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**MLS TESTING OF VRLA BATTERIES USING
PSEUDO RANDOM BINARY SEQUENCES (PRBS)**

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Abstract

Non-intrusive methods of establishing battery state offer distinct advantages to systems where complex charge and discharge profiles make implementation of conventional battery state reporting difficult. Furthermore, examination of equivalent circuit parameters for batteries and cells offers potential opportunities for State-of-Charge (SoC) and State-of-Health (SoH) reporting, irrespective of historic charge and discharge events. This paper expands the use of maximum length sequences as tools for parameter estimation within electrochemical cells, to seek to identify performance indicators within batteries. In order to facilitate this identification, Randles' model is used with Pseudo Random Binary Sequences (PRBS) as the excitation signal within the test system for the batteries being examined. Design of these sequences for experimental analysis is discussed, leading to application in the described test system, employing a monopolar current signal in order to apply the perturbation to the subject battery.

Battery impedance is investigated using a frequency domain approach, leading to characteristic impedance spectra being produced for the test batteries. The experimental results obtained allow parameters to be established, and verification against conventional battery test methods, and a sampled data model, is carried out.

This analysis is used to present characteristics which can be subsequently used to inform the design of SoC and SoH algorithms, in order to develop online systems for evaluating these batteries.

Keywords: Batteries, PRBS, modelling, parameter estimation.

1 Introduction

The increased demands for efficient energy storage are driving the optimisation of batteries and their performance metrics. The rising demand for portable electronic equipment, and particularly electric vehicles is leading to new applications for batteries. The knowledge of the

current State-of-Charge (SoC) and State-of-Health (SoH) (actual capacity vs. rated capacity) of a battery is becoming increasingly important since the battery state ultimately dictates the performance of the whole system. There are many examples of systems (laptop PCs included) which are said to be 'fully charged' only to be completely discharged within minutes due to the

capacity of the battery being degraded to the point that the system is unusable. With electric vehicles accurate SoH measurement is vital since this ultimately dictates the range of the vehicle. Additionally, with systems such as regenerative braking, recharge of the batteries occurs outside of the normal charging process. These factors, coupled with the drive for reduced recharging time are promoting the need for new methods of SoH and SoC measurement. Traditionally Coulomb counting has been the most common method for measuring state-of-charge since it involves simple current integration [1]. However, a disadvantage of this technique is that a periodic recalibration process is required due to the cumulative errors that can occur when small measurement errors are integrated, and a recalibration of the total battery capacity is also required to allow the total charge counted to be equated to battery SoC. In practice the recalibration process may require a complete discharge and recharge cycle which can be impractical for certain applications. Current pulse impedance spectroscopy has also been successfully applied but requires the battery to be disconnected from its load, or the load to be placed in a known state, which may interfere with normal system operation [2, 3] and test duration is dependent on battery capacity, which can be large. Other techniques which employ state-observers [4] have been reported but they often require specialist control systems knowledge impeding their adoption by industry. In contrast, this paper will present a parameter identification technique employing PRBS current pulse excitation, which can be applied online to provide estimates for Randles' equivalent circuit (shown later in Fig. 1), with a reduction in test time of several orders of magnitude, without the need for recalibration or load/charger disconnection.

1.1 Battery Models

In order to investigate the analysis technique, the familiar Randles' model was used for the battery. This model is a simple electrical representation of the complex electrochemical processes. Referring to Fig. 1, R_i is the lumped resistance for the cell interconnections etc. and represents the major series resistance for the cell. $C_{Surface}$ is a double layer capacitance, which is a result of the charge separation at the interface between the electrolyte and the cell plate [5].

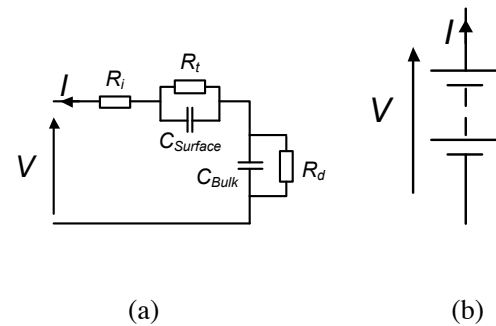


Figure 1. Randles' equivalent circuit (a) and battery showing terminal voltage and discharge current (b).

