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Fuzzy logic modelling of state-of-charge and available capacity of nickel/metal hydride batteries

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Abstract

Ni/MH batteries are playing important roles in many applications such as power tools, and a dominant role in hybrid electric vehicles (HEVs). In the case of HEVs it is particularly important to be able to monitor the state-of-charge (SoC) of the Ni/MH batteries. We have previously reported on the use of a fuzzy logic (FL) methodology to estimate the SoC of various battery chemistries, including lead-acid and lithium sulfur dioxide.

In the present work, we have measured electrochemical impedance spectroscopy (EIS) on 2.7 Ah Sanyo Ni/MH cells and two- and three-cell strings of these cells at different SoC's and over 100 cycles. We have been able to select features in this data to develop fuzzy logic models for both available capacity and SoC estimation, simply by measuring the impedance at three frequencies. The fuzzy logic model estimates the SoC to within ±5%. In this paper we will present the details of the experimental measurements, the details of the fuzzy logic models themselves, and the resulting accuracies of the developed models.
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Keywords: Nickel/metal hydride batteries; Fuzzy logic; Impedance spectroscopy

1. Introduction

Ni/MH batteries are being used extensively in power tool, portable power products, and hybrid electric vehicle (HEV) applications. State-of-charge (SoC) and state-of-health (SoH) of these batteries is generally estimated using coulomb counting in portable power products (e.g. laptop computers and camcorders). However, coulomb counting is not very reliable at low SoCs and is not very useful for determining the battery's SoH.

Two other approaches involving impedance and voltage recovery measurements have been described recently. The first approach is curve fitting techniques applied to electrochemical impedance spectroscopy (EIS) measurements. This method has been shown to provide SoC estimation of better than 10% accuracy under both open-circuit and during discharge conditions [1]. The second method reported by researchers at Toyota Motor Corp. involves a combination of three steps: (i) a transient voltage measurement, (ii) calculation of overall battery impedance at different times and current magnitudes, and (iii) determination of the maximum current [2].

Over the last 6 years Villanova University and US Nanocorp®, Inc. have collaborated on the development of fuzzy logic (FL)-based techniques for estimating the SoC and SoH of various types of batteries, including some preliminary work on Ni/MH batteries [3–7]. The fuzzy logic analysis technique has been shown to be a reliable, robust, code efficient approach to the estimation of battery SoC and SoH.

In the present work, a focused study of applying fuzzy logic modeling techniques to the estimation of Ni/MH battery SoC/SoH is presented.

2. Experimental

2.1. Potentiostatic measurements

Electrochemical impedance spectroscopy were measured on a 3-cell Ni/MH battery composed of three Sanyo "A"-size, 2.7 Ah Ni/MH cells in series over the frequency range of 65 kHz to 0.65 Hz. Data was collected using a

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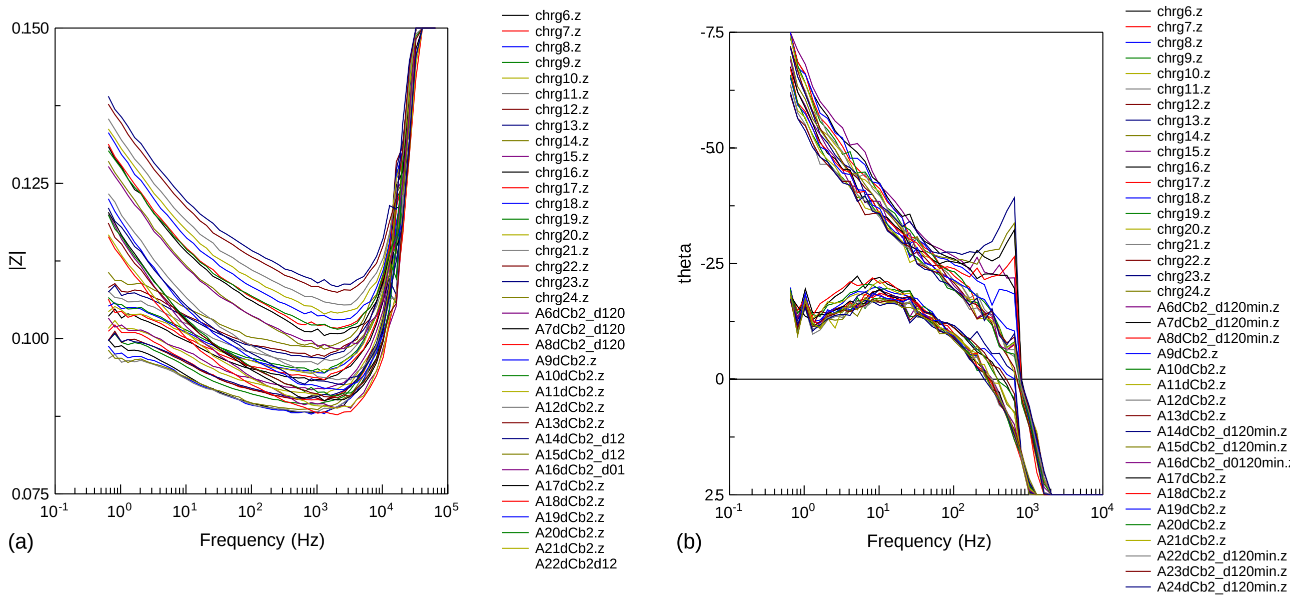

Fig. 1. (a and b) Magnitude (*l*) and phase angle (*r*) of the impedance vs. frequency for 3-cell 2.7 Ah Sanyo Ni/MH battery, cycles 6–24 at two different SoCs (nomenclature: 'chrg'—30 s after charge, 'd120' and 'dCb2'—30 s after 3 V cutoff was reached).

Solartron 1280 B Electrochemical Measurement Unit under CorrWare software control over 100 cycles of the battery. The battery was charged at the *C*/3 rate for 4.0 h. The battery was discharged at the *C*/2 rate. Impedance spectroscopy measurements were conducted after the charge cycle and discharge cycle. Also for SoC analysis, impedance spectroscopy measurements were conducted during particular discharge cycles, after successive 15 min discharges and once after the cutoff voltage of 3.0 V was reached. The remaining cycles were discharged continuously until the 3.0 V cutoff was reached. All measurements were conducted at room temperature.

Fig. 1a and b display the variation of the magnitude of the impedance and phase angle, respectively, with cycle number at two different SoCs. Impedance labeled "chrg" represents the impedance measured 30 s after the charging was completed (fully charged). The impedance labeled "d120" and "dCb2" represents the impedance measured 30 s after a 3.0 V cutoff was reached during the discharge (fully discharged). The magnitude of the impedance can be seen to vary with both cycle number and SoC. However, notice that the phase angle shows a relatively small variation with cycle number while the variation of the phase angle with SoC is quite distinct.

