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Qualitative Model for an Oxygen Therapy System based on Renewable Energy

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***Abstract* — In Ecuador, the existence of chronic obstructive pulmonary diseases and the appearance of new viruses such as Covid-19 that cause respiratory problems, influence the development of oxygen therapy services. These services improve the health of some patients and increase life expectancy in others. However, the limited care capacities in the hospital centers of Ecuador and the lack of development of self-sufficient technological equipment for the provision of therapeutic oxygen services, mean that said service is carried out mainly in large cities, leaving aside other geographical areas with populations that also require it. This article explores the implementation of an oxygen therapy system based on the use of alternative energies, to be used in the treatment of people who cannot do without supplemental oxygenation in communes and homes. In addition, a control system based on linguistic rules for oxygen supply is proposed. Finally, the closed loop response of the control system is analyzed.**

Keywords- PEM Fuel Cell, Fuzzy Controller, Energy renewable, oxygen therapy.

I. INTRODUCTION

Throughout time, human beings have been exposed to myriad of diseases that can seriously affect the health of our body, which has an impact on both our life expectancy and our quality of life. Considering the continuous appearance of new diseases, continuous medical and scientific progress is essential to guarantee an appropriate lifestyle. In fact, there are currently more and more studies associated with the different pathologies that affect the human being, in order to facilitate the development of drugs, vaccines, therapies and alternatives for existing medical service equipment. Among the main types of critical health diseases, we have those that affect the respiratory system and occur in patients of all age ranges.

According to the World Health Organization (WHO), among the 10 main causes of death in the world, 7 of these are due to non-communicable diseases, with Chronic Obstructive Pulmonary Disease occupying the third place of mortality until the year of 2019, generating an approximate of 3.32 million deaths annually worldwide [1].

By the end of 2019, the appearance of a new respiratory disease (COVID-19) due to an emerging coronavirus, called SARS-CoV-2, gave rise to a pandemic which has claimed the lives of millions of people around the world in the last couple of years. COVID-19 presents among its affectations in the most serious cases, difficulty breathing; therefore, the requirement of mechanical ventilation became necessary so that the human body can correctly execute the blood oxygenation process.

The air that surrounds us is made up of approximately 21% oxygen, which is an essential element for human life. Low O_2 levels in the blood create a condition of hypoxemia, which is due to the difficulty of the lungs in providing the adequate amount of oxygen to the cells of our body, causing damage to different organs [2]. Generally, this condition occurs in patients with Chronic Obstructive Pulmonary Disease (EPOC) or with other similar respiratory diseases, including COVID-19, where patients may require extra oxygen that helps to carry out a correct oxygenation process.

According to the 2020 Statistical Records of General Deaths of the INEC [3], it is indicated that in Ecuador of the total excess deaths, 23,793 are confirmed or suspected cases of COVID-19 and the remaining 17,284 deaths are mainly associated with respiratory diseases such as influenza and pneumonia, among others. The high number of deaths were related to the high number of people with severe respiratory conditions and a limited variety of medical oxygen supply devices and services for timely treatment at home.

Based on the groups of pathologies previously exposed, the need arises for the existence of oxygen therapy services that allow the provision of oxygen in an additional or assisted manner in recommended proportions to people who need it due to the low levels of oxygen that they present in their blood. In fact, the inappropriate infrastructure and resources of public and private health institutions in Ecuador make it impossible to meet the demand for patient care, particularly with chronic respiratory diseases, whose treatment in some cases involves the uninterrupted use of medical oxygen 6, 12 and up to 24 hours a day [4].

This paper presents an oxygen therapy system using an electrolysis process to meet the oxygen demand in the homes of oxygen dependent or requiring people. Similar solutions have been proposed in the literature but for larger-scale facilities with the aim of guaranteeing the supply of medical oxygen in hospitals, also rural, and as an alternative energy supply source [5][6].

In addition, to guarantee the quality of life of the users of the proposed system, an intelligent supervision model based on fuzzy logic has also been designed for the analysis of the required oxygenation levels and the control of the regulation system of the dispensing equipment whose operation is based on the use of renewable energy. A non-linear controller based on fuzzy logic has the advantage of providing efficiency and effectiveness in an experimental process without the need for advanced mathematics and calculations [5].

