Water Practice & Technology

Water Practice & Technology Vol 00 No 0, 1 doi: 10.2166/wpt.2022.079

Automation and control of a pressurized collective irrigation system based on fuzzy logic

Kamilla Henrique Mendonça *, Heber Pimentel Gomes and Juan Moisés Mauricio Villanueva
Laboratory of Energy and Hydraulic Efficiency in Sanitation, Federal University of Paraiba, João Pessoa, PB, Brazil
*Corresponding author. E-mail: kamillapdm@hotmail.com

KHM, 0000-0002-7765-4526; HPG, 0000-0001-8374-1469; JMMV, 0000-0002-8760-9390

ABSTRACT

In the irrigated agriculture sector, to increase productivity and profitability, it is necessary to increase efficiency in the use of water and electricity. Thus, the use of operational processes that maximize productivity in the sector, reducing water and electricity consumption, is essential for irrigation development. This work proposes developing an intelligent control system based on fuzzy logic to control the pressure and flow at the entrances to the plots of a collective pressurized irrigation system. The tests were carried out on an experimental bench that emulates an automated water distribution system installed in the Laboratory of Energy and Hydraulic Efficiency in Sanitation at the Federal University of Paraiba. The pressure was controlled by varying the frequency of the pump set, while the flow was controlled by varying the opening of the control valves upstream of the entrance of each of the plots. With the application of the proposed methodology, the system showed a reduction of 8.47% in water consumption and a 42.51% reduction in electricity consumption. The results were found to validate the use of the controller, indicating that the network could control the design flows and pressures with different set points.

Key words: automation, controller, efficiency, energy, fuzzy logic, irrigation systems

HIGHLIGHTS

- To develop an intelligent control system based on fuzzy logic.
- To control the pressure and flow at the entrances to the plots of a collective pressurized irrigation system.
- Pressure control is carried out by varying the frequency of the pump.
- Control different parameters with the same controller.
- A significant reduction in water and electricity consumption is proposed.

1. INTRODUCTION

In the irrigated agriculture sector, to increase productivity and profitability, it is necessary to increase efficiency in the use of water and electricity. The agriculture and food sectors depend on water and energy resources. About 70% of all water consumed in the world is destined for the irrigated agriculture sector (Jägermeyr *et al.* 2015). It is necessary to use energy to produce, transport, distribute and prepare food, in addition to extracting, pumping, lifting, collecting, transporting, and treating water.

The large volume of water used for irrigation justifies the development of increasingly efficient use and handling processes, reducing waste in the system as much as possible and providing the ideal volume for plant development. To increase efficiency in the use of water and energy, automation appears as an important tool to achieve this goal (FAO 2014). The application of automation and control techniques in the irrigation process helps provide a more efficient and optimized management of water and energy, aiming to stimulate the increase in agricultural productivity and the reduction of waste.

Currently, the use of soil moisture sensors and automatic control valves is quite frequent in the field of irrigation. The operation of the systems that use this equipment is based on the verification of the parameters of the field conditions (soil/plant system) and its comparison with the design values. In this way, with the humidity sensor, the operator can analyze the real condition of the soil and, with the control valves, regulate the amount of water sent to the plant. There is also an automation record in the on-off switch of the pump set (on/off control), implemented through the use of timers that start the pump within the watering intervals and at defined periods. This practice, called shift irrigation, can contribute to two common mistakes: excess water that can lead to unnecessary leaching of the soil; or lack of water, which can cause a water deficit for the crop, interfering with its full development. In this way, the use of sensors that analyze the soil moisture level and determine just the exact amount of water to reach the optimum moisture level is more suitable, characterizing the process of irrigation by demand.

The different types of controllers used in irrigation systems can be applied in open-loop, without feedback, or in closed-loop, in which case the output will adjust to the value measured in the field in relation to a predetermined reference. Most of the open-loop controllers currently found on the market are microprocessors that act as a kind of timer, controlling the pump's on and off to maintain a certain level of moisture in the soil. Their low cost and easy handling make them very attractive to producers; however, they fail to adapt to the changes resulting from the dynamic behavior of this type of system.

In the case of control systems developed in closed-loop, the robustness of the process allows changes to occur in the decision-making phase of the controller, even with the unpredictable variations that occur in the climate over the course of a day. In this type of process, the simple addition of a moisture sensor in the soil allows the readjustment of the parameters initially proposed for the eventual activation of the actuators. Some examples of automation in irrigation systems can be detected when using equipment such as humidity sensors connected to volumetric valves. Electric resistance blocks, tensiometer, thermal conductivity, and gaseous irrigation control systems are some instant measurement methods for controlling and monitoring soil moisture.

In addition to the sensors and actuators that can work without human interference, some controllers and microcontrollers record the information obtained by the sensors and send command lines to control the actuators, allowing the farmer to program the days and hours of the irrigation periods. The use of automation in irrigation enables the farmer to increase his productivity and reduce energy costs and the waste of water and fertilizers, which are then used in their necessary concentrations (Bezerra & Gomes 2013). Gomes surveyed some automation applications in irrigation systems (Bezerra & Gomes 2013):

- Irrigation Systems Operating in Real Time: In these types of systems, irrigation occurs only when there is a record of the real need to increase soil moisture levels. With the use of humidity sensors, the data are sent by telemetry to the supervisory, which after analyzing their respective levels and comparing them with the ideal established values, starts the watering process.
- Irrigation Systems with Commercial Controllers: They are generally used in small and medium-sized systems. The controllers can be applied for opening or closing valves, cleaning filters, in fertigation, or actuation of valves. The controls can be programmed depending on the irrigation time or volume of water to be supplied to the soil, without analyzing the real need for irrigation, which can lead the system to leach, in the case of excess water, or water scarcity.
- Typical Pumping System with Flow and Pressure Measurement: Automatic control in a pumping system can provide electric power ordering, automatic priming of the pump, and measurement of parameters such as flow and pressure, in addition to other advantages. In this type of system, flow meters, pressure transducers, and control valves are used. The information is sent by telemetry, cabling, or any other possible means and can be read and analyzed in the supervisory.

The techniques described above are the most widely used in the irrigation sectors, due to their easy implementation and practical operation; however, they are programmed to operate under fixed growing conditions. In addition, they do not allow changes in their settings for different operating scenarios in the same distribution network. For systems that operate with variable conditions, according to the irrigation schedule, the water demand of the network, as well as the gross cultivation blade, the use of intelligent controls associated with decision making allows greater flexibility of operation to the system.

Among the most widespread controllers, we can mention the Proportional, Integral, and Derivative control – PID. This technique consists in calculating a performance value of the process from the information of the desired value and the current value of the process variable. This does not make it mandatory to use the three elements together. The property of linearity (or quasi-linearity) ensures that the three individual control strategies (PID), when associated, allow the feedback loop to compensate for changes in plant parameters. The occurrence of a non-linearity can make it difficult or even impossible to control some systems. Due to the fact that PID controllers are single input and output (control system called SISO – single input single output), and most processes are multivariable in nature (MISO – multiple input single output), it turns out that each variable needs its own controller and reference value. In addition, it is often the case that processes and plants have dynamics subject to varying parameters, which causes the operating points to shift, which leads the PID to provide unsatisfactory performance (Bezerra & Gomes 2013).

Due to its wide application in multiple fields of knowledge, fuzzy logic is widely used in academic and scientific circles, providing reliable and accurate results. Its insertion in academic circles since the 1970s facilitated the application of controllers in systems that cannot be easily described in a good mathematical model. Thus, it helped the development of research and studies in a wide range of areas. (Sasmoko *et al.* 2019).

For the development of controls applied to automated irrigation systems, the use of fuzzy logic is frequent. Given the considerable number of uncertain variables among which irrigation systems deal, such as: soil moisture, air, wind speed, rainfall, temperature, their use aims to insert in precise measures the operator's knowledge regarding the variable conditions under which the system operates (Anand *et al.* 2015). For years, fuzzy logic has been developed and improved to create intelligent controls and systems that operate efficiently. The developed techniques point to intelligent systems that work similarly to the behavior of technicians and human operators. In addition, fuzzy logic facilitates the interpretation and solution of problems whose variables do not have clear boundaries. The use of fuzzy logic in irrigation systems, whose parameters vary under several aspects, points satisfactorily toward creating more efficient methodologies that guarantee an optimized operation with considerable reductions in water and energy.

