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DESARROLLO DE UN SISTEMA AUTOMATIZADO PARA LA GESTIÓN EFICIENTE DEL BOMBEO DE AGUA DESMINERALIZADA EN UNA PLANTA DE TRATAMIENTO DE AGUA

DEVELOPMENT OF AN AUTOMATED SYSTEM FOR THE EFFICIENT MANAGEMENT OF DEMINERALIZED WATER PUMPING IN A WATER TREATMENT PLANT

Juiña Christian [1]; Toaza Jimmy [1]; Quinatoa Carlos [1]; Camacho José Luis [1]

[1] Department of Electrical Engineering, University Technical of Cotopaxi. Latacunga, Ecuador.
Correo: carlos.quinatoa7864@utc.edu.ec.

Resumen

Este análisis aborda la creación de un sistema automatizado para gestionar eficazmente el bombeo de agua desmineralizada en una planta de tratamiento, con el objetivo de superar las deficiencias de un sistema manual que causa pérdidas de eficiencia y riesgos operativos. Esta propuesta contempla la implementación de sensores de nivel y presión, reguladores de frecuencia, controladores lógicos programables (PLC) y una interfaz SCADA, lo que facilita la monitorización en tiempo real y una operación más sostenible. Además, la simulación del sistema se realiza en MATLAB/Simulink, utilizando modelos de control PI y PID para contrastar su rendimiento. Se examinaron perturbaciones como fallos de bombas, inyecciones imprevistas y fugas simuladas para evaluar la reacción del sistema automatizado ante situaciones críticas. Finalmente, se demostró que los controladores PI y PID logran una estabilización eficaz del nivel de agua, reduciendo las pérdidas y optimizando el uso de energía. El PID mostró una reacción más precisa, manteniendo la estabilidad incluso ante cambios bruscos.

Palabras clave: Sistema automatizado, Planta de tratamiento, PI, PID, Operación, Control.

Abstract

This analysis deals with the creation of an automated system to effectively manage the pumping of demineralized water in a treatment plant, with the objective of overcoming the shortcomings of a manual system that causes efficiency losses and risks in operations. This proposal contemplates the implementation of level and pressure sensors, frequency regulators, programmable logic controllers (PLC) and a SCADA interface, facilitating real-time monitoring and a more sustainable operation. In addition, the system simulation is carried out in MATLAB/Simulink, using PI and PID control models to contrast its performance. Disturbances such as pump failures, unanticipated injections and simulated leaks were examined to assess the reaction of the automated system to critical situations. Finally, it was proved that the PI and PID controllers achieve an effective stabilization of the water level, reducing losses and optimizing the use of energy. The PID showed a more accurate reaction, preserving stability even in the face of abrupt changes.

Keywords: Automated system, Treatment plant, PI, PID, Operation, Control.

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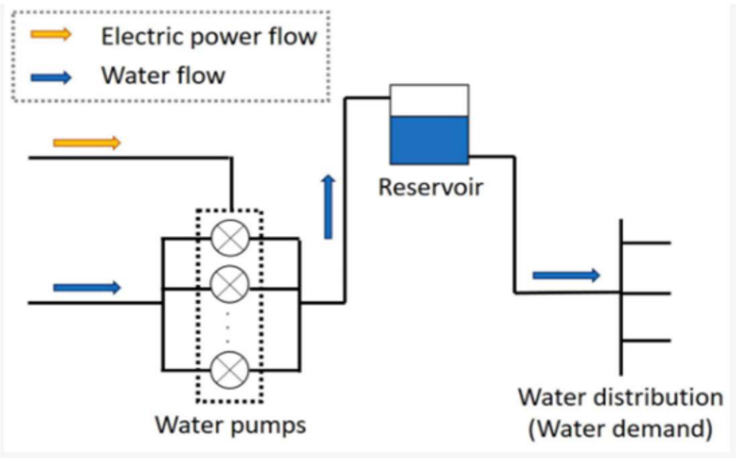
1. Introduction

Water is essential for several human tasks. Currently, water use in Ecuador is regulated under the Law of Water Resources, Uses and Development of Water. This legislation establishes the following: every individual has the right to have access to clean, adequate, safe, acceptable, accessible and affordable water for personal and domestic use in terms of quantity, quality, continuity and coverage. In Ecuador, drinking water coverage is 63%, with 83% in urban areas and 39% in rural areas, according to research from 2020 [1]. For rural areas, drinking water supply systems are not common, they are usually carried out by private companies, and their construction is generally financed by the residents. However, mayors' offices and municipalities also often pay for some construction of pumping and water storage centers for these regions [2].

