Qualitative Model of Control in the Pressure Stabilization of PEM Fuel Cell

W. Agila[12], Gomer Rubio[1], L. Miranda[1], L. Vázquez [1]

[1] Facultad de Ingeniería en Electricidad y Computación (FIEC), Escuela Superior Politécnica del Litoral (ESPOL)
Intelligent Automation (IA), Grupo de investigación en Automatización y Control Industrial (GIACI)
Km 30.5 vía Perimetral, Guayaquil, Ecuador
{wagila; grubio; livalmir; lfvasque}@espol.edu.ec

***Abstract*—This work describes an approximate reasoning technique to deal with the non-linearity that occurs in the stabilization of the pressure of anodic and cathodic gases of a proton exchange membrane fuel cell (PEM). The implementation of a supervisory element in the stabilization of the pressure of the PEM cell is described. The fuzzy supervisor is a reference control, it varies the value of the reference given to the classic low-level controller, Proportional - Integral - Derivative (PID), according to the speed of change of the measured pressure and the change in the error of the pressure. The objective of the fuzzy supervisor is to achieve a rapid response over time of the variable pressure, avoiding unwanted overruns with respect to the reference value. A comparative analysis is detailed with the classic PID control to evaluate the operation of the "fuzzy supervisor", with different flow values and different sizes of active area of the PEM cell (electric power generated).**

Keywords— PEM Fuel Cell; Fuzzy Supervisor; Fuzzy Controller, Test Station Fuel Cell. Introduction

I. INTRODUCTION

The fuel cell is a complex system that is hard to control, as it does not have a complete and accurate analytical model, as it happens in other systems (e.g., [1], [2]). In fact, from the control's point view, the PEM cell presents characteristics like: A system with a wide a group of variables to control [3]. Although this aspect is approachable with multiple simple control loops, usually PID, implanted in distributed systems, it presents the problem of interrelation between variables. Strongly coupled systems, where an example of them is the management of the water content contained in the cell, as its value is altered because of the state variables: temperature and humidity of the injected gas, flow values and used pressures, even of the own applied charge to the PEM fuel cell [4].

There are many interactions in the PEM cell and in a very low level that the prediction of their answers is practically impossible. In this case, the human operator and his own common sense could face this problem, because with his reasoning ability and his knowledge of the system's operation, is capable of determine the most suitable control action, like the adjust of the reference's values.

The present work proposes a cascade control architecture that integrates expert knowledge in a higher level and local classic control strategies in a lower level using the techniques of intelligent control. The rest of this article is organized as follows: The section II describes briefly the properties that