Recently, several works motivated by the possibility of controlling processes with several variables have been appearing and gaining expression in the field of science (Anand *et al.* 2015). Present a solution for an irrigation controller based on the fuzzy-logic methodology. The system described utilizes closed-loop control. The controller receives feedback from one or more sensors in the field that continuously provide updated data to the controller about parameters that are influenced by the system behavior (such as soil moisture level, the temperature in hothouses, and so on). According to the measurements provided by the sensors and the pre-programmed parameters (such as the kind of plants and the saltiness of the ground), the controller decides on how far to open the water valve. They concluded that some examples showed that the system operates within the acceptable range and is stable. It is important to note that such a system can save a lot of water and is very cheap to implement. The fuzzy rules are simple, making the system attractive to use by all types of agriculturists (Bahat *et al.* 2000).

In 2018, an automated irrigation model was proposed, successfully implemented by a fuzzy algorithm where the electric circuit is elementary (Hasan *et al.* 2018). Cost-effectiveness and low power consumption are the highest priority in design and implementation. Using this system on small land may seem a luxury. However, this system will be adequately effective if we consider a large area. As the model is fully autonomous, it will help a single farmer quickly keep multiple fields under surveillance. The system always ensures the required amount of water for a specific crop, so that no crop will get under- or over-irrigation.

In order to promote the application of the light-dependent irrigation control method in the production of domestic facilities, combined with the substrate moisture content and the electrical conductivity of substrate leachate, use the fuzzy control method to adjust further the irrigation amount and the electrical conductivity of irrigation nutrition, which precisely controls greenhouse irrigation and fertilization (JunHui *et al.* 2019). According to the experimental comparison, there is no difference between the advanced method and the traditional light-dependent irrigation control method in the yield of lettuce, but the water use efficiency of the plant is improved under the premise of ensuring growth. The system makes the next irrigation decision through substrate moisture content, irrigation amount, and irrigation nutrient concentration to solve the problem of timely, moderate, and automatic irrigation and saves irrigation water consumption. It provides a scientific basis for substrate lettuce irrigation cultivation and provides ideas for other plants' irrigation cultivation.

The economic and environmental need of using the right amount of water for irrigation has led to the development of different technological systems, such as simple automatic solutions that activate the irrigation process at well-defined times. (Fierro & Tello 2019; Priandana & Wahyu 2020). The main disadvantage of those systems is that they do not consider the actual amounts of water needed by the crops nor the meteorological variables that influence their development. An alternative to the use of automatic systems is intelligent irrigation systems that focus on the actual dosage of water needed by the crops.

The applications of fuzzy concepts in irrigation systems aimed at the development of controllers have already been widely disseminated in the area. As will be presented in section 2, the works developed in the area diversify the application of fuzzy logic in the control of pressure or in the control of the flow of the hydraulic network. According to the soil water demand, there are also records in controls for opening or closing valves at the entrances of the plots. However, applying the concepts of fuzzy logic to create controls that act simultaneously in controlling the flow and pressure in a collective irrigation system to reduce water and energy consumption is not common in current research.

These papers described above focus on determining the perfect moment to start irrigation and its suspension, taking into account the water needs of the crop. However, even with all the progress registered in the area of automation and control associated with the operation of irrigation systems, it is not common to use this technology applied in the operation of the hydraulic network and the impulse system necessary for pressurized systems. This work aims to increase the possibilities of controls in irrigation systems, aiming to optimize the operation of the hydraulic network that feeds the pipes that bring water with sufficient flow and pressure to the crops.

This work aims to develop an intelligent control system based on fuzzy logic to control the pressure and flow at the entrances to the plots of a collective pressurized irrigation system. The proposed configuration aims to control the flow and pressure in two different scenarios of operation of the hydraulic network, to reduce the consumption of water and energy in the network. Pressure control is carried out by varying the frequency of the pump set, while the flow is controlled by varying the opening of the control valves located upstream of each of the two outlets present on the bench. The main contributions of this paper are as follows.

(1) We propose to present a new configuration of a pressurized collective irrigation network, using the irrigation calendar associated with the flow and pressure control at the entrance of the plots, according to the water needs of the crops.
(2) In addition, with the new configuration, a significant reduction in water and electricity consumption is proposed, whose validation can be confirmed by maintaining the CMB performance associated with the use of frequency inverters, which would justify, in the long run, investment in automation equipment and instruments.

2. METHODS

2.1. Description of the workbench

For the development of this work, the tests carried out were applied in an automated water distribution system (AWDS), installed at the Laboratory of Energy and Hydraulic Efficiency in Sanitation at the Federal University of Paraiba (LENHS/UFPB). According to the scheme illustrated in Figure 1, the two exits from the water distribution network configure the entrances to the plots of the collective pressurized irrigation system, proposed for the simulation of the present case study. Before each of the simulated plots (Plot I and Plot II), there is an automatic control valve. If it is in the operator's interest, it is possible to turn off a valve and irrigate only one plot. The simulation of only one plot was carried out, but this situation illustrates something common and already practiced in irrigation fields, which is beyond the scope of this work.

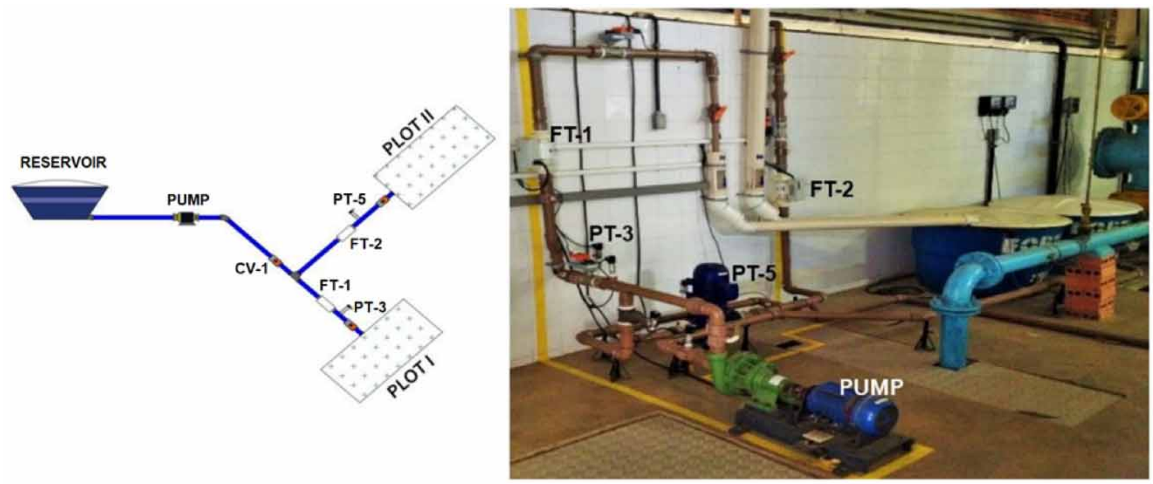

Figure 1 | Pressurized irrigation system configuration.

Due to the bench configuration, it was necessary to analyze the influence of the length of the pipes, simulating its variation from the number of turns in a register located just upstream of the high zone. As the hydraulic equations show, the greater the length of the line, the greater the frictional head loss, and consequently, the greater the hydraulic load imposed by the pump, reflected in its head.

The bench is fully instrumented and automated, the bench allows the development of studies and research in automated hydraulic networks, focused primarily on energy efficiency and conscious use of water. The reading of the hydraulic parameters provided by the sensors and actuators is carried out based on the communication established between two data acquisition boards from National Instruments, models NI USB 6221 and NI USB 6229, and the supervisory software developed in LabVIEW®, as well as the execution of control actions on proportional valves and frequency converters. For the measurement of electrical parameters, the Fluke® Model 434 energy analyzer was used. This equipment consists of current and voltage meters, and can also analyze parameters such as the power of the pump set. The Fluke® case has a 16-bit resolution and a maximum sampling rate of 200 kSamples/s per channel.

