



## Development of a PID-Fuzzy controller in the water level control of a pressurizer of a nuclear reactor

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### ABSTRACT

It is well known that safety in the operation of nuclear power plants is a primary requirement because a failure of this system can result in serious problems for the environment. A nuclear reactor has several systems that help keep it in normal operation, within safety margins. Many of these systems operate in the control of variable quantities in the primary circuit of a reactor. However, nuclear reactors are nonlinear physical systems, and this introduces complexity in the control strategies. Among several mechanisms in the thermal-hydraulic system of a reactor that actuate as a controller, the pressurizer is the component responsible for absorbing pressure variations that occur in the primary circuit. This work aims at the development of a PID controller (Proportional Integral Derivative) based on fuzzy logic to operate in a pressurizer of a nuclear Pressurized Water Reactor. A Fuzzy Controller was developed using the process of fuzzification, inference, and defuzzification of the variables of interest to a pressurizer, then this controller was coupled to a PID Controller building a PID Controller, but oriented by Fuzzy logic. Subsequently, the PID-Fuzzy Controller was experimentally validated in a Simulation Plant in which transients like those in a PWR were conducted. The PID parameters were analyzed and adjusted for better responses and results. The results of the validation were also compared to simple controllers (on / off).

*Keywords:* control, fuzzy, pressurizer, reactor.

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## 1 INTRODUCTION

Nuclear reactors are physical systems presenting a nonlinear nature. Their parameters vary with time as a function of the power level [1]. These characteristics should be considered if large power variations might occur during the operation of a nuclear power plant. As a consequence, a transient regime will develop where the pressure and the average temperature of the primary circuit will undergo significant variations. In order to absorb pressure variations and to keep the system pressurized, a system called pressurizer was adapted to the primary circuit of a pressurized water reactor (PWR).

The pressurizer is a rigid vessel, thermally insulated on the outside, and filled with a saturated mixture of liquid water and steam. The bottom is connected to the cooling system (hot leg) of the primary circuit by a conducting line called the volumetric compensation line or surge line. At the top, a sprinkler system is connected, being responsible for injecting water from the cold leg, helping in the condensation of vapor, and reducing the system pressure. Heaters are immersed in the liquid phase to provide thermal energy to the water enhancing the production of steam.

Considering the important role of this component, it is necessary to develop a water level controller in the pressurizer, aiming for more safety and inhibiting the occurrence of possible accidents. The power control of the reactor has been made under traditional base-load conditions. But with the growing share of power plants in electricity generation, load-follow operation of nuclear reactors will be unavoidable in the future. This in turn makes the control strategy difficult for a satisfactory performance [1].

The control of multi-models is a relatively effective type in the nonlinear time-dependent control strategy [2][3], but often it brings unacceptable errors [4][5]. These errors have been minimized with advanced control systems, and these intelligent systems enable the control of nonlinear systems dependent on time.

The fuzzy logic controller (CLF) is a good representative of this new generation of intelligent controllers [6], but when used in a power level control system in nuclear reactors, it is not easy to deal with the problem of imprecision in comparison with classical controllers such as proportional-integral-derivative (PID).

The most commonly used controllers used in industrial process control are proportional-integral-derivative (PID) controllers, due to their simple structure and robust performance over a wide range of operating conditions. The incorporation of CLF and PID, known as PID-Fuzzy, brings good results and its excellent properties are well-established [7][8].

The main characteristic of fuzzy logic is its representation in the form of membership functions (FP) in a specified rule base. Therefore, if the form and type of membership function are properly selected by some optimization algorithm, its performance can be significantly improved.

Differently from conventional controllers, in which the control algorithm is described analytically by algebraic or differential equations, in the fuzzy control logic, rules are used in the control algorithm with the intention of describing in a routine the human experience, its intuition and heuristic to control a process [9].

Fuzzy controllers are robust and highly adaptable, incorporating knowledge that other systems cannot easily accommodate [10]. They are also versatile, especially when the physical model is complex and difficult to be mathematically represented. Moreover, even in systems where the uncertainty is inherent, they are able to add the robustness characteristic of the method.

The insertion of new processes and techniques in the routine operation of a nuclear plant must always be preceded by a rigorous theoretical and experimental verification of all the parameters involved in the operation and safety of the plant. Experimental validation is an advance in the elaboration and construction of a PID-Fuzzy Controller for a pressurizer of a PWR Reactor, giving it more reliability and safety.

## **2 CONTROLLERS**

### **2.1 PID Controllers**

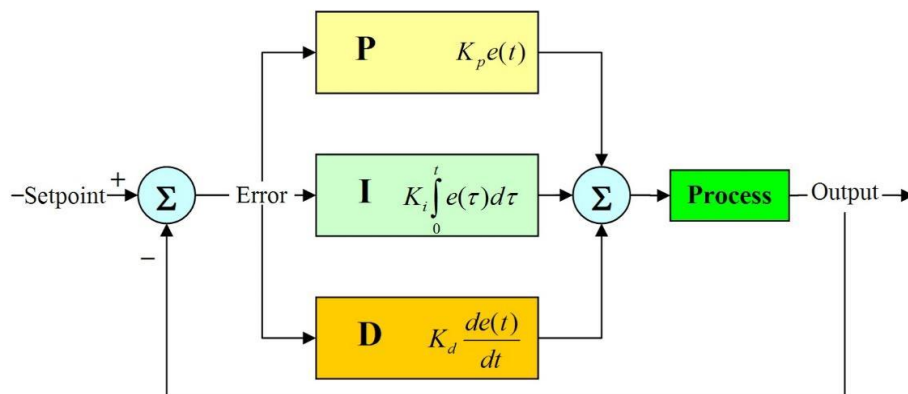
A controller is a tool responsible for stabilizing and controlling industrial processes, or part of them, through control algorithms. Programmable Logic Controller (PLC) is used to implement a Proportional-Integral-Derivative (PID) controller easily. The flexibility, low cost and robustness of PLCs and the availability of functional hardware blocks, such as central processing units (CPUs),

counters, timers, arithmetic units, schedulers, comparators, etc. make it possible to elaborate a PLC in several different ways.

