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

Gomer 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-Cedeno
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 much interest as a power source for residential applications and electric vehicles. However, the development of new applications and the validation of new components of PEMFC require the characterization of their electrical response under certain conditions, both of operation (state variables) and power to be supplied (variation of electrical load), as well as the humidity degree of the membrane (operating state of the PEMFC considered Normal). Under this context, in this study, a set of specific processes based on approximate reasoning techniques have been designed and implemented for the dynamic control of the humidification of the polymeric membrane.**

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

I. INTRODUCTION

Engineering sciences must take the lead in addressing the most pressing challenges faced by humankind, particularly the issue of energy sustainability. To tackle this problem head-on, the hydrogen fuel cell constitutes a clean energy source with great potential for the present and the future [1, 2]. The PEMFC is an electrochemical device capable of converting chemical energy from fuels such as hydrogen (H2) into electrical energy in a single process and producing reusable by-products such as water and heat. This technology exhibits advantageous characteristics such as high power density, zero carbon emissions, low working temperature, quick startup capabilities, and other diverse applications. Nevertheless, its primary drawbacks, including cost, durability, performance, and stability, are of high interest in scientific research, given that these aspects need to be enhanced by optimizing its operational conditions to overcome traditional devices [3].

Despite the conceptual simplicity of the PEMFC operation, its electrical behavior relies, 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 can lead to stagnation, reducing electrical efficiency by wasting H2. In contrast, insufficient water causes dryness of the membrane, worsens its electrical performance, and shortens the life span of the cell. This electrical response is not linear, with multiple interdependent structural and functional variables, making it challenging to create an accurate model for optimal operation. [6].

In terms of control engineering, the PEMFC exhibits traits such as: a) A system of control variables to be modeled, which needs an extensive array of sensors and multiple simple control loops, mainly PID or PI, to be implemented in distributed systems and dealing with the interrelation between variables. b) Tightly interconnected subsystems, for instance, the management of the water content within the cell membrane, since its value is altered by characteristics such as temperature, the humidity of the injected gas, flow rate used, and even the load supplied by the fuel cell. c) Absence of accurate models of PEMFC and their electrical characteristics and dynamics, so their control becomes severely limited [7,8].

Although many studies claim precise results, the fact remains that searching capacity and efficiency have improved, and precision is still a subject of scrutiny. Some studies only partially simulate specific controllers and control objectives, leading to precision, stability, and robustness deficiencies. Additionally, issues such as noise in I-V polarization curve data are yet to be fully examined [9]. This lack of integration poses a challenge and motivates the objective of this study. A control model based on approximate reasoning techniques for perception and action is proposed as the most appropriate methodology to optimize the response of the PEMFC.

After this introduction, this work is organized into various sections. The experimentation scenario outlines the key parameters and components used for data collection, characterization, and validation of the perception and control strategies that a human expert would use when controlling the system. Subsequently, the knowledge is organized in the proposed control model section, where the perception and performance models are presented. The results and discussion section provides a comprehensive explanation of the outcomes obtained during the operation of the PEMFC. Ultimately, this article presents some conclusions as its final stance.

II. TEST SYSTEM

The tests were conducted with a PEMFC (single cell) and a small 100 W stack (joining several single cells) that had platinum-catalyzed carbon cloth electrodes with a loading of 0.58 mg Pt/cm^2 and an active area of 5 cm^2. The assembly was performed using two types of seals; one made of silicone (1 mm) and another made of Teflon (0.2 mm), which was thinner and used to cover the central area thickness. This assembly technique prevented the bipolar plates from pressing onto the electrode and causing the loss of the corrugated part. One significant feature of this setup is the use of corrugated stainless steel sheets as bipolar plates (Patent Ref. [10]). The advantage of this type of bipolar plate over others is that once the fabrication matrix has been built, the sheets are manufactured in short periods of time. Nevertheless, producing graphite or stainless steel bipolar plates requires computer numerical control (CNC) machines and highly qualified personnel, which increases their manufacturing time and cost.

Table 1 presents the different components of the PEMFC in a top-to-bottom order.

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

Figure 3 depicts the final assembly of the PEMFC stack, which has been constructed while considering all essential parameters and requirements to ensure optimal sealing and efficient performance.

