Experts Agents in PEM Fuel Cell Control

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***Abstract*— In the control of the PEM (Proton Exchange Membrane) fuel cell, the existence of both deliberative and reactive processes that facilitate the tasks of control resulting from a wide range of operating scenarios and range of conditions it is required. The latter is essential to adjust its parameters to the multiplicity of circumstances that may occur in the operation of the PEM stack. In this context, the design and development of an expert-agents based architecture for autonomous control of the PEM stack in top working conditions is presented. The architecture integrates perception and control algorithms using sensory and context information. It is structured in a hierarchy of levels with different time window and level of abstraction. The monitoring model and autonomic control of PEM stack has been validated with different types of PEM stacks and operating conditions demonstrating high reliability in achieving the objective of the proposed energy efficiency. Dynamic control of the wetting of the membrane is a clear example.**

Keywords- PEM Fuel Cell ; Expert Agent; Perceptive Agents; Acting Agent ; Fuzzy Controller

I. INTRODUCTION

The PEM fuel cell is a complex system difficult to control, when not having a complete and accurate analytical model. In fact, from the standpoint of control [1], the PEM stack has features like:

a) System with a large set of sensors (variables to be controlled). Although this aspect is approachable with multiple simple control loops [2], usually PID or PI, implemented in distributed systems, presents the problem of the relationship between variables.

b) Tightly coupled subsystems, for an example of this is the management of the level of water in the stack, because its value is altered by the state variables: temperature and humidity of the injected gas, flow values used, and even the own load applied to the battery [3].

c) Lack of accurate models of the PEM stack and its electrical behavior, so its control is very limited [4]. In fact, the identification of the system to be controlled is a crucial factor if you want to use advanced control, but is only feasible when the dynamics of the process is well defined.

In the case of systems with highly variable structure, as is the PEM stack, the usefulness of a scale model and system identification, decrease [5]. Interactions in the PEM stack are many and at a so low level, that the prediction of its response is impossible.

Considering the characteristics and requirements of the PEM stack, a control architecture based on expert agents, as most appropriate model to achieve an autonomous control system of the same model is proposed.

This is a hierarchical model with various levels of competences, who gravitate to a global representation of the PEM stack and where each level is composed of a set of specialized expert agents that integrate expert knowledge and strategies for local or global control of variables and subsystems, by resorting to, in some cases, the use of intelligent control techniques [6-11].

II. TEST STATION & PEM FUEL CELL

Automation of control state variables that most affect the electrical performance and degree of wetting of the membrane of the PEM stack, enables the self-optimal performance. In this context, the integral station developed in [12] was used, the same having an open hardware-software system based in a multiprocessor local network, for measurement and control of the state variables of the PEM stack.

The same that can control the flow, temperature, humidity and pressure of the anode and cathode gases, and the electrical resistance between the cathode and anode, and measure the current and voltage generated by the PEM fuel cell..

Moreover, a cross-section of the type of PEM fuel cell used for the development and validation of the proposed architecture for autonomous control of the PEM stack in optimal operating conditions is presented in Fig. 1.

This stack PEM was designed and developed in the LERH-CSIC, and is provided with two bipolar plates of corrugated sheets. In the outer zone, the pieces from outside to inside are: 80x80mm2 end plates, 50x50 seals, 50x50 Teflón frames, membrane electrode assembly (Nafion 115) with hot pressing 55x55.

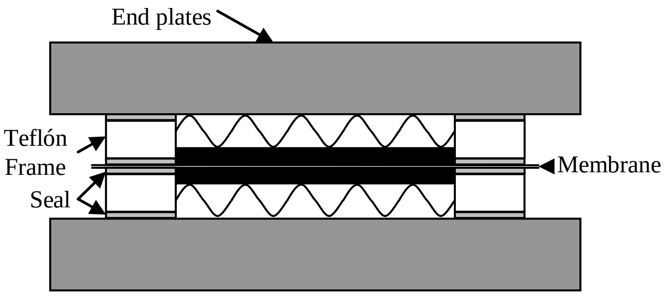

Fig.1. PEM fuel cell used in the validation of the architecture.

III. EXPERT AGENTS BASED ARCHITECTURE

The term Agent has been the subject of much controversy in many fields, especially those of Artificial Intelligence (AI), Computer Science and Control Systems [13]. In this paper, the term agent is defined as the basic unit of the control architecture and organization of knowledge, understood as "process or set of processes aimed at achieve or maintain an objective, with perceptive, deliberative and action skills without restriction in their complexity and communication by message passing or shared memory " [14].

