Fuzzy Logic-Based State-of-Health Determination of PEM Fuel Cells

Craig Fennie and David Reisner
US Nanocorp, Inc.
74 Batterson Park Rd.
Farmington, CT 06032

Joseph Barbetta
RECON Industrial Controls
9 East Sheffield Ave.
Englewood, NJ 07631

Pritpal Singh
Dept. of Electrical and Computer Engineering
Villanova University
Villanova, PA 19085

Abstract

Proton exchange membrane (PEM) fuel cells are being rapidly developed as the primary power source for advanced electric vehicles. The monitoring and control of these fuel cells is very important to ensure long life and reliable performance of these devices. In this paper we present a novel technique, based on the combination of impedance measurements, current-voltage measurements, and fuzzy logic data analysis, for the prediction of the state-of-health (SOH) of PEM fuel cells.

Galvanostatic electrochemical impedance spectroscopy (EIS) measurements were made on four different 5W H-Power PEM fuel cell stacks over a frequency range of 0.1Hz to 1 kHz at both open-circuit and with a small 10mA loading of the fuel cell stack. Also, the current-voltage characteristics of the stacks were measured over a range of 0-1A. The measurements were made under simulated conditions of flooding of the air channels, followed by purging of the channels with dry air; and under simulated conditions of membrane dryout, followed by membrane rehumidification.

Following membrane dryout, the magnitude of the impedance of the fuel cell stack was seen to increase. As the membrane became steadily rehumidified, the impedance magnitude was seen to correspondingly decrease. Flooding of the air channels resulted in very little change in the impedance of the fuel cell stacks but significant changes in the current-voltage characteristics of the stack were observed under this simulated failure condition.

The data from two of the fuel cell stacks were used to develop a fuzzy logic model to predict the SOH of the fuel cell stacks and data from the other two fuel cells were used to test the model. It was found that the fuzzy logic model was able to predict the SOH of the fuel cells under all failure modes, almost 90% of the time. This is an excellent result, particularly when the sample size that was used for developing the fuzzy logic model was so small.

Introduction

Proton exchange membrane (PEM) fuel cells are being rapidly developed as the primary power source for advanced electric vehicles. Several fuel cell companies are ramping up their production capabilities and increasing their development efforts to reduce the cost of fuel cell stacks, preparing for introduction of fuel cell stacks for commercial, residential and transportation applications. The monitoring and control of these fuel cells is very important to ensure long life and reliable performance of these devices. Diagnosing the state-of-health (SOH) of a fuel cell stack, particularly a soft, non-catastrophic failure and adjusting the gas flow rates, stack temperature, and other control variables for the fuel cell stack to compensate for changes in the behavior of the stack can improve the reliability of the stacks, improve the operating efficiency of the stack, as well as potentially extend the operating life of the fuel cell stack.

In this paper we present a novel technique, based on the combination of impedance measurements, current-voltage measurements, and fuzzy logic data analysis, for the prediction of the state-of-health (SOH) of PEM fuel cells.

PEM fuel cells suffer a variety of failure modes, some common to most types of fuel cell, and some specific to PEM fuel cells. Fuel cell failures can be either soft or catastrophic. An example of a soft failure that has been extensively explored in the present study is that due to 'Dry-Out' of the Nafion® membrane. A catastrophic failure that has been studied is that due to water buildup in the air channels of a fuel cell or 'Flooding'. Although catastrophic is the sense that the failure occurs by total loss of an individual cell or cells (where as is 'Dry-Out' a slight overall degradation of performance is observed in all four cells of the stack), failure due to 'Flooding', as well as that due to 'Dry-Out' are recoverable failures.

Two failure modes of PEM fuel cells were investigated using Electrochemical Impedance Spectroscopy (EIS) and Current/Voltage (I/V) measurements. These failure modes, membrane 'Dry-Out' and 'Flooding' of the air channels, occur commonly during operation of PEM fuel cells and can temporarily or permanently adversely affect performance. In order to collect the necessary data to detect and predict such failures, methods had to be developed to reproducibly generate, and recover from, the 'Dry-Out' and 'Flooding' failure modes. The next section describes how these failure modes and recovery from them was simulated.

Experimental Procedure for generating reproducible failure modes.

Commercially available equipment has been used for all experimental tests. This included:

1) one of four H Power PowerPEM™ 5 W (4-cell stacks) fuel cell stacks connected to an air pump, hydrogen purge valve, 7 PSI hydrogen pressure regulator, and a 0.997% dry hydrogen source.
2) a Recon fuel cell controller, which measures the fuel cell current voltage, and temperature, and controls the fuel cell air flow and periodic hydrogen purge.
3) a Recon fuel cell profiler, which monitors individual cell voltages.
4) an exit air humidity meter to infer membrane moisture content.
5) a PAR 273A potentiostat/galvanostat, to interface the fuel cell with the frequency response analyzer (FRA) (see 6).
6) a Solartron 1250 FRA to generate the EIS current signal and measure the gain and phase relationship of the resultant voltage signal.
7) Zplot and Corrware software by Scribner Associates to control the PAR 273A and Solartron 1250 in order to collect the EIS data.