It was anticipated that distinct measures of SoC could be extracted from the magnitude and phase angle of the impedance at various frequencies. These measures would then be used to train a fuzzy logic model that could predict SoC and SoH of a Ni/MH battery.

Although the impedance does vary as a function of SoC, it can be seen from Fig. 2a and b that the variation of the real component of the impedance at any frequency is no more than 2.5 mΩ between 80% SoC (d015 min) and 0% SoC (d090 min). The relatively low values of impedance are not useful for a practical commercial device.

However, as displayed in Fig. 3, the variation of the impedance with cycle number (and more importantly with available capacity) is significant.

Although the potentiostatic impedance measurements did not appear to provide an effective measure of SoC for Ni/MH batteries, preliminary analysis indicates that the variation of impedance with available capacity is significant. Modeling this variation with a fuzzy logic system could then facilitate an external SoH device.

2.2. Galvanostatic measurements

Since the potentiostatic mode measurements did not provide the desired discrimination in the EIS spectra at different SoCs, galvanostatic mode spectra at various SoCs, over the frequency range of 10 kHz–10 Hz, were collected on the 3-cell Ni/MH battery cycled at the *C*/2 rate. The applied current signal was 40 mA peak-to-peak. Typical results are shown in Fig. 4a and b *Notice that there is significant separation between impedance spectra at the various SoCs.*

EIS data were collected at various SoCs on the three-cell battery over 28 charge/discharge cycles. All discharge tests were performed at the *C*/2 rate at room temperature. The battery has been charged at the *C*/3 rate for 4 h. The data referred to as A9–A38 are actually the 109th–138th cycle of the battery.

3. Results

Figs. 5a, b, 6a and b show the variation of the impedance with SoC for cycle A9 and cycle A38, respectively. Notice

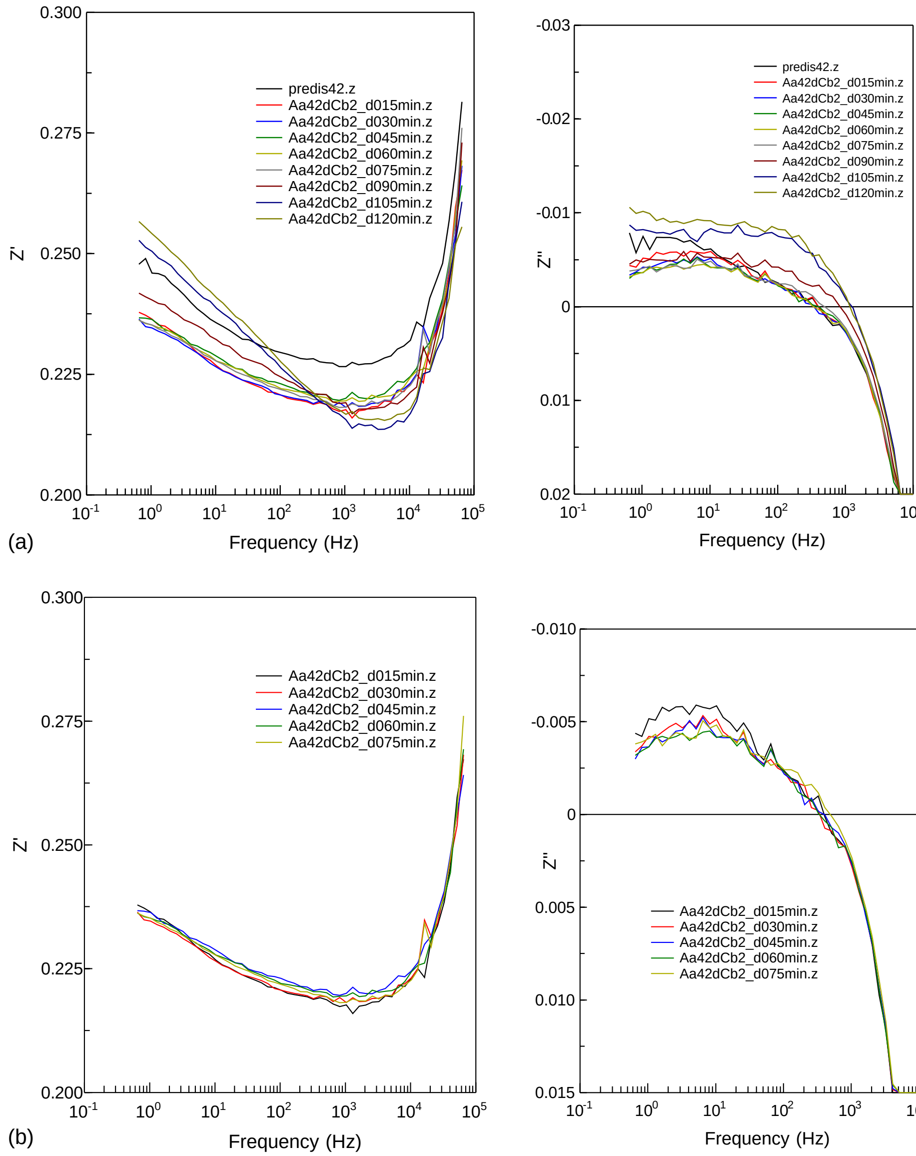

Fig. 2. (a) Real component (*l*) and imaginary component (*r*) of the impedance at various SoCs between 100 and 0% SoC for 3-cell 2.7 Ah Sanyo Ni/MH battery, cycle 42. (b) Real component (*l*) and imaginary component (*r*) of the impedance at various SoCs between 90 and 30% SoC for 3-cell 2.7 Ah Sanyo Ni/MH battery, cycle 42.

that the overall change in impedance with SoC is quite similar for both cycles even though the available full-charge capacity at cycle A38 is 20% that of cycle A9. Also, as can be seen from Fig. 7a, the real component of the impedance of the fully charged battery increases with cycle number while the imaginary component, Fig. 7b, remains relatively constant.

Before proceeding with the analysis it is necessary to define what SoC and available full-charge capacity mean. SoC refers to the percentage of available full-charge capacity remaining before end-of-discharge condition is reached, whatever that initial capacity at full-charge may be. By itself, a SoC measure may not provide the user (or for that matter, another fuzzy logic model) with enough information so as to predict the time remaining before end-of-discharge condition is reached. A SoC measure as currently defined is still a valuable quantity to predict. By itself it provides the battery user an indication of the “need of charge” condition. Also the SoC measure when combined with a measure of full-charge capacity can provide an indication of the “time remaining”.

Accordingly, the available capacity at full-charge refers to the amount of charge available for discharge at a particular rate when cell/battery is fully charged. This is a useful measure for the reason previously stated, but also because it can provide an indication of the cycle life of the battery.

