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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 to 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 a 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).

1. INTRODUCTION

Nuclear reactors are physical systems presenting a nonlinear nature. Their parameters vary with the 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 conduct 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.

If the average temperature of the primary coolant increases, an inflow of water into the pressurizer will occur through the surge line, increasing its pressure. The vapor phase will condense, preventing the pressure from reaching undesired levels. To speed up condensation, the controlled flow sprinklers act at the top of the tank injecting water from the cold leg. If the pressure exceeds specified values, relief valves at the top of the vessel discharge into a large relief tank

Conversely, if the average temperature decreases, there will be a flow of water from the pressurizer into the primary circuit and the pressure falls. Bubbles within the superheated liquid will be produced by flashing and evaporation at the liquid-vapor interface, and this additional steam will prevent further pressure drop. To generate vapor yet faster, electrical heaters are activated.

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 the 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. An 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

Programmable Logic Controller (PLC) is used to implement 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 controller is a PID controller whose temporal continuous function for input and output position control is:

$$u(t) = Kp \cdot e(t) + Ki \cdot \int e(t)dt + Kd \frac{de(t)}{dt} \qquad (1)$$

and its discrete form is:

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

2.1.1. Problems with PID control and with process modeling in general

PID controllers are automatic controllers that work well if the process is reasonably linear, where a change in process input generates a proportional change in process output. If the process input and output ratio is slightly nonlinear, periodic adjustments of the controller parameters are required.

There are several PID adjustment methods such as Ziegler-Nichols and Cohen-Coon, among others. However, in the case of highly nonlinear processes, or when control elements or substantially nonlinear actuators (e.g. control valve) are used in the feedback loop, or when the mathematical modeling of the process has difficulties due to insufficient knowledge, or the plant is complex in general, PID controllers perform poorly. In such situations, the only option is to continue using specialized human operators.

2.2. Fuzzy controllers

The techniques of fuzzy control originated with the researches and projects of Mamdani and Assilian (1975) and gained space as study area in several teaching, research and development institutions of the world, and are now an important application of fuzzy set theory.

The process generally follows the following steps: Input and output variables are used; the set of rules is defined; the defuzzification method is determined and tests are performed for the verification of the system, adjusting the details according to the initial purpose.

2.2.1. Fuzzy controller

In the PID-Fuzzy control strategy of the water level of a nuclear pressurizer, PID gains are first conceived and then the fuzzy logic-based controller (CLF) is exploited to extend the finite sets of PID gains to the possible combinations of gains of the PID in the stable region. Thus, the PID gain adapts the model to correct the water level in the pressurizer, Figure 1.

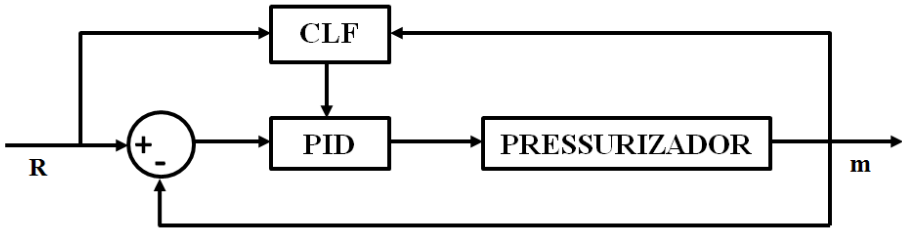

Figure 1: PID-Fuzzy water level control on pressurizer.

3. MATERIALS AND METHODS

3.1. Simulation Plant 1 (SP1)

The experiment was conducted in a Simulation Plant, henceforth called SP1, of the Process Control Laboratory of the Catholic University of Pernambuco. This plant can simulate the automatic control system pressurizer of a PWR reactor. The plant used is composed: a supervisory control (Figure 2), a pressure vessel (Figure 3); level, flow and pressure meters, resistance heating, thermocouple, pressure safety and relief valves; pumps; transducers, control valves, and air regulators.