II. Parameter Extraction Techniques

A. Continuous home oxygen therapy (OCD)

Oxygen therapy is defined as the supply of supplemental oxygen with concentrations greater than 21% of those present in ambient air for the treatment and prevention of hypoxemia, in order to increase oxygen saturation (SpO_2) to improve gas exchange, and thus prolonging the life of patients. Oxygen administration depends on the clinical picture of each patient; that is, the indications and application doses vary in each person, [8].

EPOC is defined as the supply of oxygen to patients with the presence of chronic respiratory failure, continuously and commonly indefinitely within their homes. The indications associated with EPOC are defined under the criteria of national and international guidelines. However, it is extremely important to know the patient's diagnosis to validate the therapy and to be able to adjust the equipment according to the different clinical or outpatient requirements. Table 1 shows different situations that generate the need for home oxygen in patients with EPOC, considering the existing levels of evidence.

TABLE 1. INDICATIONS FOR CONTINUOUS HOME OXYGEN THERAPY IN EPOC.

	Values PaO_2 (%)	**Strength of Recommendation**	**Quality of evidence**
Continua	> 90	Consistent	High
During exercise	< 88	Weak	Low
Nocturnal	< 90	Weak	Moderate

B. Porcentage oxygen saturation in the blood SaO_2

Pulse oximetry measures blood oxygen saturation (SaO_2) and not partial pressure of oxygen (PaO_2). However, there is a correlation between both variables, and it is given by the oxyhemoglobin dissociation curve [4]. In fact, the partial pressure of oxygen depends on the oxygen saturation in the blood and the oxygen flow to be supplied to the patient, Fig.1

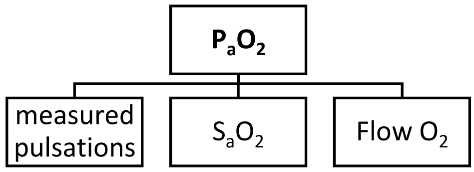

Figure 1. Partial presure oxygen factors.

Given the lack of tables that provide information on the direct relationship between SaO_2 and flow, the estimation of the PaO_2 values is made from the oxyhemoglobin dissociation curve. For which a curve is fitted using the mathematical tool "Curve Fitting Toolbox" of the MATLAB software, in which the following vectors are established:

SaO_2_standar = [30,35,40,50,60,73,80,90,95,98.4]

PaO_2_standar = [18,21,23,26,30,40,48,59,80,100]

From this, the fourth degree Fourier model is obtained, with which the best fit between pulsation, oxygen flow and partial pressure of oxygen was achieved, Fig, 2.

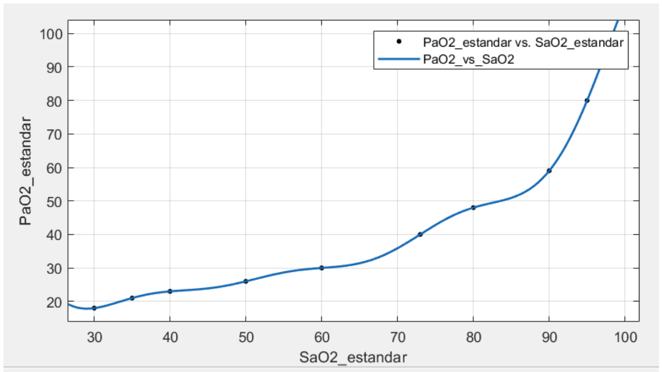

Figure 2. Fourier model of curve fitting PaO_2 vs SaO_2.

C. Oxygen flow adjustment.

Experimental tests were carried out in order to know the angular position to which the flowmeter knob must be adjusted to obtain the different output flows required for the patient. Based on these data, the correspondence of pulse widths to be generated by the fuzzy controller for self-regulation of the distribution system is established. Information about this system and the proposed fuzzy controller is detailed further.