Today, industry is facing increasing demand in terms of energy efficiency, environmental preservation and resource maximization [3]. In this scenario, process automation has become an essential tool for upgrading industrial operations and reducing operational costs, while ensuring the quality and reliability of services [4]. The handling of demineralized water is one of the most delicate and essential procedures in many industrial facilities, such as power generation, pharmaceutical, food and chemical plants. Demineralized water, or deionized water, refers to water that has been processed to remove most of its mineral salts, such as calcium, magnesium, sodium, chlorides and sulfates. This water is used in systems that require high purity to prevent corrosion, scaling and other modifications to production processes or technical equipment [5]. Considering its crucial importance in the operation of various industries, its transfer and management must be carried out in an accurate, efficient and regulated manner, preventing losses and ensuring a constant and high-quality supply [6]. Currently, the company's water treatment plant manually operates its soft water pumping system, resulting in procedural inefficiencies. Operators are required to perform repeated tasks that are time-consuming and decrease the plant's overall productivity. In addition, the lack of real-time monitoring increases the possibility of human error, such as inaccuracies in water level regulation, which can impact supply quality and equipment performance [7].

From a technological perspective, this study is significant because it demonstrates the feasibility of implementing a sophisticated control system in the automotive sector, using simulation tools such as MATLAB and Simulink to design and evaluate the performance of the PI model, as shown in Figure 1. Furthermore, from a pragmatic perspective, the proposal will facilitate the company to increase its ability to react to fluctuations in water demand, reducing costs and ensuring a constant and efficient supply. In this context, this analysis not only aims to solve a particular problem within the plant but can also serve as a guide for other industries that require similar automation needs in water resource management [8].

Fig. 1: *Proposed water distribution system*



The company's water pumping system supplies three key processes: clarified water, soft water and demineralized water. However, the lack of automation prevents optimal tank level control and efficient water distribution. Currently, the system operates with an ON-OFF controller that requires constant manual intervention, which not only increases the workload of the personnel, but also generates inconsistencies in the water supply. These deficiencies can lead to production process failures, water waste, and increased energy consumption [9].

In this line, the procedure of pumping demineralized water in a treatment plant is a major technical challenge. Traditional practices, based on manual controls or partially automated systems, often have significant constraints, such as excessive energy use, mechanical failures due to out-of-range operation, and a limited ability to monitor in real time. For this reason, it is essential to implement smarter, safer and more sustainable solutions to improve the process. The purpose of this project is the creation of an automated system for the efficient management of demineralized water pumping in a treatment plant [10]. This system is based on the use of electrical and industrial automation technologies, such as level and pressure sensors, flow meters, variable frequency drives (VFD), contactors, soft starters, programmable logic controllers (PLC) and a SCADA (Supervisory Control and Data Acquisition) interface for real-time monitoring and supervision of the system [5].

The incorporation of these elements will enable automatic control of the start-up, shutdown and speed regulation of the pumps according to need [11], in addition to the instant identification and rectification of faults or irregularities. In addition, the objective is to reduce the use of energy through frequency variators, which make it possible to adjust the operation of the motor to the demands of the system, preventing uninterrupted operation at full load when it is not essential. From an electrical engineering point of view, this project symbolizes a specific use of industrial automation to optimize water resource management processes. Its implementation not only positively influences energy efficiency and the extension of equipment durability but also enhances operational safety and the ability to react to unforeseen circumstances [12].

In recent years, it has experienced a remarkable growth in the degree of automation of its processes. Major changes in control systems have been implemented in all sectors, facilitating more profitable and efficient production. The paint shop has a pumping system in the water plant, essential for the constant use of demineralized water [13]. The constant flow of this treated water through each cleaning and purification process, thanks to its purity and lack of minerals that can cause deposits, corrosion or contamination, is useful for multiple essential uses [14]. Therefore, it is essential to have automated and modern systems that contribute to regulating and optimizing production efficiency, resulting in savings in time, resources and reduction of errors and failures. Decisions are focused on updating and improving operating systems, evidence of the company's commitment to excellence in its operations and its ability to adjust to the constant demands of a constantly changing market. In addition, the suggested system is in line with sustainable development goals [15], as it promotes logical water and energy management, reduces waste of resources and promotes the digitalization of industrial processes. These automated solutions are scalable and flexible, allowing their use to be expanded to other areas of the plant or to other industrial facilities that meet similar needs. Then, an automation proposal for the level regulation system in the demineralized water tanks of the water treatment plant is proposed, with the objective of increasing the efficiency of the operations and the supervision of the process [16].

