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FUZZY – MANDANI CONTROLLER FOR A WATER SUPPLY SYSTEM

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Abstract: *This paper aimed to develop an intelligent controller based on fuzzy systems, with a Mandani inference system and Gaussian pertinence functions (MFs). This project was applied to the pressure control of a simulated supply system in an experimental workbench at LENHS/UFPB (Laboratory of Energy Efficiency and Hydro Sanitary of the Federal University of Paraíba). The controller was developed through the relationships between system outputs and inputs and operator expertise, implemented on the LABVIEW platform through a supervisory and interconnected to the plant via a Texas Instruments SCADA (Supervision Control and Data Acquisition) system. Control is performed under a frequency inverter that varies the rotor speed of a pump. Input data is obtained and monitored using three pressure transducers (PT) and one flow meter installed on the CMB (Motor Pump Sets) discharge line. The results show the effective control of pressure , with maximum overrun and reasonable accommodation time to meet the system hydraulic inertia parameters. In addition, the reduction in electrical consumption is consistent, as indicated by the monitoring of CMB's active power and energy efficiency indicators.*

Keywords: *Fuzzy, Energy efficiency, Water distribution, Speed control.*

1. INTRODUCTION

Computational techniques have progressed in recent years and are taking the place of classical mathematics in the modeling and design of controllers for control systems. In fact, computational models had better represent very complex systems with severe nonlinearities. Fuzzy logic, or also fuzzy logic, was first proposed by Mandani (1976), based on the Fuzzy sets proposed by Zadeh (1965). It is a very particular control technique, in which it allows the modeling of human thinking or expertise in a simple, intuitive and visual way. Such a technique is robust enough to handle inaccuracies, nonlinearities and even subtle temporal changes in the system.

The applicability of Fuzzy logic in supply systems arises from the need to mitigate energy consumption. According to GOMES (2012), the sanitary supply and sewage systems are responsible for approximately 3% of the energy consumed in the world, being the pumping system responsible for up to 97% of this amount. The goal is to develop controllers that, combined with Motor Pump Sets (CMB), frequency inverters and electronic valves, can reduce the amount of electricity consumed through the effective control of system pressures, thus resulting in greater energy rationalization. Several projects were developed, such as those by Lavor (2012), Oliveira (2012), Salvino (2016), Mendonça (2016) and Barros Filho et al. (2017) focused on the development of intelligent systems for pump rotation control aiming at energy efficiency and effective control of service pressures.

The main objective of this paper is to analyze the efficiency and impact of a Fuzzy controller in the energy rationalization of water pumping systems. For this purpose, a Fuzzy - Mandani controller, with Gaussian pertinence functions (MFs) and a small number of rules, is designed and implemented in the LABVIEW platform for the control of pressure of an experimental bench supply plant, through the speed variation from CMB. In order to analyze this impact, an experiment is performed in which the hourly water demand curve is simulated and at each period, the energy indicators (CE and yield) are analyzed.

2. THEORETICAL REFERENCE

2.1 Lógic fuzzy

Recognized as the best tool for working with "black box" systems, Fuzzy logic is very effective in situations where human reasoning needs to be modeled and in cases where the mathematical model formulation of the system is complex or impossible. A controller based on Fuzzy techniques contains at least three components according to Zadeh (1965):

- Dictionary, which defines Fuzzy sets about variables (Fuzzyfication);
- Rule base, which establishes a relationship between input and output variables;
- Inference method, used to determine the output given a certain input;
- Defuzzyfication, which transforms a Fuzzy output into a real number or a classic set.

In Fig. 1 the architecture of a Fuzzy - Mandani inference system is presented. Initially the input variables are Fuzzyficated - numeric variable is transformed into linguistic variable - and grouped into a certain linguistic set. If - Then rules are referenced in the inference step. "Fuzzy rules describe specific situations that can be subjected to expert analysis and whose inference leads to some desired outcome" (Ortega, 2001). The last step is the defuzzyfication of this grouping of results, formed by "words" and their weights. Thus, there is the antecedent formed by the inputs and the fuzzyfication process and the consequent, formed by the rules and the defuzzyfication process.

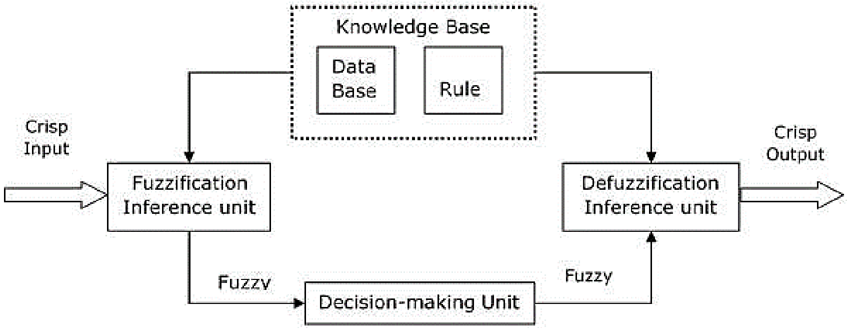

Figure 1. Fuzzy - Mandani Architecture. Available: www.tutorialspoint.com.