R_t , in parallel with the double layer capacitance is the charge transfer polarisation. C_{Bulk} represents the dominant capacitive element of the cell and R_d is the self-discharge resistance of the cell.

2 Cell parameter estimation using conventional methods

To provide a benchmark on which to assess the performance of the proposed PRBS testing technique, it was necessary first to establish the equivalent circuit parameters using conventional tests employing step load pulses, and controlled constant-current discharges.

2.1 Determination of C_{Bulk}

A new Yuasa NPL65-12i battery was charged at a constant voltage, using a temperature compensated battery charger manufactured by VxI Power Ltd. The battery was then left for a period of 4-6 hours in an open circuit condition in order to establish a stable off-charge terminal voltage. A discharge test was performed, corresponding to the 20hr discharge rate, 0.05C, and the battery discharged to an end terminal voltage of 10.5V, as recommended by the manufacturer [6]. Subsequently the ampere-hour capacity was then calculated, and from the discharge curve the value of bulk capacitance could be established [5]. The bulk capacitor stored energy equates to the product of the Ampere-Seconds capacity (charge) and the change in voltage corresponding to the settled fully-charged voltage compared with the discharged voltage.

$$W_{C_{Bulk}} = \frac{1}{2} C_{bulk} (V^2) \quad (1)$$

$$= \frac{1}{2} C_{bulk} (V_{100\%SOC}^2 - V_{0\%SOC}^2) \quad (2)$$

And therefore,

$$C_{Bulk Initial} = \frac{Rated\ capacity \times V_{100\%SOC}}{\frac{1}{2}(V_{100\%SOC}^2 - V_{0\%SOC}^2)} \quad (3)$$

2.2 Determination of $C_{Surface}$, R_i , R_t

To determine the value of $C_{Surface}$, a suitable experiment was designed which considered the time constant involved. In [7] it was shown that the time constant, associated with $C_{Surface}$ is very much smaller than that associated with the bulk energy store, and pulse testing can be used to reveal $C_{Surface}$ time constant without significantly affecting the charge stored in C_{Bulk} .

A constant current discharge of 8A was applied to the battery, during this period; short interruptions to the load (500mS) were made in order to observe the response, as presented in fig.2.

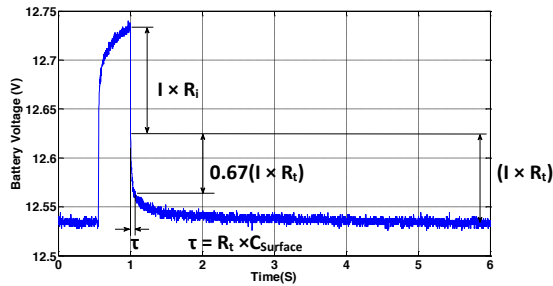


Figure 2. Calculation of model parameters

Inspection of the response yielded the equivalent circuit parameters below.

$$R_i = \frac{0.04064}{8}$$

$$R_i = 5.08m\Omega \quad (4)$$

$$0.67I R_t = 0.0619$$

$$R_t = 5.18m\Omega \quad (5)$$

$$\tau = 0.147 = C_{Surface} R_t$$

$$\text{Therefore, } C_{Surface} = 14.81F \quad (6)$$

2.3 Determination of R_d

R_d , the self-discharge resistance of the cell, was determined by observing the decay of the battery

open circuit voltage over time. Referring back to figure 1, the discharge of C_{Bulk} by R_d was then calculated and a value for R_d itself established (Table 1).

Table 1: Experimental results

$$\begin{aligned} V_{100\%SOC} &= 12.846V \\ V_{0\%SOC} &= 10.5V \\ \text{Ampere second capacity} &= 259992 \text{ As} \end{aligned}$$

$$C_{Bulk} = 121960F$$

$$C_{Surface} = 14.81F$$

$$R_i = 5.08m\Omega$$

$$R_t = 5.18m\Omega$$

$$R_d = 4955\Omega$$

3. Simulation of the equivalent circuit

Prior to the PRBS experiments simulations were carried out to predict the likely responses, based on the result obtained from the conventional tests. This was carried out with two approaches. Firstly a transfer function was derived to obtain gain and phase plots using swept frequency analysis, through simulation in Matlab. Subsequently a sampled-data model was used to verify the proposed PRBS-based parameter identification methodology. Both of these approaches informed the PRBS design process.