2. Development of the model

2.1 Control systems

In the industrial sector, it is crucial to maintain accurate monitoring of the volume of liquids in production processes to ensure constant production and prevent losses or spills. To achieve this goal, automatic filling systems for water or other fluids are set up and managed by sensors and actuators linked to a programmable logic controller (PLC) or an electrical control circuit [17].

These sensors measure the liquid level in a container and transmit signals to the controller, which in turn turns the pumps on or off as required. The most commonly used sensors for this purpose are float sensors, which produce an electrical pulse when a specific level is reached, facilitating efficient process regulation and optimizing the use of resources in the industrial sector [18].

The obligation of a control system includes the three main tasks:

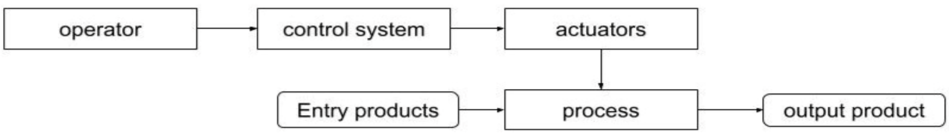
- Monitor output variables through measurements.
- Make logical decisions considering that corrective action is required based on the information of the present state of the process and the objective sought.
- Effectively implement these process decisions.

The phases to consider when designing a control system to meet your needs include setting control objectives, determining the variables to measure, choosing variables to manipulate, choosing a possible control configuration, and designing a controller [19].

2.2 Open loop control

Refers to systems where the output does not influence the control action. In an open-loop system, it is not quantified or feedback to contrast it with the input. In any open-loop control system, the output is not compared with the reference input. Thus, each reference input is attributed to a stable operating condition; therefore, the accuracy of the system is based on calibration. In the presence of disturbances, an open-loop control system does not perform the required work [20]. As shown in Figure 2, open-loop control only applies if the relationship between input and output is known, and if there are no internal or external disturbances.

Fig. 2: *Diagram of an open-loop control system*

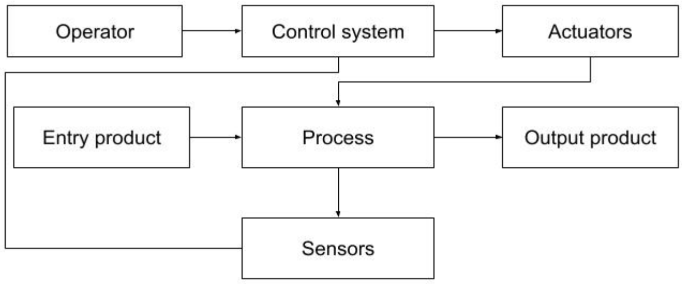


2.3 Closed loop control

Closed-loop control is distinguished by communication via sensors from the process to the control system, which allows the latter to verify whether the actions assigned to the actuators have been carried out properly in the process (Systems Engineering and Automation) [17].

In a closed loop control system, as shown in Figure 3, the controller receives the actuation error signal, which represents the difference between the input signal and the feedback output (which can be the output signal itself or a function of the same signal and its derivatives or integrals), with the objective of decreasing the error and directing the system output to an appropriate value. The concept of closed-loop control always involves the implementation of a control action that feeds back to reducing system errors [21].

Fig. 3: *Diagram of a closed-loop control system*

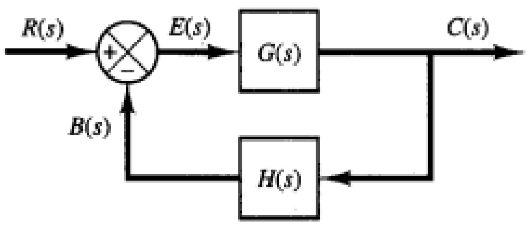


Closed-loop control is a tactic frequently employed in industrial systems for its benefits in accuracy, stability and resistance to disturbances. Among its most prominent features include [22]:

- In a closed loop system, the output affects the input, which facilitates feedback of the procedure.
- Its design facilitates the rectification of the impacts of external disturbances that may damage the system.
- It is more expensive to implement due to its higher complexity compared to an open loop system.
- It provides greater control, accuracy and precision compared to an open-loop system.

In the system shown in Figure 4, the inputs R(s) and C(s) are linked as follows, resulting in equation (1).

Fig. 4: *Closed loop system*



$$C(s) = G(s)E(s)$$

$$E(s) = R(s) - B(s)$$

$$= R(s) - H(s)C(s) \qquad (1)$$

Eliminating E(s) from these equations gives (2):

$$\frac{C(s)}{R(s)} = \frac{G(s)}{1+H(s)G(s)} \qquad (2)$$

The transfer phenomenon that links C(s) to R(s) is known as the closed-loop transfer function. Equation (3) illustrates how the transfer function links the dynamics of the closed-loop system with the dynamics of the direct and feedback path components [23].