Membrane 'Dry-Out' Failure Mode

As mentioned above one failure mode investigated was membrane dry out. High operating temperatures, high air flow rates, or low air humidity may cause one or more of the membranes of the fuel cell stack to dry out. A membrane with insufficient moisture content can have poor electrical conductivity that can lower the power performance due to a lower than expected voltage to current ratio.

The failure was produced by passing heated air at a much higher than normal flow rate through both the air and hydrogen channels of the fuel cell for 2 hours. The fuel cell was then connected to the test setup and run normally with the humidity meter monitoring the exit air humidity.

An I/V current / voltage test was then performed by measuring the fuel cell voltage as the current was ramped from 0A to 1A in 10 seconds. The lower slope of the I/V curve indicated the low performance due to the membrane's higher impedance. EIS data was then taken on the fuel cell in this membrane dry out condition.

The fuel cell was then run at a constant current of 1A to generate water internally at the membrane to accelerate the fuel cell's recovery from the dry out condition. This situation was interrupted periodically to perform additional I/V and EIS tests. The exit air humidity rise was also monitored to help determine when the fuel cell was back to its normal operating conditions with a fully moistened membrane.

‘Flooding’ Failure Mode

Another failure mode investigated was flooding. Poor internal water management, low air flow rates, or high air humidity may cause one or more of the individual cells of the fuel cell stack to flood. This excess water interferes with the transport of the reactant gases and thus degrades performance. The flooding may be local to a section of the cell or uniform across the cell. The degradation in performance can manifest itself as a drop in open circuit voltage or a low voltage to current ratio.

The failure was produced by injecting 10 to 15 ml of deionized water into the air channels of the fuel cell. This resulted in the water interfering with the air flow through the air channels. The fuel cell was then connected to the test setup and run normally.

An I/V current / voltage test was then performed by measuring the fuel cell voltage as the current was ramped from 0A to 1A in 10 seconds. The voltage of individual cells was monitored to determine a failure. The I/V test was repeated as necessary to cause one or more cells to fail. An EIS test was performed during the failure of one or more cells. The air flow rate was then increased momentarily to purge any excess water to accelerate the recovery from flooding and then additional I/V and EIS tests were performed.

Collection of Electrochemical Impedance Spectroscopy (EIS) and Current/Voltage (I/V) Data in PEM fuel cells

As previously mentioned EIS and I/V data sets have been collected on Four H Power PowerPEM^{TM} 5 W (4-cell stacks) to characterize the various stages of a particular fuel cell failure. A standard test protocol was developed so as to ensure testing consistency. The following sequence of events was followed in every test:

Test Procedure

1) Produce failure, *i.e.* Dry Out, Flooding.
2) EIS measurement, 0mA bias.
3) EIS measurement, 10mA bias.
4) I/V test, 0 to 1 A ramp current in 10s.
5) Perform corrective measure.
6) Repeat steps 2-5 until failure mechanism recovered.

All EIS measurements were performed over the frequency range of .05 Hz – 10kHz in galvanostatic mode in which a 10 mA amplitude sinusoidal current signal was applied to the fuel cell stack and the resultant voltage signal was measured.

The EIS and I/V data collected on all four stacks were used to develop and test the Fuzzy Logic model. The four fuel cell stacks were labeled, A, B, C, and D. Data from fuel cell stacks B and C were used to develop the models and the models were tested on stacks A and D. In the sections below, data for stack ‘A’ are presented in detail.

EIS and I/V Data in PEM fuel cells- ‘Dry-Out’ Failure Mode

Fig. 1a shows the magnitude of the impedance as a function of frequency at four different degrees of dry out for fuel cell stack ‘A’. The black curve shows the impedance plot for the dried out membrane (following 2hrs of hot air flow through the air and hydrogen channels to dry out the membrane.) The correction curves are for 2 minutes (red), 5 minutes (blue), and 10 minutes (green) of normal operation, in which the membrane becomes rehumidified. The highest impedance curve is observed to be the dried out membrane curve and as the membrane becomes progressively more rehumidified, the impedance is observed to monotonically decrease. Fig. 1b shows the phase angle as a function of frequency for the same fuel cell stack ‘A’ at the same four degrees of dry out as in Fig. 1a. Similar monotonic behavior with increasing rehumidification of the membrane is observed in the phase angle at high frequencies (above 80Hz). The measurements shown in Figs. 1a and 1b were taken at open circuit conditions, i.e. the fuel cell stack was not loaded with any current draw.