2.2 Supply system

According to Gomes (2012) water supply systems is the set of equipment, works and services aimed at supplying water to the community for domestic, industrial and public consumption purposes. Its design and sizing happen in an integrated manner, which generally requires the use of a team of specialized professionals. Figure 2 illustrates a simplified supply system from water abstraction to distribution to the final consumer, the final step being completed by pushing water through a pumping station.

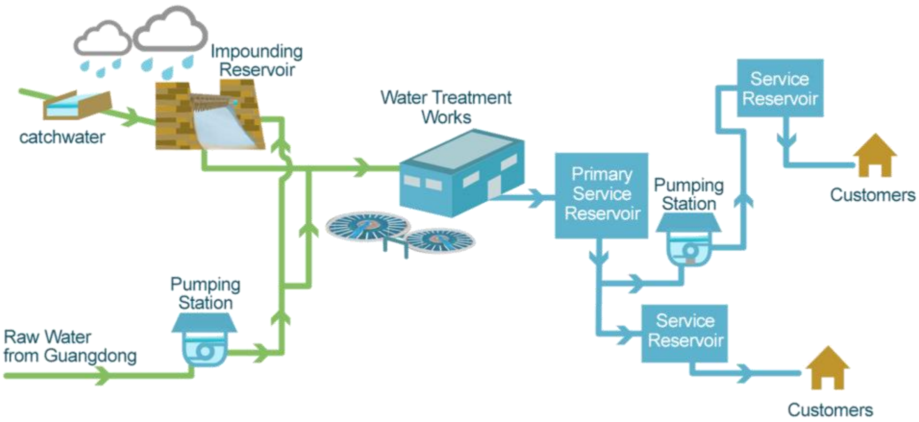

Figure 2. Supply system. Available: https://www.wsd.gov.hk

2.3 Hydroenergetic indicators

According to Alegre et al. (2004), hydro energetic performance indicators are methods that allow to evaluate the behavior of the various characteristics of the pumping system, helping to identify faults and increasing reliability and performance.

One of these indicators is the Specific Energy Consumption (CE), which represents the amount of energy required to pump a given volume of water, that is, reflecting the efficiency of the CMB coupled with the efficiency of the downstream hydraulic system of the pumping device and is expressed by Eq. (1) (Alegre et al. (2004) and Gomes (2012)).

$$CE = \frac{Energy\ consumed\ (KWhe)}{Pumped\ volume\ \ (m^3)} \tag{1}$$

On the other hand, it is possible to quantify the efficiency of the water distribution system by calculating the yield (η) of the CMB using Eq. (2), which relates the hydraulic power (P) through the pressure (H), flow (Q), specific liquid weight (γ) and active electric power (P) (Gomes (2012)).

$$\eta = \frac{\gamma * H * Q}{P} \tag{2}$$

3. METHODOLOGY

3.1 Experimental system

This paper was developed on an experimental bench at the Laboratory of Energy and Hydraulic Efficiency in Sanitation of the Federal University of Paraíba - LENHS/UFPB. The experimental bench used is shown in Fig. 3(a). In this work, however, only part of the workbench was used, summarized in: Three pressure sensors (Druck PTX 7217), one flow meter (VMS Pro 038), one CMB (5 HP DANCOR), one frequency inverter (CFW -11) and an electronic Pressure Reducing Valve (PRV), whose function is to introduce pressure losses in the system. The experimental system used is summarized by the schematic illustrated in Fig. 3(b).

In this way, water from the reservoir is pumped by a centrifugal pump (three phase 220/380 V 5 HP) through pipes and connections. The rotation speed of the centrifugal pump is controlled by means of a frequency inverter.

Finally, the electrical signals from the sensors are acquired by a data acquisition system (NI-USB 6009), processed in a computer (Dell Inspiron 5448 - 20W), through the developed controller, and a control signal is sent to the frequency inverter to increase or decrease the frequency, reducing the speed of the CMB.

