# Qualitative Model for stimation water content in PEM Fuel Cell

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***Abstract*— To maintain optimum performance of the electrical response of a fuel cell, a real time identification of the malfunction situations is required. Critical fuel cell states depend, among others, on the variable demand of electric load and are directly related to the membrane hydration level. The real time perception of relevant states in the PEM fuel cell states space, is still a challenge for the PEM fuel cell control systems. Current work presents the design and implementation of a methodology based upon fuzzy decision techniques that allows real time characterization of the dehydration and flooding states of a PEM fuel cell. Real time state estimation is accomplished through a perturbation-perception process on the PEM fuel cell and further on voltage oscillation analysis. The real time implementation of the perturbation-perception algorithm to detect PEM fuel cell critical states is a novelty and a step forwards the control of the PEM fuel cell to reach and maintain optimal performance.**

***Keywords- PEM Fuel Cell; Stimation wáter in the PEM fuel cell; Fuzzy decisión tree; Test Station Fuel Cell.***

## I. INTRODUCTION

The problem related to flooding and drying of the PEM fuel cell membrane is mentioned in [1,2] where both situations are proven to significantly deteriorate the electrical response of the fuel cell. These local phenomena caused by flooding in the electrochemical reaction area of the PEM fuel cell are referred in [3,4]. To detect such negative incidences or critical situations, off-line inspection techniques and expensive dedicated instruments are required, such as, the electrochemical impedance spectroscopy (EIS) [5] and the Nyquist diagrams to analyze the humidification degree of the membrane. Nowadays, Magnetic Resonance images (MRI) are also used to visualize the water content of the fuel cell membrane in operation [6]. Then, images are correlated with the output electric current and the fuel cell operating conditions. A method for the characterization of the flooding in the cathode, drying in the membrane and catalyst poisoning in the anode, is presented in [7,8], where two analytical models of the operation of the PEM fuel cell are validated from the results obtained analyzing the variations of the impedance spectra. Current work presents an innovative, low cost and ease to implement fuzzy technique, to real time detect the humidification degree of the membrane, so as to determine the dehydration and flooding critical state of the PEM fuel cell.

Current work presents an innovative technique, more economic, simple, non-invasive and easy to implement for monitoring and real-time control of the PEM fuel cell. The proposed technique allows the detection of the state defined as NORMAL from the ANORMAL (critic) states, such as, dehydration and flooding of the PEM fuel cell, using time series analysis of the voltage response of the fuel cell. This analysis permits the extraction of the relevant features or characteristics of the time voltage variation. Once the relevant features are selected and evaluated, a qualitative fuzzy model is proposed to classify the PEM fuel cell state.

## II. CHARACTERIZATION METHODOLOGY

### A. *The fuel cell*

The PEM fuel cell used in current work is a cell designed and built at the LERH endowed of corrugated bipolar plates. Parts from outside to inside of the fuel cell are: end plate 80x80mm2, seal 50x50mm, Teflon frame 50x50mm, and membrane electrode hot pressing assembly (Nafion 115) 55x55mm. Fig. 1.

To control the hydrogen and oxygen flows (MFC), the temperature (T), humidity (%HR) and pressure (P) of the reactant gases, as well as to measure the electrical resistance between cathode and anode and the current and voltage generated by the fuel cell, a test station has been used [9].

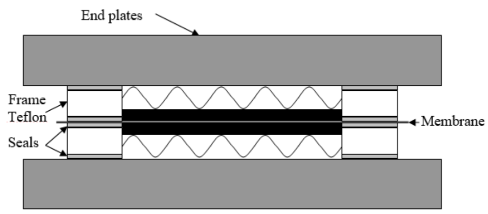


Figure 1. Cross section of the PEM fuel cell used in the experiments

### B. *Perturbation tests*

Three relevant PEM fuel cell states, corresponding to three different membrane humidification levels, were selected: DRYING, NORMAL and FLOODING. The standard operation condition described in [10] was used to fix the NORMAL state, while DRYING and FLOODING states were induced based upon previous experimentation results.

The experimental plan consists in the generation of different types of perturbation followed by the analysis of the temporal V-I electrical response. The proposed perturbations are: a) Load Step, that correpond to an increment or decrement current pulse of 40 mA, b) Current Oscillations, that is a low value oscillation of the current applied as a load, c) Flow Step, is an increment or decrement flow pulse in the cathode. This value has a direct relationship with the reference flow. These perturbations have been applied in three different points of the polarization curve V-I [10]. First point is the shortcircuit current [Icc], within the diffusion zone. Second one is located in the ohmnic losses zone and correponds to [Icc/2]. Finally, the third selected point, [Icc/10], is in the activation region. Consequently, global information of the fuel cell electrical behaviour is obtained.