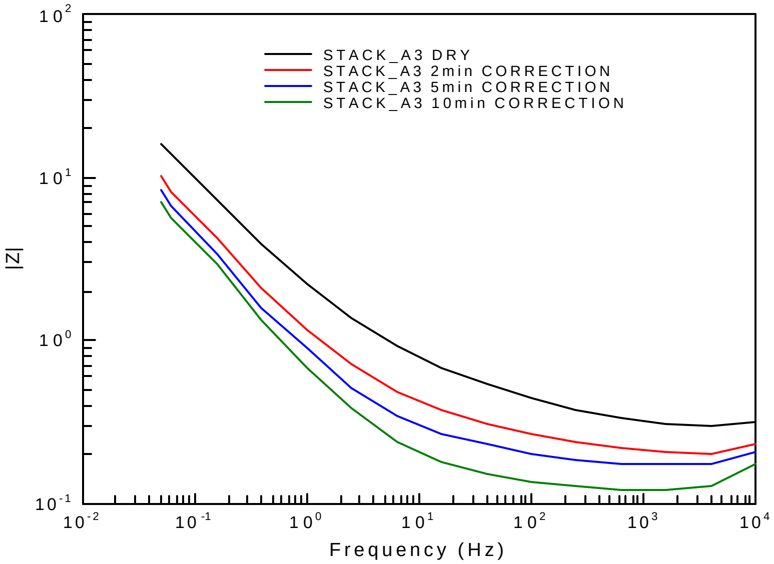

Fig. 1a. Magnitude of the Impedance |Z| vs. Frequency (Hz.) of a H Power PowerPEM™ 5 W (4-cell stacks) fuel cell for various Stages of '*Dry-Out*' Failure Mode - STACK 'A', 0 mA biased EIS.

Fig. 2 shows the fuel cell stack voltage as a function of the load current drawn from the stack for fuel cell stack 'A' for the same dry out conditions as in Fig. 1. Starting at open-circuit conditions, the voltage initially drops quickly as the fuel cell stack is loaded (up to about 25% of the maximum load current) beyond which the fuel cell stack voltage is seen to decrease in a linear manner. The open-circuit voltage is slightly depressed (by about 0.2V) with the membrane in its maximum dried out condition. However, even two minutes of normal operation results in recovery of the full open-circuit voltage. The slope of the linear segments is seen to decrease with progressive recovery from the Dry Out failure mode, indicating a lower impedance of the fuel cell, consistent with the impedance observations. Finally, the voltage under maximum load current is seen to monotonically increase with increased rehumidification of the membrane.

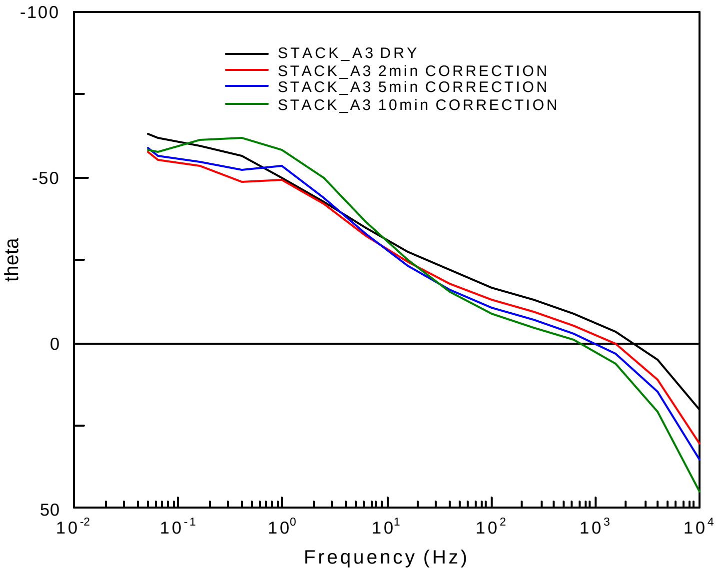

Fig. 1b. Phase Angle of the Impedance Q vs. Frequency (Hz.) of a H Power PowerPEM™ 5 W (4-cell stacks) fuel cell for various Stages of '*Dry-Out*' Failure Mode - STACK 'A', 0 mA biased EIS.

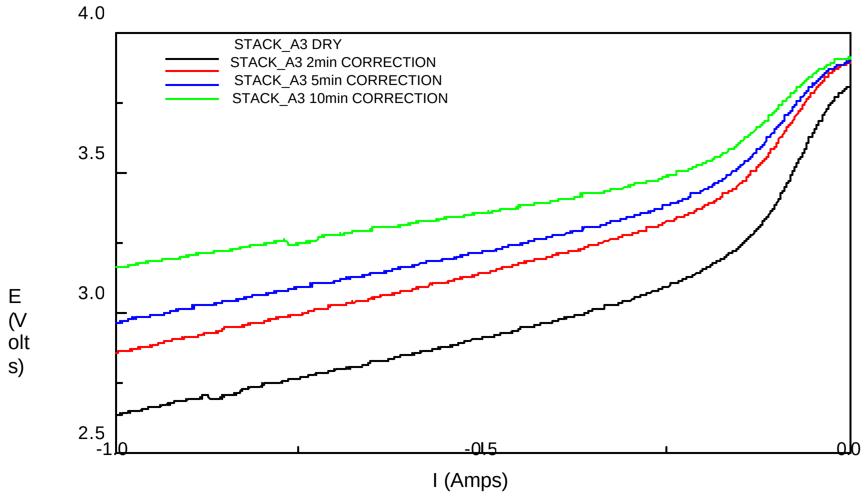

Fig. 2. Current/Voltage (I/V) Characteristics of a H Power PowerPEM™ 5 W (4-cell stacks) fuel cell for various Stages of '*Dry-Out*' Failure Mode - STACK 'A'.