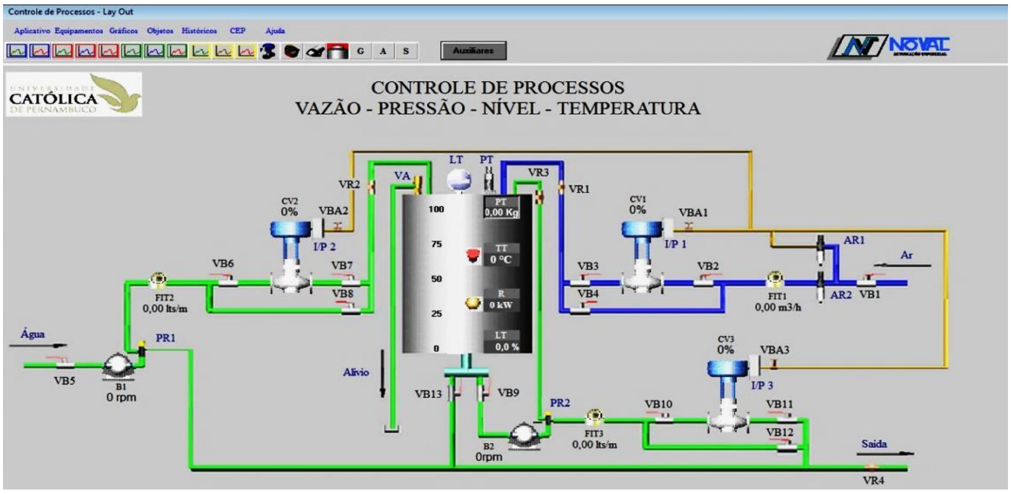

Figure 2: Supervisory control of pressure vessel used in this work

Figure 3: Pressure Vessel used in experiments.

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 were adopted in both SP1 components and controllers in general.

Figure 4 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.

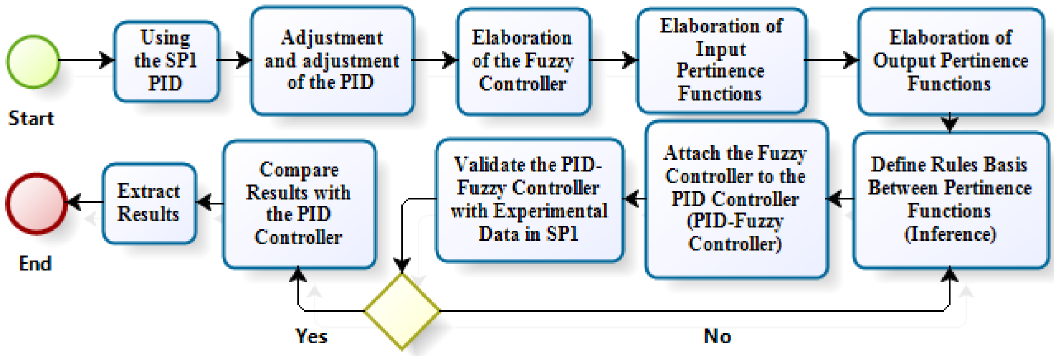

Figure 4: Flowchart of the Methodology.

3.3. PID Controller in SP1

The PID controller applied in SP1 was a built-in controller, which has only been adjusted to actuate in the situation of interest. The components under the PID control are the two motors of SP1, the feed motor and the emptying motor, which are responsible for the displacement of the water mass and will actuate to correct the water level of the vessel to the set point. By default, the constants of the built-in PID control of each motor, that is, the proportional ($\boldsymbol{Kp}$), integral ($\boldsymbol{Ki}$) and derivative ($\boldsymbol{Kd}$) constants of these are respectively:

Feed motor

$$\boldsymbol{Kp = 2,65}$$
$$\boldsymbol{Ki = 2,50}$$
$$\boldsymbol{Kd = 2,45}$$

Emptying motor

$$\boldsymbol{Kp = 2,62}$$
$$\boldsymbol{Ki = 2,50}$$
$$\boldsymbol{Kd = 2,43}$$

Figure 5 shows the Level versus Time graph of the water level in the Vessel with the PID Controller acting on set points set at 60%, 45%, 70% and 55%. This shows the behavior of the water level in time, as it can be seen, starting from a steady level at 50% the first set point is at 60%. The PID Controller achieves relative stability in order to maintain an oscillation around this reference point. After about 30 minutes, the second set point at 45% is applied, and again the PID reaches stability. About another 30 minutes later the set point is changed once more to 70%, and finally to 55%. These also have similar stability as the others.

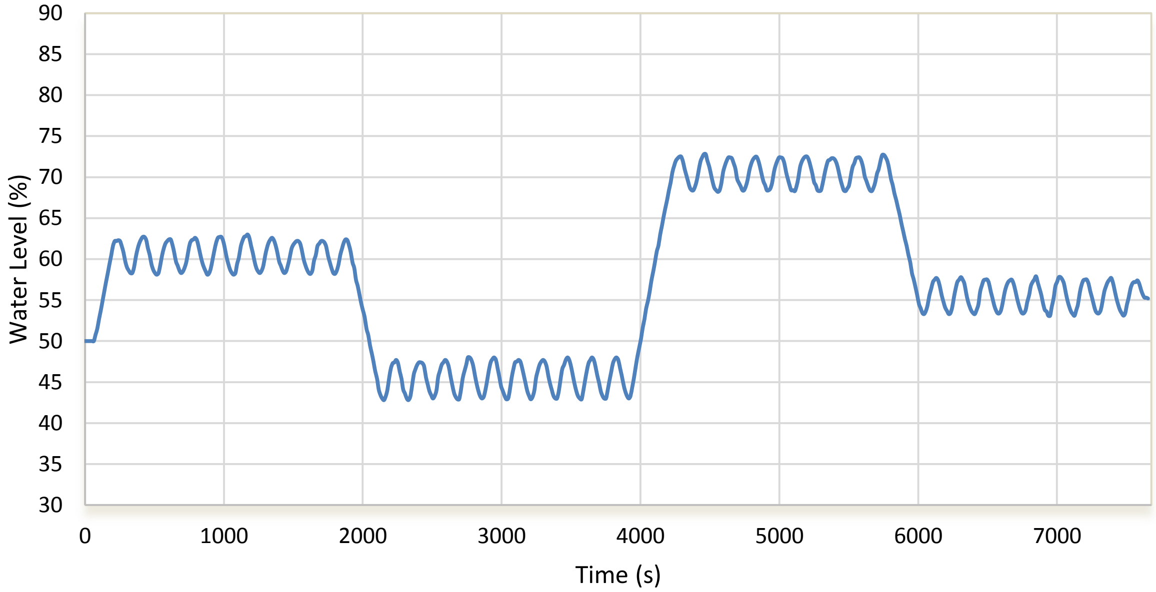

Figure 5: PID Controller in SP1

3.4. Fuzzy Controller and PID-Fuzzy Controller in SP1

The strategy to determine the Fuzzy Controller was to establish (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. The errors are the difference between the calculated value and the value at the set point. Figure 6 shows how small (erropequeno), medium (erromedio), and large (errogrande) errors were defined in MATLAB.