### *C. Voltage analysis*

The analysis of the voltage evolution in time, once the perturbation is finished, aims to the extraction of relevant features to adequately describe the three states. Such features have to display very similar values for a particular state, as well as different enough values to discriminate among the three states. Thus, the analysis of the voltage evolution after a Load Step increment, left image in Figure 2, displays a greater decrease in the FLOODING state than in the two others. These results show that in the NORMAL state, final voltage values are caused more by the load values than by the fuel cell state. For this reason, it was decided to use normalized voltage values, to compare with higher reliability the voltage values among different levels and even in opposite directions by load increments or decrements.

The analysis of the voltage evolution under Current Oscillation perturbations, middle image in Fig. 3, shows a characteristic that permits the discrimination among the three states, that is, the higher the humidity the lower the voltage oscillation. The voltage evolution after a Flow Step perturbation, right image in Fig. 3, displays that flow increments give rise to decrements in the fuel cell voltage values, just opposite than in the former experiment.

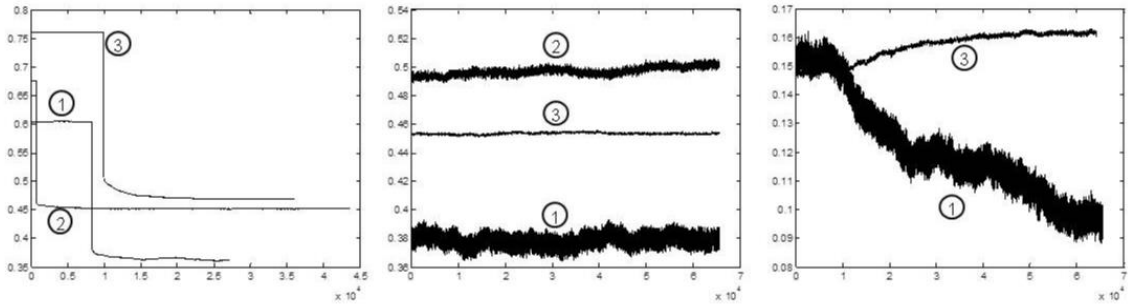

Figure 2. Temporal evolution of the voltage generated by the fuel cell in the three states under differents perturbance: 1 dry state; 2 normal state; 3 flooding state.

## III. QUALITATIVE MODEL OF DIAGNOSYS

### *A. Features extraction*

Once general trends of the fuel cell electrical behavior, once the perturbation process is finished, a set of features with high discrimination power have to be derived to be used in the automatic diagnosis of the fuel cell state based upon a qualitative model with fuzzy linguistic values. Linguistic values, described by means of fuzzy sets, are proposed as a way to embed the uncertainty inherent to the real systems measurements. To this aim some characteristic features are formulated for the state diagnosis of the fuel state. Normalized voltages are calculated, assigning value one to the initial voltage, and cero to the final voltage. These values vary linearly with measured voltages [3.1]

$$v(t) = \frac{V(t) - V_{fin}}{V_{ini} - V_{fin}} \qquad [3.1]$$

Where, v(t) is the normalized voltage in time t, V(t) the measured voltage in t, Vini the initial voltage averaged from a number of samples and Vfin the final voltage averaged after 15.000 samples, namely stabilization time. As this normalization procedure did not adequately succed to separate the three states, the point where the drop of the normalized voltage change its slope, namely SLOPE CHANGE point after a Load Step, is selected as a relevant feature. This feature corresponds to the fuel cell electrical response speed. The sensitivity to a Load Step perturbation is directly related to the membrane water content. Next selected feature is the VOLTAGE OSCILLATION amplitude after a Current Oscillation perturbation is performed. Its value is calculated from the mobile standard deviation [σv], for segments of n samples, [n<N] which are averaged [3.2].

$$\sigma_v = \frac{\sum_{i=1}^{N-n} \sqrt{\frac{\sum_{i=1}^{n} \left[V(i) - \bar{V}\right]^2}{n}}}{N-n} \qquad [3.2]$$

Where: $\bar{V}$ is the average voltage of *n* samples, equation and *N* the total number of samples.

Finally, the "delta voltage" parameter in the FLOW jump corresponds to the difference between the final voltage Vfin, after applying the disturbance, and the initial voltage of the cell Vini, before applying the disturbance [3.3].

$$\Delta V = \frac{V_{fin} - V_{ini}}{f} \qquad [3.3]$$

Where: *f* is a correction factor of sign.

*B. Fuzzy set of the features.*

The selected features: SLOPE CHANGE point and VOLTAGE OSCILLATIONS amplitude are defined as fuzzy variables, to frame the uncertainty inherent to real measurements and incomplete knowledge on the fuel cell. The fuzzy values of these variables are defined by means of fuzzy sets that have gradual transitions among them, and are defined by means of trapezoidal functions. Each numerical value belongs to one or two fuzzy sets with different membership degree [11]. The membership degree of any numerical values to a fuzzy set (fuzzy value) is showed, Fig. 3.

