Approximate Reasoning Techniques in the Control of States of Operation of the PEM Fuel Cell

Wilton Agila
CIDIS - Faculty of Engineering in Electricity and Computation, FIEC
Escuela Superior Politécnica del Litoral, ESPOL
Guayaquil, Ecuador
wagila@espol.edu.ec
ORCID: 0000-0002-8117-7777

Abel Rubio
CIDIS - Faculty of Engineering in Electricity and Computation, FIEC
Escuela Superior Politécnica del Litoral, ESPOL
Guayaquil, Ecuador
grubio@espol.edu.ec
ORCID: 0000-0002-6057-4909

Jonathan Aviles
Faculty of Engineering in Electricity and Computation, FIEC
Escuela Superior Politécnica del Litoral, ESPOL
Guayaquil, Ecuador
joabavil@espol.edu.ec
ORCID: 0000-0002-3386-0643

Leandro González
The National Hydrogen and Fuel Cell Technology Testing Centre
Ciudad Real, Spain
leandro.gonzalez@cnh2.es

***Abstract* — Among the different types of fuel cells, the proton-exchange membrane fuel cell (PEMFC) has attracted a lot of interest as a power source for residential applications and electric vehicles. However, the development of new applications or the validation of new components of PEMFC fuel cells requires the characterization of their electrical response under certain conditions, both of operation (state variables) and power to be supplied (variation of electrical charge), as well as the degree of wetting of the membrane (operating state of the PEMFC considered Normal). Under this context, in this work a set of specific processes based on approximate reasoning techniques have been designed and implemented for the dynamic control of the wetting of the polymeric membrane.**

Keywords- PEM Fuel Cell, Fuzzy Controller, Fuzzy Numbers, Expert Agent.

I. INTRODUCTION

The most severe problems facing humankind, particularly the issue of energy sustainability, must be tackled by engineering sciences, taking the "bull by the horns." For this, the hydrogen fuel cell, in the context of the "hydrogen economy," constitutes a clean energy source with great potential for the present and the future [1, 2]. The PEMFC is an electrochemical device that converts chemical energy from fuel (H2) into electrical energy in a single step and produces water and heat as by-products. It exhibits favorable characteristics such as high power density, zero carbon emissions, low working temperature, fast startup capacity, and varied applications. On the other hand, its main disadvantages, such as cost, durability, performance, and stability, are of high interest in scientific research, given that, to overcome conventional devices, these aspects must be improved by optimizing its operating conditions [3].

Although the PEMFC operation is simple in concept, its electrical behavior depends, among other aspects, on the gas diffusion processes, the homogeneous distribution of H2 and O2 gases in the membrane [4], the mixed electron-proton conduction, the successful development of the anodic and cathodic reactions, and the management of the membrane humidity degree [5]. Excessive water produces stagnation, decreasing the electrical efficiency (H2 is wasted), and the lack of water causes dryness of the membrane, worsens its electrical performance, and shortens the life expectancy of the cell. This electrical response is not linear, with multiple interactions between structural and functional variables, which makes it difficult to establish a precise model to optimize its operation [6].

From the control engineering point of view, the PEM cell presents characteristics such as: a) A system of control variables to be characterized, which needs a comprehensive set of sensors, and that can be tackled with multiple simple control loops, mainly PID or PI, implemented in distributed systems and having the issue of the variable interrelation. b) Strongly coupled subsystems, for instance, the management of the water content inside the cell (humidification degree of the membrane), since its value is modified by variables such as temperature, the humidity of the injected gas, flow rate used, and even the load connected to the fuel cell. c) Lack of precise models of PEM fuel cells and their electrical behavior, so their control becomes highly restricted [7,8].

Considering that many studies conclude that their results are precise, the truth is that searching capacity and efficiency have improved, and precision is still a subject of analysis. Some studies only partially simulate different controllers with specific control objectives, leaving deficiencies in precision, stability, and robustness, which need to be addressed and improved. Issues such as noise in the I-V polarization curve data are yet to be analyzed [9]. This lack of integration constitutes a challenge and allows us to establish the objective of this study. In order, to optimize the integral response of the PEMFC, a control model based on approximate reasoning techniques for perception and action is proposed as the most appropriate methodology for achieving the objectives.

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After this introduction, the work is organized in the following sections. The experimentation scenario, where the main parameters and elements used for data collection, characterization and validation of the perception and control strategies that a human expert would follow in system control are explained. Subsequently, the knowledge is organized in the proposed control model section, where the perception and performance models are presented. In the results and discussion section, the results obtained in the operation of the PEMFC are explained in detail. Finally, the paper ends by presenting some conclusions.