In this paper we have defined two types of agents depending on the type of processing carried out by: perceptive agents and acting agents. In such agents three key aspects are distinguished, Fig. 2.

- Computing and communication processes that define their competence.
- Required variables or parameters of shared memory.
- Inputs and outputs associated with each agent.

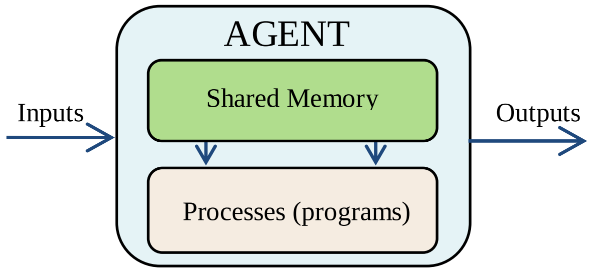

Fig. 2. Conceptual scheme of an agent

Shared memory contains the instantaneous measurements of the state variables (short term memory) and more abstract concepts (medium-term memory) and parameters related to the system and the (long term) application. The input and output signals of the agents, correspond to activation signals coming or directed to an agent, required to initiate the execution cycle. Agents are hierarchically organized so that each agent initiates execution of those whose functions need, thus allowing the reuse of agents to facilitate the inclusion of agents with new skills.

The agents are organized according to the criteria of skill reuse.

A. Perceptive processes

In the proposed architecture for controlling the PEM stack, perception is structured around a set of perceptual agents designed to detect aspects that are considered key to achieving the objectives. These agents implement processes of perception aimed at extracting relevant features of the system, which are then used by the agents of action. Perceptive agents, have only two states, alert and active, the transition from one to another state is conditioned by the verification of certain conditions, Fig. 3.

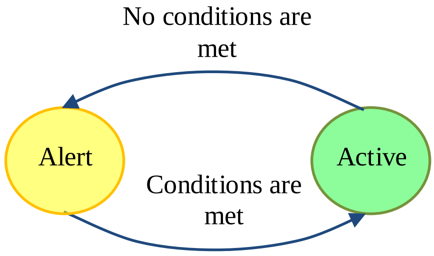

Fig. 3. State transitions in the perceptual agents

Perceptions developed by the different perceptive agents possess varying degrees of abstraction and spatiotemporal scope. The update of a particular representation is the responsibility of the perceptual agents that generate it.

B. Perfomance processes

The action is implemented by the agents of action, which along activations generate a sequence of control actions of the operating variables of the PEM stack. Acting agents are modeled following the scheme shown in Fig. 4, and can be found in 3 activation states: idle, alert and active. In the idle state the agent is a process or set of processes that do not run. The inactive state turns into a state of alert by receiving an activation signal. In this state checks periodically whether the context defined for implementation is met, and if so passes to the active state, which means it comes to decision-making for action, either on physical actuators or alertness of other agents.

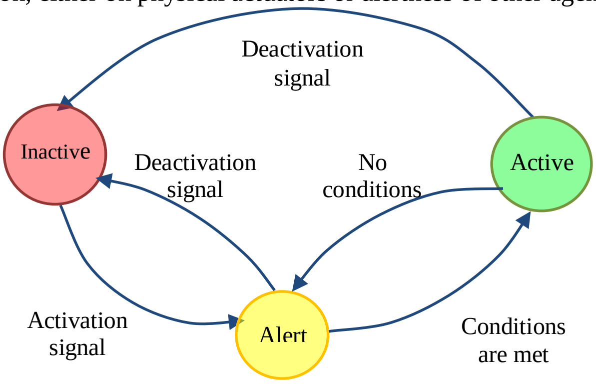

Fig. 4. State transitions in acting agents.

IV. EXPERT AGENTS IN PEM STACK CONTROL

A. Agents for the autonomous control of PEM stack

The development of new designs or validation of new components of the PEM cell passes through the characterization of the electrical response under certain conditions, both operating (state variables) and power supply (variation of electric charge) as optimum moisture (state Normal cell operation under consideration).

Adequate wetting of the membrane conditions are essential to increase the electrical efficiency, extend the life of the battery and prevent irreversible damage to its components. Indeed, in most applications where a PEM fuel cell supplies electric power individually or as a component of a system, hybrid cars (PEM + battery stack), autonomous operation is needed in optimum wetting conditions and high performance in both power and consumption.