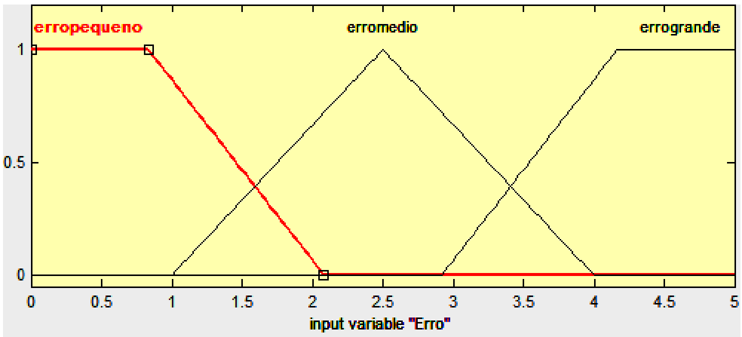

Figure 6: Definition of Errors.

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 normalized constants Kp, Ki and Kd are shown respectively in Figure 7, Figure 8 and Figure 9 below.

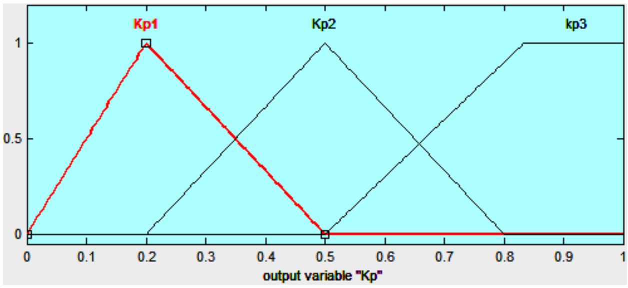

Figure 7: Output of Constant Kp.

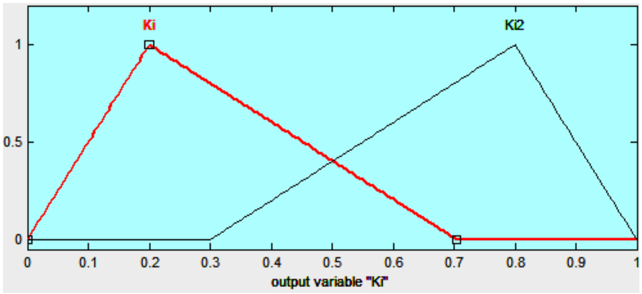

Figure 8: Output of Constant Ki.

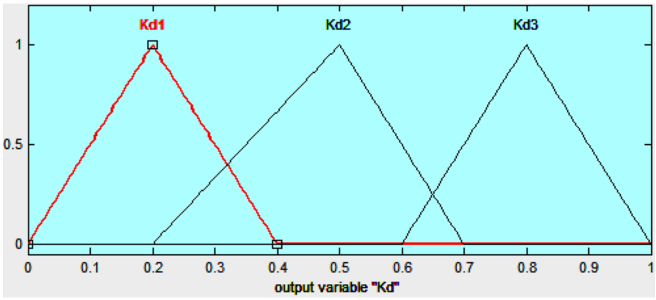

Figure 9: Output of Constant Kd.

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 Kp, Ki and Kd related to the small, medium and large errors. The basis of applied language rules is described below:

For the constant Kp:

$$\boldsymbol{If\ Erro\ is\ erropequeno\ Then\ Kp\ is\ Kp1}$$
$$\boldsymbol{If\ Erro\ is\ erromedio\ Then\ Kp\ is\ Kp2}$$
$$\boldsymbol{If\ Erro\ is\ erromedio\ Then\ Kp\ is\ Kp3}$$
$$\boldsymbol{If\ Erro\ is\ errogrande\ Then\ Kp\ is\ not\ Kp1}$$

For the constant Ki:

$$\boldsymbol{If\ Erro\ is\ erropequeno\ Then\ Ki\ is\ Ki1}$$
$$\boldsymbol{If\ Erro\ is\ erromedio\ Then\ Ki\ is\ not\ Ki1}$$
$$\boldsymbol{If\ Erro\ is\ errogrande\ Then\ Ki\ is\ Ki1}$$