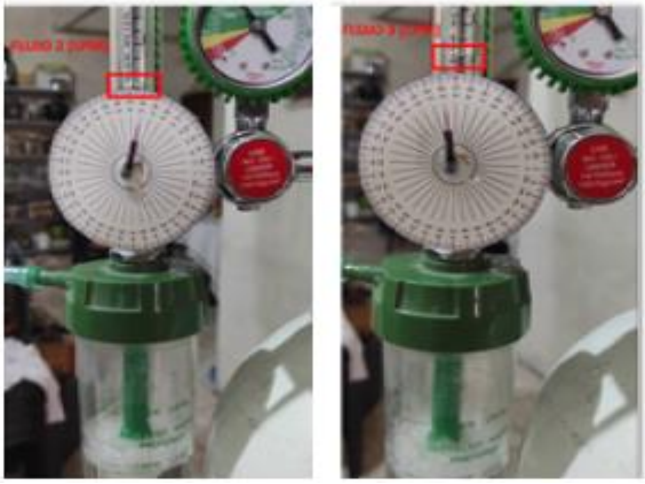

Figure 3. Flowmeter Knob Adjustment: left) 80°; rigth) 100°

Fig. 3 Shows the adjustment of the flowmeter knob, the right image places the float ball at the 3 [lpm] measurement, while the left image adjustment places the float ball at the 3 [lpm] measurement.

These experimental data allow us to then fit the Fourier model of the oxygen outflow vs. angular position of the servomotor, Fig. 4.

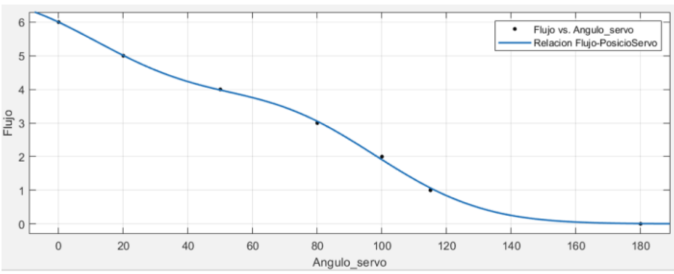

Figure 4. Fourier model of curve fitting flow O_2 vs angular position.

D. Oxygen supply time

For the time of oxygen supply to the patient it is based on the study presented in [9]. In said article it is estimated that for a patient to whom oxygen is provided through a low-flow cannula, the response time of adequate blood oxygen saturation is 60 minutes when the maximum flow rate value is applied. through the low flow cannula.

TABLE 2. BLOOD OXYGEN SATURATION RESPONSE TIME.

***Low flow nasal cannula Flow* [l/min]**	**Adequate response time of blood oxygen saturation *[min]***
1	20
2	20
3	40
4	60

Table 2 shows the relationship between the flow that must be supplied by cannula depending on the adequate response time of the partial pressure of oxygen.

E. Renewable energy for clinical O_2 supply

The green oxygen generation process comprises the stages: solar energy, water supply treatment, separation into hydrogen and oxygen by electrolysis, distribution storage and use of hydrogen in a fuel cell. Solar energy is captured by the photovoltaic panel generating electricity, which, if it is sufficient to supply the demand for oxygen production through the electrolyzer, will operate directly and all the surpluses will be used for other consumption or stored in a battery. The electrolyzer also results in gaseous hydrogen to then be stored as a gas. If the energy supplied by the sun is not enough, the PEM fuel cell comes into action that will use the stored hydrogen to produce electrical energy, which could partially or totally complement the energy demand [15].

The system model was made with the tools provided by MATLAB-SIMULINK. The system is shown in Fig. 5. At the input of the solar panel, the irradiance and ambient temperature are obtained, while the maximum power of the array of panels is extracted by means of the MPPT (Maximum Power Point Tracking) regulator inverter. The regulator delivers a voltage of 48 V to the battery, to then pass to the electrolyzer that generates hydrogen and oxygen to be stored in cylinders. At night, the fuel cell consumes the stored hydrogen to supply energy to a household load. It should be noted that at the output of the cell there is a 48 V boost converter so that said voltage enters the inverter and obtains alternating current. There is a switching block in such a way that during the day the regulator is connected to the electrolyzer and at night if necessary, it is connected to the fuel cell.