The massive presence of computer technology suggests the use of discrete digital PID controllers, and hence a PID controller becomes only another program in the computer memory. The continuous error signal at the input of the controller is sampled and converted into digital signals, while the digital output of the controller is converted to an analog signal continuously supplying to the process control.

The PID controller is a time controller of continuous input and output function that combines the derivative (D), integral (I) and proportional (P) actuation, causing the error signal to be minimized by the proportional action, zeroed by the integral action and obtained with an anticipated speed by the derivative action Figure 1.

**Figure 1: PID controller**



Source: Arturo [11]

The PID controller algorithm can be defined as [12]:

$$u(t) = Kp \cdot e(t) + Ki \cdot \int_0^t e(t)dt + Kd \frac{de(t)}{dt} \tag{1}$$

and its discrete form is:

$$u(k) = Kp \left\{ e(k) + \frac{T}{\tau_i} \cdot \sum_{k=0}^n e(k) + \frac{\tau_d}{T} [e(k) - e(k - 1)] \right\} \tag{2}$$

Where,

$u(t), u(k)$  = output signal

$e(t)$  = error signal

$K_p$  = proportional gain

$K_i$  = integral gain

$K_d$  = derivative gain

$\tau_i$  = integrative time

$\tau_d$  = derivative time

$T$  = time constant

## 2.2 Fuzzy Logic

In classical set theory, an element belongs to a particular set or not. Thus, it is possible to define the relevance of a particular element  $x$  of a set  $A$  in a given universe  $U$  through the characteristic function:

$$\mu_A(x): U \rightarrow \{0,1\} \quad (3)$$

$$\mu_A(x) = \begin{cases} 1 & \text{se } x \in A \\ 0 & \text{se } x \notin A \end{cases} \quad (4)$$

Zadeh [9] proposed a broader characterization, generalizing the characteristic function so that it could assume an infinite number of values in the  $[0,1]$  interval. A fuzzy set  $A$  in a universe  $U$  is defined by a membership function  $\mu_A(x): U \rightarrow [0,1]$ , and represented by a set of ordered pairs:

$$A = \{(x, \mu_A(x)) / x \in U\} \quad (5)$$

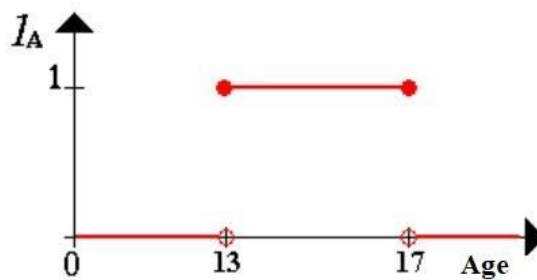
Where the membership function  $\mu_A(x)$  indicates the degree of compatibility between  $x$  and the concept expressed by  $A$ :

- $\mu_A(x) = 1$  indicates that  $x$  is completely compatible with  $A$ ;
- $\mu_A(x) = 0$  indicates that  $x$  is completely incompatible with  $A$ ;
- $0 < \mu_A(x) < 1$  indicates that  $x$  is partially compatible with  $A$ , with degree  $\mu_A(x)$ .

The difference between these concepts in relation to the age variable is illustrated in Figure 2 and Figure 3, which describe the representation of the “teenager” concept through a “crisp” (set of classical theory seen as a specific fuzzy set) and a fuzzy set, respectively.

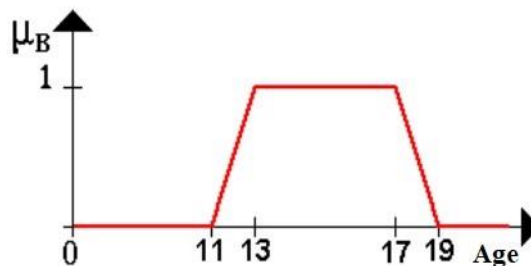
The “crisp” set  $A$  (Figure 2) does not fully express the concept of “teenager”, as a person aged 12 years and 11 months would be considered completely incompatible with this concept. In fact, any “crisp” interval that is taken to represent this concept is arbitrary. The fuzzy set  $B$  (Figure 3) allows to express that any person aged between 13 and 17 years old is a teenager, over 19 or under 11 is not considered a teenager, and in the intervals  $[11; 13]$  and  $[17; 19]$  is considered all the more teenager the closer to 13 and 17, respectively, is their age.

**Figure 2:** Characteristic function of the teenager “crisp” set



Source: SANDRI e CORREA [13]

**Figure 3:** Trapezoidal function characteristic of the teenager fuzzy set

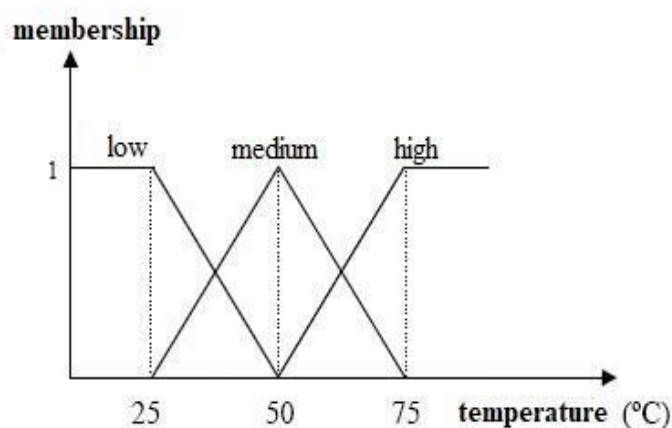


Source: SANDRI e CORREA [13]

### 2.2.1 Linguistic variables

A linguistic variable is a variable whose values are fuzzy set names. For example, the temperature of a given process can be a linguistic variable assuming low, medium, and high values. These values are described using fuzzy sets, represented by membership functions, as shown in Figure 4.