As mentioned, for purposes of developing and testing the fuzzy logic models, actual SoC was back-calculated from

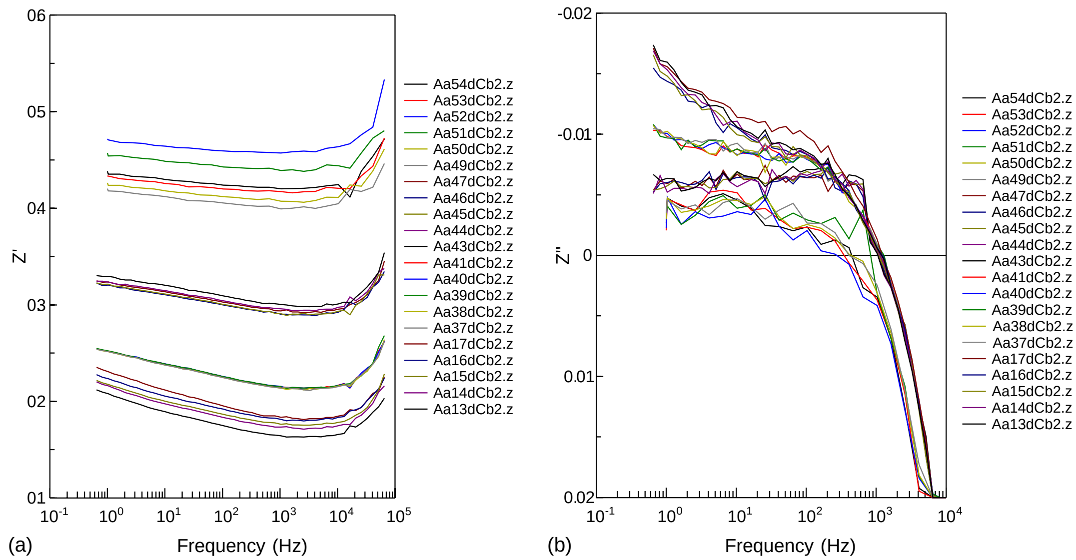

Fig. 3. (a and b) Real (*l*) and imaginary (*r*) component of the impedance as a function of cycle number for 3-cell 2.7 Ah Sanyo Ni/MH battery, at full-charge cycles 2–53.

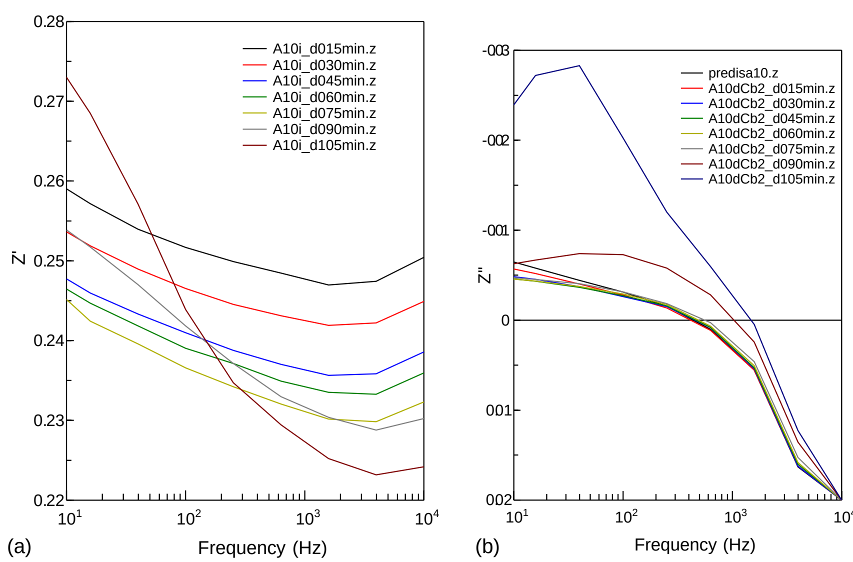

Fig. 4. (a and b) Real component (*l*) and imaginary component (*r*) of the impedance at various SoCs for 3-cell 2.7 Ah Sanyo Ni/MH battery, acquired under EIS-galvanostat mode.

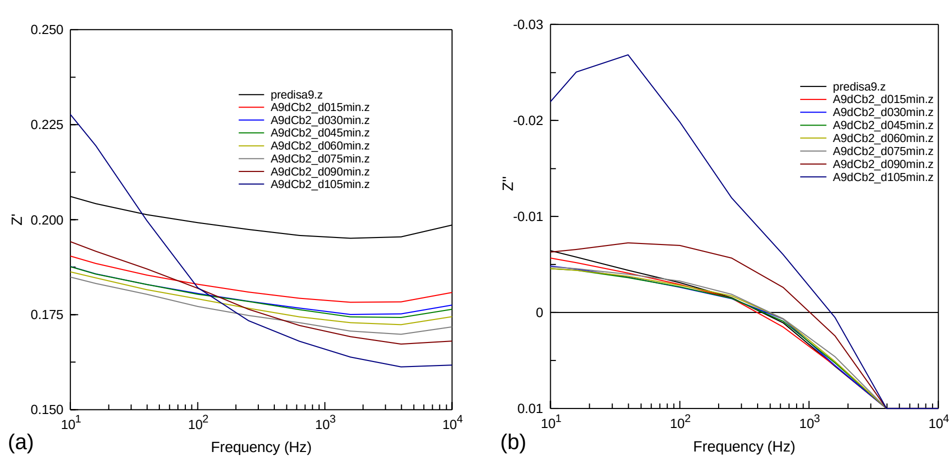

Fig. 5. (a and b) Real (*l*) and imaginary (*r*) component of the impedance as a function of SoC for 3-cell 2.7 Ah Sanyo Ni/MH battery, cycle A9.

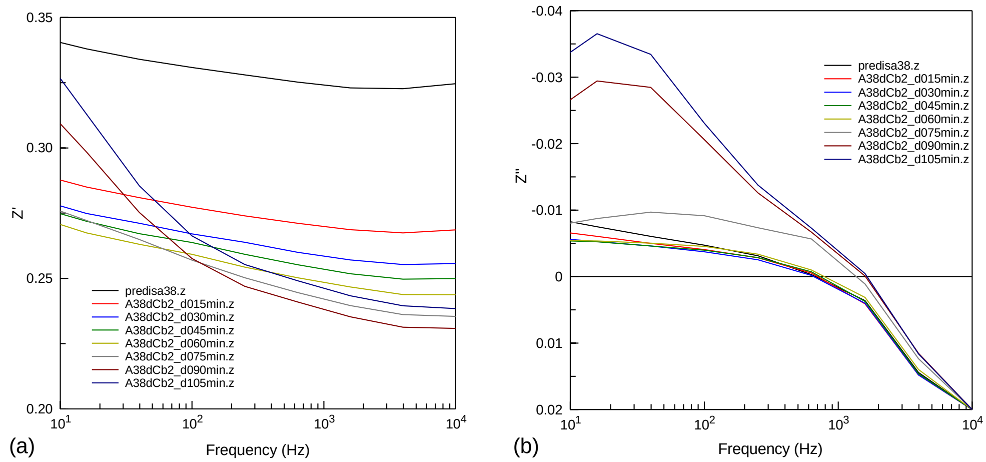

Fig. 6. (a and b) Real (*l*) and imaginary (*r*) component of the impedance as a function of SoC for 3-cell 2.7 Ah Sanyo Ni/MH battery, cycle A38.