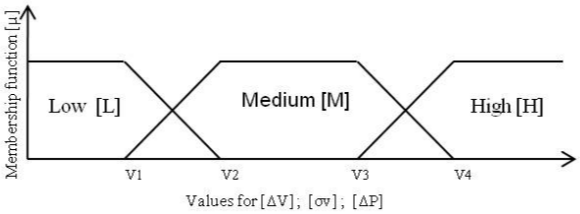


Figure 3. Representation of the fuzzy sets (Low, Medium, High) associated to the features

*C. Fuzzy decisión tree to diagnosis the water.*

This section presents the fuzzy decision tree as a classification technique in the diagnosis of the critical states of the fuel cell. Decision tree is a learning and classification method widely used due to the ease of organization and knowledge understanding. A decision tree basically represents a set of restrictions or conditions that are organized hierarchically, and are applied sequentially, in the tree, from a root node to a terminal node. Logic inferences are based upon a set of fuzzy rules. To induce the decision tree from a data set it is necessary to use an evaluation criterion for each feature to determine their priority [11]. In current study, the priority depends on the discrimination power of each selected feature for the state estimation, having the VOLTAGE OSCILLATION amplitude the highest priority, thus it is located in the root node. From this node, and depending on the measured values, the algorithm select the branch to reach the nodes of the next level and proceeds recursively to the terminal nodes (rectangles), that offer the estimation of the fuel cell state.

The calculation of the degree of membership of each branch, proceed as follows: **IF** to reach a state, several options are taken consecutively (similar to an "*and*" operator), equation [3.4], **THEN** their membership function values are multiplied, equation [3.5]. And, **IF**, a state can be reached through alternatively by various options (similar to an "*or*" operator), equation [3.6], **THEN** their membership function values are added, equation [3.7]. Finally, the state of the fuel cell is determined by the higher value of the combination of the membership degrees.

$$(\sigma v)high \wedge (\Delta P)high \qquad [3.4]$$

$$\mu(\sigma v)high \cdot \mu(\Delta P)high \qquad [3.5]$$

$$[(\sigma v)high \wedge (\Delta P)mediun] \vee [(\sigma v)mediun \wedge (\Delta P)high] \qquad [3.6]$$

$$[\mu(\sigma v)high \cdot \mu(\Delta P)mediun] + [\mu(\sigma v)mediun \cdot \mu(\Delta P)high] \qquad [3.7]$$

Even, rather than taking a single state it can be considered that the fuel cell is in more than one state at the same time, with a membership degree to each one, thus accounting for graduality and uncertainty in the state assessment.

## IV. RESULTS ANALISYS

A wide range of experiments have been accomplished to fit the vertices of the fuzzy sets for each feature and validate the state estimation using fuzzy techniques, for the three selected states of the fuel cell. The Fig. 4 illustrates the discrimination power of the feature VOLTAGE OSCILLATION amplitude. The image show a great dispersion of the values in the FLOODING estimation, due to the fact that experiments were accomplished under different humidity degrees.

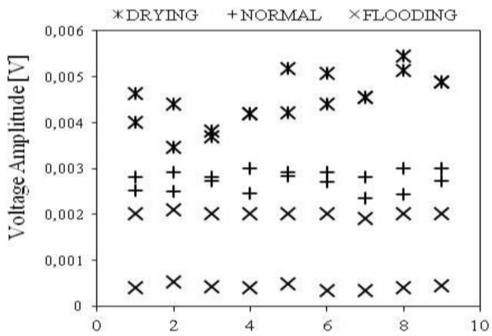


Figure 4. Reproducibility of experiments with the Voltage OSCILLATION amplitude

The Fig. 5, displays lower dispersion of the measured features for all three states. In spite of the dispersion in the FLOODING state there is not overlapping among the measured values for the selected features, pointing to the fact that both are good parameters for real time state diagnosis.

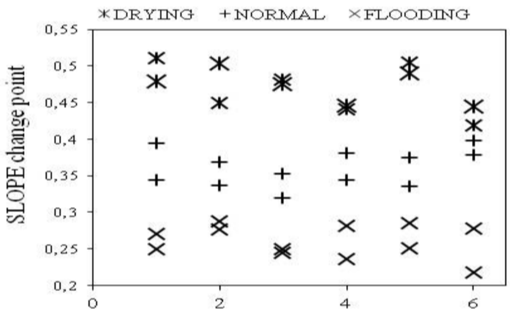


Figure 5. Reproducibility of experiments with the SLOPE CHANGE point

The jointly discrimination power of the two selected features, VOLTAGE OSCILLATION amplitude and CHANGE point is displayed in Fig. 6, were the three states are clearly separated. Highest values in both features correspond to the DRYING state zone, medium values to the NORMAL state area and lowest values to the FLOODING region. The results are in accordance with the knowledge embedded in the decision tree that use fuzzy values (fuzzy sets). Other combination of fuzzy values in the decision tree presents higher uncertainty, and would correspond to intermediate regions in the states space displayed in Fig. 6.