**Figure 4:** *Membership functions for the temperature variable*



Source: TANSCHKEIT [14]

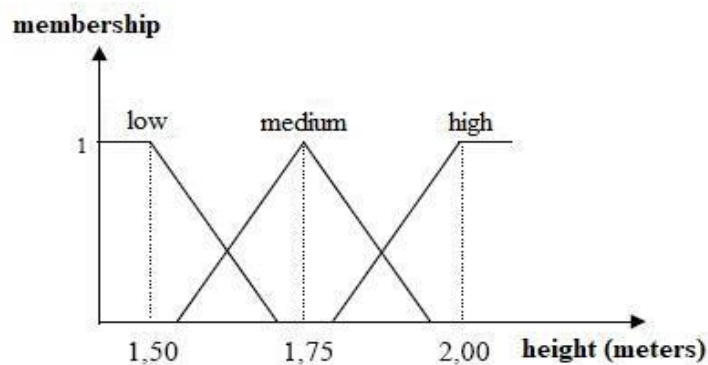
The main function of linguistic variables is to provide a systematic way for an approximate characterization of complex or poorly defined phenomena. In essence, the use of the type of linguistic description used by human beings, rather than quantified variables, allows the treatment of systems that are too complex to be analyzed using conventional mathematical terms [14].

The values of a linguistic variable can be sentences in a specified language, constructed from primary terms (high, low, small, medium, large, zero), logical connectives (non-negation, connective and, and or), modifiers (slightly, slightly, extremely) and delimiters (like parentheses).

### 2.2.2 Membership functions

The membership functions can take different forms, depending on the concept you want to represent and the context in which they will be used. To exemplify how relevant the context is in defining membership functions and their distribution over a given universe, consider the linguistic variable stature (of people) consisting of the following terms:  $T(\text{stature}) = \{\text{low, medium, high}\}$ . These correspond to fuzzy sets A, B, and C, respectively, defined by their pertinence functions. A possible choice of membership functions would be, Figure 5:

**Figure 5:** *Membership functions for the height variable*



Source: TANSCHKEIT [14]

In the previous definition, the stature of up to 1.5 meters have a degree of relevance equal to 1 in set A; the degree of relevance in this set decreases as the stature increases. Stature of 1.75 meters is considered to be "fully compatible" with set B, whereas height above 1.8 meters (approximately) has a degree of relevance different from zero in C. People with stature above 2 meters are "definitely" high. Note that in this definition of membership functions, statures around 1.75 meters have different degree of relevance of zero only on the set B, which could seem inappropriate to some observers. These would prefer the A and B membership functions to intersect at 1.75 meters (with zero degrees of membership, as in Figure 4), for example, where, according to this Figure, the closer to 50 ° C, the lower the value of the associated degree of relevance.



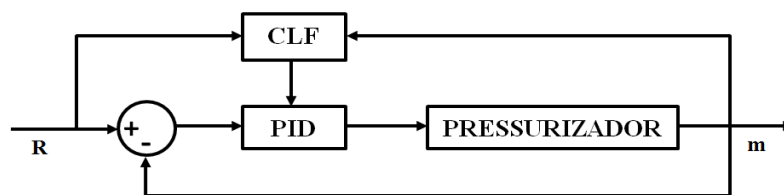
Membership functions can be defined from the user's experience and perspective, but it is common to use standard membership functions, such as triangular, trapezoidal and Gaussian. In practical applications, the shapes initially chosen can be adjusted according to the observed results [14].

### 2.3 Fuzzy controller

Unlike conventional controllers in which the control algorithm is described analytically by algebraic or differential equations, using a mathematical model, in fuzzy control, logical rules are used in the control algorithm, with the intention of describing in a routine the human experience, intuition and heuristics to control a process [9].

In the strategy of PID-Fuzzy control of the water level of a nuclear pressurizer, PID gains are first conceived and then these are explored by the fuzzy logic-based controller (CLF) that extends to finite sets for the possible combinations of PID gains in the stable region. In other words, the CLF uses the adjustment of PID gains based on the mapping of water levels to control the pressurizer. Thus, the PID gain adapts the model to correct the water level in the pressurizer, Figure 6.