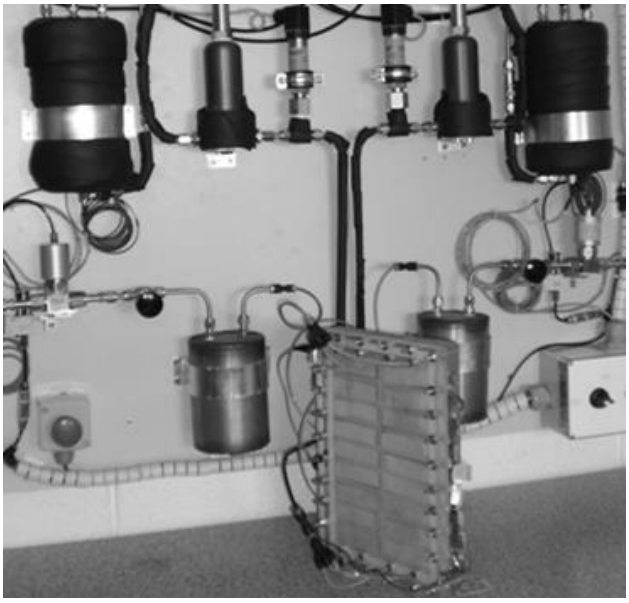

Figure 1. Final assembly of the PEM fuel cell stack.

A system that combines measurement and control functions has been developed to carry out characterization, control, and validation tests of approximate reasoning algorithms for controlling the PEMFC. The system is fully explained in [11]. Essentially, it is a fully automated system for managing PEMFC that features automated processes and monitorization of state variables to enable knowledge generation and intelligent decision-making.

III. KNOWLEDGE MODEL.

The smart and autonomous operation of the PEMFC under optimal operating conditions requires characterization, identification, and real-time control of the operating state (estimation of the amount of water contained in the membrane) of the cell. A *fuzzy weighted average* is used to implement a qualitative model for perceiving the operation state, while a *closed-loop fuzzy controller* is utilized for state control, as shown in Fig. 2. The use of approximate reasoning techniques for both perception and control of the operational state of the PEMFC 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 in linguistic terms [12].

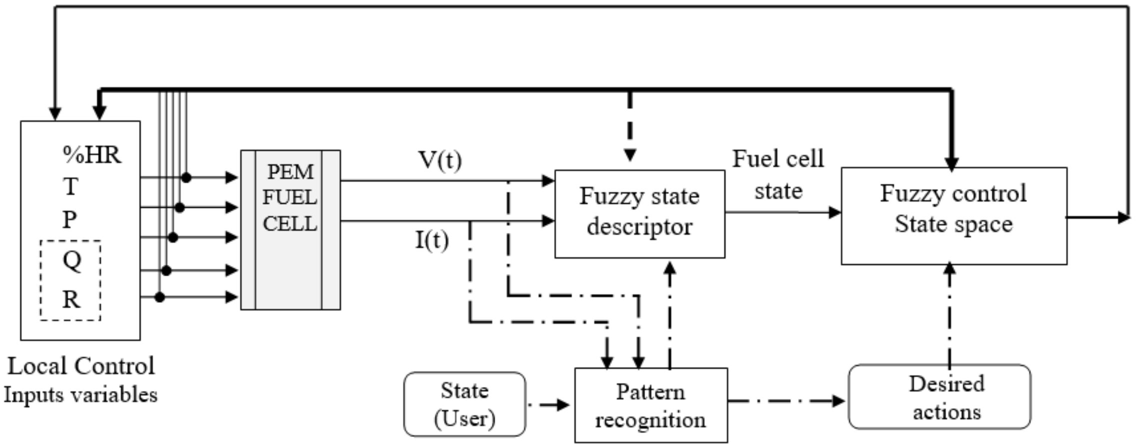

Figure 2. Diagram of the perception and control system of the operation state of the PEMFC.

Intelligent agents have incorporated perception and control capabilities. The term Agent has generated controversy in various domains, especially in Artificial Intelligence (AI), Computer Science, and Control Systems [13]. This article defines the term AGENT 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 limitations in complexity and communicating via message passing or shared memory"*. This study categorizes agents into two types depending on their processing: perceiving and acting agents.