3.1 Transfer function analysis

Breaking the circuit into branches (fig. 6), eases the derivation of the transfer function:

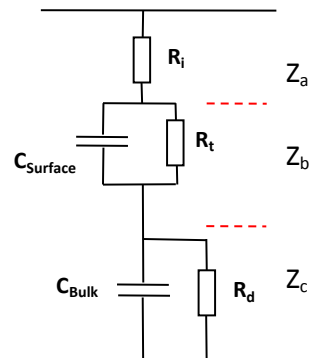


Figure 6. Branch impedances

$$Z_{total} = Z_a + Z_b + Z_c \quad (11)$$

In Laplace,

$$Z_a = R_i \quad (12)$$

$$Z_b = \frac{R_t}{SR_t C_s + 1} \quad (13)$$

$$Z_c = \frac{R_d}{SR_d C_b + 1} \quad (14)$$

So

$$Z_{total} = R_i + \frac{R_t}{SR_t C_s + 1} + \frac{R_d}{SR_d C_b + 1} \quad (15)$$

Considering figure 7 the impedances attributable to the equivalent circuit components can be seen. In stage (i) the response tends towards R_d . As the

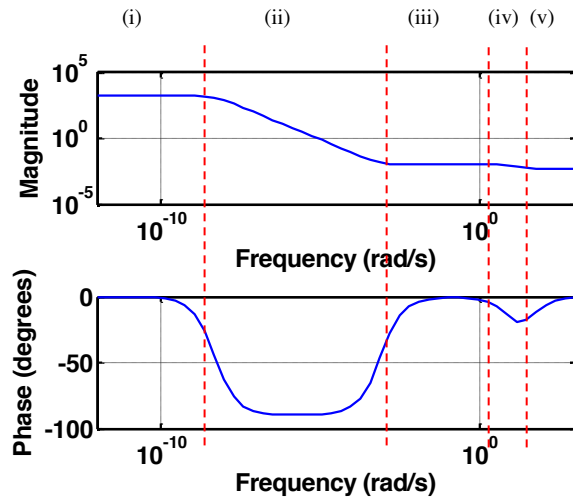


Figure 7. Magnitude and phase plots, experimental results

excitation frequency increases, stage (ii), the effect of C_{Bulk} can be seen, whilst during stage (iii) we are seeing the impedance of $R_i + R_t$. Moving towards (iv) $C_{Surface}$ is shunting R_t , until finally at (v) only R_i remains dominant. It is interesting to consider the frequencies involved – 10^{-10} rad/s for the roll-off of C_{Bulk} , which will be discussed later in the PRBS evaluation.

3.2 Sampled-data model analysis

A PRBS sequence was generated and applied to the Randles' model featuring with the same values for the equivalent circuit established earlier (see Table 1). FFTs of both the input current waveform and the corresponding voltage output of the simulated battery were evaluated. From

these spectra the impedance characteristic could then be obtained, as shown in fig. 8.