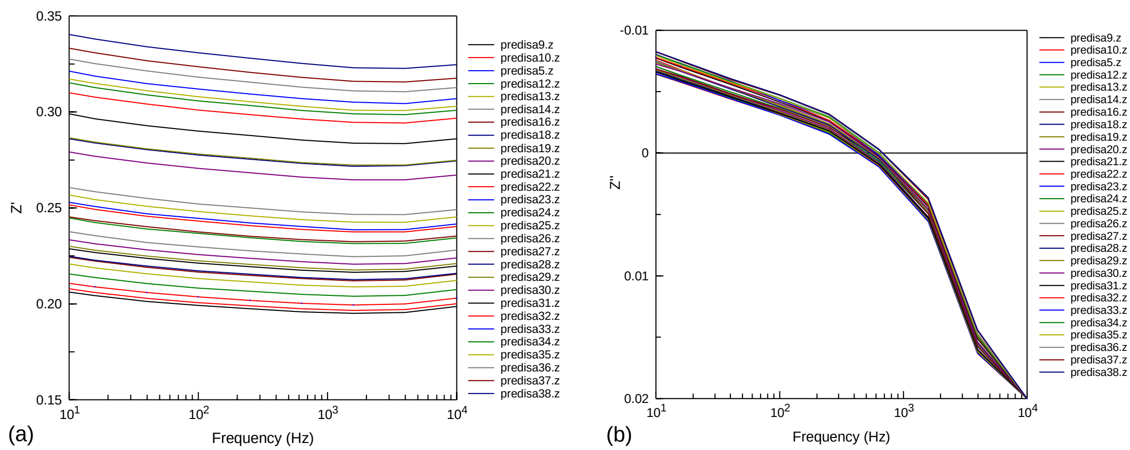

Fig. 7. (a and b) Real (*l*) and imaginary (*r*) component of the impedance as a function of cycle number for 3-cell 2.7 Ah Sanyo Ni/MH battery, at full-charge (5 h rest at open circuit prior to testing).

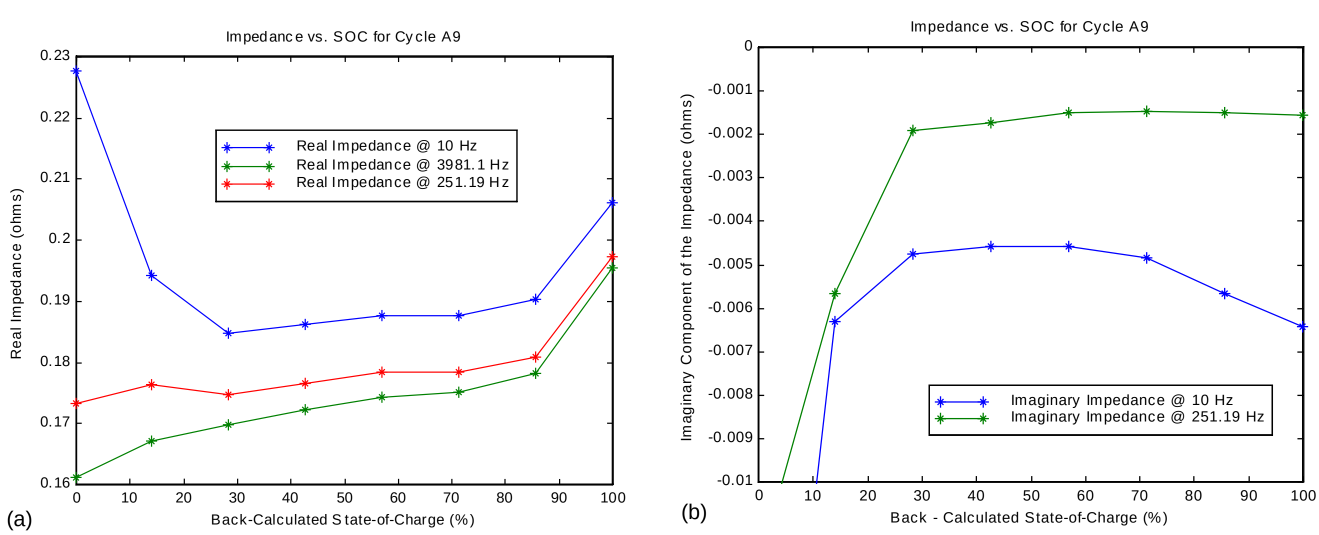

Fig. 8. (a) Variation of the real component of the impedance with SoC at various frequencies for 3-cell 2.7 Ah Sanyo Ni/MH battery; cycle A9. (b) Variation of the imaginary component of the impedance with SoC at various frequencies for 3-cell 2.7 Ah Sanyo Ni/MH battery; cycle A9.

the experimental measurements as follows:

$$\text{actual SoC}_{\text{at time}=T} = \left[\frac{1-\text{charge}(Q)_{\text{removed(at time}=T)}}{\text{charge}(Q)_{\text{total removed}}}\right] \times 100$$

For example,
Cycle 'A9'—total discharge time: 105 min.
15 min discharge at 1.33 A reduces SoC ∼14.3%.
Cycle 'A38'—total discharge time: 83 min.
15 min discharge at 1.33 A reduces SoC ∼18.1%.