**Figure 6:** *PID-Fuzzy water level control on pressurizer*



Source: Author

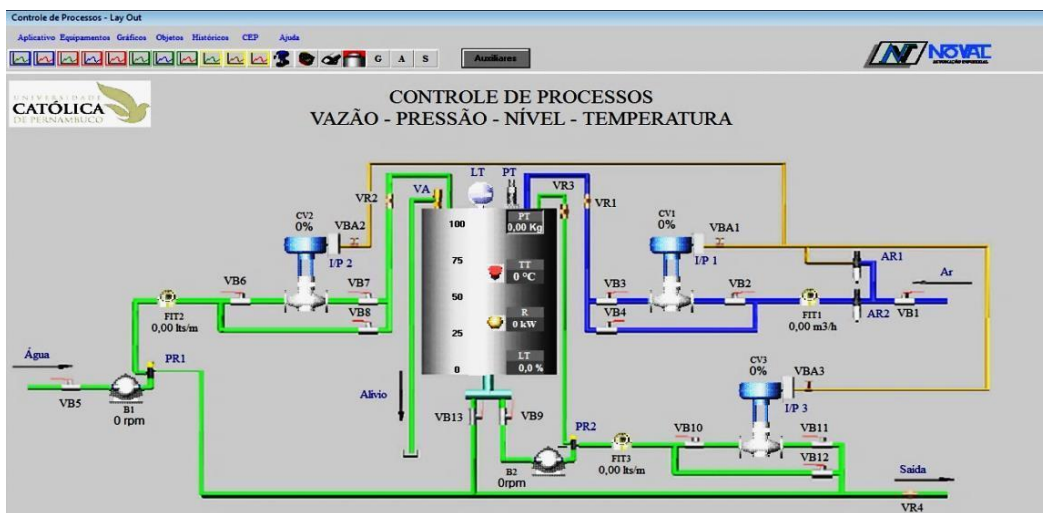
## 3 MATERIALS AND METHODS

### 3.1 Simulation Plant 1 (SP1)

The experiment was conducted in a Simulation Plant, henceforth called SP1, installed at the Process Control Laboratory of the Catholic University of Pernambuco. In this process plant, it is possible to simulate the automatic control system of the pressurizer of a PWR reactor. The plant has

a control software, an operating system based on C language, called Controle de Processos (Process Control) provided by the manufacturer. Figure 7 shows a print screen of this supervisory system. The plant also has a cylindrical vessel, level gauges, flow meters, pressure gauges, resistance heating, thermocouple, safety and pressure relief valves, flow control valves, compressed air regulators, a feed motor pump and an emptying motor pump.

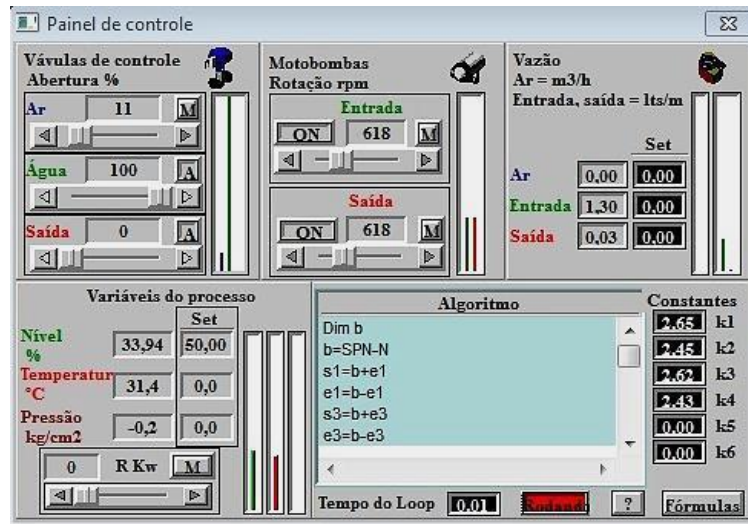
**Figure 7:** Process Control (software screen image)



Source: Author

In this supervisory system, a range of operations and features can be performed, or even customized, to manipulate a process control or simulation. Figure 8 shows the interface screen with the user, Painel de Controle (Control Panel). It contains the components of SP1 in addition to menus and functions. The Control Panel is where one can control, manipulate and monitor the main functions and equipment of SP1.

**Figure 8:** Control Panel (software screen image)



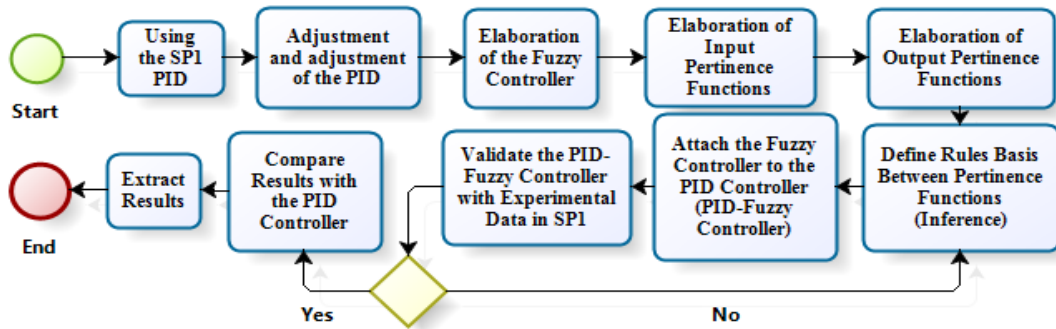
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It is in the Control Panel where the opening of valves, rotation of moto-pumps, flow of compressed air, and resistor power is controlled. It is important to note that all of the aforementioned equipment can be controlled manually or automatically, that is, by the user or by the algorithm written in the especial area shown in blue in Figure 8. This panel shows also the constants of a PID controller coming from factory and adopted in this work. For the SP1 to operate any device automatically, it is necessary for the user to write an algorithm directed to one or more equipment that is to be controlled.

### 3.2 Applied Methodology

In this stage, the applications and strategies in the elaboration of the experimental part will be described, as well as the development of the controllers and their comparisons; Reference values adopted in both SP1 components and controllers in general. Figure 9 illustrates a flowchart of the processes performed in this work, from the adjustment of the PID Controller to the extraction of the results of the PID-Fuzzy Controller.

**Figure 9:** Flowchart of the Methodology



Source: Author

### 3.3 PID Controller in SP1

As mentioned earlier, the PID controller applied in SP1 is that coming from factory, which has been adjusted to actuate in the situation of interest. The components under the control of this PID controller are the two SP1 motor pumps: the feed motor and the emptying motor; both responsible for the displacement of the water body, acting to correct the water level inside the cylindrical vessel.

As stated before, each motor pump is under the influence of a native PID controller from the SP1 itself. The PID controller constants for each pump, proportional constant (**Kp**), integral constant (**Ki**), derivative constant (**Kd**), are shown below. These constants adopted in the PID controllers for the level control are the ones that the SP1 was calibrated by its manufacturer, and, for this reason, used for PID-Fuzzy controller.