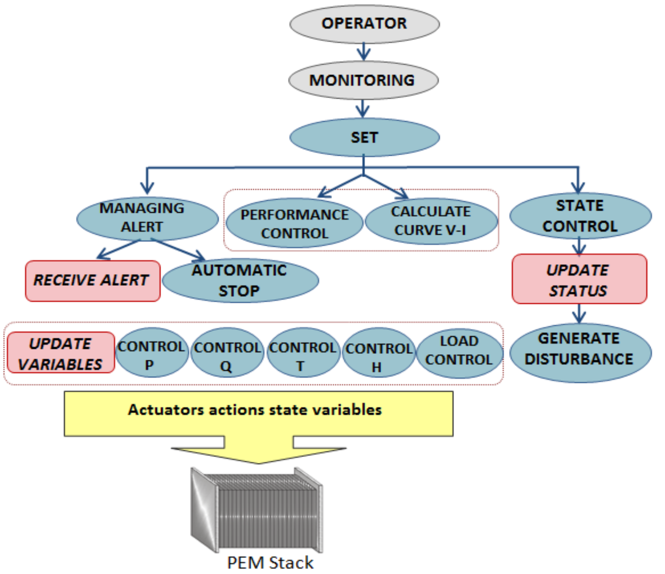

Fig. 5. Expert agents hierarchy for autonomous control of PEM stack in optimal wetting conditions.

For this purpose, a set of specific agents have been designed and implemented following generic design lines proposed in the control architecture based on expert agents. The trajectory of operating points to be followed by the control system and management of the battery is subject to restrictions and requirements imposed by the OPERATOR initially. Therefore, it is needed an initial setup process (SET Agent) of: a) state variables (temperature, humidity, flow rates and pressure); b) variables of the application or scenario to which the battery supplies power. In this case you have to meet criteria characterizing both the battery (Agent CALCULATE CURVE V-I) and the application (PERFOMANCE CONTROL), the latter concept, aims to maximize the electrical output and minimize fuel consumption. in work scenario, both in characterization and application, they share the need for security against unforeseen (Agent MANAGING ALERT); c) objective state of operation: Normal, region of the state space with the best conditions for the transport of protons, resulting in an increase in the lifetime of the membrane and the electrical performance. Dry area irreversible damage to the membrane. Flooded area of low performance and loss of fuel.

The control architecture makes use, in the higher levels of abstraction, of detection and intervention strategies which differ among the operation scenarios. In fact, some agents such as low level (agents CONTROL P, CONTROL Q , CONTROL T, CONTROL H and LOAD CONTROL) embedded in the network of microprocessors can be reused, thus optimizing design time and development of architecture for other systems and / or scenarios (applications).

The hierarchy in the control architecture based on expert agents proposed to achieve the autonomous operation of the PEM stack, in optimal humidity conditions of the membrane is shown in Fig. 5.

A global representation segmented into three levels of the agents involved in the control architecture based on expert agents for autonomous operation in optimum wetting conditions of the PEM stack, is shown in Fig. 6.

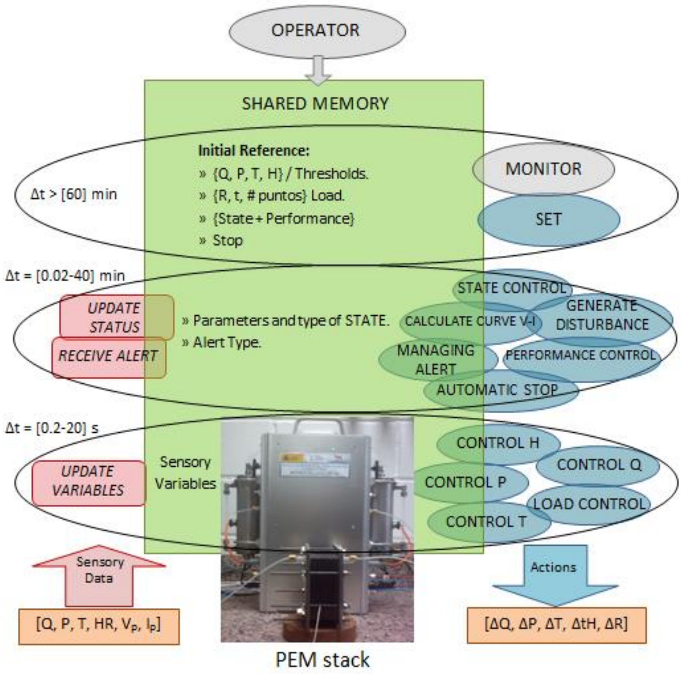

Fig. 6 Architecture of expert agents of perception and action: shared memory variables and temporal resolution levels.