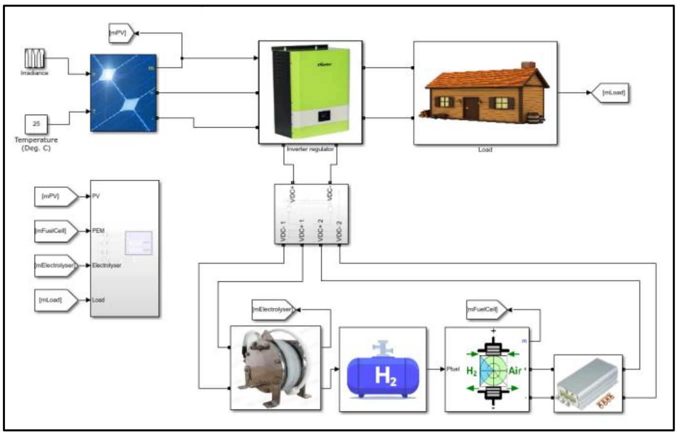

Figure 5. Renewable energy system

III. QUALITATIVE DIAGNOSTIC MODEL.

In this work, fuzzy logic was chosen as the method for intelligent supervision. This methodology was chosen; first, because the oxygen therapy process (adequate oxygen supply to patients with chronic breathing) depends: on variables such as pulse oximetry, oxygen saturation in the blood and response time of the human organism, and these cannot be measured, but are estimated, existing uncertainty; and, second, the ease of this methodology in translation in terms of easily describable control objectives in linguistic terms **¡Error! No se encuentra el origen de la referencia.** [12].

In this work, to simulate the intelligent supervision process MATLAB software was used, using the platform called 'Fuzzy System Designer' [13].

A. Input and output variables

The system has a degree of inference and a source of knowledge [14], which will be a reference point when receiving inputs.

For the input to the controller, 3 linguistic variables are assigned, which are: Partial pressure of oxygen "PaO_2", Adequate response time of oxygen saturation in the blood "Duration", and Angular position error of the servomotor "Error-Position". While for the output the parameter corresponding to the desired flow "Flow-Desired" is established, which is the signal from which the reference value that the angular position of the servomotor must reach is estimated; and the "Action" pulse width modulation, signal through which the positioning control of the motor is generated.

Table 3 includes the input variables with their operating ranges and the number of membership functions, while Table 4 describes the output variables.

TABLE 3. INPUT VARIABLES OF FUZZY SYSTEM.

Name	**Range**	**Number of membership functions**
Partial pressure of oxygen PaO2 (mmHg)	0 - 100	3
Duration (min)	0 – 60	3
Error-position angle "degrees"	-130 – 130	3

In Table 4, the negative type of action output is associated with a clockwise angular displacement, while a positive type of action is associated with a counterclockwise angular displacement and finally a zero action represents that no angular displacement is required.

TABLE 4. OUTPUT VARIABLES OF FUZZY SYSTEM

Name	**Range**	**Number of membership functions**
Action (PWM)	-1 – 1	3
Flow-Desired (ml/min)	0 – 4	3

Each of the input variables and the output Action variable are defined by three fuzzy set terms, defined by trapezoidal functions, with non-zero overlap, Fig. 6. In this case, the transition from one value to another is gradual and picks up uncertainty and gradualness of real systems. Thus, to certain values of the variables (numerical measurements) two fuzzy sets are assigned, but with different degrees of membership [15] [16].

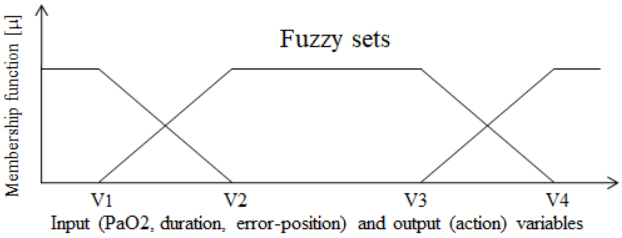

Figure 6. Fuzzy set of the input and output variables.

The membership functions of the fuzzy sets of the input and output variables to the controller have the same profile and number of fuzzy sets, but different numerical values of the parameters that define the trapezoidal function: V1, V2, V3 and V4. The values of these four parameters are presented in Table 5.