II. TEST SYSTEM

The tests were conducted with a PEMFC (single cell) and a small 100 W stack (joining several single cells) with platinum-catalyzed carbon cloth electrodes, 0.58 mg Pt/cm^2, and an active area of 5 cm^2. The assembly was carried out with two types of seals; one made of silicone (1 mm) and another thinner one made of Teflon (0.2 mm) to cover the thickness of the central area. In this manner, the bipolar plates are not pressed on the electrode and do not lose the corrugated part. One of the most relevant characteristics is using corrugated stainless steel sheets as bipolar plates (Patent Ref. [10]). The advantage it presents over other types of bipolar plates is the ease of production since once the fabrication matrix has been built, the sheets are manufactured in short periods of time. Nevertheless, the manufacture of graphite or stainless steel bipolar plates requires computer numerical control (CNC) machines and highly qualified personnel, which increases their manufacturing time and cost [2w].

The Table 1 presents the different components of the PEMFC, from top to bottom respect to its assembly.

Table 1. Thickness and dimensions of the components of the PEM fuel cell.

Components	Thickness (mm)	Surface area (cm x cm)
Teflon gaskets and thin seals	1,4	7x7
Passive-aluminum corrugated bipolar plate	1,0	5x5
Electrode	0,35	5x5
Nafion-112 membrane	0,127	6x6
Electrode	0,35	5x5
Passive-aluminum corrugated bipolar plate	1,0	5x5
Teflon gaskets and thin seals	1,4	7x7

Fig. 3 shows an image of the PEM fuel cell stack final assembly. In the assembly, all the necessary parameters and requirements have been considered to guarantee good tightness and thus achieve efficient behavior.

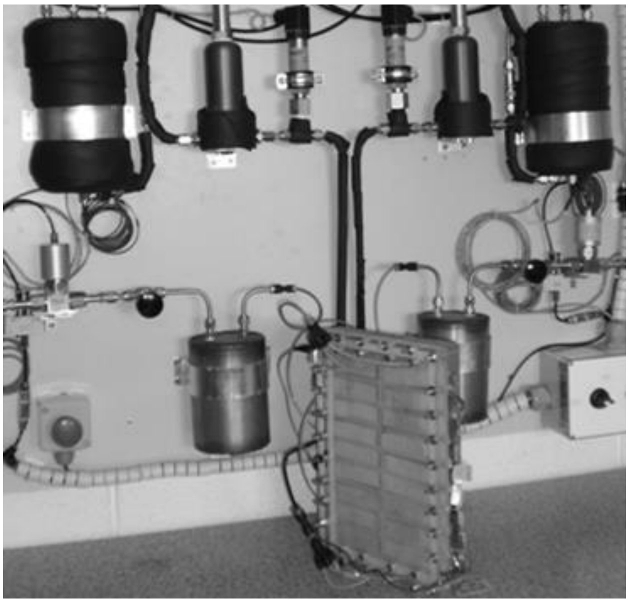

Figure 1. Final assembly of the PEM fuel cell stack.

To implement the characterization, control, and validation tests of the approximate reasoning algorithms in the control of the PEMFC, an integrated measurement and flexible control system is used, with a detailed explanation in [11]. In summary, this is an integrated automated system for the control of the PEM fuel cell, equipped with automatic action mechanisms and monitorization of state variables required for the generation of knowledge and smart decision-making.

III. KNOWLEDGE MODEL.

The smart and autonomous operation of the PEM fuel cell under optimal operating conditions requires characterization, identification, and real-time control of the operating state (estimation of the degree of water contained in the membrane) of the PEMFC. For the perception of the operation state, a qualitative model is implemented using a *fuzzy weighted average*, and for state control, a *closed-loop fuzzy controller* is utilized; Fig. 2. The use of approximate reasoning techniques both in the perception and in the control of the operation state of the PEM fuel cell is considered a good solution, not only because it is adequate to model the non-linearity inherent to the system, but, fundamentally, due to the existing uncertainty and the ease of translation in terms of control objectives easily describable linguistically [12].

