect both the phase and magnitude information in the battery spectrum. *Figure 3* illustrates the typical impedance behaviour of a VRLA battery subjected to different charge and float conditions. There are clearly two distinct spectra in the capacitive reactance region. One has an easily discernible higher impedance at low frequency than the other. This high impedanceresponse is ***only*** observed ***after*** the fully charged and float condition is attained. That is, a lower impedance is observed for a battery charged with nominal capacity

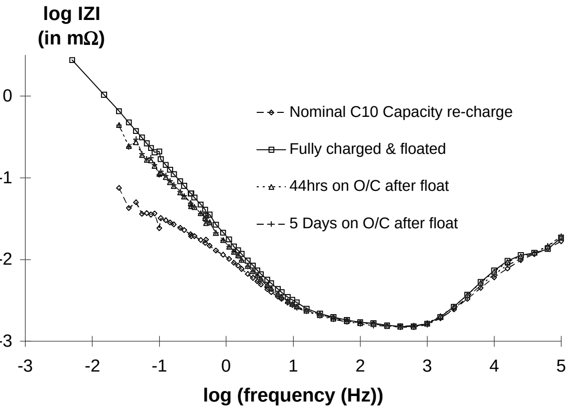

Figure 3: Bode magnitude spectra of impedance response to a AGM VRLA battery subject to float charging.

replacement but not subjected to a period of float overcharge. Furthermore, the high impedance spectral response is not significantly affected by measurement under float polarisation or time on float charge. The high impedance behaviour only very slowly decreases with time on open circuit. There are no discernable differences in impedance response for frequencies higher than about 10 Hz for any of these conditions.

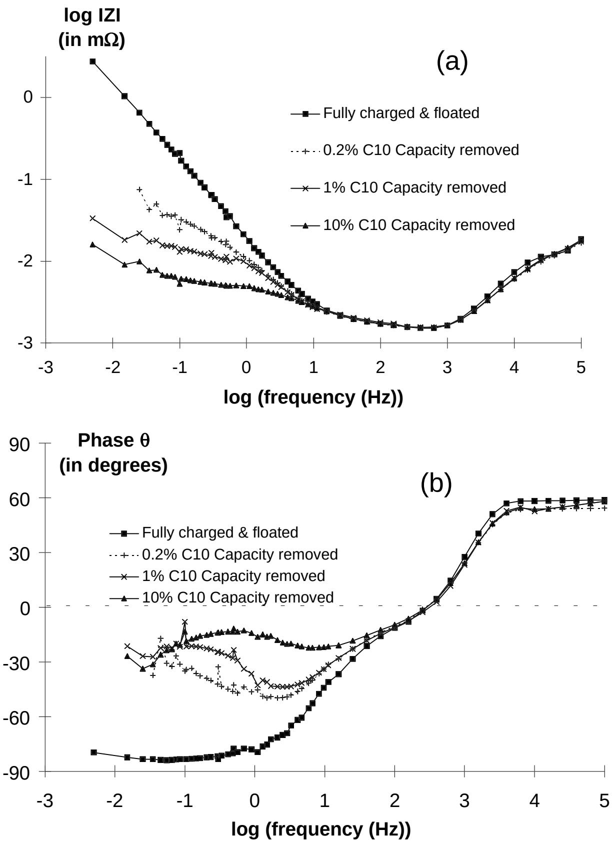

Figure 4: Comparison of impedance behaviour of a AGM VRLA battery in the float condition with those after minor capacity depletion.

Figure 4a compares the impedance behaviour of a floated battery with the open-circuit impedance spectra of the same battery after minor capacity removal. A very small capacity depletion (by discharge) results in the immediate collapse of the high impedance spectrum to the condition seen when the battery is not subjected to overcharge. The phase spectra is similarly interesting. *Figure 4b* shows that the higher impedance region over low frequencies corresponds to a very large increase in the capacitive reactance of a floated cells compared to the non-floated battery. That is, under float conditions the battery is passivated (increase in absolute impedance). Again, the high capacitive reactance is only observed once the battery has attained float conditions. Any capacity removal results in a collapse of the capacitive phase behaviour and resembles that of *Figure 2b*. The cell thus becomes predomiantly resistive over these same low frequencies. Neither the phase nor the magnitude of the impedance is significantly affected for frequencies above about 100 Hz, and there is no measurable affect in the ohmic resistance of the battery as a function of float or very minor capacity depletion. This phenomen appears to be generic and has been observed, to a similar extent in all the VRLA batteries and to a lesser extent in all the vented batteries studied in this work. For vented cells the effect appears to be linked to the extent of gassing charge used. Profound impedance changes at 0.1 Hz and 0.01 Hz during advanced charging and over charging have been reported in plate behaviour studies of model AGM VRLA cells [12].