Based on equation (3), C(s) can be obtained by the following technique:

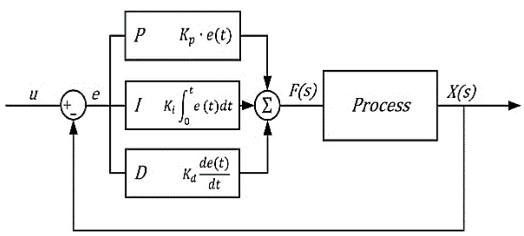
$$C(s) = \frac{G(s)}{1+H(s)G(s)}R(s) \qquad (3)$$

2.4 PID control

PID control is a regulation system that, by means of a feedback loop, facilitates the regulation of speed, temperature, pressure and flow among other variables of a process as a whole [8]. The PID controller determines the difference between our actual variable and the desired variable (Set Point). In pumping systems, we are often concerned with maintaining constant pressure or flow [24]. Therefore, the PID control evaluates the difference between the pressure in the pipeline and the required pressure and acts by modifying the motor speed to ensure that we keep our pressure or flow stable.

The importance of PID controls lies in their almost universal application in most control systems. Specifically, when the mathematical model of the plant is not known and, therefore, analytical design methods cannot be used, PID controls are most beneficial. In the field of process control systems, it is widely recognized that basic and modified PID control schemes have proven effective in providing rewarding control, although perhaps in many particular circumstances they do not provide ideal control [1].

Fig. 5: *Block diagram of a PID control*



The PID controller is the best known in the industrial sector. This product is the result of the linear mixing of three modes, the proportional mode (P), the integral mode (I) and the derivative mode (D) [7].

The error signal present is multiplied by a constant factor known as the proportional mode gain (K_r). This results in the proportional mode corrective effect (4):

$$P = k_r e(t) \quad (4)$$

As the name suggests, the integral mode incorporates the current error and the integral is influenced by a constant $\frac{K_r}{T_i}$, where T_i is known as the integral action time. Therefore, the corrective effect of the integral mode (5) is obtained:

$$I = \frac{K_r}{T_i} \int_0^t e(t)dt. \quad (5)$$

The derivative method obtains the error signal present by multiplying that result by a constant $K_r T_D$, where T_D is known as the derivative action time. Therefore, the impact of the derivative mode is presented (6):

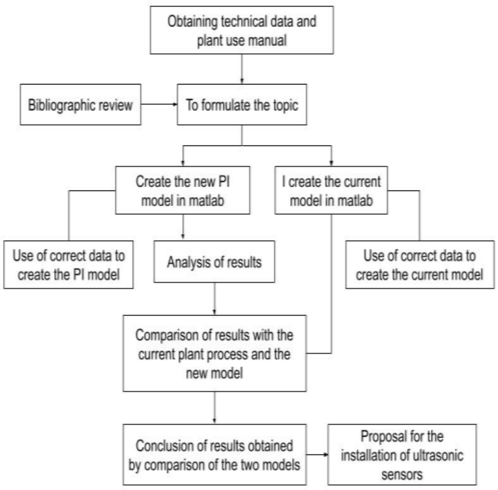
$$D = K_r T_D \frac{det}{dt} \quad (6)$$

2.5 Analysis of the control model

Figure 6 describes the work process for the creation and study of a factory control model. It begins with the collection of technical information and literature review and then formulates the topic. Based on this data, two models are generated in MATLAB: the current model and a recent PI model, using the relevant data for each [4].

Then, a study of the expected results and a comparison between the current model and the recent model is carried out based on the actual process of the plant. Finally, conclusions are derived based on this analysis, leading to the suggestion of installing ultrasonic sensors to improve the system [7].