TABLE 5. VALUES OF THE PARAMETERS V1, V2, V3 AND V4 FOR EACH FUZZY SET OF EACH OF THE INPUT AND OUTPUT VARIABLES

Name	**Fuzzy sets**	**V1**	**V2**	**V3**	**V4**
PaO_2	High	50	55	100	100
	Half	35	40	45	50
	Low	0	0	35	40
Duration	Small	0	0	20	30
	Medium	10	20	30	40
	Large	30	40	60	60
Error-position	Negative	-130	-130	-55.2	-22.1
	Zero	-55.2	-22.1	22.1	55.2
	Positive	22.1	55.2	130	130
Action	Negative	-1	-1	-0.5	-0.2
	Zero	-0.5	-0.2	0.2	0.5
	Positive	0.2	0.5	1	1
Flow-desired	Low	0	0	1	1.5
	Medium	1	1.5	3	3.5
	High	3	3.5	4	4

The model of the oxygen therapy system was made with the MATLAB tool. In Fig.7 the complete oxygen supply system to the patient is shown. The Fuzzy controller responds to 3 basic characteristics. The first two correspond to the arterial oxygen pressure and flow evaluation time delivered to the patient that allow us to infer the belonging functions and universe of discourse of its output, to establish the reference value of the desired flow. While the last two correspond to the angular position error of the servomotor and the derivative of the error allow us to infer the membership functions and the universe of discourse of its "Action" output.

B. *Definition of fuzzy rules*

After setting input and output variables, we proceed to define the fuzzy rules. Fuzzy rules involve the antecedent proposition with the consequent proposition. The fuzzy rules are in charge of receiving an input value, and after that determine which level of the output is the most suitable with those values [17] **¡Error! No se encuentra el origen de la referencia.**.

There are cases where an entry value satisfies more than one fuzzy rule; for those cases, the value that will be considered should be the one with the highest degree of membership regarding the fuzzy output sets.