In practical terms, the observed increase in impedance at low frequencies for the fully charged or float condition of the all batteries may itself form the basis of a simple *on-line* determination of "correctly" floating cells within a battery string. The results also indicate that "ohmic" determinations at lower frequencies may be influenced by the increased capacitive contribution arising from fully charge cells. This may contribute to the some of the reported diversity between correlation of cell impedance or conduction determinations and measured cell capacity [7,8].

Effect of capacity

Battery impedance spectra were observed to change as a function of residual battery capacity. *Figure 5* shows the typical open-circuit impedance behaviour for AGM VRLA battery subjected to various known amounts of capacity removal. Clearly evident from *Figure 5a* is the unilateral increase in absolute impedance over mid-frequencies as capacity is removed from the battery. *Figure 5b* illustrates that there is no general correlation between phase and residual capacity. After significant capacity removal, the phase spectrum collapses and the battery becomes predominantly resistive for frequencies as low as 0.01 Hz. The behaviour illustrated by *Figure 5* is again found to be generic, although the range of

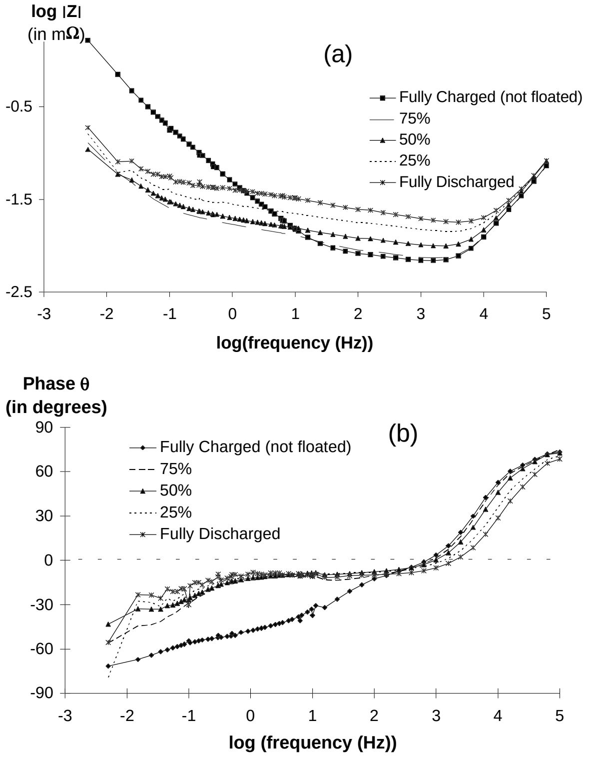

Figure: 5: Typical open-circuit impedance spectra as a function of nominal residual capacity.

impedance change depends on both battery capacity and battery technology. In general, vented cells exhibit smaller relative impedance changes than AGM or gelled VRLA cells. This indicates increased discrimination is needed to track the impedance with changes in capacity in vented batteries. In practical terms, the increase in battery impedance with removed capacity is the basis of single-frequency impedance and conductance measurements. The typical correlation of the impedance changes as a function of residual capacity for a number of single frequencies in the resistive region is shown in *Figure 6*.