Feed motor:

$$Kp = 2,65 \qquad Ki = 2,50 \qquad Kd = 2,45$$

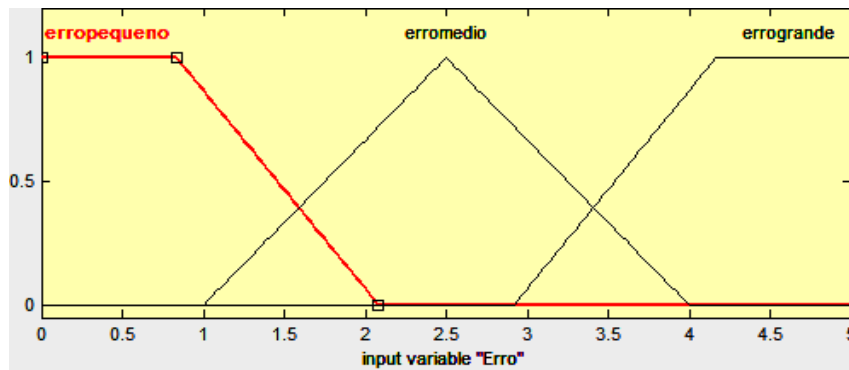
Emptying motor:

$$Kp = 2,62 \qquad Ki = 2,50 \qquad Kd = 2,43$$

### 3.4 Fuzzy Controller and PID-Fuzzy Controller in SP1

The strategy to determine the Fuzzy Controller was to determine (from a nebulous point of view), the definition of the errors, considering how the degree of error would relate to the output of each PID controller constant. For these steps, the MATLAB software fuzzy toolbox was used. Figure 10 shows how small (erropequeno), medium (erromedio), and large (errogrande) errors were defined in MATLAB.

**Figure 10:** *Definition of Errors*



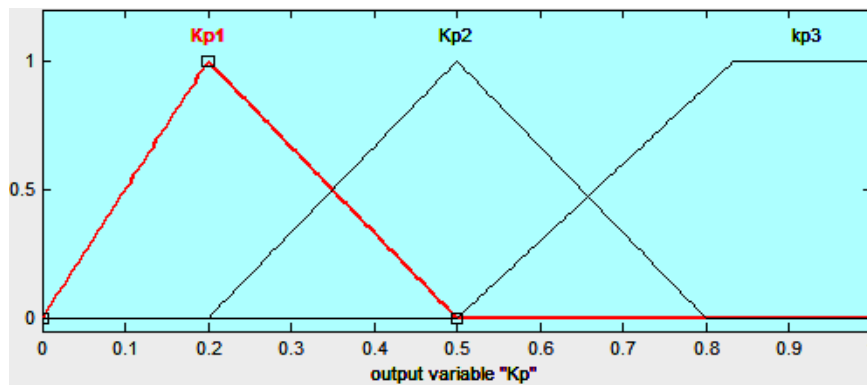
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In other words, it was defined that if the error in relation to the setpoint is up to 1% it is considered a small error (erropequeno). If the error is equal to 3%, the error is medium (erromedio). And if it is greater than or equal to 5%, the error is large (errogrande). Among these values, the error is related to the degrees of pertinence shown in Figure 10.

After the classification of the errors, the next step is to define how the outputs of each PID Controller constant should be in the classification in the fuzzy logic and in the experience of an SP1 expert, to relate them to the linguistic rules in the fuzzification process.

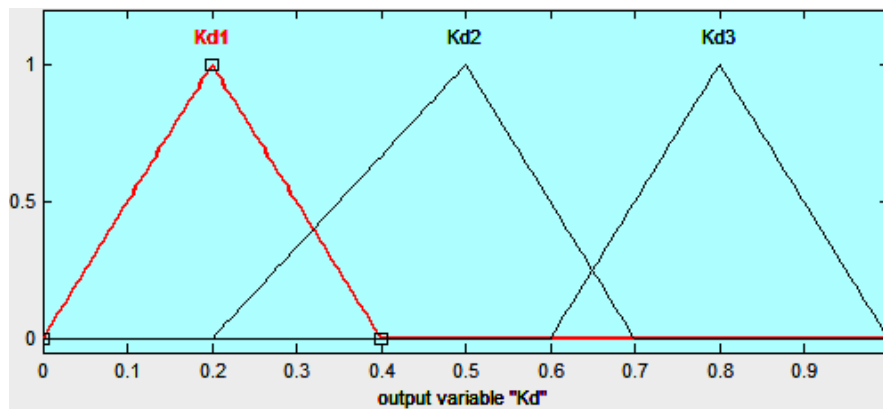
The behavior of each of the constants  $K_p$ ,  $K_i$ , and  $K_d$  s shown respectively in Figure 11, Figure 12, and Figure 13 below, using the MATLAB software fuzzy toolbox.

**Figure 11:** *Output from Constant Kp*



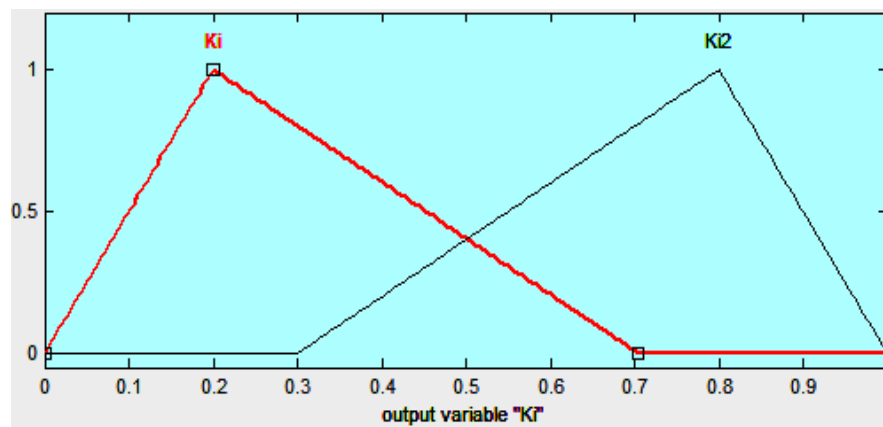
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**Figure 12:** *Output from Constant Kd*