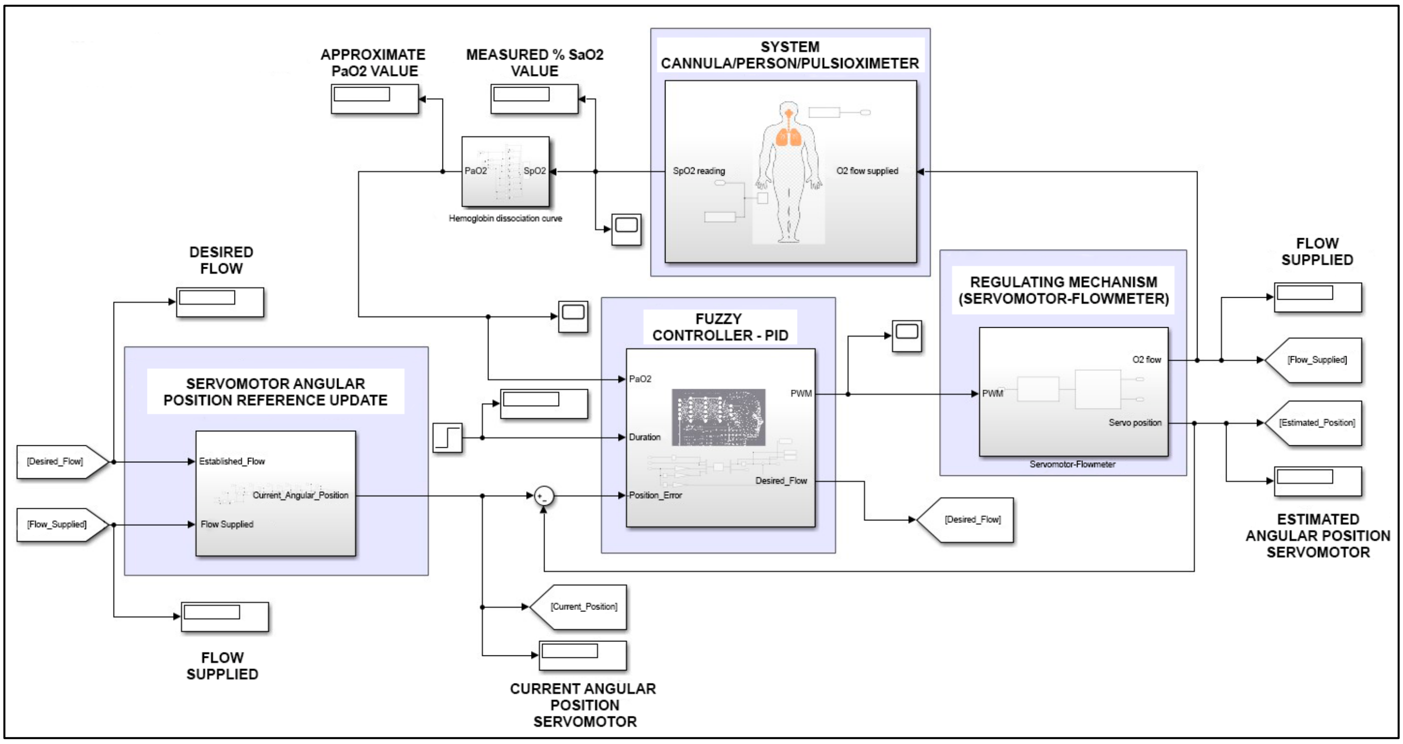

Figure 7. Matlab model of the control of the oxygen therapy system.

By integrating this controller, it becomes feasible to deal with the imprecision and uncertainty that naturally exists within the system[15]. 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 described in Fig. 8.

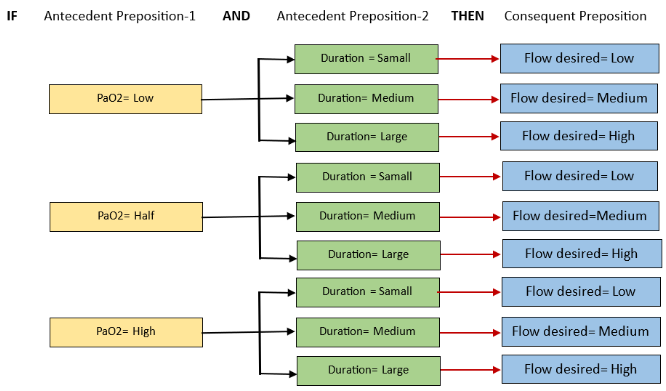

Figure 8. Rules implemented in the system.

IV. ANALYSIS OF RESULTS

To evaluate the response of the implemented Fuzzy System, we analyze the scenario in which the patient needs oxygen supply.

To do this, a step signal was applied that emulates the changes in saturation percentages in the blood, a signal given by pulse oximetry, after having supplied oxygen to the patient through the nasal cannula, these values are adjusted to values of partial pressure of oxygen (PaO_2) using the curve shown in Figure 2. The result is the graph presented in Fig. 9, which shows that initially the patient registers a partial pressure of oxygen in the blood of 33.64 [mmHg] and after 20 minutes, the expected time to obtain a change in blood oxygen saturation, its value changes to 42.82 [mmHg].

Fig. 10 shows the signals that represent the behavior of the self-regulation mechanism of the system where, when making a change in the position reference of the servomotor, the system proceeds to adjust the angular position of the servomotor until it reaches the desired position that allows the opening of the flow to be supplied to the patient. The blue signal corresponds to the angular position in which the servomotor axis is located, while the red signal establishes the reference where said axis should be located; that is, the new angular position to supply the oxygen flow required by the patient. The system presents an overdamped response to a step change signal of oxygen partial pressure to the patient.

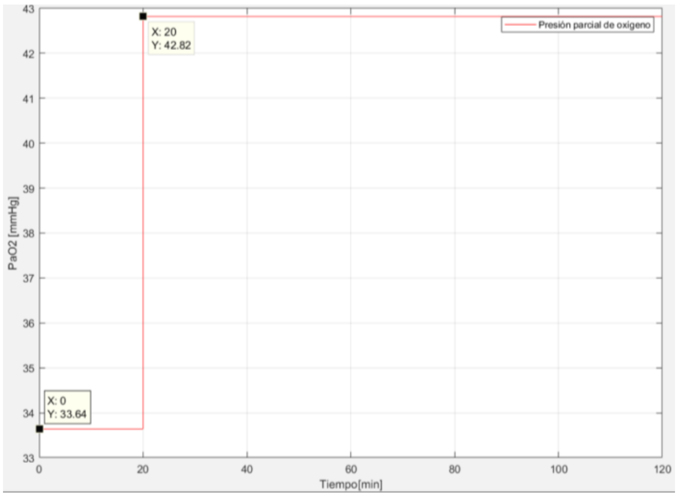

Figure 9. Change in the partial pressure of oxygen of a patient.