2.2. Irrigation sectors – dimensioning of flow and pressure at the entrances of the plots

The bench used to apply this work simulates a pressurized irrigation system equipped with flow and pressure meters at each of its entrances. The flow and pressure conditions at the entrance of each irrigated zone may vary depending on the hydraulic operation of the collective water distribution network. Table 1 shows the parameters chosen as input values to characterize each plot. The values adopted for the phenological and edaphological data were extracted from technical circulars issued by the Empresa Brasileira de Pesquisa Agropecuária – EMBRAPA (EMBRAPA 1999).

Table 1 | Crop soil parameters

Culture phenological data	Initial		Development		Mid-season		Late-season		Harvest	
	P	B	P	B	P	B	P	B	P	B
Culture coefficient Kc	0.45	0.35			1.15	1.1			0.85	0.9
Phenological phase duration	10	10	30	20	50	45	15	15	105	90
Rooting depth	0.6	0.2			0.8	0.4				
Critical depletion	0.4	0.5			0.4	0.5	0.4	0.5		
Yield response factor	0.6	0.2	0.6	1.1	0.7	0.75	0.2	0.2		
Edaphological data										

	Potato	Bean
Total available soil moisture (mm/meter)	140	140
Maximum rain infiltration rate (mm/day)	35	35
Maximum rooting depth (cm)	60	70
Critical percentage of soil moisture (%)	0	0

In addition to the parameters chosen to characterize the soil and the crop, it was also necessary to insert data related to the climate, such as: maximum and minimum temperatures, relative humidity, wind speed, precipitation of the day, and the number of hours of solar irradiation. The values referred to the period from 2010 to 2018 and were obtained directly from the Brazilian National Institute of Meteorology (INMET 2020).

To determine the gross irrigation necessary for calculating the flow and pressure required at the network entrance, the CROPWAT program was used, free software developed by the Food and Agriculture Organization (FAO), the United Nations (UN) specialized agency for Food and Agriculture. By entering all the values in the CROPWAT program, it is possible to obtain the irrigation calendar. In it, the days for irrigation are indicated and the gross irrigation that must be applied, taking into account evapotranspiration (calculated by the Penman-Monteith equation) and the soil and climate conditions.

The data that were used to perform the simulations took into account the hydraulic support capacity of the emulated network. In the testing phase, after carrying out different simulations with different parameters from those adopted in Table 1, the calculated values for the pressures and flows adopted as a reference for the proposed controller also managed to achieve the expected response. Thus, it is highlighted that the values obtained for the flows and pressures would be different from those presented here for a different set of parameters. However, the concept adopted for creating the controller, as well as its inference rules and its pertinence functions, could be replicated in another system.

For the determination of the reference values of the flow and pressure in the two zones, the procedures illustrated by Bezerra & Gomes (2013) for a drip irrigation system were used. To validate the controller, two operating scenarios were established for the AWDS network. In the first setup, the largest gross irrigation was considered for both corps. In the second setup, the smallest gross irrigation provided by CROPWAT from the irrigation calendar was used. The goal is to use AWDS in two different scenarios, with different flow and pressure requirements for each setup. Thus, Table 2 presents the values after the design.

Table 2 | Low zone and high zone (largest demand) parameters

	Low Zone LZ – Bean		High Zone HZ – Potato	
Parameter	**Setup I**	**Setup II**	**Setup I**	**Setup II**
Gross blade (mm)	53.30	40.10	54.40	48.0
Irrigation period (day)	5	4	5	4
Cultivation area (m × m)	40 × 80	40 × 80	100×120	100 × 120
Flow (m^3/h)	9.00	8.00	4.00	4.00
Pressure (m)	11.00	7.00	14.00	10.50

The bench used for the application of the controller has two pressure zones, named low zone – LZ (flow readings in FT-1 and pressure in PT-3) and high zone – HZ (flow readings in FT-2 and pressure in PT-5). From the results obtained with the simulations described above, the rules of fuzzy control were created. Taking into account a large number of variables, it was decided to create a decentralized controller. Decentralized control, in a system that operates with two different zones, acts individually on the actuators, so that the variables of interest reach their reference values. In the bench used for validation of the proposed controller, four variables were controlled, PT-3, FT-1, PT-5, and FT-2. The pressure in the PT-3 was controlled by the performance of the controller in the frequency inverter (F) and CV-1 (control valve), also called the pressure reducing valve (PRV). The pressure in the PT-5 was controlled by the actuation of the controller in the FI. The flow control in the LZ (FT-1) was achieved by the actuation of the controller in the CV-2 valve; finally, the FT-2 control was the result of the controller acting on the CV-3 valve. The controller structure operates according to the diagram shown in Figure 2. According to Figure 2, after starting the system, it is necessary to choose the operating setup, since each configuration will provide different reference values for the flow and pressure in the network. After selecting the setup, the decentralized control is activated separately for each of the four sensors. The actuators for PT-3 are the FI and the angle of CV-1, while the actuator for the control of FT-1 is the opening of CV-2. For the control of the PT-5 the actuator is the FC, and FT-2 is controlled by varying the opening of the CV-3.

If the sensors reach their reference values, the system is turned off; otherwise, the controller must continue acting on the FI and on the valves so that the sensors reach the set-points established for each setup. Controllers based on fuzzy logic require the specialist to thoroughly understand the network's operation. It is necessary to know how the control variables interact with each other based on the operating variables of the plant's actuators. In order to elaborate the rules of decentralized control applied to each of the four sensors, motor pump set performance studies were developed based on the variation of the frequency of the inverter and its relationship with the pumped flow.

Another necessary study concerns the analysis of flows and pressures based on the plant's operating conditions variation. The behavior of the flows in the two zones was studied from the variation in the opening of the control valves and the CV-1, which operates as a PRV upstream of the LZ. Through these studies, it was realized, for example, that as the demand for water by the LZ increases, there is a

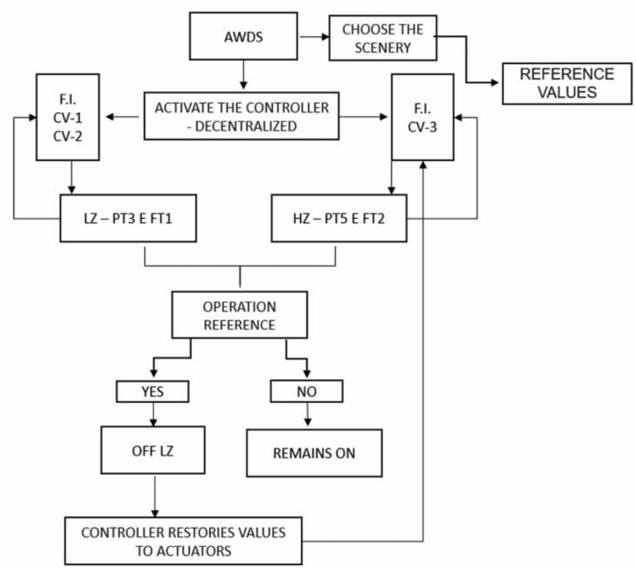

Figure 2 | Flow chart of controller operation.

subsequent decrease in pressure in the network, which can be compensated by the increase in the rotation of the motor pump set.

In addition, it is necessary to consider the physical configuration of the experimental bench, the study of a physical change of equipment, such as opening or closing a valve, or even increasing or decreasing the rotation of the motor pump set, can generate a more positive response, if the equipment hydraulically meets the general need of the system, or a negative answer, if the equipment is not capable of meeting the desired operating points by the bench. For this study, the operating points were chosen according to the operating range of the bench, to hydraulically meet the simulated situation.