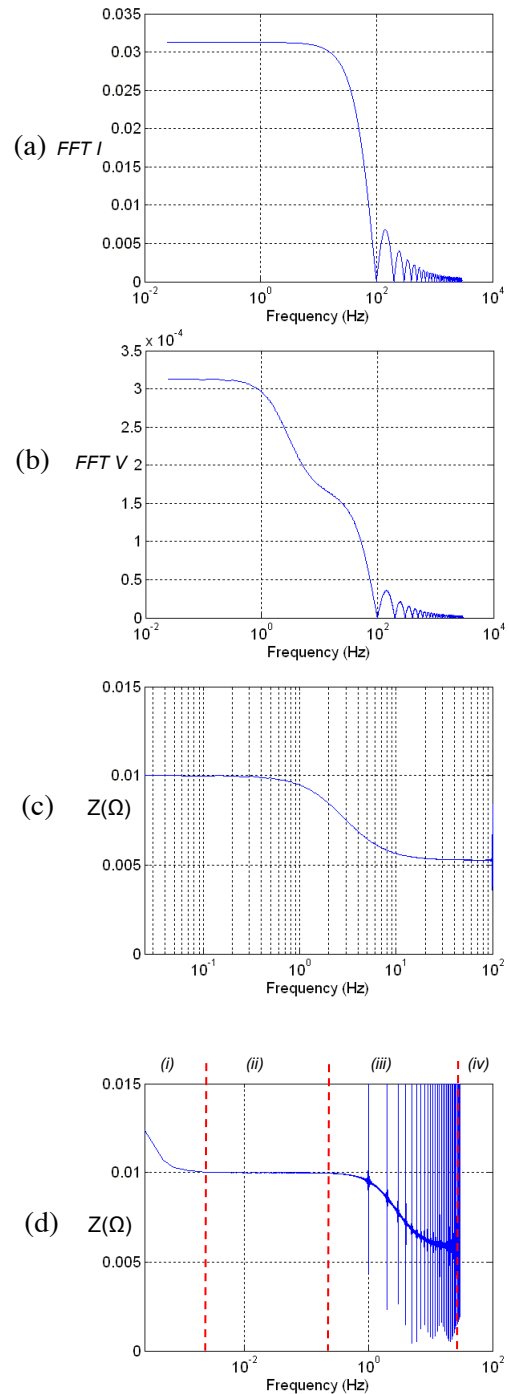


Fig. 8 Predicted responses obtained through simulation (a) Input current FFT, (b) Battery terminal voltage FFT, (c) Resultant impedance plot (higher frequencies), (d) Wider bandwidth plot with slower clock showing bulk capacitor response.

Again, at lower frequencies, section (i) of fig 8(d), we see a gradient due to C_{Bulk} . In considering the plateau in the centre of the response (ii) we have

the sum of $R_i + R_t$. Beyond this plateau, (iii) C_{Surface} becomes dominant before the curve asymptotically approaches R_i (iv) as the response becomes purely resistive with increasing frequency. It follows that this analysis gives rise to the following set of equations, respectively:

$$Z_4 = \frac{1}{\sqrt{\left(\frac{1}{R_d^2} + \frac{1}{X_{cb}^2}\right)}} + \frac{1}{\sqrt{\left(\frac{1}{R_t^2} + \frac{1}{X_{cs}^2}\right)}} + R_i + R_t \quad (16)$$

$$Z_2 = R_i + R_t \quad (17)$$

$$Z_3 = \frac{1}{\sqrt{\left(\frac{1}{R_t^2} + \frac{1}{X_{cs}^2}\right)}} + R_i \quad (18)$$

$$Z_4 = R_i \quad (19)$$

4. Pseudo Random Binary Sequence (PRBS) parameter identification

Frequency domain analysis is a commonly used tool for parameter estimation, finding many applications in system modelling. Using electrical analogues and frequency response plots is a convenient way for Electrical Engineers to seek to model the complex electrochemical reactions within batteries and cells. Swept sinusoids (chirp) or white noise signals are usually employed to excite the system under test. However, in this particular application large currents are required to generate sufficient terminal voltage variation and this places strict requirements on the excitation system (i.e. amplifier power dissipation). PRBS or maximum length sequences (MLS) are signals with a spectrum that is a good approximation to band-limited white noise, and, being a binary sequence, they do not impose the same restrictions for amplification. A further benefit is that the PRBS signal can be used in addition to the usual input/control signal, and the output response measured. Fourier analysis techniques can then be employed to determine the system's frequency response. Applications of this technique include hearing aid analysis [8], impedance spectroscopy [9], and switched mode power supply control loop analysis [10].

4.1 Characteristics and design of PRBS

Unlike ideal white noise, MLS are bandwidth limited signals and, therefore, they must be carefully designed to excite all the modes of the

system under test. MLS generators are usually realised with a shift register featuring modulo 2 (XOR) feedback at predetermined "tap" positions [11], fig. 3 shows a 4-bit MLS generator.