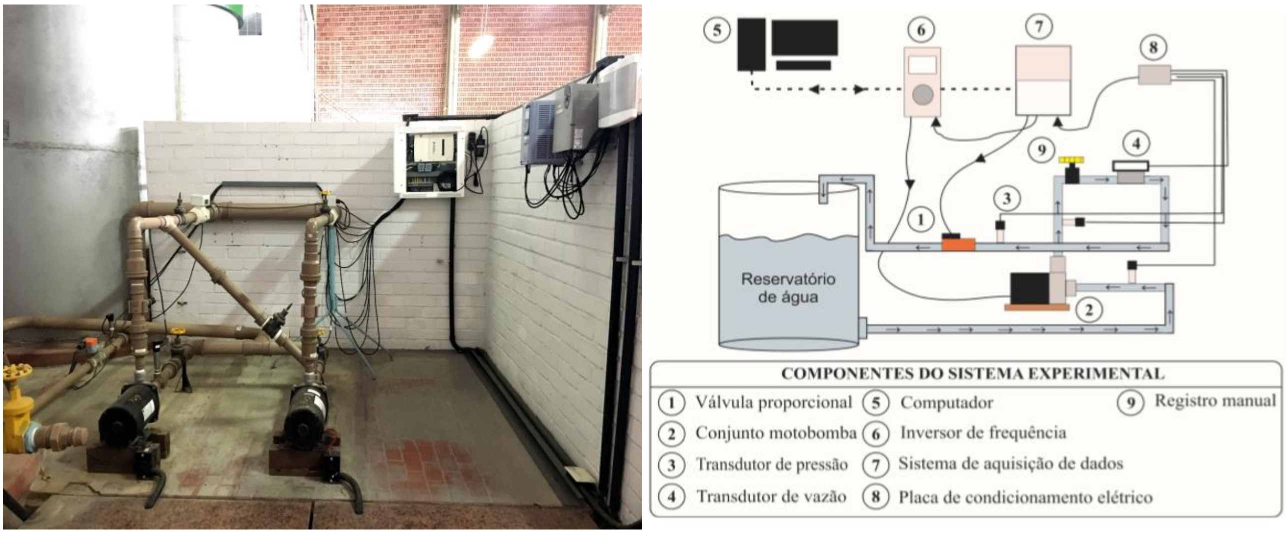

Figure 3. Bench used in experiments located in LENHS/UFPB.

3.2 Fuzzy Controller

The development of the Fuzzy controller started from the expertise gained by operating the inputs and monitoring the system outputs, as well as the technical knowledge of the equipment and instruments used. Figure 4 shows the schematic of the MISO (Multiple Input - Single Output) type controller, the input signals are the pressures and the pressure variations acquired by the Pressure Transducer 3, illustrated in Fig. 3(b). The output signal is a frequency delta for CMB rotation control.

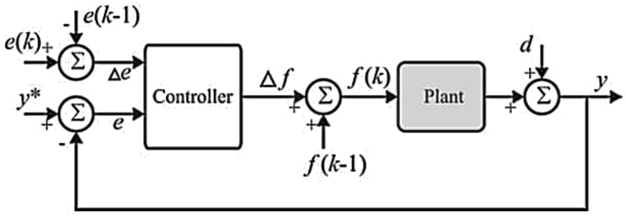

Figure 4. MISO Fuzzy Controller.

The sets on variables and the Fuzzies rule base were developed through this interrelation of data . In addition, Gaussian membership functions were used to reduce the number of controller rules, since these nonlinear membership functions would better represent the system that is also nonlinear, resulting in only nine rules. The Fuzzies sets and the control surface are shown in Fig. 5.