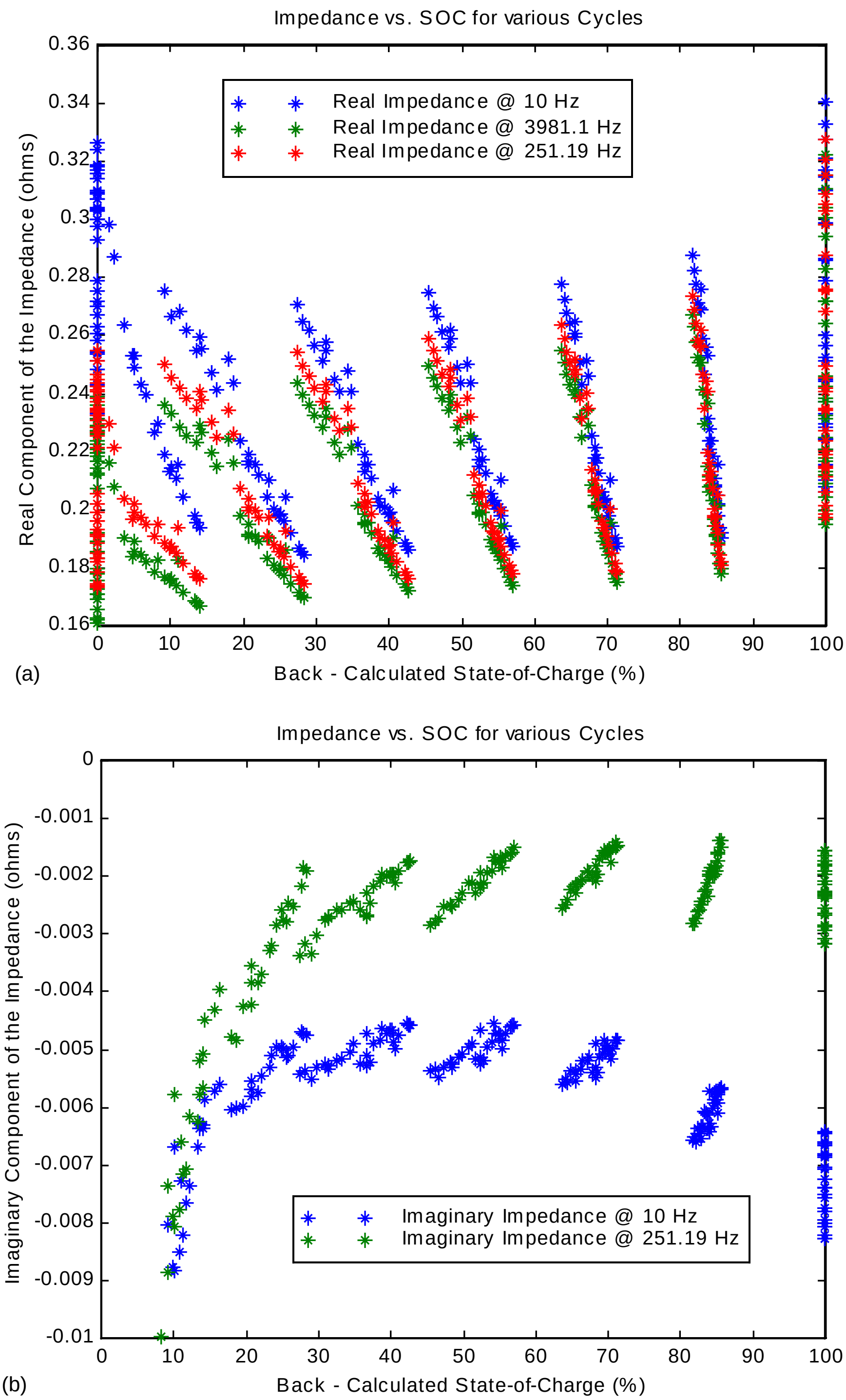

Fig. 9. (a) Variation of the real component of the impedance with SoC at various frequencies for 3-cell 2.7 Ah Sanyo Ni/MH battery; cycle A9 through A38. (b) Variation of the imaginary component of the impedance with SoC at various frequencies for 3-cell 2.7 Ah Sanyo Ni/MH battery; cycle A9 through A38.

As further analysis of the data will show, it is possible, based on the impedance at only three frequencies, to predict both the SoC of the battery (irrespective of the initial full-charge capacity) and the available capacity at full-charge of the battery, at any SoC, using a fuzzy logic system.

4. Fuzzy logic modeling

4.1. Data preprocessing

The acquired EIS data set was reduced to a form that could be easily manipulated by fuzzy logic models. This involved finding one or more frequencies where the variation in the real component and/or imaginary component of the impedance could provide "enough discrimination" between successive SoC, while still providing a robust measure to account for changes in the impedance with cycle number. The impedance at the chosen frequencies did not have to vary monotonically (or at all) over the entire range of SoC. A key attribute of the fuzzy logic approach is in combining several measures of SoC, each containing partial information. Once these frequencies are found, the impedance at these frequencies can be readily available as inputs to the FL-model.

It was found that the impedance at three frequencies vary sufficiently with SoC so as to be adequate inputs for the FL-model (real component and imaginary component of the impedance at 10 and 251.1 Hz and the real component of the impedance at 3981.1 Hz). Fig. 8a and b display the variation of these FL inputs with SoC for cycle A9. As mentioned the impedance at the specified frequencies must provide a robust measure of SoC. Simple curve fitting will not work due to the variation of the overall battery impedance that typically occurs with cycling. This point can be appreciated by reviewing Fig. 9a and b which shows the variation of the impedance at the specified frequencies with SoC for cycles A9 through A38.

It is also desired to predict the available full-charge capacity based on this reduced data set. The variation of full-charge capacity with cycle number is displayed in Fig. 10 Also shown is the variation of the real component of the impedance (at 10, 251.1, 3981.1 Hz) of the fully charged battery with cycle number. It is to be noticed that as the battery is cycled the available capacity at full-charge decreases while it's impedance (at full-charge) increases. Fig. 11a and b show, for the battery at full-charge, the variation of the full-charge capacity with the real component and the imaginary component of the impedance, respectively.

4.2. Fuzzy logic SoC model

A Fuzzy Logic model was developed using MATLAB and the Fuzzy Logic Toolbox for MATLAB to predict the SoC of the 3-cell 2.7 Ah Sanyo Ni/MH battery. A 5-input, 1-output model was developed, using the Sugeno Inference approach. In order that the FL-model be able to accurately predict

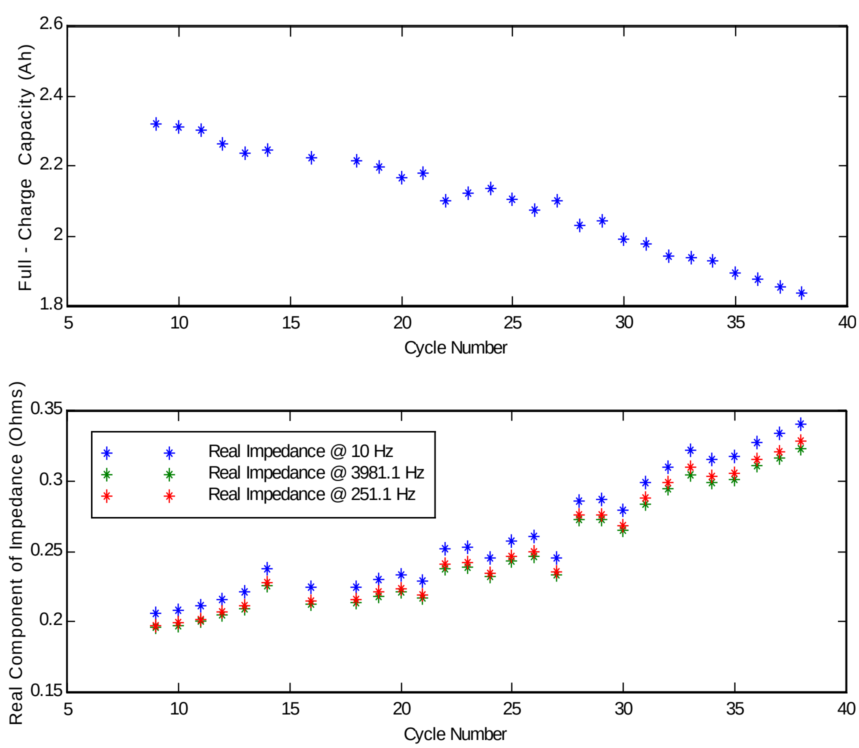

Fig. 10. The full-charge capacity (top) and the real component of the impedance (bottom) vs. cycle number for 3-cell 2.7 Ah Sanyo Ni/MH battery. *Note*: Cycle A9–A38 correspond to the 109th and 138th cycle, respectively, of the battery.