Fig. 6: *Methodological analysis*



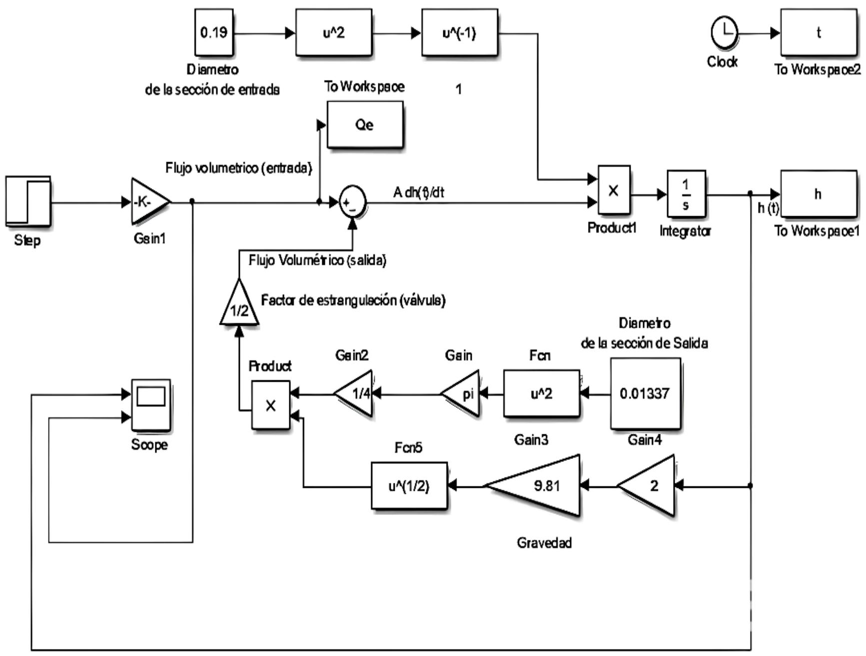
3. Results

This section shows the findings derived from the design of an automated system for the efficient management of demineralized water pumping in a water treatment plant. The development involved the simulation of the process in a controlled environment using MATLAB/Simulink, which allowed demonstrating the dynamic performance of the system under various operating circumstances. Responses to tank level, control signals and the impact of simulated modifications, such as variations in inflow and outflow, were studied. The commissioning of the PI controller proved to be effective in maintaining the predicted level, even in the face of drastic alterations in demand. The findings corroborate the proposal as a feasible and reproducible alternative to other similar facilities.

The creation of an automated system for the efficient management of demineralized water pumping in a water treatment plant satisfies the demand of improving hydraulic processes through the application of computer tools such as MATLAB and Simulink. The dynamic behavior of the water level in a tank is simulated in the model shown in Figure 7, taking into account both the inlet and outlet volumetric flow. This method enables the accurate representation of the system's vital variables, which facilitates the creation of control strategies that guarantee a constant and stable supply, reducing energy losses and enhancing operational efficiency.

The model created in Simulink includes important physical parameters, such as pipe diameter, gravitational acceleration and valve throttling factors, enabling a realistic representation of the hydraulic system. Through the implementation of mathematical functions and integration blocks, the temporal progression of the water level is modeled, which is crucial for defining automatic control algorithms. This technique contributes significantly to the development of intelligent pumping systems that not only maximize energy use, but also ensure the stability of the treatment process, meeting the technical criteria required in contemporary industrial environments.

***Fig. 7:** Simulation of dynamic water level control by means of block diagram*



3.1 Presentation of Disturbances:

- 300-350 (s): Reduction of the inlet flow rate (simulates a pump failure).
- 600-620 (s): Sudden increase in flow rate (simulates an unexpected injection).
- 800-820 (s): Increase in output (simulates a leak or accidentally opened valve).

3.2 Tank level response with PI control and perturbations

Figure 8 shows that, within 0 to 300 seconds, the system manages to stabilize the tank level around the 5-meter equilibrium point. However, when simulating a pump failure for 300 to 350 seconds, a gradual reduction in inflow is noted, although the change in level is not considerable due to the corrective intervention of the PI controller. This ability to rectify early on demonstrates a robust reaction to initial disturbances of low intensity and short duration, which is crucial in industrial contexts where minimal failures should not jeopardize the overall process.

Then, between 600 and 620 seconds, excess water is immediately injected. This disturbance causes a sharp increase in the level in the tank, reaching a point of maximum at the setpoint. Although the controller operates to balance the excess, the system requires significant time to return to the expected value. Finally, the change produced between 800 and 820 seconds, which is equivalent to a leak, causes a rapid reduction in the level. Despite the abruptness of the event, the system manages to gradually recover the level, demonstrating its ability to recover from situations of flow loss.

3.2.1 Control signal generated by the PI

The control signal remains constant at the beginning, with slight variations representing the initial stabilization process. As the first disturbance occurs (300-350 s), the signal undergoes a small increase, which compensates for the reduction of the inflow. This verifies that the PI controller is functioning properly, regulating the water inflow to the tank to keep the level within the set limits without causing over-control.