A. Perception of the operational state

The UPDATE STATE agent takes the *state parameters* {slope change ΔP, moving standard deviation σ'_v, and voltage change ΔV} provided by the GENERATE STIMULUS acting agent. These state parameters represent patterns detected in the electrical response of the PEMFC when exposed to specific stimuli. The UPDATE STATE agent generates the linguistic term *"Type of State"* to indicate the current operational state of the PEMFC. The three distinct operational states are *Normal, Dry,* and *Flooded*. The first state provides a stable operating point for the PEMFC, while the remaining two are critical as they may result in irreversible damage to the PEMFC. The variance between these states depends on *the level of water content in the membrane*.

From here, the *fuzzy number* of the parameter is computed by taking the average of the membership function values for the linguistic labels of the state: *Dry*, *Normal*, and *Flooded*. Additionally, a weighted combination of their fuzzy numbers is suggested to account for the varying reliability levels of different parameters. The *weights* assigned to each parameter depend on its 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 operational state of the PEMFC is determined by calculating the weighted average of the fuzzy numbers. This fuzzy number provides an indication of the water content of the membrane.

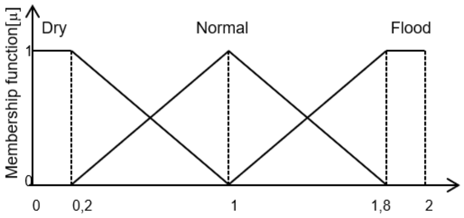

Figure 3. Fuzzy set of the variable *State Type*.

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. Operating state management.

To maintain the operational stability of the PEMFC, its control system needs to prevent critical operating conditions by redirecting it toward the normal operating space. This requires implementing intelligent perception and control strategies that can handle the nonlinear electrical response of the fuel cell. In fact, to move from one operating state 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.

In the operational state management process, a closed-loop control system that employs approximate reasoning techniques is suggested within this framework. The output variable is partitioned into five segments using trapezoidal membership functions; the linguistic labels for these terms are: SM (high humidity rise), SP (low humidity rise), M (maintain humidity), BP (low humidity drop), BM (high humidity drop).

By integrating this controller, it becomes feasible to deal with the imprecision and uncertainty that naturally exists within the system. The control strategies that an experienced operator would execute can be explicitly formulated in natural language by utilizing a set of **IF-THEN** rules. The selected group of fuzzy rules that accurately describe the operation of the system are as follows, Fig. 4.