EIS and I/V Data in PEM fuel cells- 'Flooding' Failure Mode

Fig. 3 shows the magnitude (Fig. 3a) and phase angle (Fig. 3b) as a function of frequency for fuel cell stack 'A' under different flooding conditions. The black curve represents the impedance immediately following injection of the water into the air channels at open-circuit conditions. It was observed that the flooding failure was induced only after the fuel cell stack had been loaded. Thus, the red curves in the figures represent the impedance characteristics measured following a current ramp excursion to the maximum load current which caused the stack to fail. The third curve in the figures, the blue curve, represents the impedance measurements following a purging of the air channels which resulted in the recovery of the fuel cell stack from the flooding failure mode. At high frequencies, the magnitude of the impedance is observed to be independent of the flooded condition of the stack. However, at low frequencies, below about 5 Hz, a small separation of the impedance curves is observed under different flooding conditions. Similarly, monotonic changes in the phase angle of the stack is observed over a frequency band of approximately 10Hz to 100Hz with different flooding conditions.

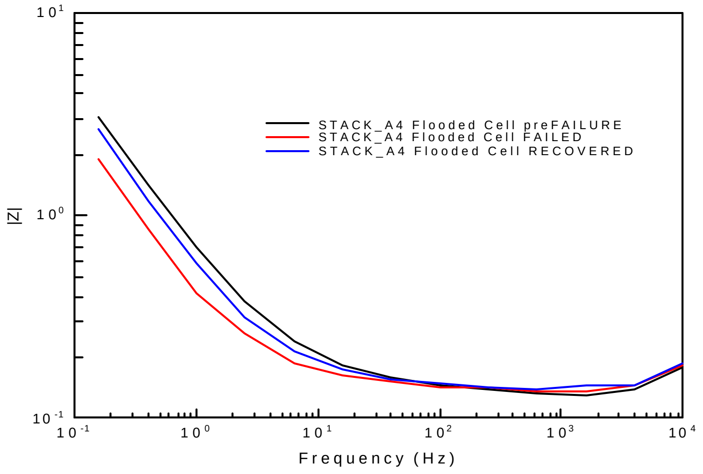

Fig. 3a. Magnitude of the Impedance |Z| vs. Frequency (Hz.) of a H Power PowerPEM™ 5 W (4-cell stacks) fuel cell for various Stages of '*Flooding*' Failure Mode - STACK 'A', 0A

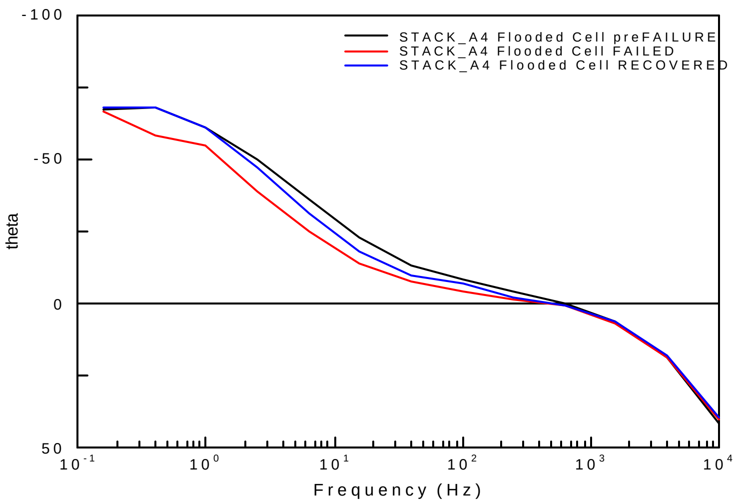

Fig. 3b. Phase Angle of the Impedance Q vs. Frequency (Hz.) of a H Power PowerPEM™ 5W (4-cell stacks) fuel cell for various Stages of *'Flooding'* Failure Mode - STACK 'A', 0 mA biased EIS.