To create the decentralized system, four controls were created. One for pressure in LZ (PT-3), one for flow in LZ (FT-1), one for pressure in HZ (PT-5), and one for flow in HZ (FT-2). To control the pressure in the LZ, two input variables and two output variables were used, featuring a MIMO-type controller (multiple inputs and multiple outputs). The input variables chosen were the PT-3 error and the derivative of the error, while the output variables were an incremental delta for the frequency and an incremental delta for the valve opening. The interaction of the two input variables with the two output variables was based on five membership functions. The interaction of input variables with output variables totalled the elaboration of 25 rules. For the flow control in the LZ, the FT-1 error and the derivative of the error were used as input variables, and for the output variable an increment delta for the CV-2, characterizing the development of a MISO-type controller (multiple inputs and one output). With the use of five membership functions, the interaction between the input variables and the output variable allowed the development of 25 rules.

For the control of PT-5, the system was of the MISO type, where the input variables were the PT-5 error and the derivative of the error, and as an output variable, the FI delta increment was chosen. For the flow control (FT-2), the error and its derivative were used as input variables, and the output variable was the increment of the CV-3 angle delta. The interaction between the input and output variables of PT-5 and FT-2 was possible from the creation of five membership functions for each of the sensors. That is, the proposed decentralized control was created from the elaboration of 100 rules: 25 for the flow control; 25 for the control of pressure in the LZ; added 25 more rules for flow control; and 25 rules for pressure control in HZ. For each set of determined set points, occasionally, it was necessary to make small adjustments to the rule sets. The input and output variables adopted for LZ and HZ are described in Table 3. For each input and output variable, five membership functions were created. Table 4 shows the interaction of the input variables with the output variables, formulating, then, the 25 rules for the flow control and 25 rules for the pressure control, both in the LZ. Table 5 shows the interaction of the input variables with the output variables, thus formulating the 50 rules for controlling the flow and pressure in the HZ.

Table 3 | Controller input and output variables for LZ and HZ

Decentralized System			
Input Variables	**Initials**	**Output Variables**	**Initials**
Error FT-1 and FT-2	EFT	ΔVRP (CV-1)	DACV1
Derived from the error	DEFT	ΔIF	DF
Erro PT-3 e PT-5	EPT	ΔCV (CV-2)	DACV2
Derived from the error	DEPT	ΔCV (CV-2)	DACV3

Table 4 | Relevance functions for the flow and pressure control in the LZ

	HNE	NE	EZ	PE	HPE
FT-1					
DHNE	DAV2PA	DAV2P	DAV2Z	DAV2N	DAV2NA
DNE	DAV2PA	DAV2P	DAV2Z	DAV2N	DAV2NA
DEZ	DAV2PA	DAV2P	DAV2Z	DAV2N	DAV2NA
DPE	DAV2PA	DAV2P	DAV2Z	DAV2N	DAV2NA
DHPE	DAV2PA	DAV2P	DAV2Z	DAV2N	DAV2NA
PT-3					
DHNE	DFNH/DHPA	DFN/DPA	DZF/DZA	DFP/DNA	DFHP/DHNE
DNE	DFNH/DHPA	DFN/DPA	DZF/DPA	DFP/DNA	DFHP/DHNE
DEZ	DFNH/DHPA	DFN/DPA	DZF/DZA	DFP/DNA	DFHP/DHNE
DPE	DFNH/DHPA	DFN/DPA	DZF/DZA	DFP/DNA	DFHP/DHNE
DHPE	DFNH/DHPA	DFN/DPA	DZF/DZA	DFP/DNA	DFHP/DHNE

Table 5 | Relevance functions for the flow and pressure control in the LZ

FT-2	HNE	NE	EZ	PE	HPE	PT-5	HNE	NE	EZ	PE	HPE
DHNE	DPA	DPA	DPA	DPA	DNA	DHNE	DFNH	DFNH	DFN	DFHP	DFHP
DNE	DZA	DZA	DZA	DZA	DZA	DNE	DFNH	DFNH	DFNH	DFP	DFHP
DEZ	DZA	DZA	DZA	DNA	DZA	DEZ	DFN	DFN	DZF	DZF	DFN
DPE	DZA	DZA	DZA	DZA	DZA	DPE	DFP	DFP	DFP	DFP	DFHP
DHPE	DNA	DNA	DNA	DNA	DNA	DHPE	DFHP	DFHP	DFP	DFP	DFHP

where: HNE – High Negative Error, NE – Negative Error, EZ – Zero Error, PE – Positive Error, HPE – High Positive Error, DHNE – Derived from High Negative Error, DNE – Derived from Negative Error, DEZ – Derived from Zero Error, DPE – Derived from Positive Error, DHPE – Derived from High Positive Error, DHNA – Delta High Negative Angle, DNA – Delta Negative Angle, DZA – Delta Zero Angle, DPA – Delta Positive Angle, DHPA – Delta High Positive Angle, DFHP – Delta Frequency High Positive, DFP – Delta Frequency Positive, DZF – Delta Zero Frequency, DFN – Delta Frequency Negative, DFNH – Delta Frequency Negative High.

The input variables interact with the output variables through the membership functions. For each interaction proposed in the set of rules, the fuzzy control releases an output, which relates the relevance of the input set to the output set. Figure 3 shows the surface of the variables.

3. RESULTS AND DISCUSSION

For each of the four proposed simulations, different set points were tested for each control variable. In the LZ, the reference values for flow (FT-1) and pressure (PT-3) were established for the highest and lowest gross depth of the irrigation calendar; the same procedure was adopted, calculating the reference values for flow (FT-2) and pressure (PT-5) in the HZ.

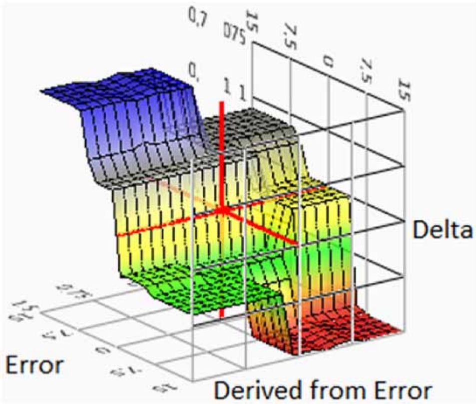

Figure 3 | Rules surface.

Here, we reinforce the idea of the physical configuration of the network, which has two pressure zones or two simulated plots. At the entrance of each plot, the controller was applied in two different network operation configurations. In the first configuration, the controller was designed to bring the flows and pressures in each zone to their reference values for the system operating at the maximum gross irrigation. In the second configuration, the controller brought the flows and pressures to the reference values in the Setup of minimum gross irrigation. In the decentralized system, the developed controller is of the MIMO type: multiple inputs (flow/pressure error, derived from the error) and various outputs (angle of the valves, frequency of the inverter). Different set points were tested for each of the four control variables for each simulation, as shown in Table 6.

Table 6 | Set-point of flow and pressure in the two zones of the network

	Setup I		Setup II	
Parameter	**LZ**	**HZ**	**LZ**	**HZ**
Pressure (m)	11.00	16.00	7.00	10.50
Flow (m^3/h)	9.00	4.00	8.00	4.00

3.1. Controller applied to the decentralized system – setup I

In setup I, the controller must operate satisfactorily, reaching a pressure of 10 m and a flow of 5 m^3/h in the LZ, and a pressure of 15 m and 6 m^3/h in the HZ, with an energy consumption lower than the nominal operation of the motor pump set. Figures 4 and 5 show the performance of the fuzzy controller in controlling pressure and flow, respectively, in the LZ. In Figure 4, it is observed that the system presents a dead zone of approximately 10 seconds in the pressure control. In addition, the response of the controlled variable has a time constant of