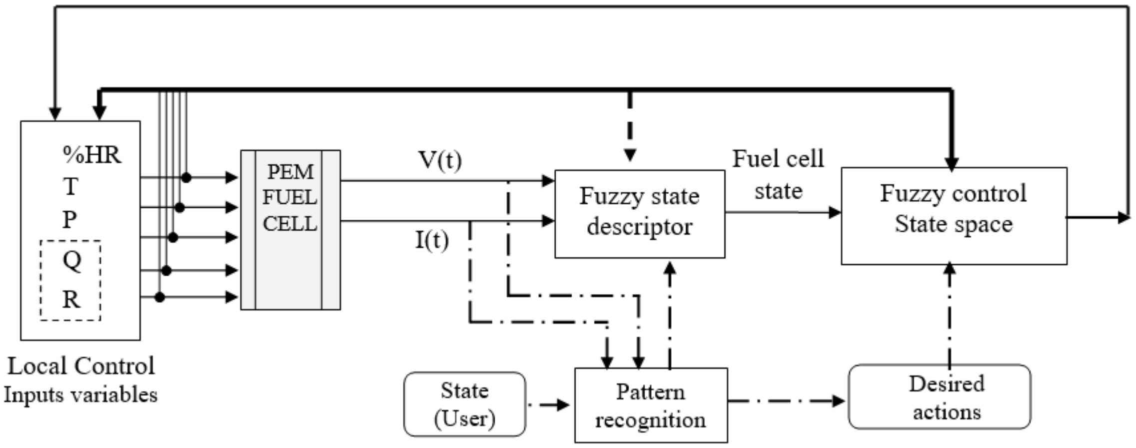

Figure 2. Diagram of the perception and control system of the operation state of the PEM fuel cell.

Perception and control abilities have been encapsulated in intelligent agents. The term Agent has been controversial in multiple fields, especially in Artificial Intelligence (AI), Computer Science, and Control Systems [13-16]. In this paper, the term AGENT is defined as the basic unit of knowledge organization and control architecture, understood as *"a process or set of processes aimed at achieving or maintaining an objective, with perceptual, deliberative, and acting abilities, without restriction in its complexity and communication via message passing or shared memory"*. This work defines two types of agents depending on their processing: perceiving and acting agents.

A. *Perception of the state of operation*

The agent takes the *state parameters* {slope change ΔP, moving standard deviation σ'_v, and voltage increment ΔV} provided by the GENERATE STIMULUS acting agent when activated within the perceiving agent UPDATE STATE. These state parameters correspond to patterns observed in the electrical response of the PEMFC when subjected to certain stimuli. The UPDATE STATE agent outputs the linguistic term *Type of State* that indicates the current operating state of the PEMFC. Three operating states have been defined as follows: *Normal*, *Dry,* and *Flooded.* The first state sets a starting point with the PEMFC operating stably, and the other two states are *critical zones,* given that operating in these states may cause irreversible damage to the PEMFC. The difference between these three states lies in the *degree of membrane water content.*

From here, the *fuzzy number* of the parameter is calculated by averaging the values of the membership functions of the parameter value to the linguistic labels of the state: dry, normal, and flooded. Additionally, since not all the parameters are equally reliable, it is proposed to combine the *fuzzy numbers* of each parameter using weighting, that is, assigning *different weights* to each parameter depending on its level of reliability; the greater the reliability, the greater the weight, as follows: 45% to the *voltage oscillation amplitude*, 40% to the *slope change point* and, 15% to the *voltage change*. The weighted average of the fuzzy numbers of the parameters indicates the state where the fuel PEMFC is operating. Intuitively, this fuzzy number measures the degree of water content in the membrane.

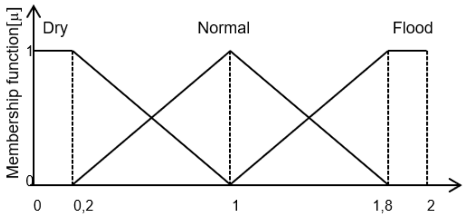

Figure 3. Fuzzy set of the variable *State Type*.

Finally, the *fuzzy weighted average* is converted to linguistic labels corresponding to each operating state of the fuel cell. Three linguistic labels describe the State Type variable as follows: I (flooded state), N (normal state), and S (dry state), Fig.3.

B. *Operation state management.*

A PEMFC management system must be able to keep it operating away from critical operating states, diverting its trajectory towards the normal operating subspace, for which intelligent perception and control strategies are required to deal with the nonlinearities of the electrical response of the PEMFC. In fact, to move from one state of operation to another, it is possible to act on: 1) *the humidifying time*, the longer it is, the higher the water content in the PEMFC stack; 2) *the temperature of the humidifiers*; the higher it is, the higher the water content in the PEMFC will also be, if the gas is humidified, and the lower the water content if the gas is not humidified; and 3) *cathode flow rate*, the higher it is, the lower the water content in the PEMFC.

Under this context, in the operational states management process, a closed-loop control system based on approximate reasoning techniques is proposed. The output variable is divided into 5 terms, defined by trapezoidal membership functions; the linguistic labels for these terms are: SM (high humidity rise), SP (low humidity rise), M (maintain humidity), BP (low humidity low), BM (high humidity drop).