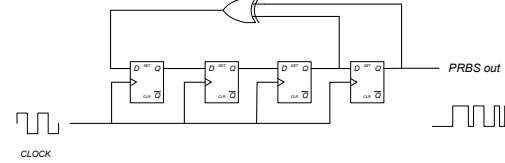


Figure 3. 4-bit PRBS generator example

The number of stages, n , defines the number of terms, N in the sequence.

$$N = (2^n - 1) \quad (7)$$

In order for a PRBS to be a maximal length sequence all possible bit patterns apart from "all zeros" must be present. This gives rise to a sequence which repeats every N terms (fig 4), as can be seen by the autocorrelation function. The relative amplitudes are shown for the sequence, and the autocorrelation function.

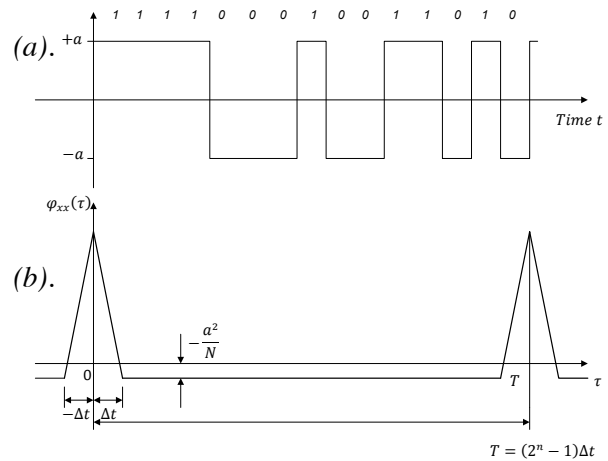


Figure 4. (a) Example PRBS sequence and (b) Typical Autocorrelation response

4.2 Limitations of bandwidth for the PRBS

The minimum frequency, $f_{\min}$, contained within the MLS is defined by the number of terms in the

sequence (N) and the duration of the clock pulse (Δt). The maximum frequency, $f_{\max}$, can be found from the Wiener-Khintchine theorem which states that the power spectral density of a wide sense stationary random process is the Fourier transform of the corresponding autocorrelation function.

$$\Phi_{xx}(\omega) = 2 \int_0^T \varphi_{xx}(\tau) \cos(\omega\tau) d\tau \quad (8)$$

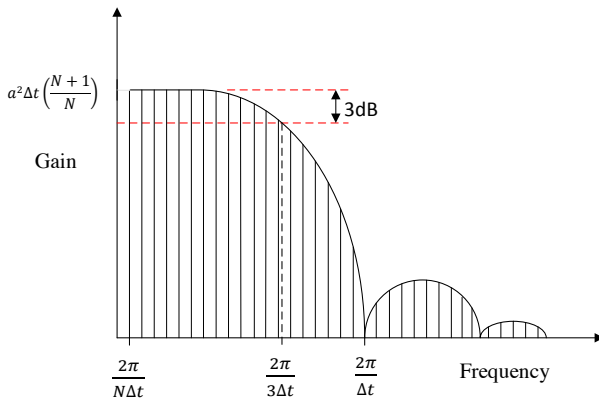


Figure 5. Power spectrum (FFT) of a PRBS showing usable frequency band

The proof is outside of the scope of this paper [11], however solving the integral defines the upper frequency of the PRBS, giving a useful frequency band of (fig. 5):

$$f_{\min} = \frac{1}{N\Delta t} \quad \text{to} \quad f_{\max} = \frac{1}{3\Delta t} \quad (9)$$

The two base design parameters for the PRBS are therefore the fundamental clock pulse frequency and the number of stages of the generator itself. Considering defined band above, the clock MLS frequency, $f_c = 1/\Delta t$, as a general rule of thumb should be chosen to be approximately:

$$f_c = 2.5f_{int} \quad (10)$$

where f_{int} is the maximum frequency of interest [12].

4.3 Data acquisition and sampling rate.

The MLS must be acquired and processed as a complete sequence to maintain its white-noise-like properties. This leads to the consideration of the duration of the test itself, as the MLS duration (T) will define the amount of data which needs to be acquired. This can lead to very long test times

if a MLS is chosen which has a large number of stages. Data acquisition (sample) rate is dictated by f_c and the normal requirements of the Nyquist–Shannon sampling theorem must be met. A sampling rate of 2 to 5 times f_c was used during the tests.