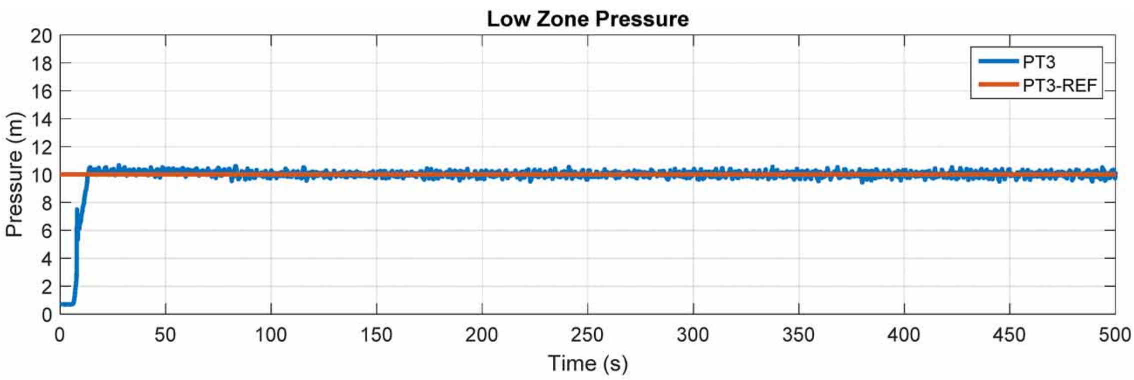

Figure 4 | LZ pressure control (Setup I).

around 12 seconds, being characterized by a first-order response. When analyzing the response of the flow variable, represented in Figure 5, the behavior of control actions in a first-order system is verified, without presenting overshoot, with a dead zone of approximately 12 s, and a response with a time constant of 18 s. For the two situations represented in the two previous figures, the performance of the MIMO controller applied in the FI, and CV-1 is highlighted for controlling the pressure in PT-3 (Figure 4), as well as the performance of the MISO controller applied at CV-2, for flow control in FT-1 (Figure 5).

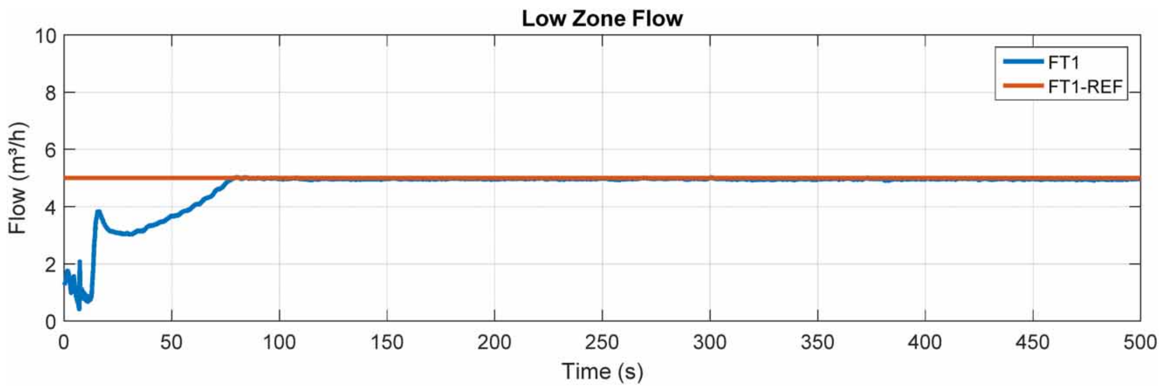

Figure 5 | LZ flow control (setup I).

This simultaneous operation in a hydraulic network increases the complexity of the system's behavior. In hydraulic networks, pressure or flow control, carried out individually, is quite common. However, the proposed method operates by simultaneously controlling four hydraulic variables, whose actuators interfere with the response of each other. For example, when increasing the frequency of the inverter, there is an increase in pressures and flow rates. To reduce the pressure in the LZ, the opening of the CV-1 is changed upstream from PT-3. The closing of the valve interferes with the flow rates of the two zones, decreasing the flow of the LZ and increasing the flow of the HZ. For flow control, the actuators must act on the CV-2 and CV-3 control valves, which, when partially closed, modify the pressure pattern in the network. These dynamics need to be understood by the fuzzy controller, which must find the ideal values for the frequency of the inverter and the valves' angle. The responses presented by the sensors ensure the efficiency of the controller designed to bring the pressures and flows to their reference values (Figures 6 and 7).

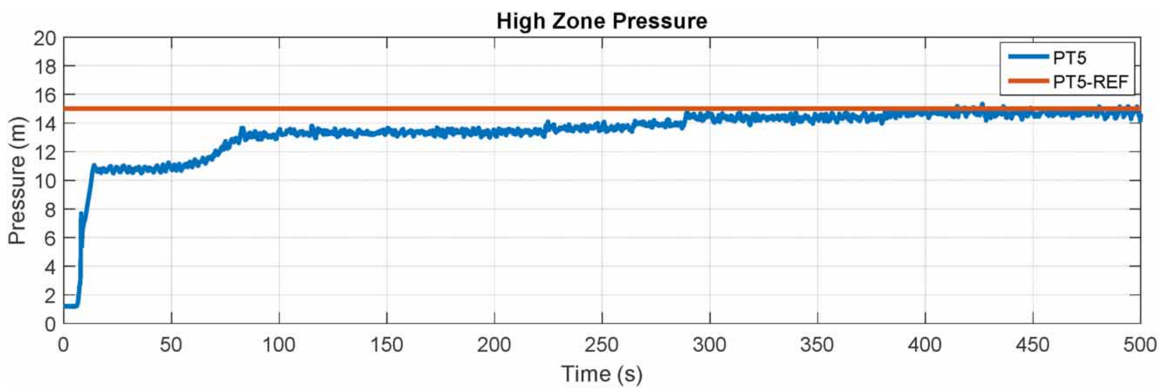

Figure 6 | HZ pressure control (setup I).

The actuators responsible for modifying the system's operating conditions were the control valves (CV-1/PRV, CV-2, and CV-3) and the FI. The behavior of these variables is shown in the graph in Figure 8. In order to take the flow rates of the two zones to their reference values, a gradual opening of the CV-2 is observed, which generates a reduction in pressure in the LZ (PT-3), while CV-3 acts to close the valve, increasing the pressure in PT-5. The variation in the opening of CV-2 and CV-3 interferes with the pressures of the two zones. In this way, the

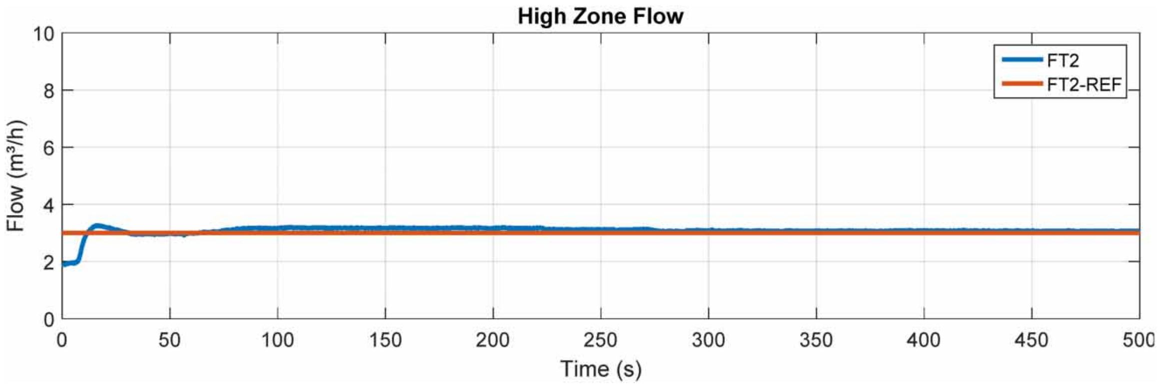

Figure 7 | HZ flow control (Setup I).