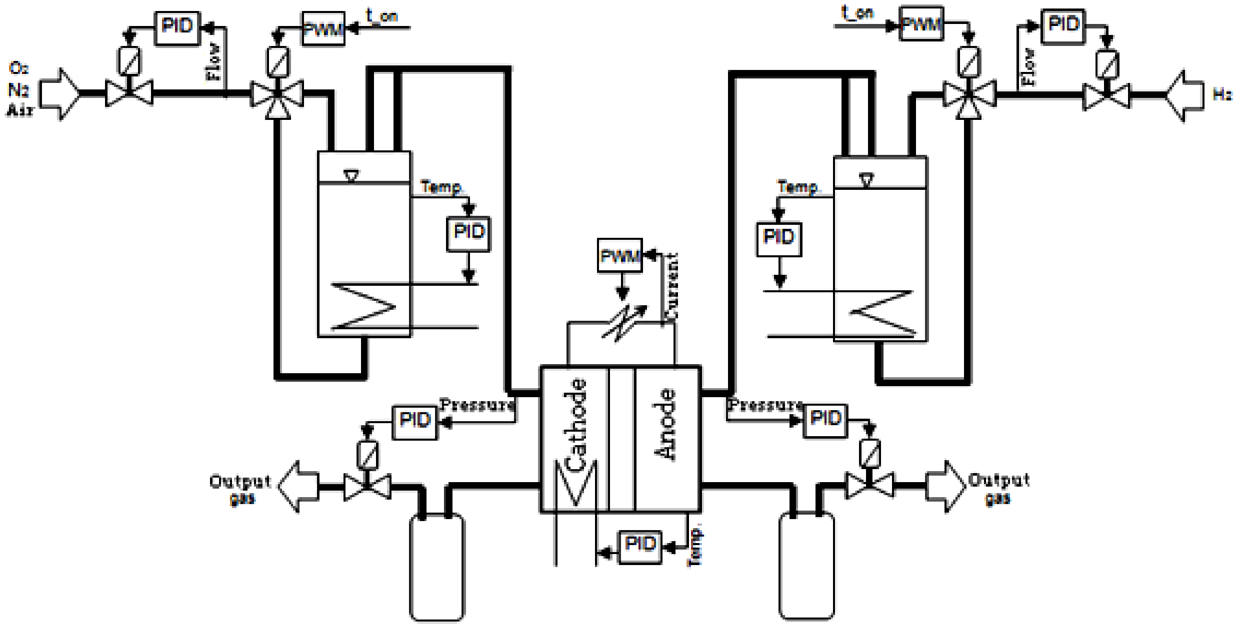

Figure 1 System of measurement and control of a PEM Fuel Cell or Stack.

presents the characterization system of the PEM cells (control of the state variables). The classic PID control model of pressure and its limitations are shown at section III. The section IV details the qualitative model of the reference's supervisor and reference's control of the low level PID. At section V are expressed the obtained results with the fuzzy supervisor in the pressure's stabilization at the PEM cell. Finally, the conclusions are summarized in section VI.

II. Description of the problem

In the PEM fuel cell of open cathode to the atmosphere, the air flow must simultaneously regulate three critical values: oxidizer flow, evacuation of generated water and cell's temperature, for the correct operation of it. This process implies a compromise between flows, pressures and humidity of the gas inlet so that the flow of oxygen reaches the points of catalysis of the cathode without causing damage to the operating water conditions of the membrane and cooling the PEM cell sufficiently so that the operating temperature is stabilized to an appropriate value. In these conditions the requirement of a variable demand, often unpredictable like the required power of a vehicle, means a problem that it doesn't always has a response although the PEM fuel cell offers the nominal power needed. This, together with the lack of homogeneity in the set-up of a new fuel cell model that is done with an artisanal methodology, since the selection of the materials until its conformation to operating conditions.

To investigate and offer solutions to this type of situations it is necessary to have measuring systems and integral controllers for surveillance and regulation of the most significative state variables belonging to the electro-chemical and fluid-dynamic processes presented in the PEM cell. In fact, in these recent years there were developed and marketed different models of monitoring and testing systems for the PEM cells, named as stations or experimental test benches. These systems are capable of measure and control the most significative variables that affect directly the performance of the PEM cell. As examples there are the systems developed by Hydrogenics [5], Electrochem [4], and the mentioned in some other works [6], [7]. These instrumental systems have the advantage of being operational from the moment of their acquisition, but with the inconvenient that their operation is usually limited to a small number of options.

Another option postulates the use of independent controllers for each variable [9] or a part of them, meanwhile the rest are being controlled by a test station [10]. The objective is manipulating the variables that produces fluctuations in the energy generation [12].

The analysis of the benefits of these measuring and controlling systems in PEM cells shows that there are serious limitations. The principal obstacle for the acquirement and use is due to the difficulty for integrate the operation with the information from other equipment or measure techniques, characterization and regulation of the operating variables from the PEM cell, like reviewed in the article by M. Baloch, where a dynamic model for a wind system is developed using control techniques [13]. This systems the pressure's regulation is done generally with electronic pressure's controllers "backpressure", using needle valves at the modulation of the gas outlet section, which implies serious problems of water condensation because the gases pressure at saturation conditions and higher temperatures with respect to room temperature make the use of regulating valves of needle's pressure very difficult for the condensation phenomena. This difficulty is increased in higher power systems due to the use of higher flow rates, which requires the use of moisture extractor equipment. [11].

A novel solution to stabilize the anodic and cathodic pressure of the PEM cell is presented in this section. The pressure's stabilization is done using membrane valves of high fidelity and industrial robustness, with pneumatic performance in Pulse Width Modulation (PWM) located at the PEM cell's output, strategy applied by S. Kumar Mishra [16]. The pressure's fluctuations, proper to this type of control, are soften with an in-line integration of a small deposit (buffer). A global scheme that integrates dispositives of measurement and low-level PID control developed for the characterization and control of PEM cells is shown in Fig. 1

A. *Technical Sepecifications of the System*

The present state variables at the basic operation of the PEM cell is classified in two groups:

a) Fluid-Dynamic Variables: corresponding to gas supplies as: flow (Q); relative humidity (HR); pressure (P); and temperature (T).

b) Electrical Variables: That correspond to the cell temperatur (T) and charge or electrical resistance (R) applied to the cell in order to analyze its electrical behavior.