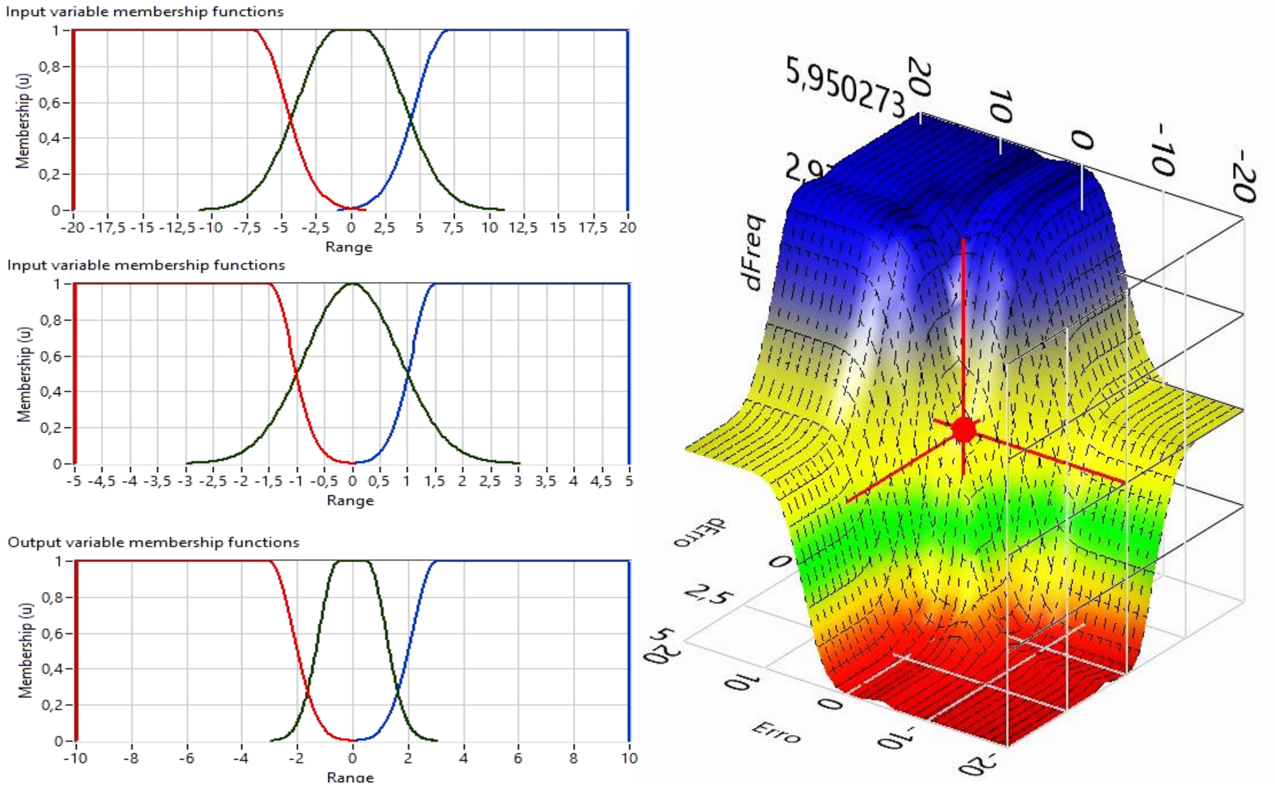

Figure 5. Fuzzies sets (a) and control surface (b).

4. RESULTS

In this section, we present and discuss the results of the proposed Fuzzy controller compared to two other controllers, PID (Proportional - Integrative - Derivative) and P. Then, the proposed Fuzzy controller is applied to a case study, where the water demand curve of on the experimental bench is simulated. The objective is to evaluate the energy rationalization achieved by the system with controller, this simulates two operating conditions:

- CMB operating at rated speed and in the absence of any type of flow and/or pressure control;
- CMB driven by a frequency inverter, subjected to intelligent closed loop control based on fuzzy logic.

All experiments were performed on the experimental bench, as described in section 3.1 the data obtained were analyzed in MATLAB using a low pass filter with cutoff frequency equal to 0.01.

4.1 Controller analysis

The results show the control of the operating pressure at the desired set point, and the Fuzzy controller presented the best results. The rise time presented was reasonable for all controllers, and was within acceptable limits for the system, however, the maximum overrun for the proportional controller was outside the acceptable parameters, as can be seen in

Fig. 6. The regime error Permanent is only acceptable for the Fuzzy controller. Table 1 summarizes the results for the 3 controllers tested on the experimental bench.

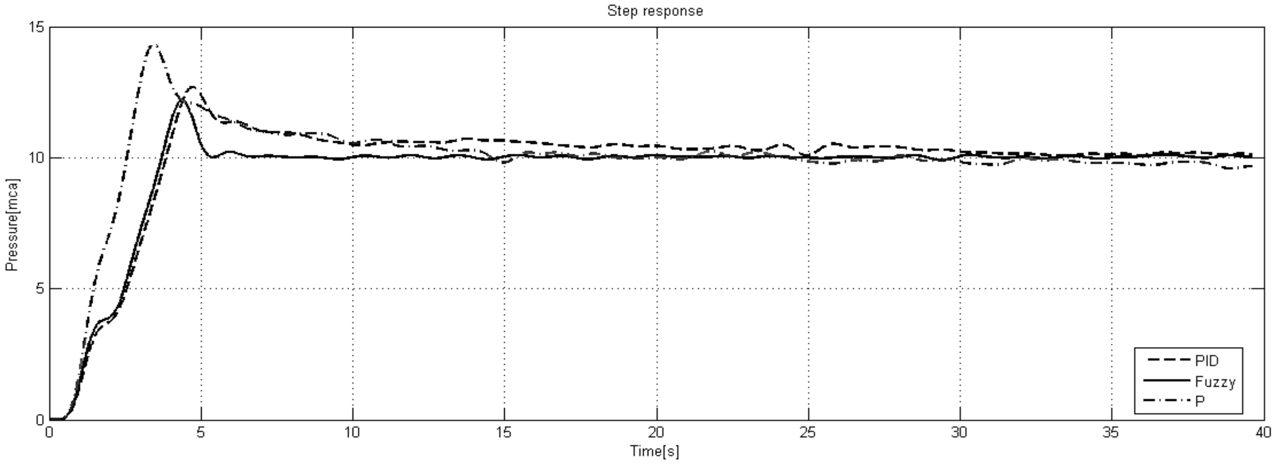

Figure 6. Transient response with valve electronica adjustment in 35 degrees.

Table 1. Summary of controller performance under study.

Controller	Rise time [s]	Accommodation time [s]	Maximum overtaking [%]	Steady state error [%]
Fuzzy Gaussian 9R	4.4	6.1	13.47	0.4
PID	4.8	14.5	13.5	1.5
P	3.5	34	15.25	2

In a second analysis, where the system set point was varied, as shown in Fig. 7, the Fuzzy controller was robust enough to maintain the operating pressure at the desired set points, with rise time and steady state error are satisfactory. The PID controller had a too long rise time, however, had a low steady-state error of up to 12.5 [mca]. The proportional did not present performance for the case study.