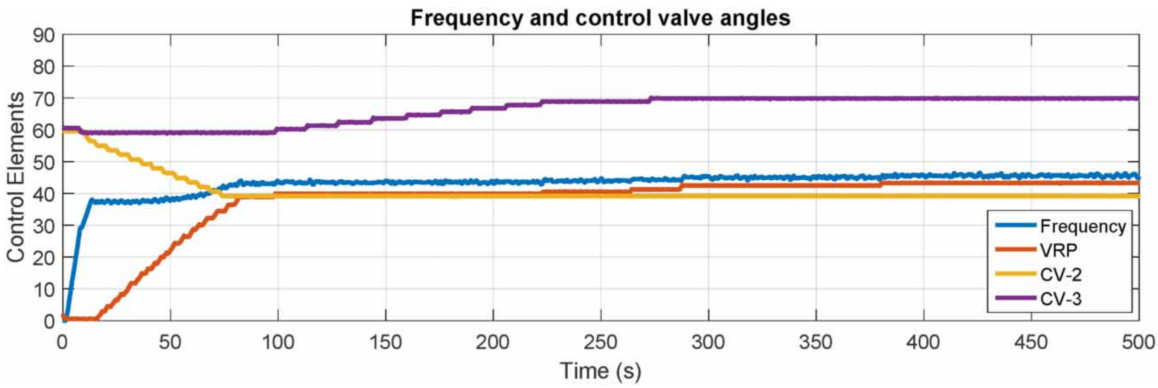

Figure 8 | Control elements (setup I).

developed controller needs to act intelligently, to supply the increase or decrease in pressure, which occurs in both zones, with the variation of the opening of the valves, and change the value of the frequency of the motor pump set, as well as the CV-1 angle.

The graphical presentation of the results after the controller has acted on the system shows its effectiveness in bringing the flow and pressure signal to their reference values in each of the two zones. Table 7 shows the values of the actuators after the system reaches its stationary regime. In setup I, the pressures were controlled with a frequency of 44.5 Hz and an opening angle of 42° for CV-1. For flow control, valves CV-2 and CV-3 registered a closing angle of 39.1° and 69.8°, respectively. Table 8 presents the control parameters after applying the proposed controller and its performance in the response variables. According to the values presented, the controlled system presents a satisfactory result, showing an adequate performance given the applications of this work. Only FT-1 took more than one minute to reach 90% of its value in the permanent regime for the rise time. None of the four sensors had a surplus greater than 6.5%, which demonstrates the system's stability. FT-1 and PT-5 were the signals that presented a longer time to reach their stationary regime for the establishment

Table 7 | Parameters of the plant with the controller acting – setup I

	LZ		HZ	
System parameters	**System value**	**Reference value**	**System value**	**System value**
Pressure (m)	10.04	10.00	14.72	15.00
Flow (M^3/h)	4.96	5.00	3.07	3.00
VRP/CV-1 (°)	42.00°			
CV-2 (°)	39.14°			
CV-3 (°)	69.83°			
Motor pump set (Hz)	44.53			

Table 8 | Parameters of the plant with the controller acting – setup I

Parameters	Rise time	Overshoot	Establishment time	Steady state error
PT-3 (m)	6.00 s	6.27%	13.25 s	0.40%
FT-1 (m^3/h)	1 min 33.5 s	4.21%	4 min 20.75 s	2.00%
PT-5 (m)	9.75 s	5.16%	4 min 34.50 s	1.87%
FT-2 (m^3/h)	58.75 s	1.41%	1 min 19 s	0.80%

time. This does not cause damage to the hydraulic network, since this time is considerably short, when it is a network that operates in periods of 3–12 hours. In setup I, all sensors obtained a less than 2% steady state error.

The rise times recorded by the flows are significantly longer when compared to the pressure rise times. This delay is due to the response time of the control valves, which are responsible for the flow control. The CV's take one second for each opening variation, while the frequency converter varies by 1 Hz every 0.0167 s. However, the controller acted efficiently even with a rise and establishment time of more than one minute. It controlled the flows and pressures with the motor pump set operating at a frequency below 60 Hz.

3.2. Controller applied to the decentralized system – setup II

Setup II corresponded to the dimensioning using the smallest gross irrigation provided by the CROPWAT irrigation calendar. The alteration of the gross irrigation allowed the variation of the reference values of the network. That is, the controller must act in the same irrigation system but take the pressures and flows to its new design levels. With this, it is expected that the irrigant will have greater flexibility in agricultural management, allowing it to change the cultivation conditions and operate with different irrigation systems for the same crop.

In the setup II, the controller acted on the same elements, that is, CVs and frequency inverters, so that LZ could operate with a pressure of 12 m and a flow of 7 m^3/h, and HZ, with a pressure of 17 m and a flow of 5 m^3/h. Figures 9 and 10 show the performance of the controller in controlling pressure and flow, respectively, in the LZ. Figure 9 represents the PT-3 response variable, with a dead zone of approximately 10 seconds. After applying the controller, the system can be characterized as of second order, due to its overshoot, until it reaches its stationary regime. After changing the reference values for the four sensors, the FT-2 sensor showed some instability in the responses obtained in the first 20 seconds. Nevertheless, once its reading stabilized, its behavior proved to be satisfactory, reaching its reference value (see Figure 10). The experimental procedure adopted for the second setup was similar to the first one. In the setup II, the controller had a longer set up time, as well as a much greater surplus for flow compared to that one recorded in setup I. However, after about 130 s, the controller acted on the system and brought the flow to its reference value. The time recorded for the pressure to reach its reference value was approximately 120 s.

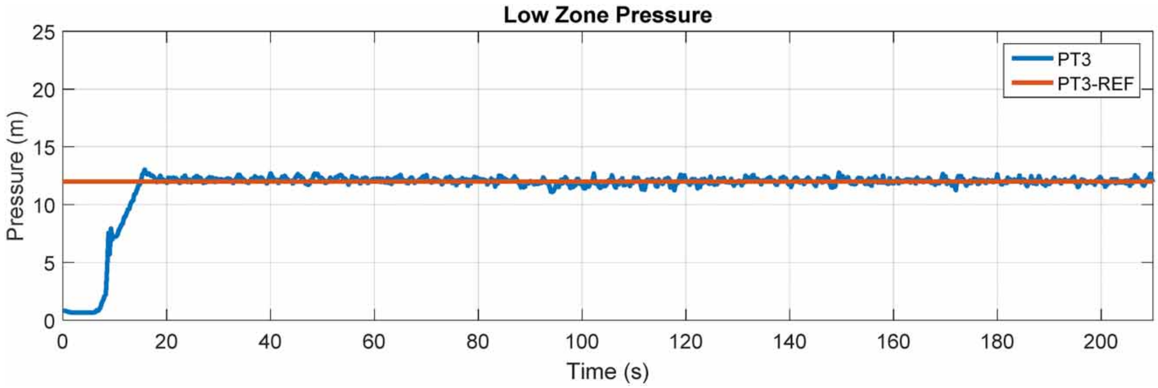

Figure 9 | LZ pressure control (setup II).

In HZ, smoother behavior of the controller was observed when taking the signals to their reference values about 120 s after the start of the system operation (see Figures 11 and 12). Figure 12 shows the control elements, or actuators, of the plant. As in setup I, CV-2 and CV-3 valves, responsible for the flow control, start the operation

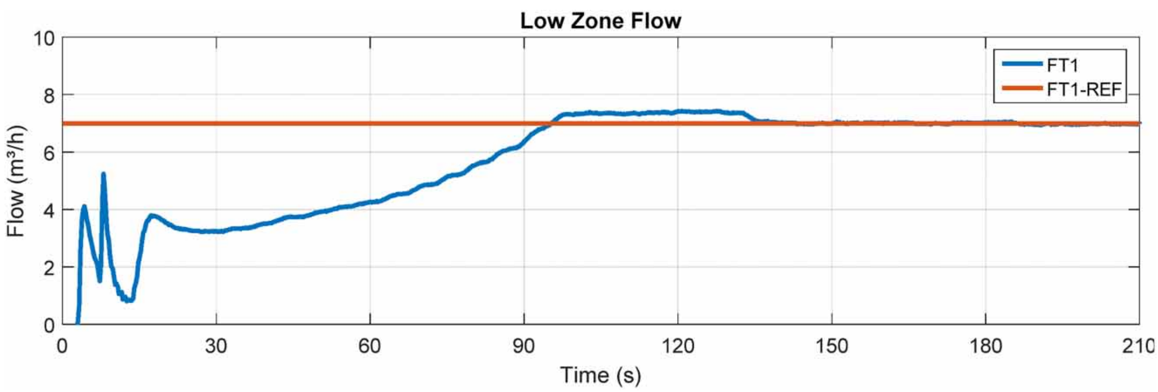

Figure 10 | LZ flow control (setup II).