An approximately linear relationship between the logarithm of the impedance and nominal residual capacity is observed from the discharge state to observed to about 80% capacity. Over this range, the impedance decreases with increase in the residual capacity. Between 80%-100% capacity, however, the impedance behaviour becomes non-linear, and the impedance increases as the battery approaches fully charge. The data is more resolved for the VRLA battery. *Figure 6* also demonstrates that the most linear relationship between the logarithm of the impedance and residual capacity is not necessarily at the frequency of the lowest impedance, and the gradient of the relationship is not necessarily the same for each "chosen" single frequency. Further, the frequency of ohmic resistance is observed to increase as the battery residual battery capacity decreases. These results indicate that an "optimum" measurement frequency

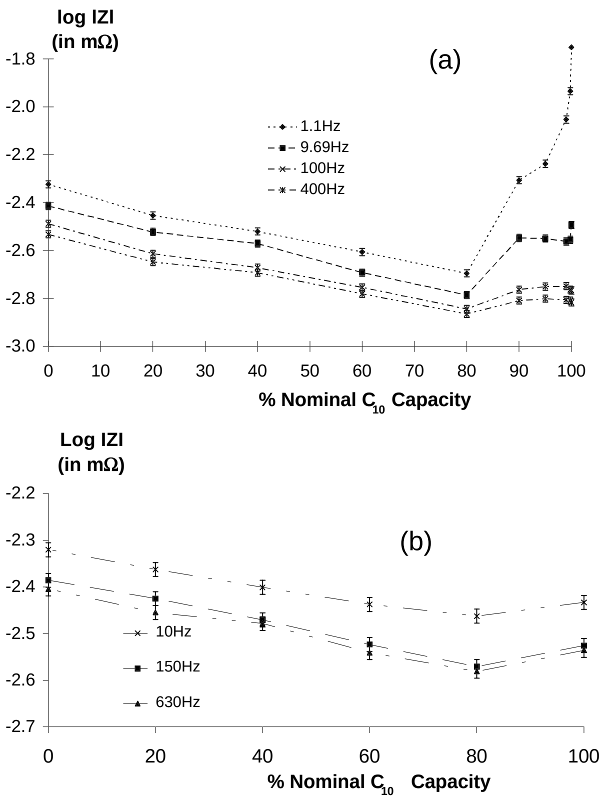

Figure 6 : Variation in battery impedance as a function of residual capacity determined for a number of single frequencies for (a) 6V, 110 Ah AGM VRLA monoblock and (b) 2V, 225Ah flooded cells.

might need to be established for a particular battery. There appears to be a general correlation between residual capacity and impedance for all types of lead-acid battery.However, useful capacity prediction may require specific frequency selection and "calibration" of the impedance-capacity relationship for specific batteries. Furthermore, dimensioning for service use, and end-of-service life criteria is usually based on 80% of the nominal battery capacity rating. The capacity-impedance behaviour observed in this work diminishes the claimed usefulness of single frequency impedance determinations as a fuel gauge for standby batteries.

Effect of Temperature

The effect of temperature on the impedance spectrum was studied for a variety of lead-acid batteries. *Figure 7* illustrates the typical impedance response of a 2V, 250 Ah (C_{10}) gelled VRLA cell over the temperature range of 25°C - 75°C. The cell was fully charged at 25°C, but not float charged during the higher temperature determinations. The characteristic float condition impedance appears to collapse for the higher temperatures. Over the entire mesurement frequency range, the impedance appears to be relatively insensisitve to the ambient temperature. This general behaviour was observed for both AGM and vented cells. Smaller capacity AGM batteries have been observed to exhibit a relatively larger, and less