Fig. 4 shows the I/V measurements on fuel cell stack 'A' for three 'Flooding' conditions. The black curve labeled 'Pre-failure' was measured immediately after the water was injected into the air channels. As can be seen, there is little noticeable failure of the fuel cell stack until the fuel cell is loaded to about 50% of the maximum load current after which the voltage depresses significantly compared to a healthy fuel cell stack. Following the 'Pre-failure', the cell is brought back to open-circuit and the current load ramp reapplied. The red curve in Fig. 4 shows the fuel cell output voltage as a function of the load current following the second current ramp. It is clear from this curve that a single cell in the stack has failed as a result of flooding. The air channels are then blown dry and the blue curve of Fig. 4 shows the I/V characteristics of the fuel cell stack following the purging of the air channels. Clearly the failed cell has recovered and the fuel cell stack has returned to its original healthy condition.

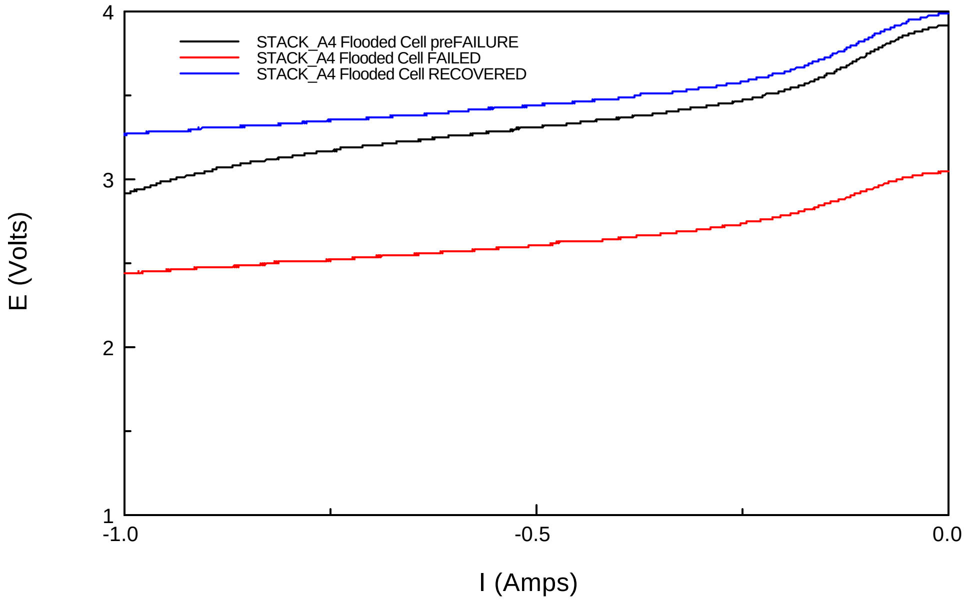

Fig. 4. Current/Voltage (I/V) Characteristics of a H Power PowerPEM™ 5 W (4-cell stacks) fuel cell for various Stages of *'Flooding'* Failure Mode - STACK 'A'.

Preprocessing of Electrochemical Impedance Spectroscopy (EIS) and Current/Voltage (I/V) Data Sets

To make a low-cost, practical diagnostic system for PEM fuel cells the acquired EIS and I/V data sets that characterize the various stages of the ‘Dry-Out’ and of the ‘Flooding’ failure modes, must be reduced to a form that can be easily manipulated by fuzzy logic models. For the EIS data, this involves finding one or more frequencies where the variation in the magnitude and/or phase angle of the impedance can provide “some discrimination” between the different failure modes and a healthy fuel cell. For the I/V data sets, this data reduction involves finding a feature of the performance curve, such as the sum and the difference of the initial voltage and final voltages of the I/V test. As indicated, each feature must provide some discrimination among the various modes of fuel cell operation, but the impedance at the determined frequency (EIS) and the extracted I/V features do not have to separately provide a unique measure of this mode, for as we have seen the variation in impedance for a ‘Flooded’ and a ‘Healthy’ fuel cell is very small while the variation in the I/V characteristics are substantial. A key attribute of the FL approach is the ease with which several related and/or unrelated measures, each containing only partial information of a particular state of a system, can be combined to predict the state of the system.

In order to be able to quantify the SOH of the fuel cell and to indicate the degree of failure either in the direction of membrane ‘Dryout’ or air channel ‘Flooding’, a scale needed to be developed. The following scale based on a 1-10 range was proposed with a rating of 5, 6 representing a ‘healthy’ fuel cell stack, low numbers representing a ‘Flooding’ failure with lower numbers corresponding to increased degree of failure by ‘Flooding’, and higher numbers than 6 representing a ‘Dryout’ failure with higher numbers indicative of a higher degree of membrane dryout.