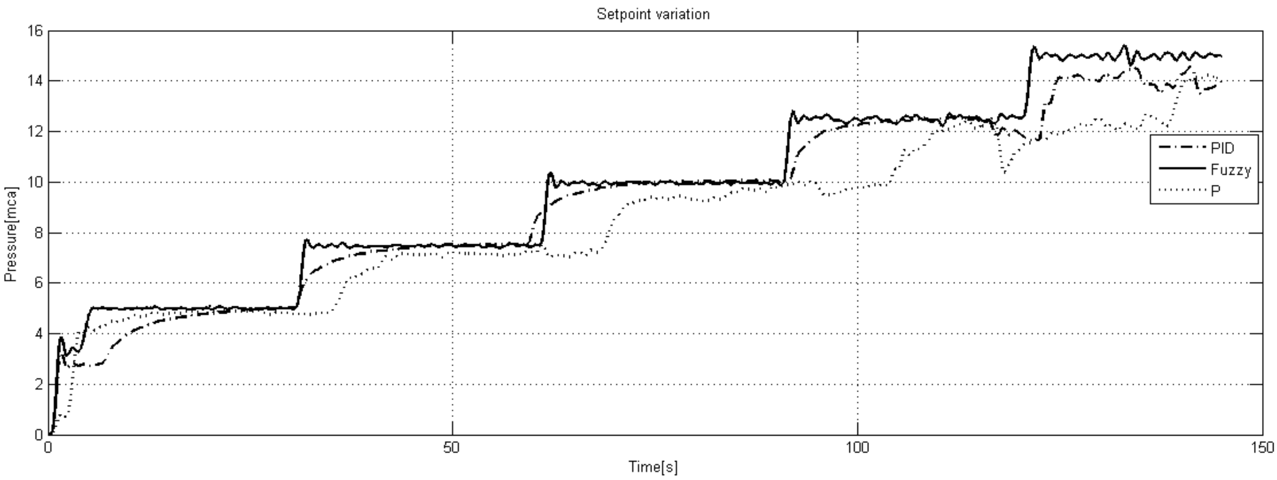

Figure 7. Changing the set points with valve electronica adjustment in 35 degrees.

The stability of the proposed controller in relation to the disturbances was also analyzed. The VRP had its angle varied at a constant velocity, between 30º and 70º (from partially open to partially closed), so that the pumping system pipe loss curve was displaced. Thus, the controller must act upon the speed of the CMB in order to maintain pressures at desired levels. In Fig. 8 the result of this test is presented, for the Fuzzy controller the maximum observed error was 1.55%, which emphasizes the robustness of the controller. For the other cases, the observed error was 11.6%.

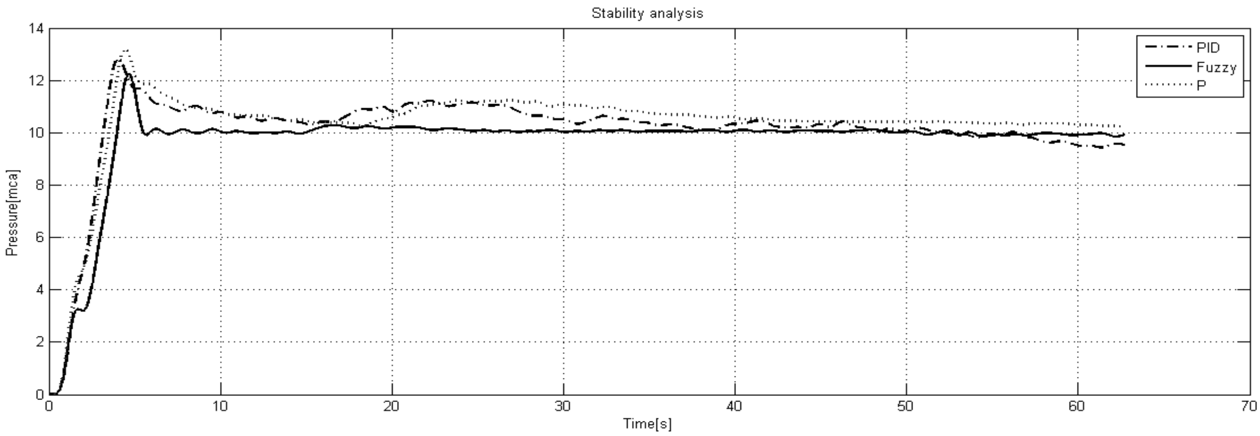

Figure 8. Analysis of controller in relation to disturbance by varying the VRP.

In other analysis, the control action was evaluated, which basically shows how much the controller tries to correct the system set point, the smaller the amplitude of this action, the smaller the variation of the output signal, in this case the inverter frequency (see Fig. 4). This action is directly related to the stability and robustness of the controller. For the specific case, the control action for opening the VRP was monitored keeping the same set point (see Fig. 8). The action for the Fuzzy controller was lower compared to the PID, which results in lower amplitudes at CMB startup and greater stability on steady state.