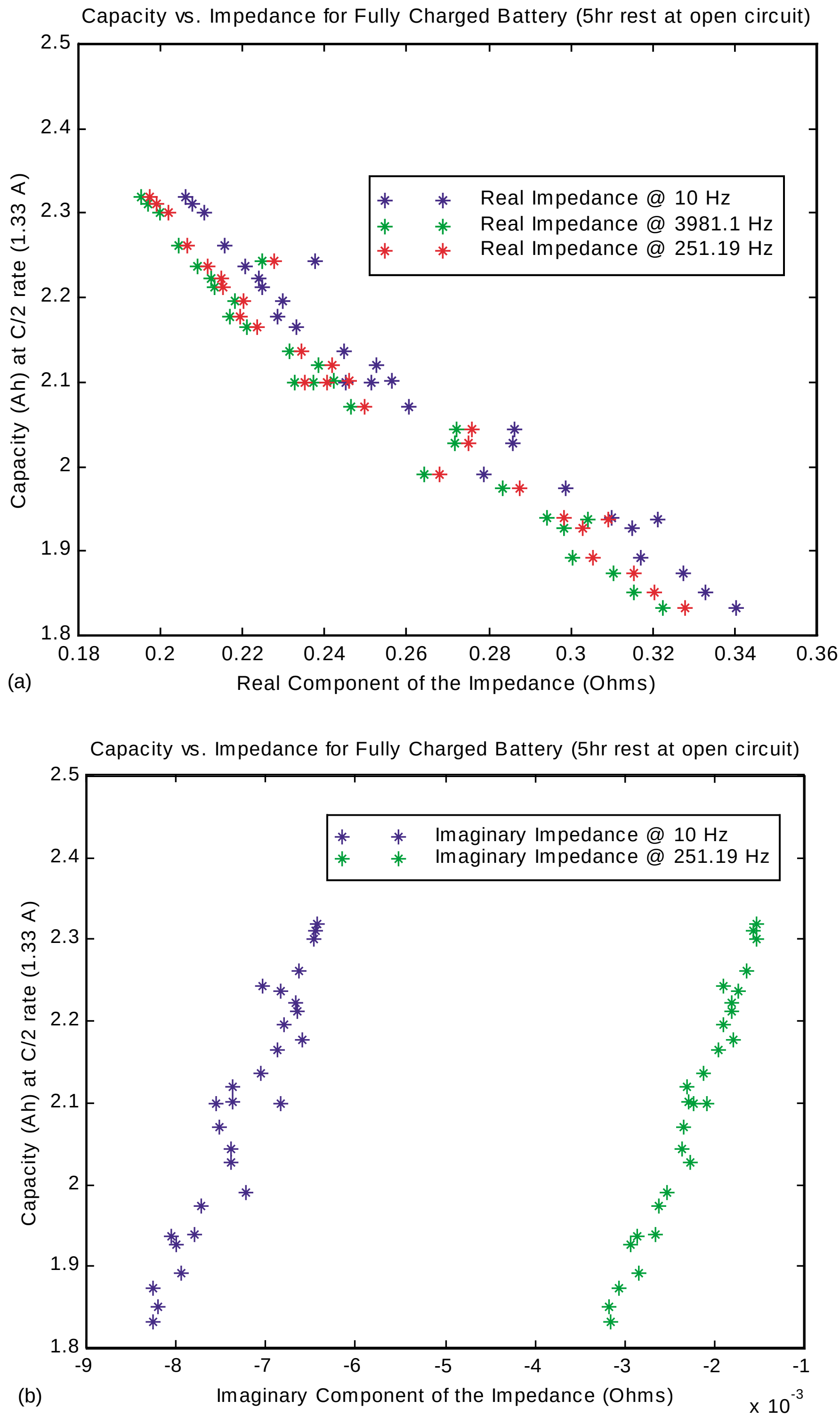

Fig. 11. (a) Variation of the full-charge capacity with the real component of the impedance for 3-cell 2.7 Ah Sanyo Ni/MH battery. (b) Variation of the full-charge capacity with the imaginary component of the impedance for 3-cell 2.7 Ah Sanyo Ni/MH battery.