5. Experimental PRBS investigation

5.1 Test system description

The test set for the battery including the MLS generator, power stage and data acquisition is shown in fig. 9. The demand signal was provided by a Microchip DSPic development board. A bank of parallel MOSFETs provide charge/discharge to the device under test (discharge only during the cell tests). Closed-loop analogue control of the device bank provides a tight transient response improving damping and reducing rise/fall time effects. On board high speed current measurement is provided for, with data acquisition integral to the system, allowing off line data analysis.

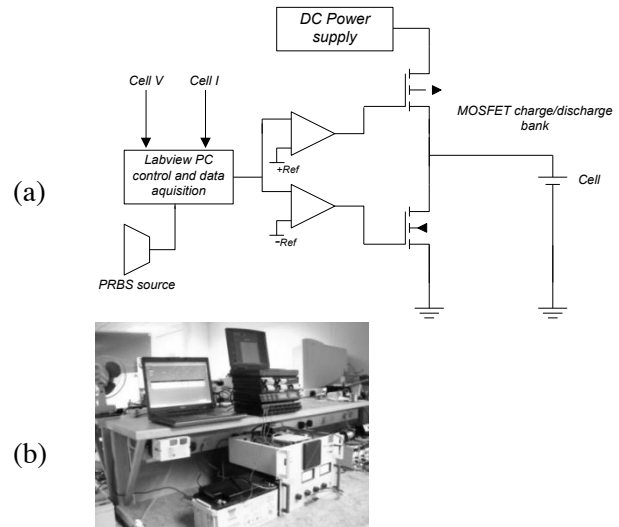


Figure 9. (a) Test system block diagram and (b) photograph of test rig

5.2 Test procedure

The battery was fully charged, and allowed to establish a steady-state terminal voltage before the tests were carried out. The current pulse amplitude was selected in order to provide good signal-to-noise ratio, without producing a

significant discharge. Further tests under float charge conditions, and with a steady state DC load were carried out to establish the on-line response under realistic operating conditions.

6. Results

6.1 Acquired data length and signal processing

Fig. 10(a) shows an example of the PRBS current perturbation, and the resultant battery terminal voltage, (b)

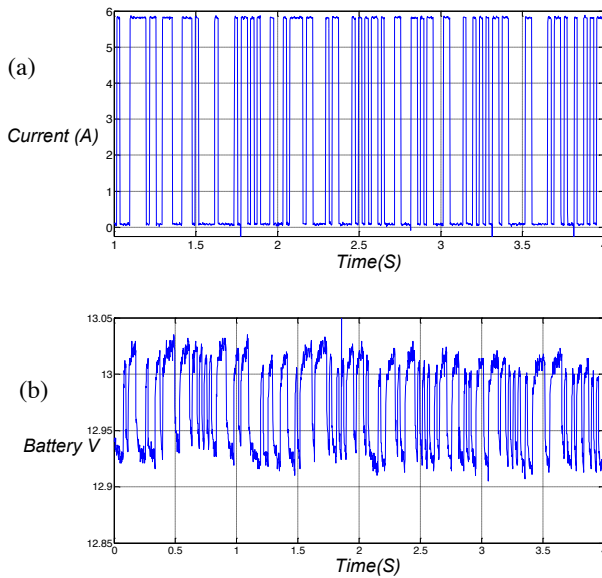


Figure 10. (a) excerpt from acquired PRBS current perturbation and (b) battery voltage during test.

An example FFT is shown, fig 11.

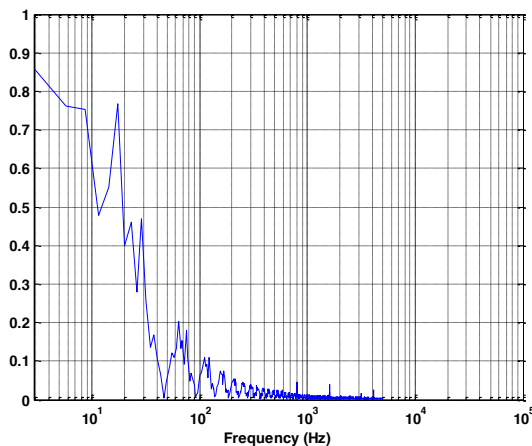


Figure 11. Example FFT of battery terminal voltage during test.