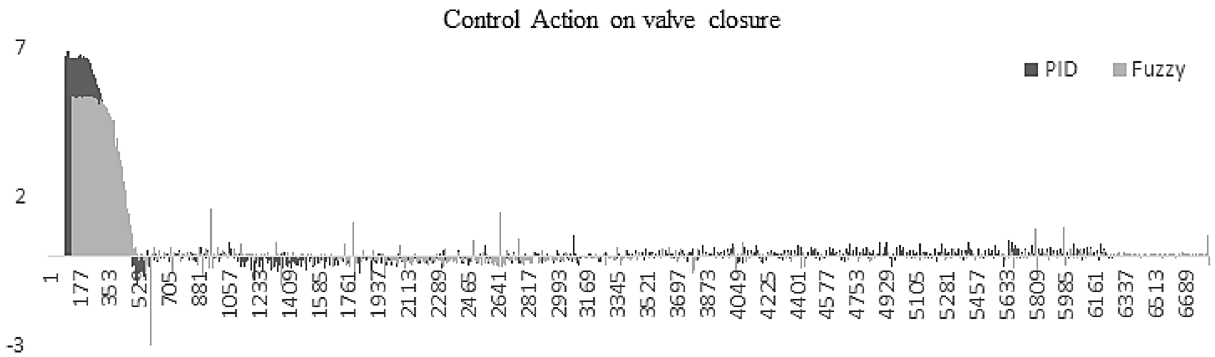

Figure 10. Amplitude of controller action (ΔF) by sample number at open valve situation.

In the last analysis compared the proposed controller with another Fuzzy controller built with triangular and trapezoidal MFs and 49 rules. It is noticed that the current controller, with a smaller number of rules, has a higher maximum override and this was already expected. However, the steady-state error is less than 0.4% versus 1.33% for the controller with triangular MFs, as shown in Fig. 9.

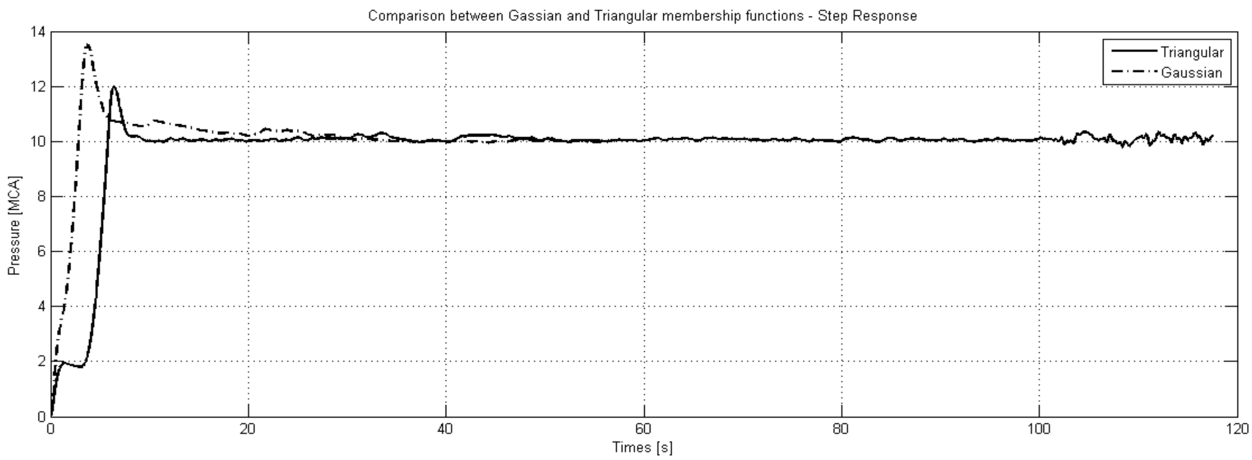

Figure 9. Comparison between Gaussian nine rules controller and triangular forty nine rules.

4.2 Energy efficiency

To evaluate the energy efficiency of the controlled and uncontrolled system, the consumption profile proposed by Gomes (2012), shown in Fig. 11, which indicates the average hourly water consumption was simulated. The variation in consumption causes significant fluctuations in the operating pressure, the controller objective is to maintain the operating pressure, seeking the highest energy efficiency, by varying the speed of the CMB. The average water consumption for the case analyzed was 0.765 l/s (k = 1), for the consumption of the other times simply multiplies the average consumption by the coefficient.