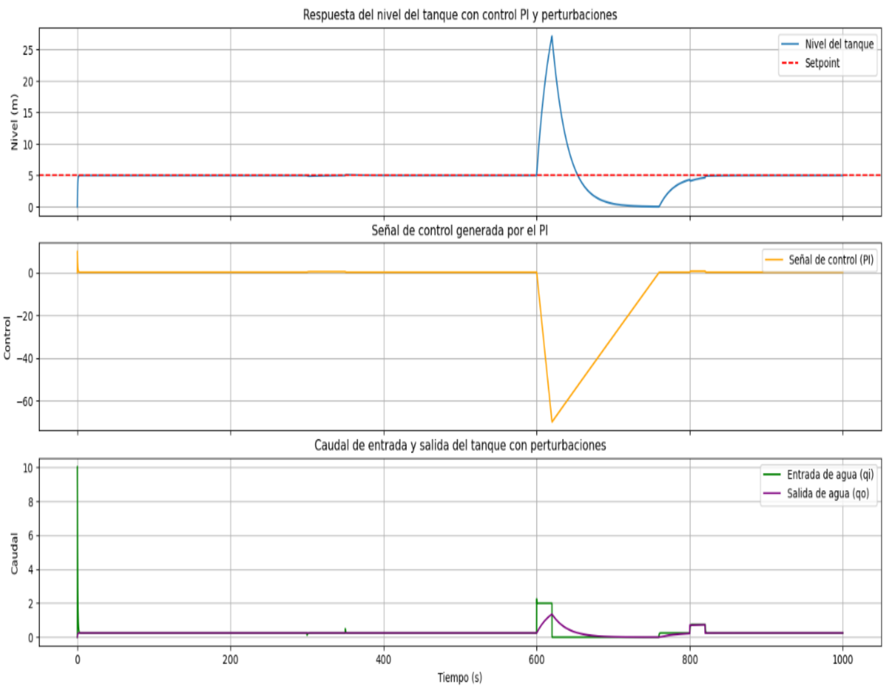
With the immediate administration of water in the range of 600 to 620 seconds, the control signal shows a significant reduction, even reaching negative values. This response of the controller seeks to reduce the excessive amount of water in the tank. Then, in the simulated leakage during the 800-820 seconds, a gradual increase of the control signal is observed in order to neutralize the loss of water. The reaction shows the system's response to disturbances and its ability to adjust to preserve the hydraulic balance.

3.2.2 Tank inlet and outlet flow rate with disturbances

During the initial phase, the inflow and outflow remain relatively constant. In the interval from 300 to 350 seconds, the inflow decreases significantly, indicating a pump failure. This drop is regulated by the system, and although the output is not significantly impacted, the mass balance is preserved thanks to the intervention of the controller.

In the second context (600-620 s), the sharp increase in inflow causes a significant difference in relation to outflow, resulting in an increase in the level in the reservoir. The third change (800-820 s), linked to a simulated leak, is illustrated as an increase in the outflow. This generates a negative variation in flow that decreases the reservoir level. The graph illustrates the reaction of the system to these abrupt changes in water conditions, reflecting its ability to self-regulate to operational disturbances.

Fig. 8: *Analysis of the dynamic response of a PI control system to disturbances in the pumping of demineralized water*



3.3 Tank level response with PI control

The initial section of Figure 9 presents the dynamic reaction of the tank level to the intervention of a PI (Proportional-Integral) controller. It is noted that the system quickly reaches the 5-meter setpoint, which demonstrates proper tuning of the controller. The stability and lack of noticeable fluctuations indicate that the system exhibits positive behavior, which allows maintaining the water level within the operating limits established by the industrial process of demineralized water treatment, favoring the efficiency of the pumping system.

The rapid determination of the level, without significant overshoot or steady state failure, is evidence of the effectiveness of the automatic control applied. This is particularly significant in industrial environments, where ensuring a stable level in the tanks ensures a constant flow for subsequent processes. In this context, the application of artificial intelligence control in the pumping system not only optimizes hydraulic performance but also enables safer and more energy-efficient operation, a crucial aspect for a demineralized water treatment plant.

3.3.1 Control signal generated by the PI

The second segment of the diagram shows the control signal produced by the PI controller. At the beginning of the procedure, the controller provides a large value signal to quickly rectify the discrepancy between the present and desired level. Then, the signal decreases as the error is reduced, stabilizing at a stable value that makes it possible to maintain the system in a steady state. This reaction is common in properly regulated systems, in which the integral action suppresses the steady-state error without jeopardizing the overall stability of the process. The constant control signal over time indicates that the system has reached an ideal operating state.