Both the reactant gas supply in anode and cathode and the fuel cell temperature should comply certain operating conditions [17] before establishing a contact through the polymer membrane. This is mainly due to a certain value that belongs to one of the state variables that produces a certain electrical response in the PEM cell, which usually doesn't match with the desired one; hence the importance of determining the value intervals of state variables. In fact, the maximum requirements are determined in order of the active area of the PEM cell's membrane, in other words, of the maximum electrical power generated [18]. However, the minimum values depend a lot of the measurement intervals of used sensors and actuators. The Fig. 2 illustrates the minimum and maximum values assigned to the state variables of the cathode and anode gas management.

STATE VARIABLE	MINIMUM VALUE	MAXIMUM VALUE
Caudal: H_2/N_2	0.05 [L/min]	5 [L/min]
Caudal: Aire/O_2	0.10 [L/min]	10 [ml/min]
Presión: H_2/O_2	0 [bar]	5 [bar]

Figure 2 Value intervals of the controlled state variables

III. CLASSIC PID MODEL CONTROL

The PEM cell is subject to an internal pressure through the gas flows (gas pressure), the fact of having pressure differences between anode and cathode may cause perforations in the membrane. This difference is a main point with cells with distribution channels of gases in corrugated plates, as is our case. The electronic-pneumatic system with PWM modulation in in-line supply of gas proposed to stabilize the pressure at the PEM cell is shown in Fig. 3.

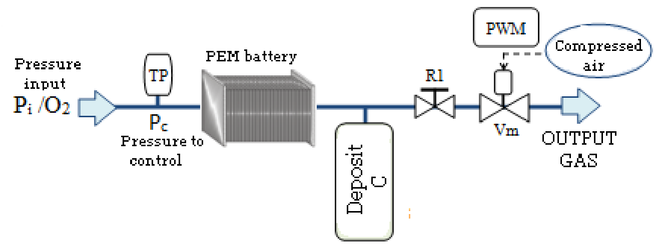

Figure 3 Pressure's control system

For pressure increases at the PEM cell, pressure to control, Pc. The controller closes the membrane valve Vm located at the output line of gas supply clogging with it the passage of the gas flow, which produces an increase of the pressure at the PEM cell. On the other hand, a decrease at the reference of the pressure at the cell, produces from the controller an opening of the valve Vm, allowing a decrease of the pressure at the PEM cell. The electric model of the supply of the gas flow at the cathode of the PEM cell, allows an easy design and controller optimization for each particular application.

The current gas flow through the hydraulic restriction of the tube R, Fig. 3, is a function of the gas inlet pressure's difference Pi and gas outlet Po at the supply's line. Considering the position of the membrane valve Vm in its two operating states, these are, open and close and, applying the capacitance and resistance concepts in pressure gas systems [15], the transfer function for the control pressure Pc is defined by the Eq. (2.1), as a first order system.

$$P_c = \begin{cases} Pc(s) = \dfrac{Pi(s)}{RCs+1} & \textit{close valve} \\[2ex] Pc(s) = \dfrac{Pi(s)}{RCs+\left(1+\dfrac{R}{R1}\right)} & \textit{open valve} \end{cases} \qquad (2.1)$$

To analyze the viability of the pressure's stabilization system and the robustness of the PID controller in modulate the valve Vm, it is proceeded in a first phase to implement the Eq. (2.1) in an advanced simulation software, for that, there should be re-ordered the transfer functions of Eq. (2.1) to obtain Eq. (2.2).

$$Pc(s) = \frac{1}{RCs}\left[Pi - Pc\left(1 + k\frac{R}{R1}\right)\right] \qquad (2.2)$$

Where Pi is the input pressure at the supply line of oxidizing gas; R and R1 are the resistances to the gas flow and the k term represents the operating state of the valve Vm, taking only two values: closed valve and open valve.

In the model it was introduced the PWM block that has as an input the output of the PID controller multiplied with the saturation block (deleting the win-up effect) to limitate the integral action.