For the constant Kd:

$$\boldsymbol{If\ Erro\ is\ erropequeno\ Then\ Kd\ is\ Kd1}$$
$$\boldsymbol{If\ Erro\ is\ erromedio\ Then\ Kd\ is\ Kd2}$$
$$\boldsymbol{If\ Erro\ is\ errogrande\ Then\ Kd\ is\ not\ Kd1}$$

After the linguistic rules, follows the process of defuzzification. Moreover, in this case, the defuzzification method of the Centroid was selected. The behavior of each constant Kp, Ki, and Kd after this process is plotted below, respectively in Figure 10, Figure 11 and Figure 12:

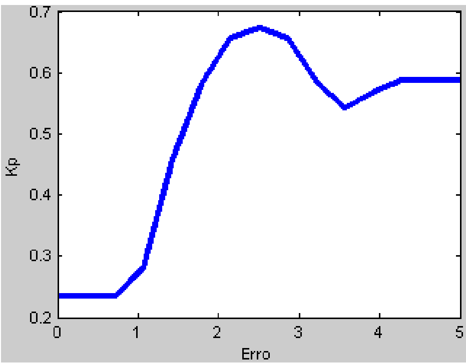

Figure 10: Behavior of the Constant Kp.

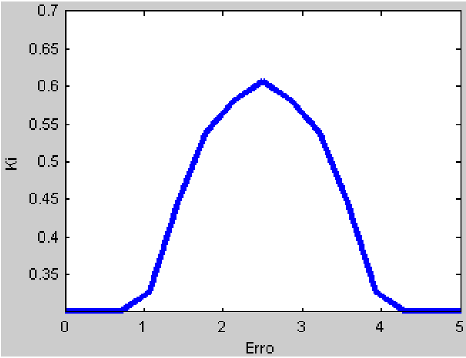

Figure 11: Behavior of the Constant Ki.

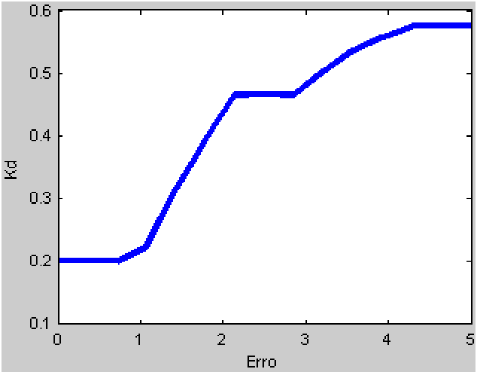

Figure 12: Behavior of the Constant Kd.

Figure 10, Figure 11 and Figure 12 above show the percent changes of each constant 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:

$$u(t) = 2.65 \cdot e(t) + 2.50 \cdot \int e(t)dt + 2.43\frac{de(t)}{dt} \tag{3}$$

Where:

$$\boldsymbol{Kp = 2,65}$$
$$\boldsymbol{Ki = 2,50}$$
$$\boldsymbol{Kd = 2,43}$$

The PID-Fuzzy Controller is a PID Controller that has its Proportional (Kp), Integral (Ki), and Derivative (Kd) constants regulated by a Fuzzy Controller. Then, three Fuzzy blocks will actuate on Kp, Ki and Kd through the fuzzy factors Fp, Fi and Fd, respectively, until a optimized response is reached. Values ranging from 0 to 1 are assigned to the factors Fp, Fi and Fd.

In summary, there is a Fuzzy Proportional (Fp), Fuzzy Integral (Fi) and Fuzzy Derivative (Fd), acting on each constant of the PID Controller and Equation (3) can be written as:

$$u(t) = FpKp \cdot e(t) + FiKi \cdot \int e(t)dt + FdKd\,\frac{de(t)}{dt} \tag{4}$$

4. RESULTS

4.1. Validation of the PID-Fuzzy Controller in SP1

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 a water input (insurge) and a water outlet (outsurge).

Figure 13, Figure 14 and Figure 15 show how the Simple Controller, the PID Controller, and the PID-Fuzzy Controller, respectively, behaved. As regards stability, significant differences are evident. The Simple Controller exhibits subcritical damping behavior, rapidly reaching a stable level.