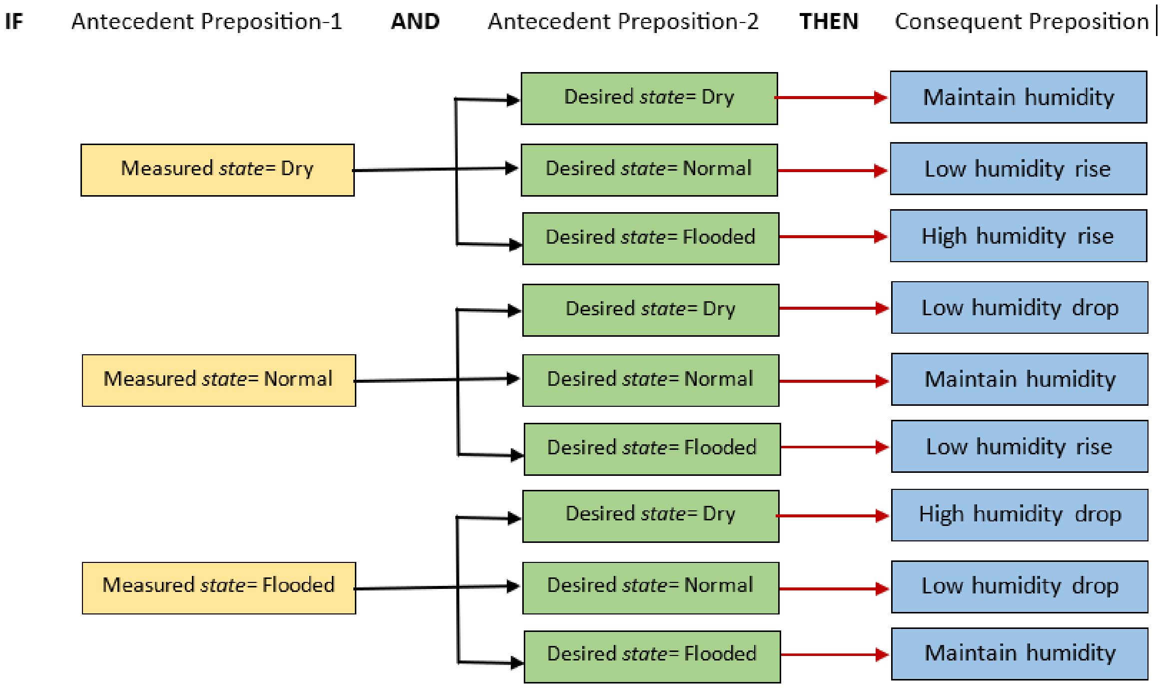

Figure 4. Rules implemented in the control system.

IV. RESULTS AND DISCUSSION

A. *Estimation of the operating state*

The reproducibility of the experimental results is illustrated in Fig. 4. The value of the *fuzzy weighted average NB* generated from the state parameters in the three operating states of the PEMFC is plotted along the abscissa of Fig. 4. At first glance, differences between experiments in the three operating states of the PEMFC can be observed, indicating that the state estimator through the value of the *fuzzy weighted average* is superior, as it considers information of all three state parameters, unlike the *fuzzy tree* state estimator which only 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. 5 corresponds to the value of the *voltage change* parameter that presents very low ranges in the three operating states of the fuel cell and great overlap among them. Hence, the reliability of obtaining the *fuzzy weighted average* is considered lower for this parameter.

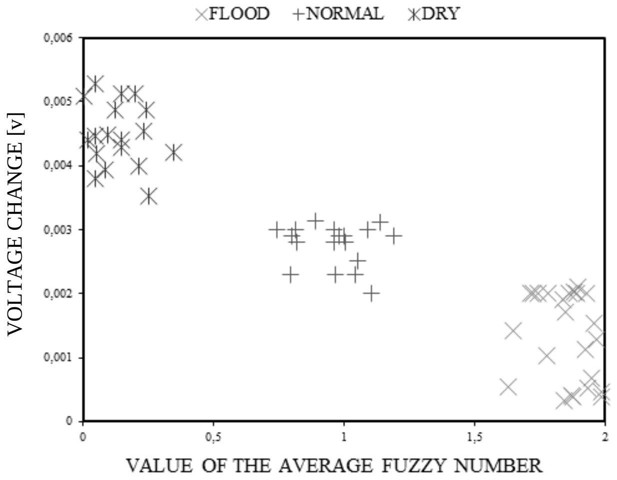

Figure 5. Value of the average fuzzy number, state estimation of the PEMFC.

B. *Control of the operating state*

The control state process of the PEMFC operates by executing appropriate control actions based on predetermined rules, which consider the humidifying time and the flow rate of the gas injected into the fuel cell. Fig. 6 illustrates the evolution of the voltage swing state parameter: (1) initial 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 water content in the fuel cell increases.

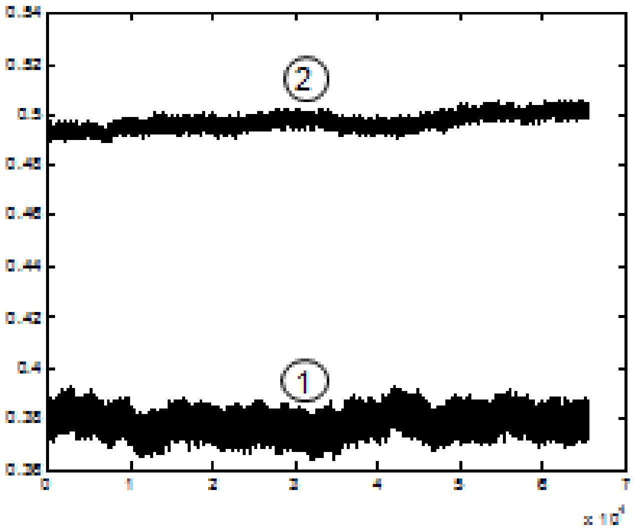

Figure 6. Evolution of the voltage oscillation parameter in the state control

V. CONCLUSIONS

Dealing with the non-linear electrical response of the PEMFC necessitates more intricate perception and decision-making techniques. By combining stimuli-response techniques and an approximate reasoning model in the UPDATE STATE perceptual process, the operational state of the PEMFC can be accurately characterized. Furthermore, by incorporating a fuzzy controller in the management of the operating state of the PEMFC, it becomes possible to address the inherent imprecision and uncertainty of the system. This allows for the formulation of control strategies in natural language to regulate the humidification time of the PEMFC, for instance, to control the normal state of the fuel cell.