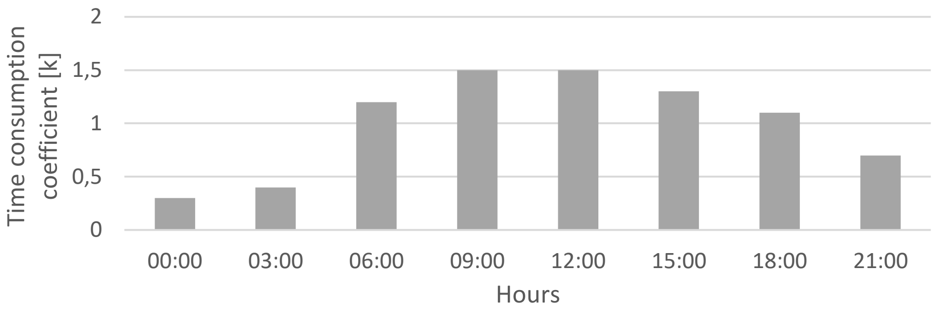

Figure 11. Hourly consumption coefficients according to Gomes (2012), the higher the coefficient the higher the consumption.

In Figure 12(a) it is possible to observe the reduction of the active power of the CMB in periods of lower consumption, as for example, at dawn. Figure 12(b) shows the effective control of pressures at the same level during the entire operating time. Compared to the uncontrolled system, the intelligent controller aims to dramatically reduce system pressure fluctuations.

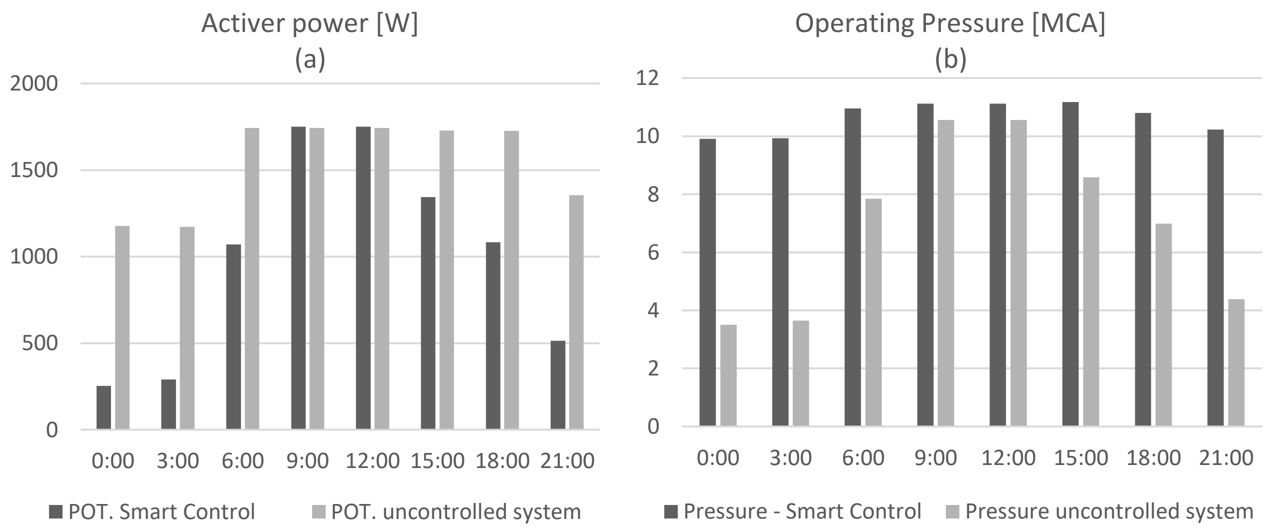

Figure 12. Active power of the CMB (a) and the operating pressure control (b).

Figure 13(a) shows the yield, calculated by Eq. 2, of the CMB which, for the case of the Fuzzy-controlled system, has a higher yield. Figure 13(b) shows the CE, calculated by Eq. 1, which indicates the amount of energy used to pump a specific amount of water, the lower this value, the less energy the system uses. In the case of the controlled system, the CE has the lowest values for times of lower demand. For cases where the system demand is maximum, the CE of both cases are almost equal. However, it is possible to see a maximum reduction of 383 % at 00:00 when comparing the operating system with the fuzzy pressure controller and manually controlled through a register.