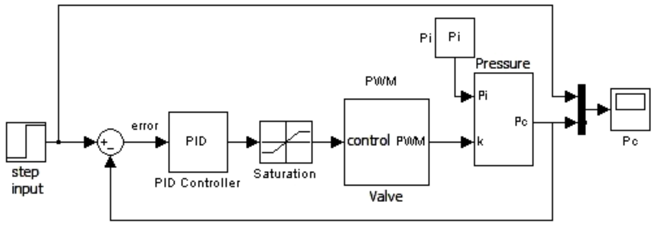

Figure 4 Block diagram of the pressure's regulation system with a PID controller

A. *Simulated and experimental results*

The temporal response obtained through the simulation of the pressure at the PEM cell (green line), when it is applied a step signal input of 2 bars of amplitude (blue line), is shown in Fig. 5. In that figure, it is observed small fluctuations on the pressure as a characteristic response to the modulation of the valve Vm.

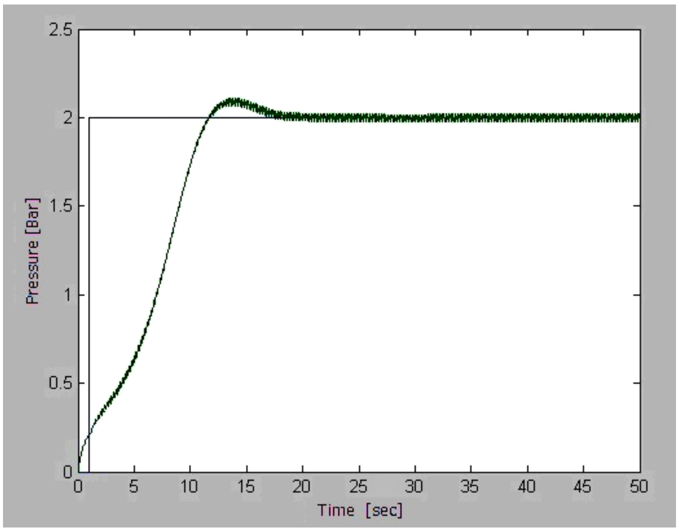

Figure 5 Simulation results of the pressure's stabilization at the PEM cell

One of the obtained results during the performance of the PEM cell, in which, it was used oxygen as a principal gas with a flow of 05L/min, is shown in Fig. 6. The results were obtained for some slogan values of pressure, in the cathode side of 1, 2, 3 and 4 bars. The simulation and real tests results are very similar, which indicates that the PID controller allows a reference following and, the pressure's system regulation with in-line modulation, introduces small pressure. Fluctuations, being those fluctuations much bigger as the flows increase when the size of active area of the PEM cell gets bigger, even to become the pressure unstable at the PEM cell, problem that is solved when it is incorporated a supervisor element in cascade with the PID controller.

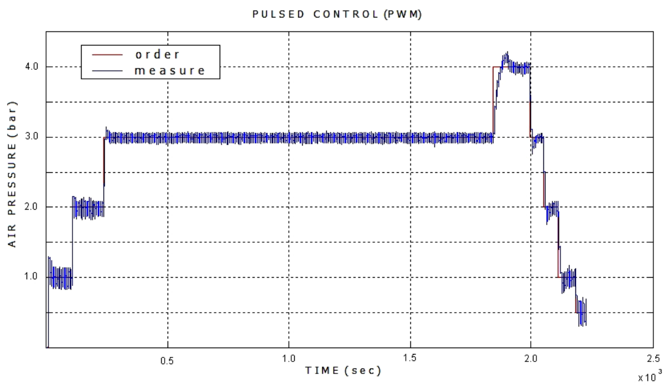

Figure 6 Real results of the pressure's stabilization at the PEM cell with slogan changes

IV. QUALITATIVE CONTROL MODEL

Sometimes, control processes are done in two stages or more, where the input to the first controller is a variable error and the inputs to the next controllers are the outputs of the previous adjacent controller. These controllers are especially useful when one of the stages of the control processes is hard to change. This is what precisely occurs with the implemented PID controller for the pressure regulation, where the controller is programmed in a microprocessor and any other parameters adjust forces a reprogramming of it. In Figure 7 is shown a blocks diagram of the implemented two-stages controller for pressure stabilization. The fuzzy controller modifies the "reference false" reference of the PID controller to obtain at the end a more accurate control of the variable.