Considering the time constants involved for C_{Bulk} and R_d , it was deemed practical to examine the values of R_i and $C_{Surface}$ and R_t , as previous work had indicated these as good indicators of SoC[4].

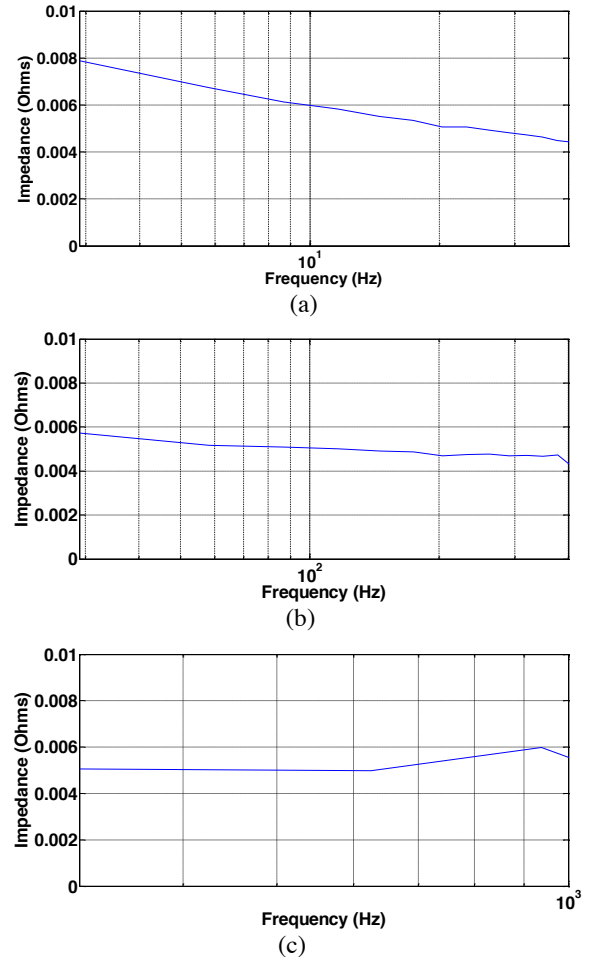


Figure 12 (a) 3Hz-40Hz (b) 30Hz-400Hz, (c) 300Hz-1kHz, Impedance responses, 65Ah battery

6.2 Analysis of results

Considering figure 11, the effects of $C_{Surface}$ and R_i can be directly observed. In (d) we are seeing R_i directly which has a value of 5mΩ. This compares with 5.08mΩ for the pulse current tests (table 1.) The rising tendency of the plot at higher frequency (Fig. 12(c)), is attributable to the edge of the usable bandwidth for the test and is therefore invalid data.

$C_{Surface}$ and R_t can therefore be calculated using equation (14):

$$Z_3 = \frac{1}{\sqrt{\left(\frac{1}{R_t^2} + \frac{1}{X_{Cs}^2}\right)}} + R_i \quad (20)$$

Considering several points on the responses a series of equations were created, which when solved for R_t and equated gave the following results:

$$\begin{aligned} C_{\text{Surface}} &= 15.6 \text{ F} \\ R_t &= 5.1 \text{ m}\Omega \end{aligned} \quad (21)$$

Comparisons of the results to the initial experimental results show a good correlation, as can be seen in table 2.

Table 2: Comparison of results

	Conventional	PRBS
C_{Surface}	14.81F	15.6F
R_i	5.08 m Ω	5.0 m Ω
R_t	5.18 m Ω	5.1 m Ω

7. Conclusion

This paper has demonstrated an MLS based monopolar current pulse load parameter identification methodology for VRLA batteries. Known indicators of state of charge (R_i , C_{Surface} and R_t) were readily identified, allowing the methodology potentially to be used as a basis for a SoC indication. Comparisons to conventional current pulse methods show clear advantages of the technique. The parameters were identified with short duration tests, which were validated for a range of perturbation amplitudes. During the tests a reduced current signal was used which demonstrated an acceptable level of noise immunity, with the inherent advantage of reducing the effect of the test on the actual SoC of the test battery. It is intended that this work will be expanded, to encompass a range of charging and discharge conditions, at various SoC/SoH.

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