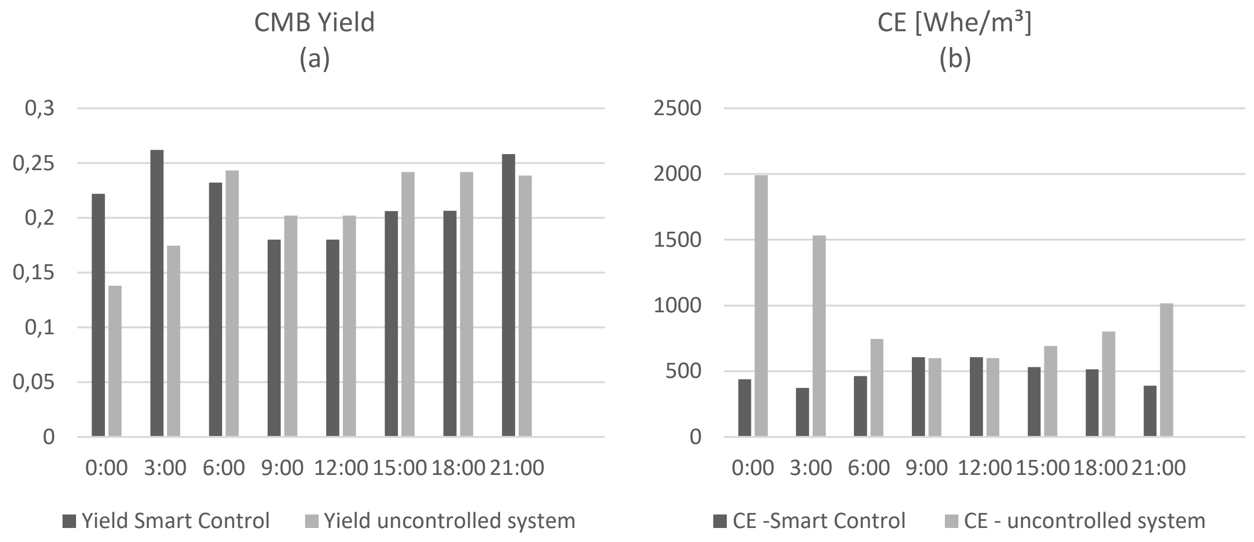

Figure 13. Yield of the CMB (a) and specific consumption coefficient (b).

The use of intelligent controllers for water supply systems is mainly justified when there are fluctuations in water demand. When the system operates at its designed capacity, the controller ends up being expendable. However, in times of varying demand, the controller is effective in controlling the speed of the CMB.

5. CONCLUSIONS

This paper dealt with the use of Fuzzy logic for the automation of a pumping system aiming at the control of the service pressures and, consequently, the reduction of the electric consumption. The desired objectives were achieved, the controller proved robust enough to control step-type disturbance and set point change. In addition, the reduction in electrical consumption was consistent with a study that compared the energy expenditure of a workbench with and without the controller. It was also observed a maximum increase of 9.16% of yield and a maximum reduction of 383% of Specific Energy Consumption during the time of minimum demand compared to other methods presented in this work.

Future work may address the CMB Life Cycle Cost (LCC) study, since once engine speed is reduced there may be a significant reduction in equipment maintenance costs as well as an increase in service life.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Barros Filho, E. G.; Salvino, L. R.; Bezerra, S. T. M.; Salvino, M. M.; Gomes, H. P. INTELLIGENT SYSTEM FOR CONTROL OF WATER DISTRIBUTION NETWORKS. WATER SCIENCE & TECHNOLOGY: WATER SUPPLY, p. 1-12, 2017.

Carvalho, P. S. O. CONTROLE PARA BOMBEAMENTO DISTRIBUÍDO COM VISTAS À MINIMIZAÇÃO DOS CUSTOS ENERGÉTICOS APLICADO A SISTEMAS DE ABASTECIMENTO DE ÁGUA, 2012. Tese (Doutorado em Engenharia Mecânica) – Programa de Pós Graduação em Engenharia Mecânica, UFPB, João Pessoa, PB, 2012.

GOMES, H.P., 2012. Eficiência Hidráulica e Energética em Saneamento – Análise Econômica de Projetos. 2ª Ed., UFPB/Ed. Universitária, João Pessoa, PB, Brasil, 146p. ISBN: 978-85-7745-461-7.

H. Alegre, W. Hirner, J. M. Baptista and R. Parena. Indicadores de desempenho para serviços de abastecimento de água. Série Guias Técnicos, LNEC and IRAR, 2004.

Salvino, L. R. EFICIÊNCIA ENERGÉTICA EM SISTEMAS PRESSURIZADOS DE DISTRIBUIÇÃO DE ÁGUA COM O USO DE REDES NEURAIS ARTIFICIAIS, 2016. Tese (Doutorado em Engenharia Mecânica) – Programa de Pós Graduação em Engenharia Mecânica, UFPB, João Pessoa, PB, 2016.

Mendonça, K. H. SISTEMA DE CONTROLE FUZZY NA OPERAÇÃO OTIMIZADA DE REDES SETORIZADAS COM BOMBEAMENTO DIRETO, 2016. Dissertação (Mestrado em Engenharia Mecânica) – Programa de Pós Graduação em Engenharia Mecânica, UFPB, João Pessoa, PB, 2016.

Oliveira, J. K. C. LÓGICA FUZZY APLICADA NA OTIMIZAÇÃO OPERACIONAL DE REDE SETORIZADA DE DISTRIBUIÇÃO DE ÁGUA. 2017. 147f. Tese (Doutorado em Engenharia Mecânica) – Programa de Pós Graduação em Engenharia Mecânica, UFPB, João Pessoa, PB, 2017.

ORTEGA, N.R.S. Aplicação da Teoria da Lógica Fuzzy a Problemas de Biomedicina. Tese de doutorado IF-USP. São Paulo. 2001. 153p

Zadeh, L. A. Fuzzy sets. *Information and Control*, 1965. Ed. **8** (3): 338–353. Doi: 10.1016/S0019-9958(65)90241-X

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