1	2	3	4	5	6	7	8	9	10
‘Flooding’				‘Healthy’				‘Dry-Out’	

The criteria for assigning these numbers was non-rigorously established for each failure mode, and needs to be further developed in Phase II. The scale representing the degree of ‘Dry-Out’ is roughly based on the impedance of the cell, for in the previous section it was shown that the impedance monotonically increases for a particular fuel cell with the degree of ‘Dry-Out’. The scale for the ‘Flooded’ condition was based on the open-circuit voltage and voltage under maximum load current of the fuel cell during the I/V performance test. For instance if it was shown that open-circuit voltage of a fuel cell during the I/V test was roughly 2 V the degree of ‘Flooding’ was assigned a ‘2’, while if the open-circuit voltage was roughly 3.8 V but still failed during the I/V test, the degree of flooding was assigned a value of ‘4’. Although this assignment is somewhat arbitrary, what is meaningful at this stage of development is that stacks labeled ‘1’ through ‘4’ are failed fuel cells due to ‘Flooding’, stacks labeled ‘7’ through ‘10’ are failed fuel cells due to ‘Dry-Out’ while stacks labeled ‘5’ and ‘6’ are both ‘Healthy’ fuel cells that have recovered from a particular failure.

Fuzzy Logic Model – Prediction of Failure Mode

A Fuzzy Logic (FL) model was developed using MATLAB and the Fuzzy Logic Toolbox for MATLAB [5]. A 3-input, 1-output model was developed, using the Standard Additive Model (SAM) Inference approach [4] to determine whether or not a fuel cell failure had occurred, and if one had occurred, predict the particular failure mode. An initial step in developing a FL model is to divide the collected data into two sets. One set labeled “training” data will be used to construct the FL model. Another data set labeled “testing” data will be used to test the accuracy and robustness of the constructed FL model. The “training” data consists of ‘Healthy’ and ‘Failed’ (both ‘Flooded’ and ‘Dry-Out’) data from two fuel cells only, stack B’ and stack ‘C’, while the testing data consists of data collected on the remaining two stacks (‘A’ and ‘D’). In constructing the model a clustering algorithm, in particular Subtractive Clustering, was used to find initial membership functions and rules. Further enhancement of the SAM model could easily be performed using gradient descent-based supervised learning algorithms if necessary. Table 1 shows the extracted rules while Figs 5 a-c show the membership functions for this model.

Table 1. Fuzzy Logic Model I - Failure Mode Prediction Rules.
H Power PowerPEM^{TM} 5 W (4-cell stacks) fuel cell.

1. **If** (in1 is in1mf1) *and* (in2 is in2mf1) *and* (in3 is in3mf1) **then** (Healthy)
2. **If** (in1 is in1mf2) *and* (in2 is in2mf2) *and* (in3 is in3mf2) **then** (Failure is Dry Out)
3. **If** (in1 is in1mf3) *and* (in2 is in2mf3) *and* (in3 is in3mf3) **then** (Healthy)
4. **If** (in1 is in1mf4) *and* (in2 is in2mf4) *and* (in3 is in3mf4) **then** (Failure is Dry Out)
5. **If** (in1 is in1mf5) *and* (in2 is in2mf5) *and* (in3 is in3mf5) **then** (Failure is Dry Out)
6. **If** (in1 is in1mf6) *and* (in2 is in2mf1) *and* (in3 is in3mf1) **then** (Failure is Flooding)
7. **If** (in1 is in1mf7) *and* (in2 is in2mf2) *and* (in3 is in3mf2) **then** (Failure is Flooding
8. **If** (in1 is in1mf8) *and* (in2 is in2mf3) *and* (in3 is in3mf3) **then** (Failure is Flooding)
9. **If** (in1 is in1mf9) *and* (in2 is in2mf4) *and* (in3 is in3mf4) **then** (Failure is Flooding)
10. **If** (in1 is in1mf10) *and* (in2 is in2mf5) *and* (in3 is in3mf5) **then** (Failure is Dry Out)
11. **If** (in1 is in1mf10) *and* (in2 is in2mf5) *and* (in3 is in3mf5) **then** (Failure is Dry Out)

where input1 is real part of impedance @ 16 Hz
input2 is Voltage @ I=0A - Voltage @ I=1A
input3 is Voltage @ I=0A + Voltage @ I=1A

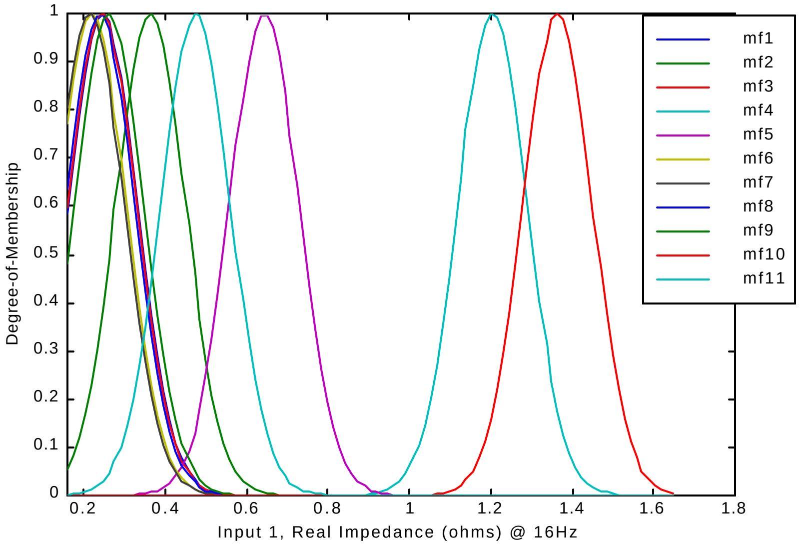

Fig. 5a. Fuzzy Logic Model Membership Functions, Input-1, Real Impedance (ohms) @ 16 Hz. H-Power PowerPEM^{TM} 5 W (4-cell stacks) fuel cell.