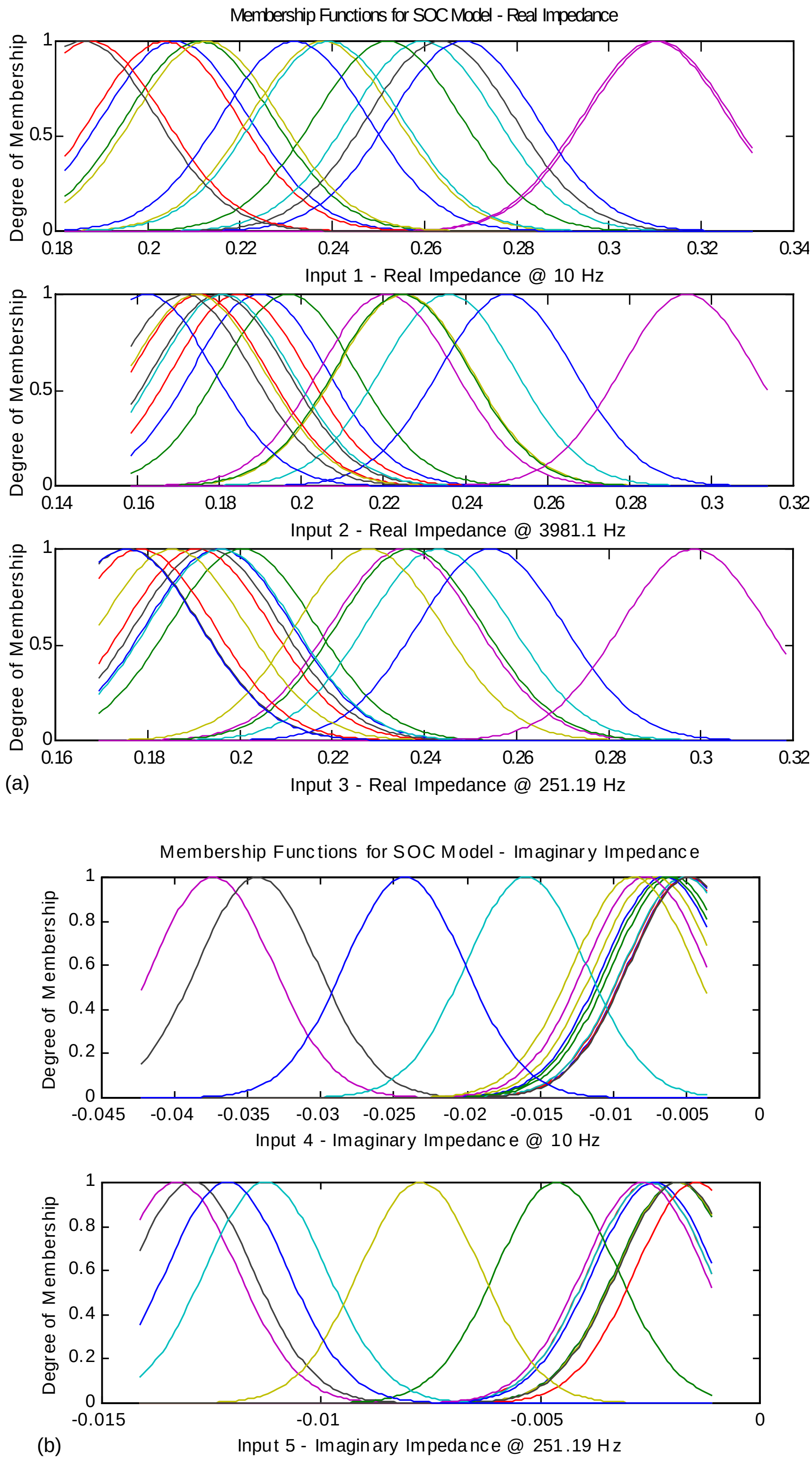

Fig. 12. (a) Membership functions for FL SoC-model, inputs 1–3, real component of the impedance. (b) Membership functions for FL SoC-model, inputs 4–5, imaginary component of the impedance.

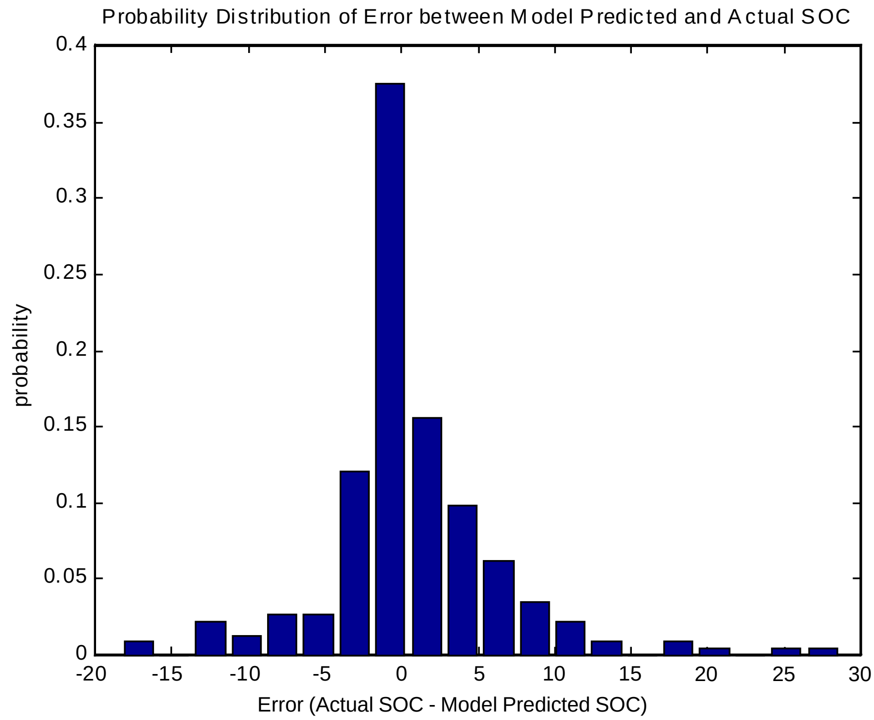

Fig. 13. Probability distribution of error between actual SoC and FL-model predicted SoC.

the SoC of the battery irrespective of the initial capacity, a "training" data set was developed that used EIS data from cycles A9, A10, A13, A14, etc. while a testing data set was developed using EIS data from all the cycles. Clustering algorithms were used to find the membership functions and the rules.

The input membership functions are shown in Fig. 12a and b. The output membership functions are first order polynomials consistent with the Sugeno inference approach. Fifteen rules of the type:

If (in1 is in1mf1) and (in2 is in2mf1) and (in3 is in3mf1) and (in4 is in4mf1) and (in5 is in5mf1) then (out1 is out1mf1) (1)

where:

in1—real component of the impedance @ 10 Hz
in2—real component of the impedance @ 3981.1 Hz
in3—real component of the impedance @ 251.1 Hz
in4—imaginary component of the impedance @ 10 Hz
in5—imaginary component of the impedance @ 251.1 Hz
out1—state-of-charge

were found. The probability distribution of the error between the FL-model predicted SoC and the actual SoC is shown in Fig. 13. Notice that the model predicts the SoC to within approximately ±5% SoC.

4.3. Fuzzy logic full-charge capacity model

Another fuzzy logic model was developed using MATLAB and the fuzzy logic toolbox for MATLAB to predict the full-charge capacity of the 3-cell 2.7 Ah Sanyo Ni/MH battery. A 5-input, 1-output model was developed, using the Sugeno Inference approach. Initially, from review of Figs. 9 and 11, it was thought that the full-charge capacity could only be predicted if the battery was fully charged, or perhaps if the SoC was first known. But it is strongly desired to be able to predict full-charge capacity at any SoC without explicit knowledge of such. Therefor the input training data (the impedance at the specified frequencies) used to develop the FL-model of SoC was used to develop the model of the available full-charge capacity, with the Full-Charge Capacity replacing the SoC as output. Clustering algorithms were again used to find the membership functions and the rules.

The input membership functions are shown in Fig. 14a and b. The output membership functions are again first order polynomials consistent with the Sugeno inference approach. Ten rules of the type:

If (in1 is in1mf1) and (in2 is in2mf1) and (in3 is in3mf1) and (in4 is in4mf1) and (in5 is in5mf1) then (out1 is out1mf1) (1)

where:

in1—real component of the impedance @ 10 Hz
in2—real component of the impedance @ 3981.1 Hz
in3—real component of the impedance @ 251.1 Hz
in4—imaginary component of the impedance @ 10 Hz
in5—imaginary component of the impedance @ 251.1 Hz
out1—available full-charge capacity (Ah)

were found. The probability distribution of the error between the FL-model predicted SoC and the actual SoC is shown in Fig. 15. Notice that the model predicts the full-charge capacity to within approximately ±0.05 Ah or to within a 2 min discharge at the $C/2$ rate (1.33 A).