The temporal evolution of the estimated and desired oxygen flows is presented in Fig. 11. The red graph shows the expected flow to be supplied to the patient and corresponds to one of the controller outputs, this value serves as feedback to set the reference partial pressure of oxygen. The estimated flow, shown in blue, is obtained from an indirect measurement of the patient's pulse oximetry and only represents an approximation of the oxygen flow that is actually expected to be delivered, since its values are obtained from the adjustment of the curve that relates the position angle of the servo motor and the open position of the knob.

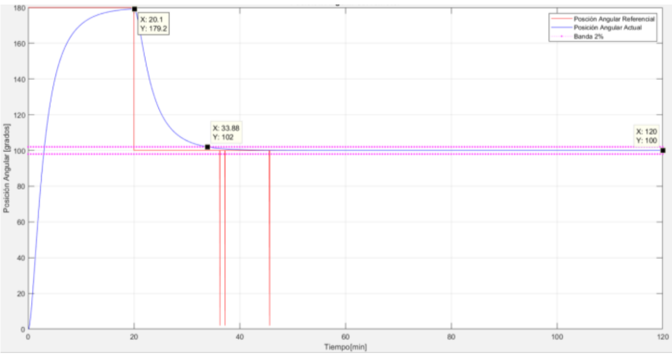

Figure 10. Angular position of the servomotor.

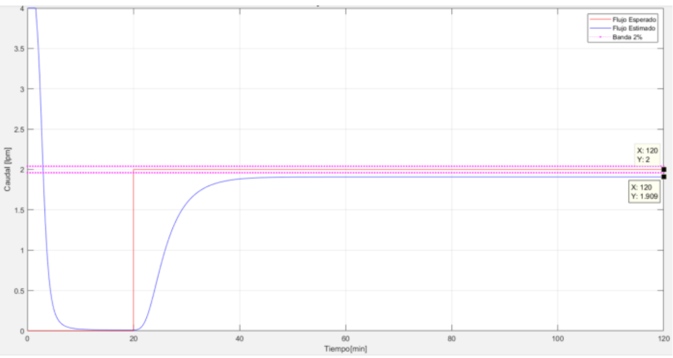

Figure 11. Temporal evolution of the estimated (blue) and desired (red) oxygen flows

Fig.12 shows the temporal evolution of the electrical variables and gas production of the renewable system during the day, the first half of the time corresponds to the day and the rest is at night. The first half of the blue curve is the power of the panels, and their behavior corresponds to the sum of the power of the electrolyzer (purple curve) and the load during the day (orange curve), while the curve in brown color is null, since the fuel cell does not deliver energy during the day. At night, the fuel cell delivers energy only to the load and therefore has the same power value of the load during the entire night period.

Figure 12. Evolution temporal del sistema renovable

V. CONCLUSIONS

A fuzzy logic system was chosen, due to intelligent monitoring was implement with its linguistic variables and the membership functions that are related to this kind of control system. The main reason for using this controller is based on partial pressure of oxygen is estimated, good results were obtained.

A MIMO controller system based on fuzzy logic was modeled, which two inputs were manipulated with a nonlinear system to obtain based on statistic two outputs. A nonlinear system provides efficiency and effectiveness without the use of advanced calculations where a good approximation was obtained

The proposed study is focused mainly on facilitating oxygen therapy in communes or homes of alleged residents of the city, where there is no national electrical network.

The green oxygen dispenser for oxygen therapy is characterized using alternative energies, both for obtaining medical oxygen and for its supply and use of hydrogen to supply energy to the home.

As future work, it is expected to develop a prototype of the oxygen dispenser equipment for oxygen therapy in order to improve the design and adapt it to the regulatory requirements for medical use in homes.

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