Incorporating this controller makes it possible to address the imprecision and uncertainty inherent to the system, directly formulating, in natural language, the control strategies an expert operator would perform, i.e., the control strategy is formulated using a set of **IF-THEN** rules. The set of fuzzy rules that have been selected as good descriptors of the system's operation is the following:

R1: If (measured_*state*=S and desired_state=S) Then M
R2: If (measured_*state* =S and desired_state =N) Then SP
R3: If (measured_*state* =S and desired_state =I) Then SM
R1: If (measured_*state* =N and desired_state =S) Then BP
R2: If (measured_*state* =N and desired_state =N) Then M
R3: If (measured_*state* =N and desired_state =I) Then SP
R1: If (measured_*state* =I and desired_state =S) Then BM
R2: If (measured_*state* =I and desired_state =N) Then BP
R3: If (measured_*state* =I and desired_state =I) Then M

IV. RESULTS AND DISCUSSION

A. Stimation of the Operating state

The reproducibility of the experimental results of the value of the *fuzzy weighted average NB* generated from the state parameters in the three operating states of the PEMFC is shown on the abscissa of Fig. 4. At first glance, differences can be identified in the three operating states of the PEMFC between the different experiments, which confirms that the state estimator through the value of the fuzzy weighted average seems to be the best, considering the information of the three state parameters, unlike the *fuzzy tree* state estimator that considers two parameters [6] and presents a very small range of values in the three states of operation of the PEMFC. This confirms the potential use of *fuzzy weighted average* techniques for the estimation of the operating state of the PEMFC. On the other hand, the ordinate of Fig. 4 shows the value of the *voltage change* parameter, whose value presents very low ranges in the three operating states of the PEMFC and great overlap among them. Hence, this parameter is considered to have a lower level of reliability in obtaining the fuzzy weighted average.

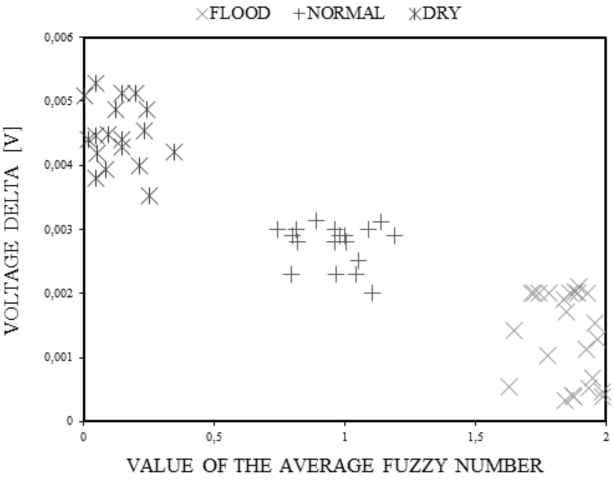

Figure 4. Value of the average fuzzy number, stimation of State of the PEMFC.

B. Control of the Operating state

Based on the current state of operation of the PEMFC, the process of the control state proceeds to execute the proper control action based on rules to determine the value of the action to perform, either in the humidifying time or in the flow rate of the gas injected into the fuel cell. Fig. 5 shows the evolution of the voltage swing state parameter: (1) start state before performing the state control, in our case dry state; (2) the operation state of the cell tends towards the normal state, that is, the voltage oscillation amplitude decreases as the degree of water in the fuel cell increases.

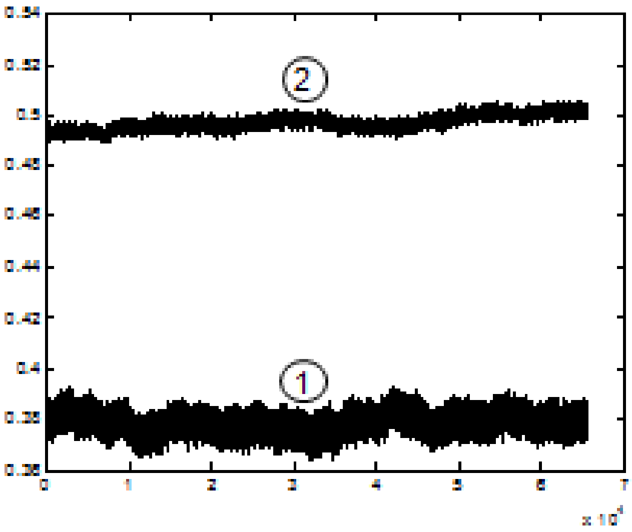

Figure 5. Evolution of the voltage oscillation parameter in the state control

V. CONCLUSIONS

More complex perception and decision strategies are required to deal with the non-linearities of the electrical response of the PEMFC. The integration of stimuli-response techniques and the approximate reasoning model in the UPDATE STATE perceptual process, guarantees the characterization of the operating state of the PEM fuel cell. In addition, the incorporation of a fuzzy controller in the management of the operating state of the PEM fuel cell allows addressing the imprecision and uncertainty inherent to the system, directly formulating, in natural language, the control strategies to regulate the wetting time in the PEM fuel cell, an example of this is the control of the normal state of the PEM cell.

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