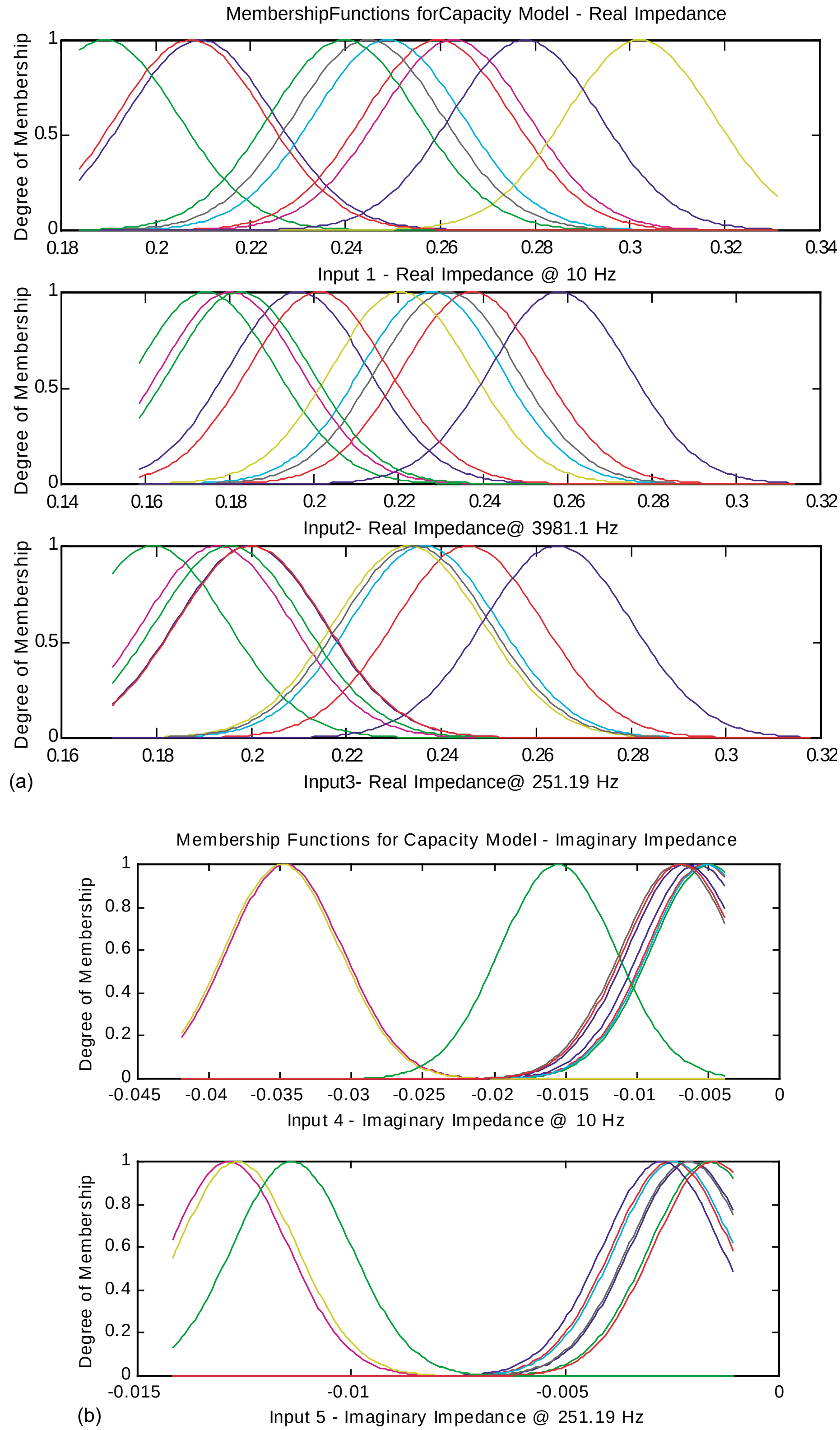

Fig. 14. (a) Membership functions for FL full-charge capacity model, inputs 1–3, real component of the impedance. (b) Membership functions for FL full-charge capacity model, inputs 4–5, imaginary component of the impedance.

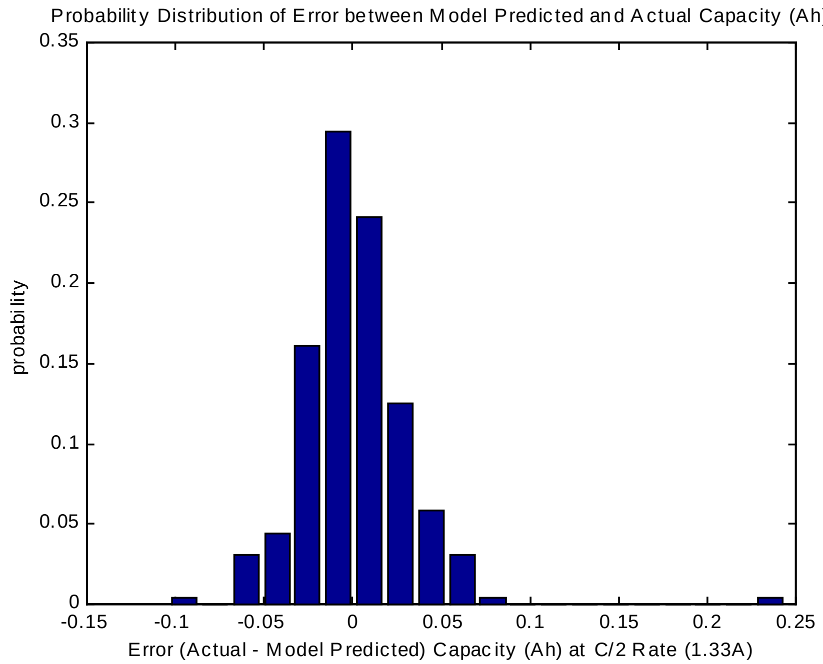

Fig. 15. Probability distribution of error between actual full-charge capacity and FL-model predicted full-charge capacity.

5. Conclusion

It was shown that a fuzzy logic model has been developed that takes as inputs the real and imaginary components of the impedance at 10 and 251.1 Hz and the real component of the impedance at 3981.1 Hz and outputs the SoC of a 3-cell 2.7 Ah Sanyo Ni/MH battery over 28 charge/discharge cycles of the battery. It is noteworthy that although the available full-charge capacity of the battery decreased by 20% from the first cycle (cycle A9, actual 109th cycle of the battery), used to develop the model to that of the last cycle (cycle A38, actual 138th cycle), the model predicted the SoC to within ±5% SoC.

Also a second FL-model has been developed that takes as inputs the same five values of impedance as those of the FL-SoC model and that outputs the available full-charge capacity. It is to be noted that although the impedance at the specified frequencies change with both available full-charge capacity and SoC, the FL-model is able to predict the available full-charge capacity to within ±0.05 Ah (or to within 2 min discharge at the *C*/2 rate) without explicit knowledge of the battery's SoC.

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