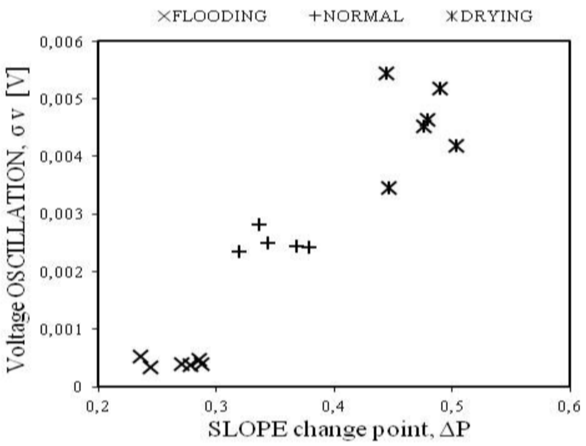


Figure 6. Voltage OSCILLATION versus change of SLOPE for the three states of the fuel cell: DRYING, NORMAL, FLOODING

Finally, electrochemical impedance spectroscopy (EIS) [12] was used to validate the fuel cell state estimation methodology here proposed. Preliminary results highlight that the dryer the fuel cell, the higher the membrane resistance [Rm] of the electrical equivalent derived from the experimental data of the impedance spectrum, reinforcing the fuel cell states discrimination method, here proposed.

The impedance spectra for DRY, NORMAL and FLOODING states of the fuel cell are exhibited in Fig. 7. The FLOODING state presents a slight overlap with the NORMAL state.

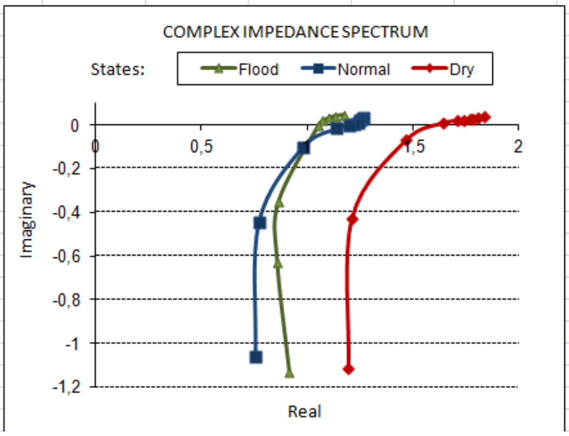


Figure 7. Complex impedance spectra for the three states of the PEM fuel cell

Then, making an extension on the real axis of the graph, it can be easily perceived the crossing point of the spectrum of impedance, Fig. 8. These results confirm that the drier is the membrane, furthest from the imaginary axis is the crossing point on the real axis of the impedance curve, the greater is the increase of the membrane resistance.

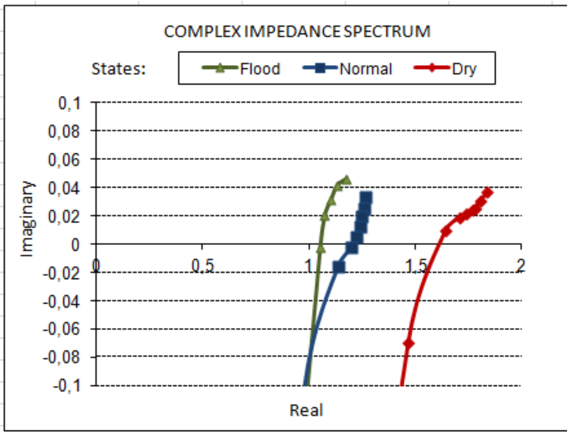


Figure 8. The crossing point on the real axis of the impedance spectra for the three states of the PEM fuel cell

## V. CONCLUSIONS

Current work presents the implementation of a methodology of perturbation of the fuel cell for real time detection of the critical states DRYING and FLOODING. The integration of fuzzy techniques and decision trees algorithms gives flexibility to the proposed qualitative model for fuel cell state diagnosis to gradually incorporate the detection of intermediate states. The discrimination power of the two selected features is very high as no overlapping is found among the three selected states in the bi-variable states space representation. The real time diagnosis process would permit the autonomous surveillance of the fuel cell by incorporating control actions to recover the system from critical states to get optimum performance of the fuel cell.

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