Source: Author

**Figure 13:** *Output from Constant Ki*



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With both the input (the errors) and the outputs of each constant of the PID controller, the linguistic rules were defined so that each constant  $K_p$ ,  $K_i$ , and  $K_d$  related to the small, medium, and large errors. The basis of applied language rules is described below:

For the constant  $K_p$ :

***If Erro is erropequeno Then Kp is Kp1***  
***If Erro is errormedio Then Kp is Kp2***  
***If Erro is errormedio Then Kp is Kp3***  
***If Erro is errogrande Then Kp is not Kp1***

For the constant  $K_i$ :

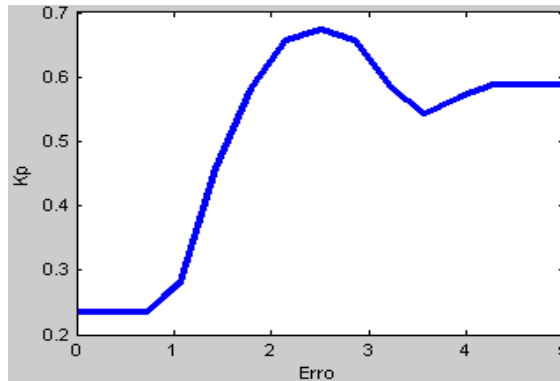
***If Erro is erropequeno Then Ki is Ki1***  
***If Erro is errormedio Then Ki is not Ki1***  
***If Erro is errogrande Then Ki is Ki1***

For the constant  $K_d$ :

***If Erro is erropequeno Then Kd is Kd1***  
***If Erro is errormedio Then Kd is Kd2***  
***If Erro is errogrande Then Kd is not Kd1***

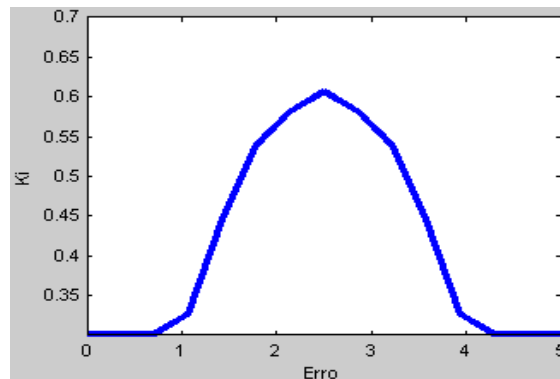
After the linguistic rules, follows the process of defuzzification. The defuzzified value is obtained by several methods, an example of a method widely used in the literature is the defuzzifier via the centroid method, also called the center of mass [1]. This is the most common method that is part of the Mamdani method, obtained via the arithmetic mean weighted by the pertinence of each element of the fuzzy set. Therefore, in this case, the centroid defuzzification method was selected. The proportional behavior of each constant  $K_p$ ,  $K_i$ , and  $K_d$  after this process is plotted below in Figure 14, Figure 15 and Figure 16, respectively. Values are normalized to unity:

**Figure 14:** Behavior of the Constant  $K_p$



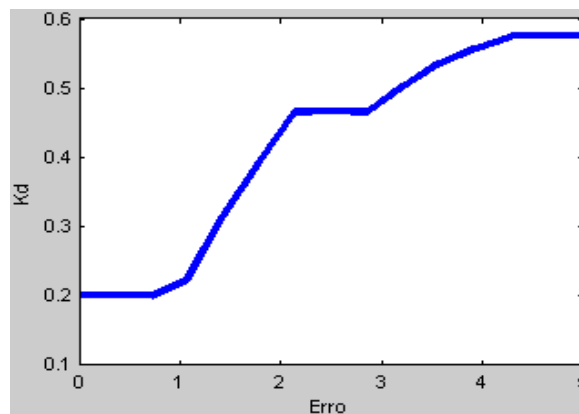
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**Figure 15:** Behavior of the Constant  $K_i$



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**Figure 16:** Behavior of the Constant  $K_d$



Source: Author



The figures above show how each constant percentage will behave in the PID Controller, varying its value according to the error in relation to the established set point. For example, observing Equation (1) of the PID Controller, it is noted that if it were acting on the feed motor, it would be like the following generic form:

$$u(t) = 2.65 \cdot e(t) + 2.50 \cdot \int_0^t e(t)dt + 2.43 \frac{de(t)}{dt} \quad (6)$$

Where:

$$Kp = 2,65 \qquad Ki = 2,50 \qquad Kd = 2,43$$

This is the pure PID Controller. But, with the determination of how the constants should vary, or better, how the behavior of the constants is linked in relation to the degree of error is the performance of the Fuzzy Controller. This coupling of the relationship between the variation of the constants in relation to the error and controlled under the fuzzy logic that we call the PID-Fuzzy Controller.

So, a PID-Fuzzy Controller is a PID Controller that has its Proportional (Kp), Integral (Ki), and Derivative (Kd) constants regulated by a Fuzzy Controller.

As can be seen and according to the error, the maximum variation in the behavior of the constants in the Fuzzy Controller can adopt values ranging from 0 (zero) to 1 (one), this means that if the value is zero the constant also has value zero and if the value is 1 the constant will have its full value. Thus, if at any time the Fuzzy Controller assigns a value of 1 to the constant Kp of the Supply Motor, it will have a value of 2.65; for a value of 0.50, Kp will have a value of 1.325; for a value of 0.30, Kp will have a value of 0.795 and so on.