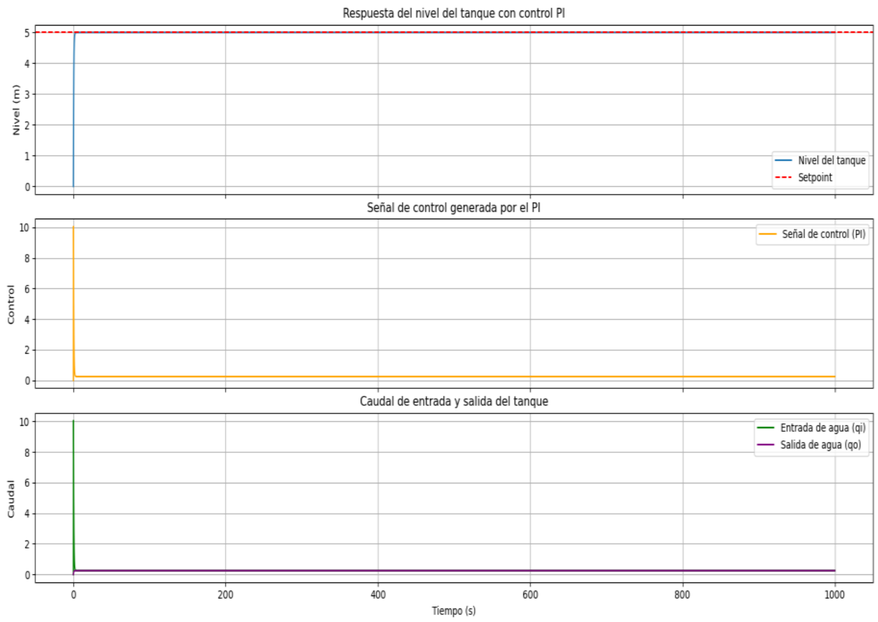
This behavior is crucial in industrial applications, since it decreases the mechanical exhaustion of the pumping system mechanisms and reduces energy use. In the scenario of a demineralized water treatment plant, where reliability and energy efficiency are crucial elements, the stability of the control signal underlines the importance of automating the process by means of a properly established artificial intelligence strategy.

3.3.2 Tank inlet and outlet flow rate

The third segment of the diagram shows the correlation between the inflow and outflow of the reservoir. Initially, the inflow is high, which facilitates a rapid accumulation of water to reach the required level. When the set point is reached, both flows balance, representing a steady-state system in which the inflow balances the outflow, keeping the volume of water in the tank unchanged. This equilibrium is crucial to prevent interruptions in the supply to subsequent treatment processes.

The detected flow behavior corroborates the effectiveness of the automated system in controlling the water conditions in the tank. The fast reaction of the inlet flow and its precise adjustment to balance the outlet flow make it possible to reduce losses and enhance the overall performance of the system. In a demineralized water purification facility, this ensures continuity of operations without overloading the pumps or compromising water quality, underscoring the importance of incorporating automatic control methods into pumping management.

Fig. 9: *PI controller for automated demineralized water level system*



3.4 Tank level with PID control

The initial section of Figure 10 shows the reaction of the tank level to the intervention of a PID controller. An accurate stabilization of the level around the set point of 5 meters is noted, without a considerable jump and with a fast convergence. This behavior demonstrates an optimal tuning of the controller, crucial to ensure the hydraulic stability of the system and to prevent energy losses related to oscillations or overloads.

The application of the PID controller facilitates the maintenance of the demineralized water level within the established operating parameters, which is crucial for sensitive industrial processes. This precise regulation increases the efficiency of the pumping system, preventing superfluous start-up and shut-down cycles and decreasing the deterioration of the electromechanical elements of the treatment system.

3.4.1 PID control signal

The control signal produced by the PID algorithm is shown in the second part. It is shown that, after a large initial impulse, the signal quickly reaches a stable operating zone, signaling an effective control effort at the start followed by a continuous response with minimal intervention. This suggests a properly balanced system, with proportional, integral and derivative control parameters set appropriately.