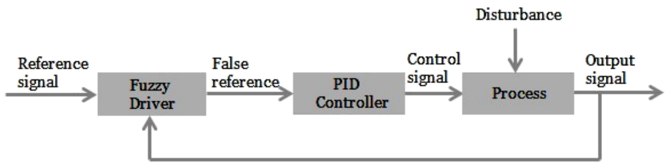

Figure 7 Fuzzy supervisor for reference change

There were selected two inputs for the fuzzy pre-controller:

- The pressure increases through time (ΔP/Δt)
- The pressure error (PReference-Pmeasured)

An output: the added reference value "reference false".

The input variables of the controller are described linguistically through five terms, defined with trapezoidal membership functions, through a conjunct of linguistical labels: big negative (NG), short negative (NP), zero (Z), short positive (PP) and big positive (PG), Figure 8. The values of the input labels are combined through logic operators like: OR, AND and NOT to calculate the output levels.

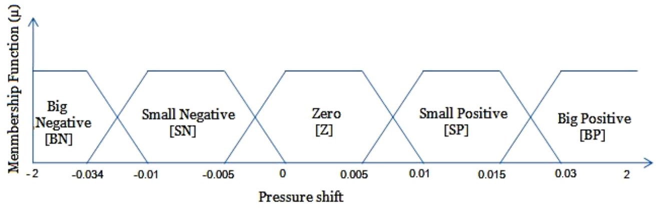

Figure 8 Linguistic labels of the input and output variables of the fuzzy supervisor

A. *Knowledgment base*

The fuzzy rules of the supervisor (Ri), show a strong dependence of the output over the pressure's rate of change, being the last one a relevant measure of how the state variable pressure is going to exceed the false reference. Four of the twenty-five fuzzy rules that build the qualitative model are formulated:

R1: IF (camb_presion = NG) AND (error = NG) THEN (falsa_ref = PG)

R2: IF (camb_presión = NG) AND (error = PG) THEN (falsa_ref = PP)

R3: IF (camb_presion = NP) AND (error = PG) THEN (falsa_ref = Z)

R4: IF (camb_presion = Z) AND (error = PG) THEN (falsa_ref = NP)

The simulation of fuzzy supervisor has been implemented using Fuzzylib [14]. Application which calculates the output of the fuzzy supervisor from the inputs in real time of the fuzzy variables, linguistic labels and fuzzy rules IF-THEN. The variables, labels and rules are read from a file previously designed, that encapsulates the qualitative model of the system.

V. COMPARATIVE ANALYSYS IN PRESSURE STABILIZATION

To evaluate the fuzzy controller operation, these two parameters have been taken into account: the stationary error ess and time delay td. These parameters are used normally in Control Theory to quantify the accurate and speed of the system, respectively [9]. Time delay is the time that requires the system to reach half of the reference value, Eq. (2.3).

$$t_d \Rightarrow \frac{\mathrm{Re}\,ference}{2} \tag{2.3}$$

The stationary error is the difference between the measured pressure value and the required reference once the transitory period is finished, Eq. (2.4).

$$e_{ss} = \lim_{t\to\infty} e(t_d) \tag{2.4}$$

In Fig.9, it is shown the temporal evolution of the pressure at the input of the fuel cell using the classic PID controller (blue line). The graphic results show that this controller doesn't comply with the specifications for a flow of 1L/min, this is: even if it responses against a step signal in a hundred of seconds (td = 100s), it shows a maximum overrun percentage of 22 %.

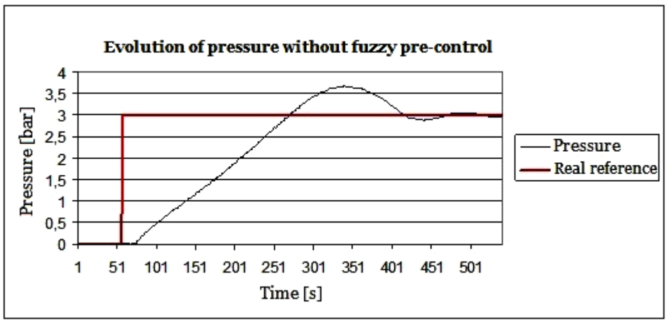

Figure 9 Pressure’s temporal evolution, without fuzzy supervisor

This is an underdamped behavior, with some oscillations until the measured pressure is stabilized near the reference value (ess = 0.06 bar), with a stabilization time of 402 s. Nevertheless, imports that the pressure control in the fuel cell shows an overdamped behavior to prevent excessive pressure differences at the membrane that could damage it irreversibly; especially if it is working with corrugated sheet fuel cells.