The ellipses in blue and gray, to the right of Fig. 6 correspond to the agents of action. The rectangles with rounded corners in red, on the left are the perceptual agents. In the center of the green image, the contents of the shared memory is displayed. Shared memory contains the global variables required for agents, both acting as perception, thus acting as asynchronous communication channel between them.

B. *Results in wetting control of PEM stack.*

In the proposed architecture, one of the aspects that should prevail is to maintain controlled the operating point of the battery within a given operating state, in this case the normal state. So the agent STATE CONTROL, which manages the water content in the stack, can distinguish when and how to act, it is necessary to perfectly identify what state of operation the battery is, this forces the agent UPDATE STATUS to keep the variable state of the stack constantly updated..

In the Agent UPDATE STATUS, knowledge for estimating operating status of the battery is acquired by analyzing the electrical response time (voltage) generated by the battery when it is subjected to particular stimuli. In this sense, once it passes to the active state, the agent UPDATE STATUS sends trigger signal to acting agent GENERATE DISTURBANCE, generated disturbances are: load jump, fluctuations of intensity (Osc. I) and cathode flow break (QCA), the characteristics of the operating state of the stack are extracted by analyzing the temporal electrical response (tension and intensity) generated by eh stack when it is exposed to such disturbances, Fig. 7.

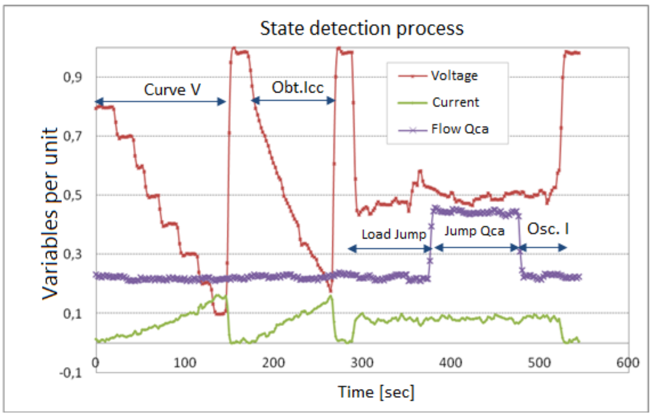

Fig. 7. Time evolution of the flow and electrical variables of the stack in the process of disturbance and state detection.

The values of the operating state of the stack correspond to the following parameters: delta voltage (ΔV), oscillatory voltage (σv) and delta slope (Δp), such parameters are related to the input linguistics variables (see Fig. 8) to the state estimation algorithm based on the decision fuzzy tree and implemented in the agent UPDATE STATUS.

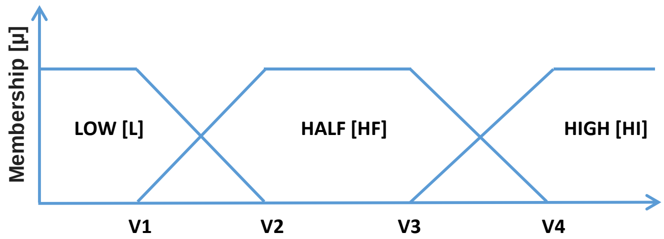

Fig. 8. Representation by fuzzy sets of values of status parameters: ΔV, σv, y Δp

The equation (1) shows how to determine the value of belonging to each state of operation of the PEM stack based on the value of belonging to the linguistic labels of state parameter.

$$\mu_i = \sum_{j=\max(0,i-2)}^{\min(i,2)} \mu'_j \cdot \mu'_{i-j} \qquad (1)$$

Where: i represents the states of operation of the PEM stack, terminal nodes of the fuzzy tree; µ'and µ" represents the belonging value of the parameter to their respective labels; j represents the linguistic parameter label.

The UPDATE STATUS agent, which outputs a linguistic term which indicates the status of the stack, Fig. 9.

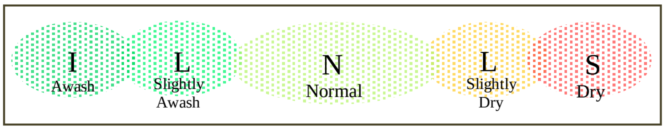

Fig. 9. Operating states of the PEM stack, output of the angent UPDATE STATUS..