The PID Controller shows itself oscillating around the value of the set point. In the case of the PID-Fuzzy Controller, low-amplitude overshoots and undershoots appear, with rapid recovery to a stable level.

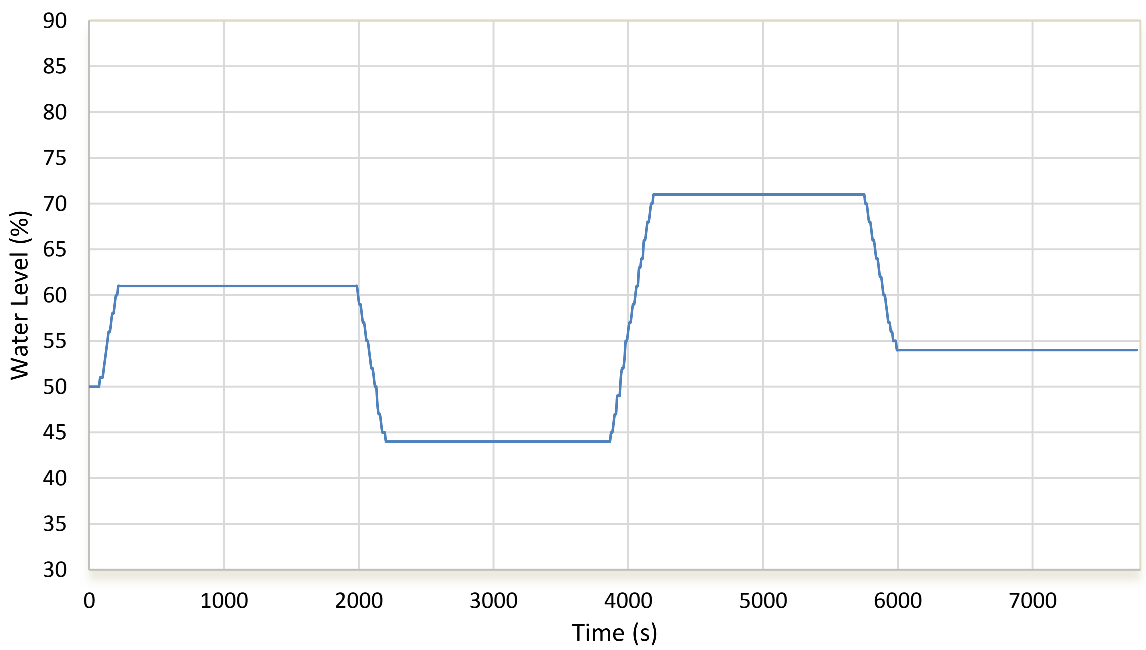

Figure 13: Simple Controller (on/off).