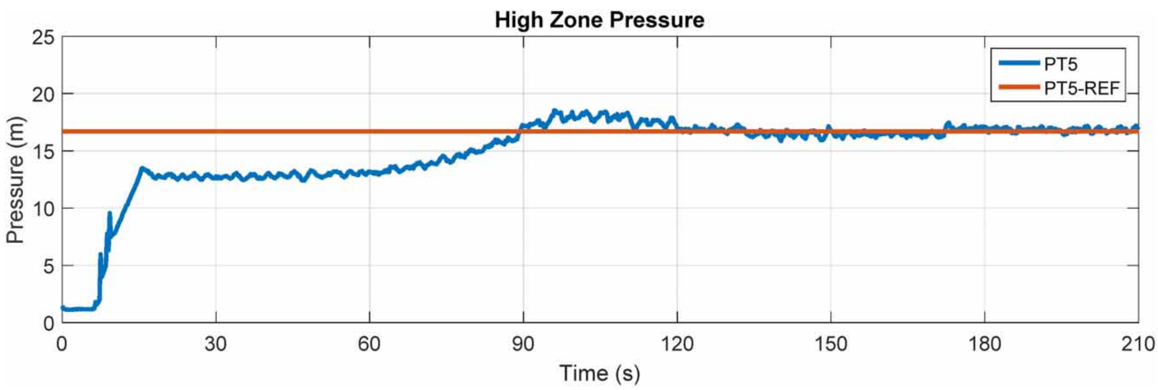

Figure 11 | HZ pressure control (setup II).

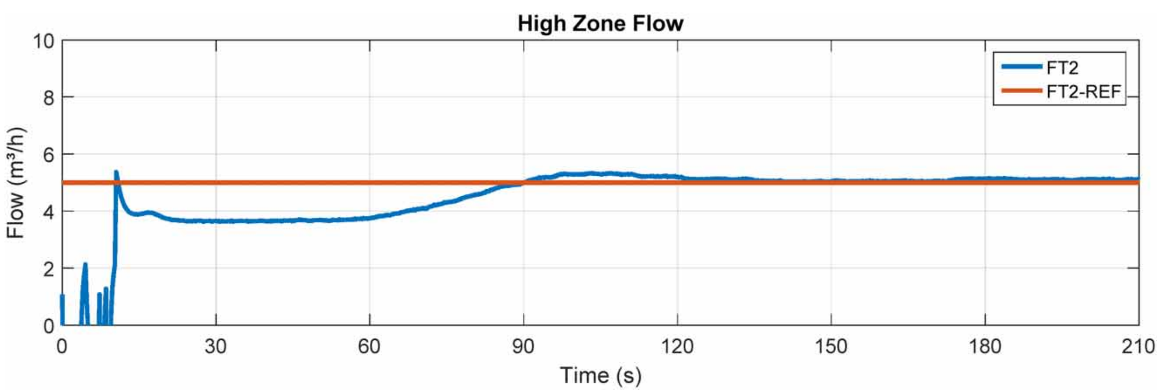

Figure 12 | HZ flow control (setup II).

at 60° and gradually open until reaching the proposed reference values. As setup II presents greater demands than setup I, the behavior of the valves is consistent, as they take their angles to a greater opening of operation. Despite the pressure in the LZ quickly reaching its reference value, the time taken for PT-5 was much longer, which can be explained by the closing of the CV-1, which aims to maintain the pressure in the LZ. At the same time, the FI must find the ideal value to pressurize the two zones.

Figure 13 shows the control elements, or actuators, of the plant. As in Setup I, CV-2 and CV-3 valves, responsible for the flow control, start the operation at 60° and gradually open until reaching the proposed reference values. As setup II presents greater demands than setup I, the behavior of the valves is consistent, as they take

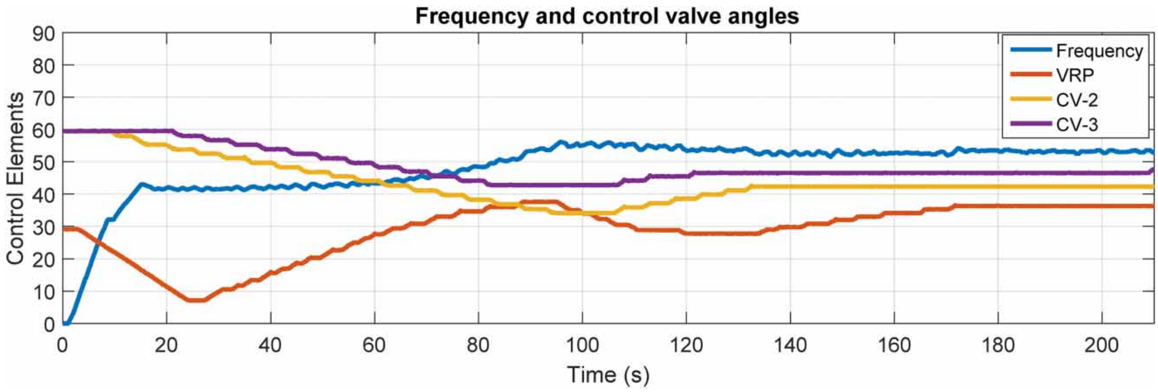

Figure 13 | Control elements (setup II).

their angles to a greater opening of operation. Despite the pressure in the LZ quickly reaching its reference value, the time taken for PT-5 was much longer, which can be explained by the closing of the CV-1, which aims to maintain the pressure in the LZ. At the same time, the FI must find the ideal value to pressurize the two zones.

Table 9 shows a summary of the hydraulic variables, sensors, and actuators, for setup II. Even with reference values higher than those established in setup II, after simple adaptations in the controller range, the system reached its new reference values. The pressures were controlled at 53 Hz and with the VRP at 36.33°, while the flow control in FT-1 and FT-2 lead the CV-2 and CV-3 to an opening of 42.36° and 46.58°, respectively.

Table 9 | Parameters of the plant with the controller acting – setup II

	LZ		HZ	
System parameters	**System value**	**Reference value**	**System value**	**Reference value**
Pressure (m)	12.06	12.00	16.94	17.00
Flow (m^3/h)	7.12	7.00	5.10	5.00
VRP/CV-1 (°)	36.33°			
CV-2 (°)	42.36°			
CV-3 (°)	46.58°			
Motor pump set (Hz)	53.00			

In parallel with the analysis of the hydraulic parameter, studies of the control parameters were also performed (see Table 10) to evaluate the developed and applied controller. The rise time of the four sensors was less than 1 minute and 40 seconds, and their establishment time. These values were measured for signals with a steady-state error less than or equal to 2%. The PT-5 was the sensor that showed the largest overshoot in this setup, superior to the others but less than 10%.

Table 10 | Parameters of the plant with the controller acting – setup II

Parameters	Rise Time (tr)	Overshoot (Mp)	Establishment Time (ts)	Steady State Error (ess)
PT-3 (m)	11.75 s	9.19%	12.50 s	0.99%
FT-1 (m^3/h)	100.00 s	5.15%	114.00 s	0.75%
PT-5 (m)	90.50 s	18.02%	178.00 s	0.67%
FT-2 (m^3/h)	15.50 s	23.46%	170.00 s	1.25%

3.3. Hydraulic and energetic analysis of the system

To carry out the hydro-energetic analysis proposed in this work, besides evaluating the data related to the hydraulic behavior of the plant, it was necessary to carry out measurements that would provide the electrical characterization of the system in operation. Thus, with the use of the Fluke® energy analyzer (Figure 14), online measurements of parameters such as current and voltage of the frequency inverter were performed, with the system operating with the controller.

Figure 14 | Fluke® energy analyzer.