To deal with non-linearities of the electrical response of the PEM stack, more complex strategies of perception and decision are required. STATE CONTROL agent is dedicated to this task, from the response of UPDATE STATUS agent. Agent STATE CONTROL ensures the operation of the PEM stack outside of critical operation zones (*Flooded and dry state*). In order to drive the operation of the system away of the critical operating zones, it is possible to actuate over: *the wetting time, temperature of the humidifiers and cathode flow*. In this development stage, the agent STATE CONTROL operates over the wetting time.

Incorporating a fuzzy controller in STATE CONTROL agent can address the vagueness and uncertainty inherent to the system, asking directly, in natural language, control strategies for estimating the state of operation of the PEM stack, Fig. 10.

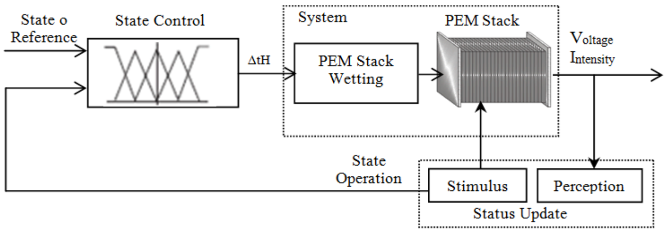

Fig. 10. Scheme of fuzzy controller of state of PEM stack.

The input variables to the controller are: operating state of the stack and reference state. Both are described through five fuzzy sets defined by trapezoidal membership functions {S, LS, N, LI, e I}. The output variable: *wetting time* is defined by five linguistic terms {non-wetting NH, PH low moisture, low moisture BH, MH average moisture, high moisture AH}, defined by trapezoidal membership functions. In Fig. 11 the different polarization curves V-I obtained in each execution cycle of agent STATE CONTROL are compared.

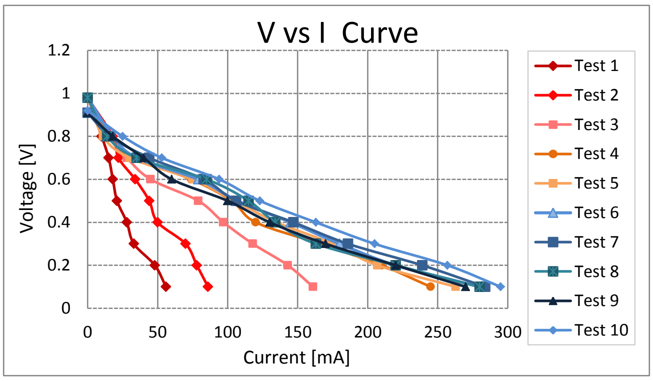

Fig. 11. Evolution of V-I curve of PEM stack in state control process.

The Fig. 12 shows the time evolution of the short circuit current Icc of the PEM stack, blue curve, moments before each execution cycle of STATE CONTROL agent, a clear improvement is observed in the electrical response of the stack as increases the degree of moisture in the membrane, confirming that the operating point of the PEM stack stays away from the dry state, starting state, Test_1.

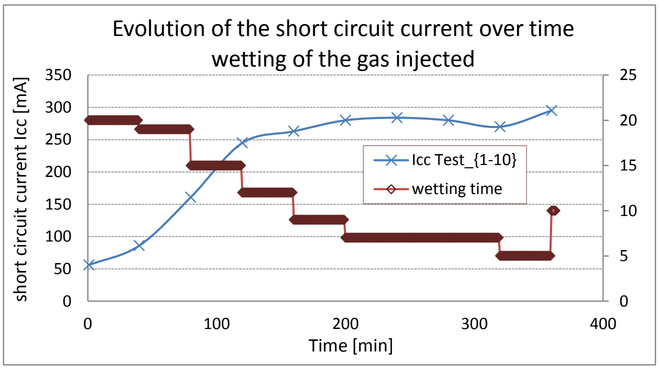

Fig. 12. Evolution of Icc during the execution of agent STATE CONTROL

V. Conclusions

The perception and control architecture based on expert agents possesses a hierarchy of levels with different degrees of abstraction and temporal windows. In which, the integration between different agents, techniques and models: classical control, qualitative control based on expert knowledge, supervisory control is observed.

The modular approach of the proposal, both functional and physical, is based on the following criteria: a) Independent in the development of control processes; b) scalability; c) Reliability, versatility and robustness to faults and contingencies; d) Ease of maintenance.

The hierarchical architecture model with expert agents has been experimentally validated with mono-cells and PEM fuel cells in different working conditions and scenarios focused as an example to the management of water phenomena on the stack.

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