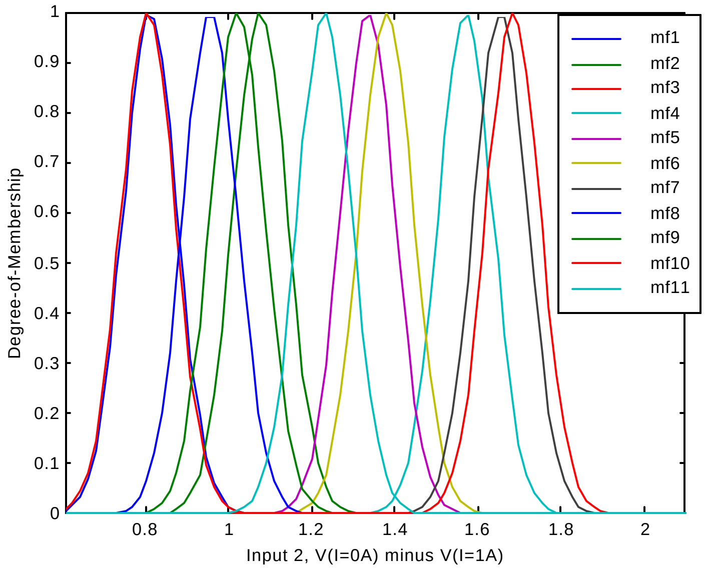

Fig. 5b. Fuzzy Logic Model Membership Functions, Input-2, Voltage @ I=0A minus Voltage @ I=1A. H-Power PowerPEM^{TM} 5 W (4-cell stacks) fuel cell.

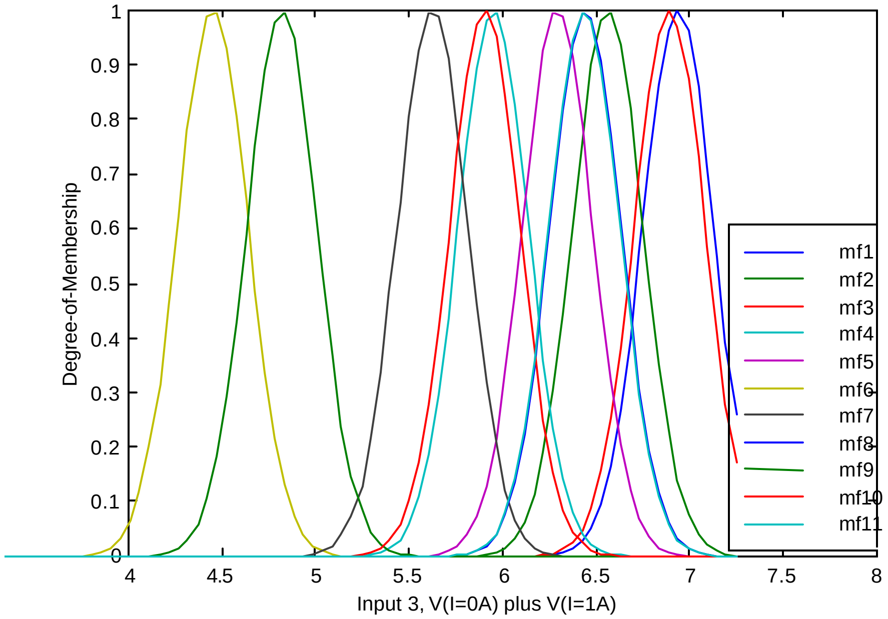

Fig. 5c. Fuzzy Logic Model Membership Functions, Input-3, Voltage @ I=0A plus Voltage@ I=1A. H-Power PowerPEM^{TM} 5 W (4-cell stacks) fuel cell.

Results and Discussion

The results of the FL model are summarized in Table 2. As can be seen the FL model correctly predicted whether or not a failure occurred, and if so what type of failure had occurred for the "training" data used in constructing the model (Stack 'B' and 'C'). It also correctly identified 13 out of 15 (87%) "test" data patterns from stacks not used in the construction of the model (Stacks 'A' and 'D'). In each misclassification the FL model predicted a 'Healthy' cell when in fact a failure had occurred, although the actual degree of failure in each case was within ± 1 of the 'Healthy' range. Noting the simplistic approach used to develop the model, and the limited data set, the model accuracy is very good. With collection of further EIS and I/V data sets, "fine tuning" of the model using supervised learning algorithms should further increase the accuracy and robustness of the model.