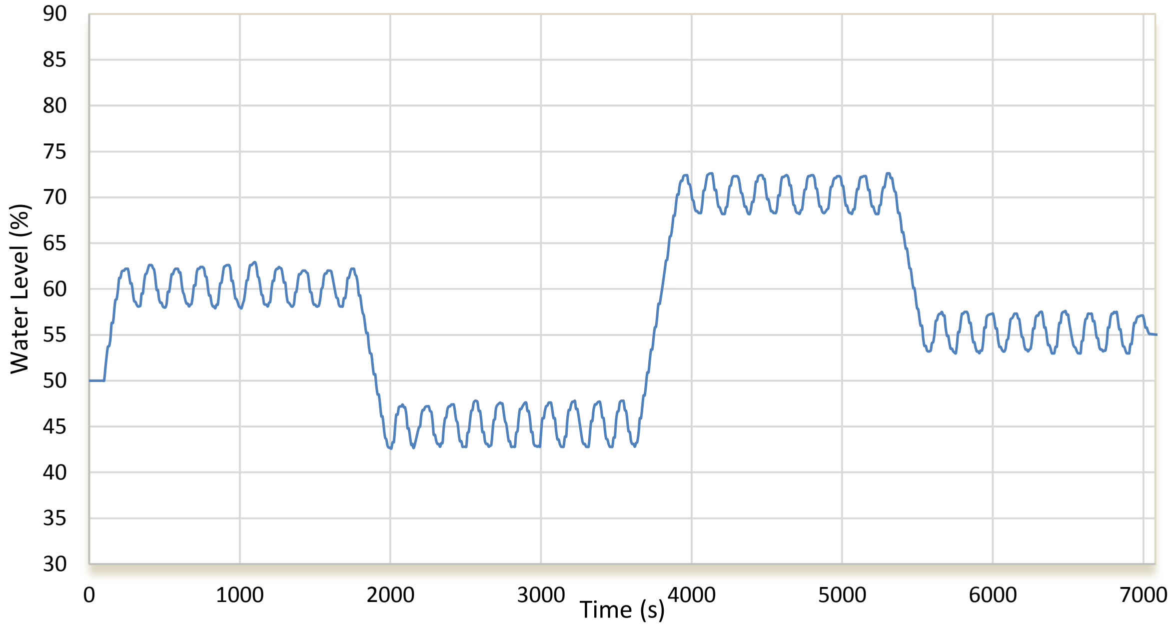

Figure 14: PID Controller.

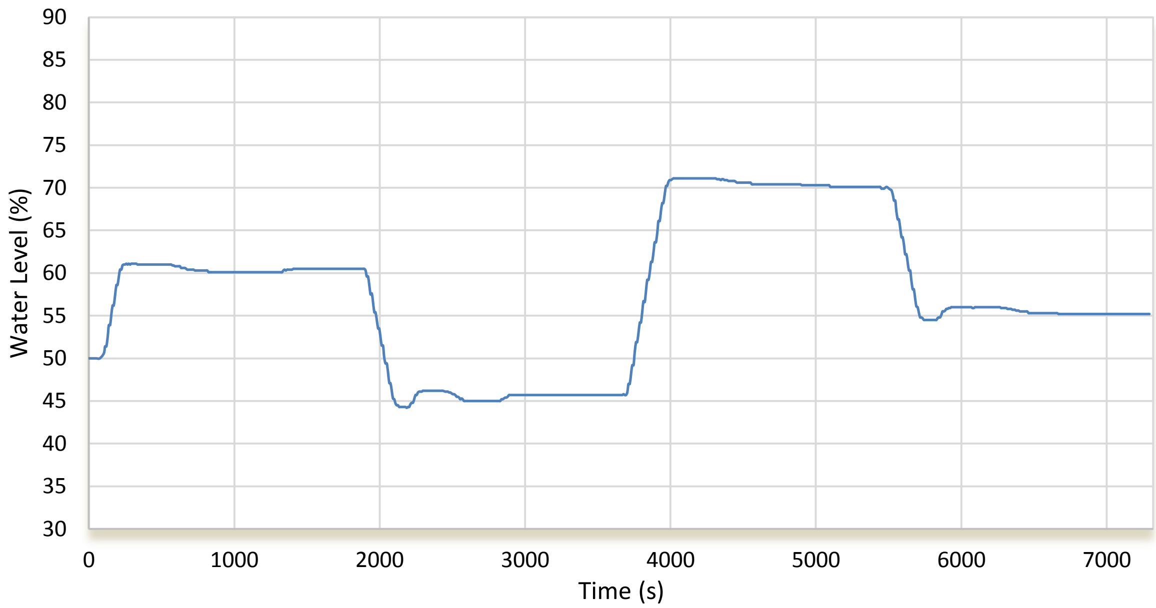

Figure 15: PID-Fuzzy Controller.

5. CONCLUSIONS

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 a greater reliability and safety in the applications.

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