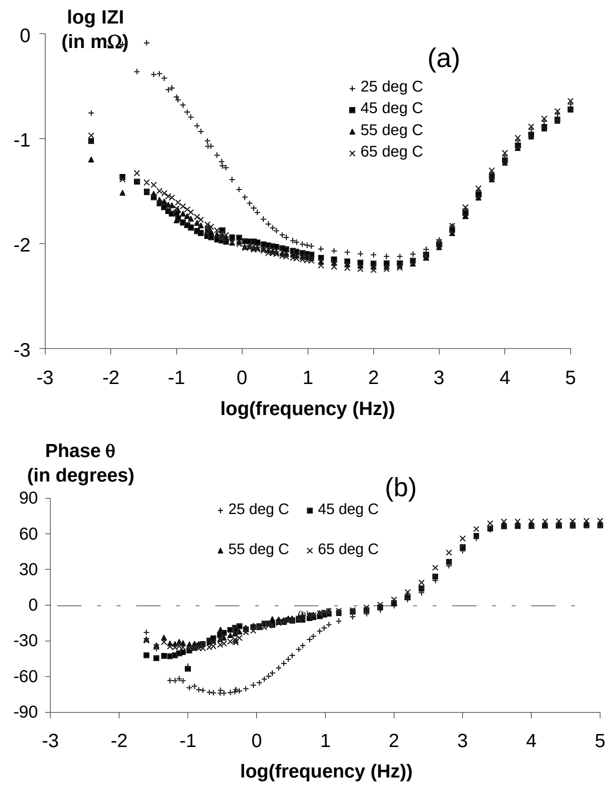

Figure 7 : Typical temperature effect on the impedance reponse of a gelled VRLA battery.

reproducible, temperature effect at low frequencies [12]. However, for the mid range frequencies commonly used in commercial impedance measuring equipment, the impedance behaviour appears to be largely insensitive to temperature. *Table 2* compares the change in impedance at various frequencies for different temperatures for a selection of batteries used in the Telstra network. The gelled battery shows the greatest sensitivity to temperature over the frequency range 1 Hz - 1 kHz, although in absolute terms, the impedance is not significantly affected by temperature for any of the batteries.

Battery type	Freq (Hz)	Temperature (°C)					
		25	35	45	55	65	75
6V 110 Ah AGM	10	2.1	2.2	2.1	1.9	1.8	2.8
	100	1.5	1.5	1.5	1.4	1.4	1.3
	1000	1.7	1.9	1.8	1.7	1.7	1.6
2V 225 Ah vented	10	0.9	0.9	0.9	0.9	0.8	0.8
	100	0.8	0.8	0.8	0.7	0.7	0.7
	1000	0.9	1.2	1.1	1.1	1.0	1.1
2V 400 Ah AGM	10		0.3	0.3	0.3	0.3	0.3
	100		0.2	0.2	0.2	0.2	0.2
	1000		0.5	0.5	0.5	0.5	0.5
2V 250 Ah gelled	10	0.9	0.8	0.7	0.7	0.6	0.6
	100	0.7	0.7	0.6	0.6	0.5	0.5
	1000	1.0	0.9	0.9	0.9	0.9	0.8

Table 2 : Absolute impedance values (in ***mΩ***) as a function of frequency and ambient battery temperature for four batteries types.

Figure 8 plots the ohmic resistance as a function of battery temperature for the batteries in *Table 2.* A small trend to lower impedance at higher temperatures is evident. However, over the 50°C range, the measured impedance for any of the frequencies in the "resistive" region changes less than approximately 10% in absolute terms. This is a level similar to the previously reported temperature sensitivity of conductance measurements of VRLA batteries [14].

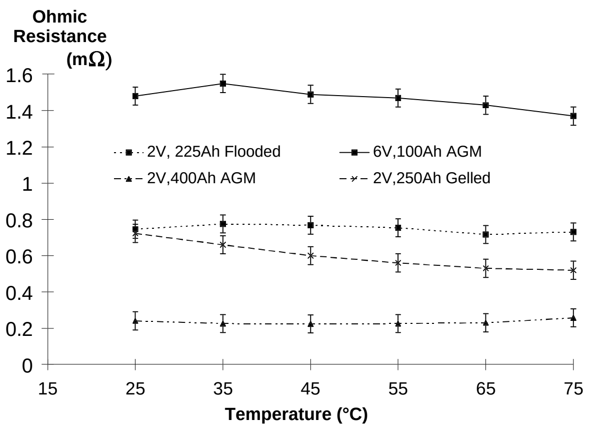

Figure 8: Variation in ohmic resistance as a function of ambient temperature for four different lead-acid batteries

Conclusions

The general AC impedance characteristics over a wide frequency range for a number of different types of lead-acid batteries has been studied. Generally similar behaviour is observed and all batteries exhibit predominantly resistive behaviour between 10 Hz and 1kHz. The impedance is found to affected by the state of charge of the battery. The impedance in the resistive region of the impedance characteristics does not exhibit any significant variation with temperature between 25°C and 75°C. The impedance behaviour at low frequencies can be used to discern the fully charged and float condition, and thus may be meritorious for in-service standby batteries.

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