Conclusions

The goals of this project were to prove the feasibility of a novel fuzzy logic-based approach to determining the SOH of PEM fuel cell stacks. Three different failure modes needed to be simulated – dryout of the fuel cell stack's membrane(s), flooding of the air channels, and burn-through of a fuel cell membrane. We successfully developed techniques to simulate these PEM fuel cell failure modes. As the fuel cell stack failures were induced and recovered from, current-voltage performance tests and EIS measurements were taken. The data was collected on four 5W H-Power PEM fuel cell stacks. The EIS and I/V performance data from two of the fuel cell stacks were used to develop fuzzy logic models to estimate the SOH of the fuel cell stacks and data from the other two stacks were used to test the models. These models were found to successfully predict the SOH of the fuel cell stacks.

Table 2. Fuzzy Logic Model - Failure Mode Prediction Results.
H Power PowerPEM$^{\text{TM}}$ 5 W (4-cell stacks) fuel cell.

Stack – A. ‘Dry-Out’ Failure Test

Input 1	*Input 2*	*Input 3*	*Predicted Output*	*Actual Output*
0.6011	1.1800	6.4400	‘Dry-Out’	‘Dry-Out’
0.3360	1.0450	6.7550	‘Dry-Out’	‘Dry-Out’
0.2472	0.9400	6.8700	‘Healthy’*	‘Dry-Out’
0.1623	0.7550	7.0750	‘Healthy’	‘Healthy’

Stack – A. ‘Flooding’ Failure Test

Input 1	*Input 2*	*Input 3*	*Predicted Output*	*Actual Output*
0.1696	1.0050	6.8250	‘Flooded’	‘Flooded’
0.1570	0.6050	5.4850	‘Flooded’	‘Flooded’
0.1651	0.7200	7.2500	‘Healthy’	‘Healthy’

Stack – B. ‘Dry-Out’ Failure Test

Input 1	*Input 2*	*Input 3*	*Predicted Output*	*Actual Output*
1.2047	1.5700	5.9500	‘Dry-Out’	‘Dry-Out’
0.4748	1.2300	6.4400	‘Dry-Out’	‘Dry-Out’
0.3182	1.0150	6.6650	‘Dry-Out’	‘Dry-Out’
0.2680	0.8350	6.8650	‘Healthy’	‘Healthy’

Stack – B. ‘Flooding’ Failure Test

Input 1	*Input 2*	*Input 3*	*Predicted Output*	*Actual Output*
0.2388	0.9550	6.4450	‘Flooded’	‘Flooded’
0.2185	1.3800	4.45007	‘Flooded’	‘Flooded’
0.2134	1.6550	5.6250	‘Flooded’	‘Flooded’
0.2317	0.8050	6.9950	‘Healthy’	‘Healthy’

Stack – C. ‘Dry-Out’ Failure Test

Input 1	*Input 2*	*Input 3*	*Predicted Output*	*Actual Output*
1.3647	1.6850	5.9050	‘Dry-Out’	‘Dry-Out’
0.6434	1.3350	6.2950	‘Dry-Out’	‘Dry-Out’
0.3637	1.0750	6.5650	‘Dry-Out’	‘Dry-Out’
0.2438	0.8050	6.8950	‘Healthy’	‘Healthy’

Stack – C. ‘Flooding’ Failure Test

Input 1	*Input 2*	*Input 3*	*Predicted Output*	*Actual Output*
0.2604	1.0200	4.8200	‘Flooded’	‘Flooded’
0.2458	0.8100	6.9400	‘Healthy’	‘Healthy’

Stack – D. ‘Dry-Out’ Failure Test

Input 1	*Input 2*	*Input 3*	*Predicted Output*	*Actual Output*
1.6486	2.0050	5.4550	‘Dry-Out’	‘Dry-Out’
0.8676	1.5950	5.9150	‘Dry-Out’	‘Dry-Out’
0.4854	1.2550	6.3050	‘Dry-Out’	‘Dry-Out’
0.2462	0.8200	6.8800	‘Healthy’	‘Healthy’

Stack – D. ‘Flooding’ Failure Test

Input 1	*Input 2*	*Input 3*	*Predicted Output*	*Actual Output*
0.2334	2.4000	4.5800	‘Flooded’	‘Flooded’
0.2059	0.9020	2.1040	‘Flooded’	‘Flooded’
0.2205	1.4450	6.2550	‘Healthy’**	‘Flooded’
0.2205	0.8550	7.1250	‘Healthy’	‘Healthy’

where
Input 1, real impedance (ohms) @16 Hz
Input 2, Initial Voltage (V) minus Final Voltage of I/V performance test
Input 3, Initial Voltage (V) plus Final Voltage of I/V performance test

* predicted ‘6’, actual ‘7’
* * predicted ‘5’, actual ‘4’

Note: Data of Stacks ‘B’ and ‘C’ were used to construct the model.