Then, three diffuse blocks will act on Kp, Ki, and Kd through the fuzzy coefficient Fp, Fi, and Fd, respectively, until an optimized response is achieved. Values range from 0 to 1 and are assigned to the coefficients Fp, Fi, and Fd.

Thus, in the PID-Fuzzy Controller, there is a Proportional Fuzzy (**Fp**) coefficient responsible for Kp, Integral Fuzzy (**Fi**) responsible for Ki, and Derivative Fuzzy (**Fd**) responsible for Kd. The PID controller Equation (1) can be written as:

$$u(t) = FpKp \cdot e(t) + FiKi \cdot \int_0^t e(t)dt + FdKd \frac{de(t)}{dt} \quad (7)$$

## 4 RESULTS

With the definitions already established, SP1 was activated with the PID-Fuzzy Controller. And for comparison of the obtained data, SP1 was also used with a Simple Controller, that is, an on/off controller, and with the pure PID Controller. For this validation, both the Power Engine as the SP1 Emptying engine ran ranging from 0 (zero) to 1000 (one thousand) rpm (revolutions per minute), except for the Single Controller because it is an on/off.

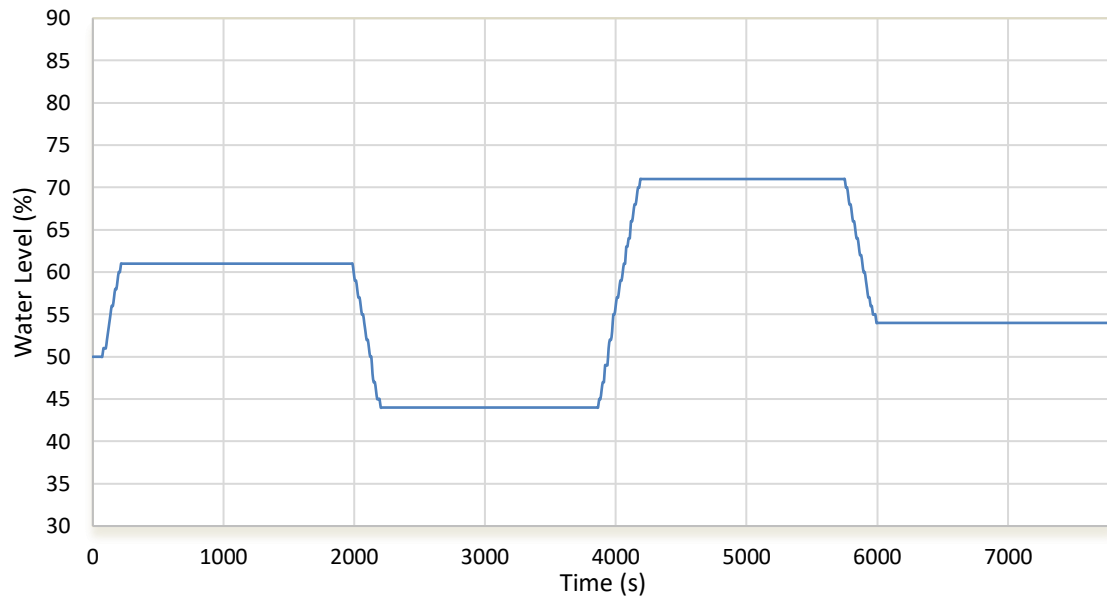
Then, for each type of controller, SP1 started from the water level in the Vessel by 50% to achieve, interspersed in approximately 30 minutes, the new set points at 60%, 45%, 70% and 55%. Conditions similar to those that could occur in a PWR reactor pressurizer were applied to the SP1 vessel, treating it as a pressurizer. It was verified how each controller responds to the situations of water input (insurge) and water outlet (outsurge).

Figure 17, Figure 18 and Figure 19 show how the Simple Controller, the PID Controller, and the PID-Fuzzy Controller, respectively, behaved. In regard to stability, significant differences are evident. The Simple Controller (Figure 17) exhibits subcritical damping behavior, rapidly reaching a stable level. This behavior reflects its accuracy in relation to the setpoint, after reaching it, it does not seek a finer correction or adjustment. This is confirmed by noting that stability is not embedded in the setpoint.

The PID Controller (Figure 18) shows itself oscillating around the value of the set point. This is because the controller constantly seeks correction of the reservoir level closest to the setpoint. In this behavior, it can be inferred that the average of the peaks and valleys of the oscillations is equal to or very close to the setpoint.