ACKNOWLEDGMENT

The authors thank the group of Advanced Control of Energy Systems (Control Avanzado de Sistemas de Energía CASE-CIDIS) of ESPOL (Escuela Superior Politécnica del Litoral), the National Hydrogen and Fuel Cell Technology Testing Centre (Centro Nacional del Hidrógeno de España CNH2) and the Centre For Automation and Robotics (CAR-CSIC).

REFERENCES

[1] Rubio, A.; Agila, W. Sustainable Energy: A Strategic Overview of Fuel Cells. In Proceedings of the 2019 8th International Conference on Renewable Energy Research and Applications (ICRERA), Brasov, Romania, 3–6 November 2019; pp. 239–243.

[2] Rubio, A.; Agila, W. A Novel System-Level Model for a Fuel Cell in a Strategic Context. In Proceedings of the 2018 7th International Conference on Renewable Energy Research and Applications (ICRERA), Paris, France, 14–17 October 2018, pp. 1044–1048.

[3] S. Munjewar, S. Thombre, y R. Mallick, "A comprehensive review on recent material development of passive direct methanol fuel cell", Ionics, 2017, pp. 1-18.

[4] Lin-Kwong-Chon, C., Grondin-Pérez, B., Kadjo, J. J. A., Damour, C., & Benne, M. (2019). A review of adaptive neural control applied to proton exchange membrane fuel cell systems. Annual Reviews in Control, 47, 133-154.

[5] Yang, B., Li, J., Li, Y., Guo, Z., Zeng, K., Shu, H., ... & Ren, Y. (2022). A critical survey of proton exchange membrane fuel cell system control: Summaries, advances, and perspectives. *International Journal of Hydrogen Energy*.

[6] Rubio, G.A.; Agila, W.E. A Fuzzy Model to Manage Water in Polymer Electrolyte Membrane Fuel Cells. Processes 2021, 9, 904. https://doi.org/10.3390/pr9060904

[7] A. Rubio, W. Agila, L. Miranda, B. Lima, "Real-Time Qualitative Model for Estimate Water Content in PEM Fuel Cell", ICRERA, IEEE, 2019, pp. 455-459.

[8] A. Rubio, W. Agila, "Dynamic Model of Proton Exchange Membrane Fuel Cells: A Critical Review and a Novel Model", IEEE, International Conference on Renewable Energy Research and Applications (ICRERA), Brasov Rumania, November 2019, pp. 353-358.

[9] Yang, B., Li, D., Zeng, C., Chen, Y., Guo, Z., Wang, J., ... & Zhu, J. (2021). Parameter extraction of PEMFC via Bayesian regularization neural network based meta-heuristic algorithms. Energy, 228, 120592.

[10] Ref. Patente [1a] D. Guinea; E. Villanueva; M. C. García-Alegre; D. M. Guinea; David Martín. Pila de combustible de membrana única. Número de Patente solicitada: P2010_00043.

[11] David Sanaguano; W. Agila; Gomer Rubio, 2019 IEEE Fourth Ecuador Technical Chapters Meeting (ETCM), Open Control Architecture for the Characterization and Control of the PEM Fuel Cell, **DOI:** 10.1109/ETCM48019.2019.9014893

[12] M. Santos, (2011), "Un Enfoque Aplicado al Control Inteligente". Elsevier-RIAI, 8 pp (283-296), DOI:1016/j.riai.2011.09.016.

[13] García-Alegre, M. C. y Recio, F. (1998). Basic Visual and Motor Agents for Increasingly Complex Behavior Generation on a Mobile Robot. Autonomous Robots, 5:1–10.