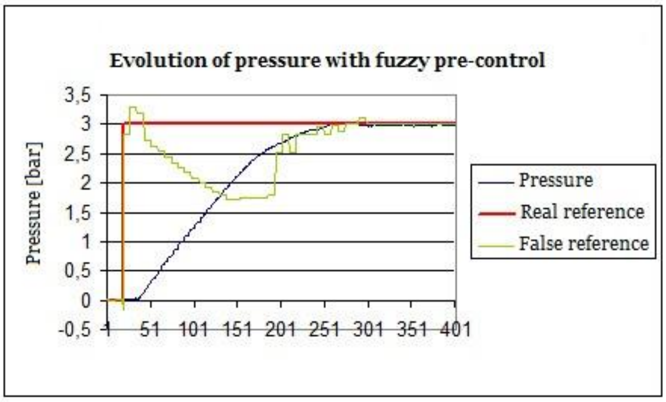

Figure 10 Pressure’s temporal evolution, without fuzzy supervisor.

The Fig. 10., shows the obtained results using the fuzzy controller “fuzzy pre-controller” in the pressure stabilization, under the same flow and step-jump (3 bars) conditions are shown in Figure 4.29. It is observed now how the system behavior is overdamped, being that, the pressure doesn’t exceed the reference value and the stabilization time is 228 seconds.

Thus, the inclusion of the fuzzy pre-controller achieves short time stabilization and prevents oscillations and excess pressure at the fuel cell input. This occurs because the fuzzy pre-controller generates a false reference much less than the measured pressure is approaching the reference, reducing the increase rate of the measured pressure. This is, as soon as the pre-controller detects a deceleration, it increases the false reference value. According to the speed of change of measured pressure, the pre-controller continues to vary the false reference until it reaches the aim reference.

VI. CONCLUSIONS

The fuzzy supervisor working in cooperation with the classic low-level PID controller, has shown that it could be possible to obtain less stabilization time of the pressure respect to a controller without supervisor (classic PID). Also, the supervisor avoids excesses of pressure over the reference, as well as wide oscillations. Therefore, it is achieved a shorter stabilization time, approximately 57% of time with a PID controller. For low-power PEM cells, less than 200W, the pressure system is practically linear and with the classic PID controller it can be obtained good results. For bigger flows, this is, for higher power, until 2000W, the fuzzy controller in conjunction with a PID controller, constitutes a better option.

ACKNOWLEDGMENT

The investigation area in Intelligent Automation (IA) thanks to the Grupo de Investigación en Automatizacón y Control Industrial (GIACI) of Escuela Superior Politécnica del Litoral (ESPOL).

REFERENCES

[1] R. J. de Andrade Vieira, M. A. Sanz-Bobi, and S. Kato, “Wind turbine condition assessment based on changes observed in its power curve,” in 2013 International Conference on Renewable Energy Research and Applications (ICRERA), Oct 2013, pp. 31–36.

[2] C. K. Lo, Y. S. Lim, and S. Y. Kee, “Improvement of bifacial solar panel efficiency using passive concentrator and reflector system,” in 2013 International Conference on Renewable Energy Research and Applications (ICRERA), Oct 2013, pp. 42–45.

[3] P. Breeze, “Chapter 1 - an introduction to fuel cells,” in Fuel Cells, P. Breeze, Ed. Academic Press, 2017, pp. 1 – 10. [Online]. Available: http://www.sciencedirect.com/science/article/pii/B9780081010396000017

[4] D. Ko, S. Doh, H. S. Park, and M. H. Kim, “Investigation of the effect of operating pressure on the performance of proton exchange membrane fuel cell: In the aspect of water distribution,” Renewable Energy, vol. 115, pp. 896 – 907, 2018. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0960148117308212

[5] “Fuelcon ships fuel cell test stations for major german project,” Fuel Cells Bulletin, vol. 2018, no. 2, pp. 12 – 13, 2018. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1464285918300610

[6] J. Lee, R. Yip, P. Antonacci, N. Ge, T. Kotaka, Y. Tabuchi, and A. Bazylak, “Synchrotron investigation of microporous layer thickness on liquid water distribution in a pem fuel cell,” Journal of The Electrochemical Society, vol. 162, no. 7, pp. F669–F676, 2015.[Online]. Available: http://jes.ecsdl.org/content/162/7/F669.abstract