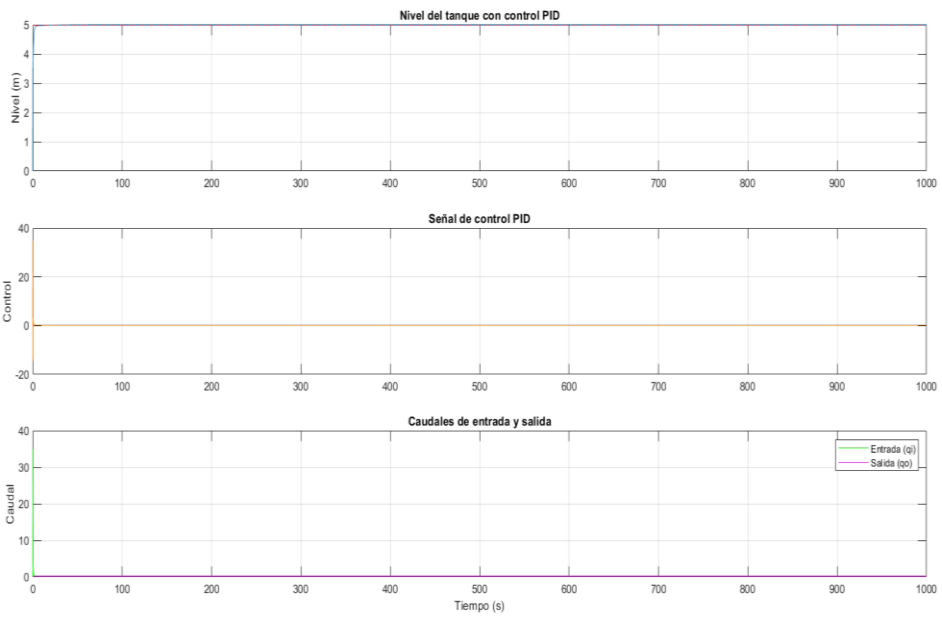
The constant behavior of the regulating signal ensures an accurate modulation of the inflow to the tank, reducing variability and favoring energy savings. The signal output evidences the ability of the automated system to maintain optimal operation without the need for human intervention, achieving the efficiency objectives in water treatment plants.

3.4.2 Inlet and outlet flows

The third part shows the inflow and outflow of the tank. Initially, the inflow increases abruptly to balance the desired level, while the outflow remains reduced. Once the desired level has been reached, the two flows stabilize, indicating that the system has reached hydraulic equilibrium, an essential requirement for a constant and safe treatment process.

The stabilization of flow rates shows the effectiveness of the applied control, since the excessive use of the pump is prevented, decreasing the use of energy and extending the durability of the device. This behavior is fundamental in the creation of automated demineralized water pumping systems, in which the aim is to optimize operational efficiency without affecting the quality of the processed water.

Fig. 10: *PID controller for demineralized water level control system*



4. Conclusions

The automated system for pumping demineralized water was tested through MATLAB/Simulink simulations, which allowed demonstrating the dynamic behavior of the water level under different operating conditions. This shows that the suggested control strategy is viable for implementation in industrial environments, where process continuity and system reliability are crucial factors for the overall effectiveness of the water treatment plant.

The simulation tests contemplated disturbances such as pump failures, unexpected water injection and leaks. In all situations, the controller was able to recover the tank level with acceptable response times, demonstrating its ability to control itself. The robustness of the control signal in the face of unforeseen events indicates a robust and adaptable system. This skill is crucial in industrial companies, where interruptions or deviations in operating parameters can compromise the quality of treatment and cause significant losses.

The PI regulator produced a control signal that showed invariable behavior after the initial adjustment stage, avoiding oscillations that could generate an excess of control. During the immediate injection event (600-620 s), the signal decreased significantly, even reaching negative values, reflecting an immediate action to avoid tank overfilling. Then, before the simulated leak (800-820 s), the signal experienced a sustained increase. This adaptive capability avoids unnecessary mechanical wear of the pumps and decreases energy use, meeting the efficiency and sustainability requirements demanded by the uninterrupted operation of water treatment plants.

The system experienced three fundamental changes: a pump failure (300-350 s), unplanned water management (600-620 s) and a leak (800-820 s). In each circumstance, the PI controller managed to recover the water level without serious overshoot or dropping. For example, the rapid rise in level after administration was adjusted in a subsequent period without compromising operation. For the leak, the level dropped rapidly but recovered while maintaining stability. These findings are evidence of the system's ability to handle real operating circumstances without compromising quality or process continuity.

The use of the PID controller in the automated system allowed a precise and agile stabilization of the tank level around the 5-meter set point, thus preventing large impulses. The system's response showed effective convergence to the set point, even in the face of initial variations, thus ensuring robust hydraulic control. This performance is vital in sensitive industrial processes, as it avoids disturbances that could compromise treatment quality. In addition, PID control contributes to reducing mechanical wear and tear, reducing unnecessary start-ups and promoting continuity of operations under stable and energy-efficient circumstances.

The PID produced a control signal with ideal behavior: after an intense start to correct the discrepancy with the setpoint, it quickly stabilized in a constant operating area. This characteristic evidence an adequate organization of the proportional, integral and derivative parameters, allowing effective flow regulation without requiring human intervention. Precise regulation of the inflow ensures logical and sustainable energy operation. In demineralized water treatment centers, this reaction contributes to maintaining optimal operating conditions, reinforcing system reliability and process excellence.

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