The validity of the proposed methodology, applying a controller based on fuzzy logic to control the flows and pressures in a collective pressurized irrigation system, is attested when the proposed method shows a reduction in water and energy consumption. Setups I and II represent the crop's water requirement at two different stages of development. In this way, the system starts to operate more efficiently by reducing the water demand according to the necessary gross irrigation. According to the data in Table 11, there was a saving of 34.45% in water consumption, a reduction of 88.62 m^3 of water per week.

Table 11 | Water consumption in the two irrigation scenarios

Variable	Setup I		Setup II	
Irrigation frequency (day)	1	1	1	1
Daily pumping time available (hour)	12	12	12	12
Application time (hour)	3	3	3	3
Flow at the entrance of the parcel (m^3/h)	4.96	3.07	4.96	3.07
Water consumption for a period of 7 days (m^3)	104.16	64.47	104.16	64.47
Water consumption per system (m^3/week)	168.63		257.25	

To perform the energy analysis of the system, with and without the action of the controller, it was necessary to obtain the electrical power consumed by the motor pump set. The electrical powers were measured using the energy analyzer, which was coupled to the FI. For the system operating without a controller, the motor pump set at 60 Hz, the recorded electrical power was 1.67 kW. With the use of the controller, there was a reduction in the power consumed by the motor pump set. Setup I (SI) operated with an electrical power of 0.80 kW, and setup II (SII) registered, as expected due to its higher frequency, a power of 1.25 kW. In percentage terms, setup I showed a reduction in electrical power of 52.10% compared to the system operating without a controller.

On the other hand, setup II showed a reduction of 25.15% when compared to the system operating with a frequency of 60 Hz. When analyzing setups I and II, which operate with a controller with different hydraulic demands, supplying the soil with only the required amount of water, the reduction in electrical power was 36%. This reduction directly reflects the irrigation network's annual cost of pumping. For the weekly pumping cost calculation, some design parameters were taken into account, as indicated in Table 12.

Table 12 | Water consumption in the two irrigation scenarios

Project parameters	Without controller	With controller (WCI)	With controller (WCII)
Number of pumping hours (h/day)	12	12	12
Frequency (Hz)	60	44.53	53.00
Electric power (kW)	1.67	0.80	1.25
Rate ($/kWh)[a]	0.27	0.27	0.27
Number of pumping hours/week	84	84	84
Pumping cost ($)	37.88	18.15	28.35

[a]Tariff adopted according to regulations of the National Electric Energy Agency (ANEL) -Brazil.

With the controller's application, the irrigation system not only showed a reduction in water consumption (see Table 11) but also proved to be efficient in reducing the electrical power consumed by the motor pump set. The reduction in electrical power directly reflects the decrease in weekly electricity consumption, justifying the reduction in pumping costs recorded in Table 12.

All the results presented in this article were extracted from the simulation of the controller applied to an experimental bench, with proportions similar to a small pressurized irrigation system, however, the study was not applied to a real system.

CONCLUSIONS

The advancement of control and automation engineering has enabled several tools to improve processes related to irrigation systems. Currently, there is a wide application of sensors that analyze the water level in the soil and calculate the exact amount to be sent to the soil. However, the intelligent automation associated with the hydraulic networks responsible for supplying the system has not received the same attention. The objective of this work was to present a controller based on fuzzy logic for the dynamic control of a hydraulic network aimed at feeding an irrigation system with multiple plots. The controller was not only able to regulate the pressure, a common variable to be controlled in hydraulic systems, but also controlled the flow at the entrance of the simulated plots. With the efficient performance of the proposed controller, the hydraulic system can operate with frequencies below the 60 Hz nominal value of the motor pump set. As a result, the hydraulic network operated only as often as necessary to allow the sensors to reach their reference values. Even after changing the reference values with two operating scenarios, the system still proved to be efficient, quickly controlling the new flows and pressures demanded by the network. In setup I, there was a 25.78% reduction in the frequency of the motor pump set, while in setup II there was a reduction of 11.67%, both calculated in relation to the nominal frequency of 60 Hz. In the simulated hydro-energy setup, by creating two operating scenarios with different hydraulic demands, according to the gross irrigation requested by the crop, it was expected to register a reduction in water consumption, which, in fact, occurred. By reducing the gross irrigation and thus the flow at the entrance to the network, the system showed a 34.45% reduction in weekly water consumption. Finally, through the energy analysis carried out when comparing the electrical power of the network, setup I showed a reduction of 52.10%

in the consumption of electricity, while setup II was responsible for the reduction of 25.16%. The results are achieved to validate the application of intelligent control techniques based on fuzzy logic, mainly in already automated systems that use frequency inverters and automatic control valves. Thus, using the proposed method, it is possible to operate in plots with different reference values in a collective irrigation system, allowing the operation with the exact values required by the hydraulic network. This guarantees the producer greater flexibility in agricultural management and a reduction in water and energy consumption for the different stages of development of the irrigated crop.

ACKNOWLEDGEMENTS

To the Laboratory of Energy and Hydraulic Efficiency in Sanitation (LENHS) and to the Graduate Program in Mechanical Engineering (PPGEM) of the Federal University of Paraiba (UFPB) and the Coordination for the Improvement of Higher Education Personnel (CAPES).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Anand, K., Jayakumar, D. C. & Muthu, M. 2015 Automatic drip irrigation system using fuzzy logic and mobile technology. In: *IEEE International Conference on Technological Innovations in ICT for Agriculture and Rural Development*.

Bahat, M., Inbar, G., Yaniv, O. & Schneider, M. 2000 A fuzzy irrigation controller system. *Engineering Applications of Artificial Intelligence* **13**, 137–145.

Bezerra, S. T. M. & Gomes, H. P. 2013 *Automação em sistemas de irrigação*. Heber Pimentel Gomes Org(s), Ed(s). Sistemas de irrigação: Eficiência energética, João Pessoa.

EMBRAPA – Brazilian Agricultural Research Corporation 1999 Technical Circular No. 001 – *Tensiometer: practical device for irrigation control.* Distrito Federal.

FAO (Organização das Nações Unidas para a Agricultura e a Alimentação) 2014 *FAO at World Water Week 2014 Why Water and Energy Matter for Agriculture?* Available from: http://www.fao.org/land-water/news-archive/news-detail/en/c/267274/ (accessed 2 June 2020).

Fierro, A. C. & Tello, J. T. 2019 Fuzzy logic that determines sky conditions as a key component of a smart irrigation system. In: *2019 Sixth International Conference on EDemocracy & EGovernment (ICEDEG)*.

Hasan, M. F. M. M., Haque, M. M. M. R., Khan, M. R., Ruhi, R. I. & Charkabarty, A. 2018 Implementation of fuzzy logic in autonomous irrigation system for efficient use of water. In: *2018 Joint 7th International Conference on Informatics, Electronics & Vision (ICIEV), and 2nd International Conference on Imaging, Vision & Pattern Recognition (icIVPR)*.

INMET – National Institute of Meteorology 2010–2018. Available from: http://www.inmet.gov.br/portal/index.php?r=estacoes/estacoesConvencionais. (accessed 03 July 2020).

Jägermeyr, J., Gerten, D., Heinke, J., Schaphoff, S., Kummu, M. & Lucht, W. 2015 Water savings potentials of irrigation systems: global simulation of processes and linkages. *Global Simulation of Irrigation* **19**, 3073–3091.

JunHui, W., Yaping, M., Jie, C. & Yusheng, W. 2019 Fuzzy control system of substrate lettuce cultivation based on light-dependent irrigation control method. In: *IEEE 2nd International Conference on Electronics and Communication Engineering*.

Priandana, K. & Wahyu, R. A.-F. 2020 Development of automatic plant irrigation system using soil moisture sensors for precision agriculture of chili. In: *International Conference on Smart Technology and Applications (ICoSTA)*.

Sasmoko, W. B. & Harjanto, P. 2019 Self-diagnostic using fuzzy logic for teaching learning quality improvement in universities. *ICIC Express Letters* **13**(3), 247–253.

First received 22 April 2022; accepted in revised form 6 July 2022. Available online 12 July 2022