[7] A. Ploner, A. Hagen, and A. Hauch, “Classical statistical methodology for accelerated testing of solid oxide fuel cells,” Journal of Power Sources, vol. 395, pp. 379 – 385, 2018. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0378775318304920

[8] J. Zhang, H. Zhang, J. Wu, and J. Zhang, “Chapter 3 - techniques for pem fuel cell testing and diagnosis,” in Pem Fuel Cell Testing and Diagnosis, J. Zhang, H. Zhang, J. Wu, and J. Zhang, Eds. Amsterdam: Elsevier, 2013, pp. 81 – 119. [Online]. Available: http://www.sciencedirect.com/science/article/pii/B9780444536884000036

[9] Y. Saygl, S. Kncal, and I. Eroglu, “Development and modeling for process control purposes in pems,” International Journal of Hydrogen Energy, vol. 40, no. 24, pp. 7886 – 7894, 2015, hydrogen and Fuel Cell Systems for Clean Energy Applications. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0360319914029929

[10] A. Tabanjat, M. Becherif, M. Emziane, D. Hissel, H. Ramadan, and B. Mahmah, “Fuzzy logic-based water heating control methodology for the efficiency enhancement of hybrid pvpem electrolyser systems,”

International Journal of Hydrogen Energy, vol. 40, no. 5, pp. 2149 – 2161, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0360319914032698

[11] J. J. Hwang, W. R. Chang, J. K. Kao, and W. Wu, "Experimental study on performance of a planar membrane humidifier for a proton exchange membrane fuel cell stack," Journal of Power Sources, vol. 215, pp. 69 – 76, 2012. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0378775312007847

[12] S. Sahoo, B. Subudhi, and G. Panda, "Comparison of output power control performance of wind turbine using pi, fuzzy logic and model predictive controllers," International Journal of Renewable Energy Research, vol. 8, no. 2, pp. 1062–1070, 2018, cited By 0. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85049118222partnerID=40md5=faf3d4fc4fa5271f8d3fcd5be8875d70

[13] M. Baloch, W. Jie, and G. Kaloi, "Dynamic modeling and control of wind turbine scheme based on cage machine for power system stability studies," International Journal of Renewable Energy Research, vol. 6, no. 2, pp. 599–606, 2016, cited By 3. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84977677006partnerID=40md5=c997517759f26c0bd222fcd6fafcd912

[14] N. Jayalakshmi, D. Gaonkar, and P. Nempu, "Power control of pv/fuel cell/supercapacitor hybrid system for stand-alone applications," International Journal of Renewable Energy Research, vol. 6, no. 2, pp. 672–679, 2016, cited By 11. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84977603176partnerID=40md5=e2fba1ff549a8e621c4c60be824b6e2a

[15] Y. Choi, C. Lee, and J. Song, "Review of renewable energy technologies utilized in the oil and gas industry," International Journal of Renewable Energy Research, vol. 7, no. 2, pp. 592–598, 2017, cited By 6. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85020525629partnerID=40md5=f29e07bf0e100d1a521ab71f542a807f

[16] S. Mishra, S. Purwar, and N. Kishor, "An optimal and non-linear speed control of oscillating water column wave energy plant with wells turbine and dfig," International Journal of Renewable Energy Research, vol. 6, no. 3, pp. 995–1006, 2016, cited By 2. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84995701473partnerID=40md5=a487a1ee752d8bbe5b4cf5528b6997a2

[17] W. Agila, R. Cajo, and D. Plaza, "Experts agents in pem fuel cell control," in 2015 International Conference on Renewable Energy Research and Applications (ICRERA), Nov 2015, pp. 896–900.

[18] C. Hhnel, V. Aul, M. Schultze, and J. Horn, "State estimation of exhaust valve position by kalman filter in pem fuel cell systems," in 2015 International Conference on Renewable Energy Research and Applications (ICRERA), Nov 2015, pp. 590–595.

[19] S. Mane, P. Kadam, G. Lahoti, F. Kazi, and N. M. Singh, "Optimal load balancing strategy for hybrid energy management system in dc microgrid with pv, fuel cell and battery storage," in 2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA), Nov 2016, pp. 851–856.