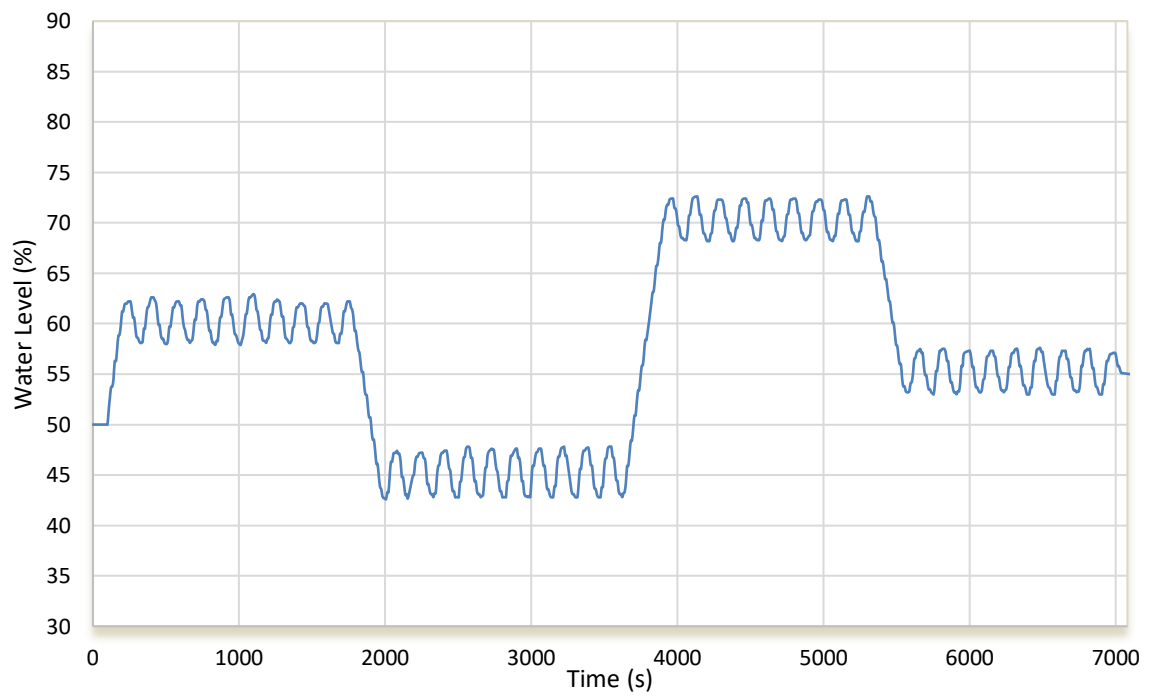
In the case of the PID-Fuzzy Controller (Figure 19), low-amplitude overshoots and undershoots appear, with rapid recovery to a stable level. This controller provides less oscillations, and, unlike the Simple Controller and the PID Controller, it manages to achieve some stability set in the established setpoint several times. This reflects a greater precision in relation to the other applied controllers.

**Figure 17:** Simple Controller (on/off)



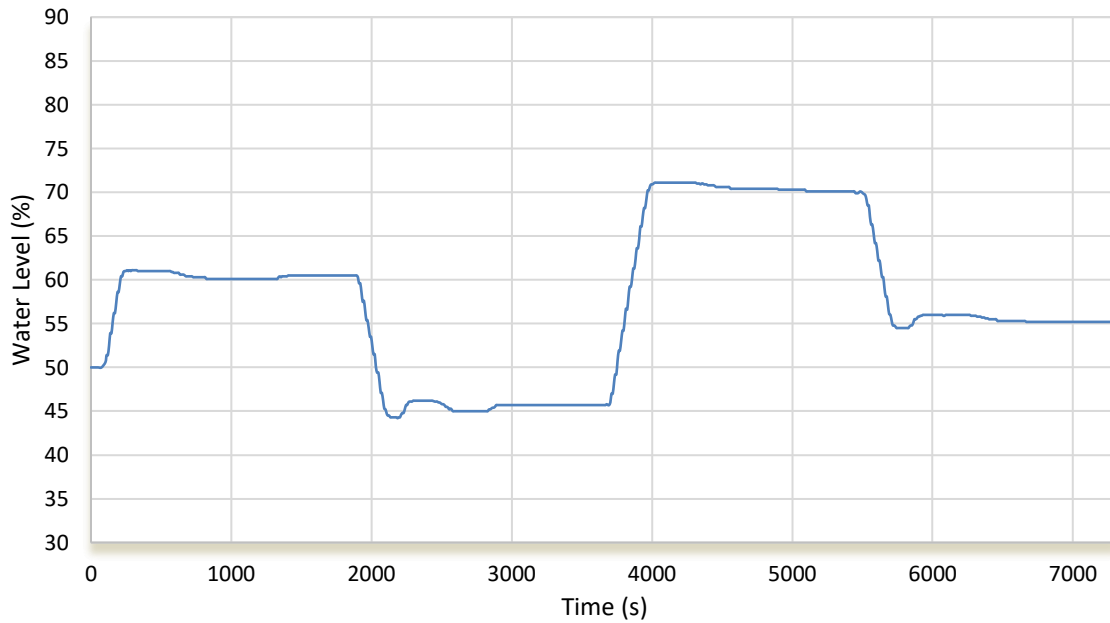
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**Figure 18:** PID Controller



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**Figure 19: PID-Fuzzy Controller**



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## 5 CONCLUSIONS

Analyzing the results of the experimental validation and comparing them, it can be said that the Simple Controller, among the 3 controllers, is the one that achieves the fastest stability in relation to the outsurge and the insurge. But the precision is not adjusted in relation to the setpoint in time, as can be seen in Figure 17. Another fact is that the Simple Controller, an ON / OFF model, whenever activated by the sensors, uses the maximum power of the equipment in which it is operating, that is, the two pumps of the SP1.

It can be noted that the accuracy of the PID Controller on average is better than that of the Simple Controller because even oscillating it is always trying to reach the defined setpoint. Also, the PID does not use the maximum power of the SP1 motor pumps at all times, which means less stress and more precision, despite oscillatory stability.

The PID-Fuzzy Controller, among the 3 controllers, is the one with the highest precision and the one that comes closest to the setpoint. Due to its structure, it is the least demanding of the power of the pumps, because when the water level is close to the reference value, it uses the minimum response to correct the error. It is also noted that the PID-Fuzzy Controller, because it is a real experimental system, and, due to the response time between the level sensors and the controller, makes it still oscillate with low amplitude. However, it achieves better accuracy and less wear on equipment compared to the PID controller.

. Considering the perturbations applied to the SP1 Vessel and the responses of the Simple Controller, PID Controller, and PID-Fuzzy Controller, it can be concluded that PID-Fuzzy obtained a better response and greater precision in insurges and outsurges. That is, among the controllers, it presented better performance, allowing the system to have more stability and less mechanical stress because it only uses the power needed to correct the level variations. As it has been said, its accuracy is superior to the others, which incorporate to this type of controller greater reliability and safety in the applications

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