Implementation of PID and MPC controllers for a quadruple tank process in a 3D virtual system, using the hardware in the loop technique

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Latacunga

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Abstract. In this article, the design of an advanced MPC controller and a PID control have been proposed and implemented in a programmable logic controller (PLC) for a quadruple process of tanks, developing a comparison between the 2 controllers. The design of the controllers is carried out from the initial conditions of the process, the same conditions that must have an opening value of the valves between 60% - 80% to have interaction between the 4 interconnected tanks, the PID controllers were developed in Tia Portal V16 by means of programming in Ladder language using PID blocks for process control, while the MPC controller was designed using structured language SCL exported from Matlab-Simulink to Tia portal V16. The industrial process was virtualized in a unity 3D graphic engine, using the hardware in the loop technique and the Profinet protocol as well, it was possible to establish communication between the virtualized plant and the PLC. Finally, different tests were developed between the controllers, allowing to show that the MPC controller presents an optimal settling time and better compensation before disturbances

Keywords: Quadruple Tank Process, MPC, PID, HIL, PLC, Matlab, Unity 3D, SCL.

1 Introduction

Nowadays, Industry 4.0 is related to the fourth Industrial Revolution because of the appearance and introduction of new technologies and work methods enabling machines, people and devices to be digitized and connected to each other. Nevertheless, technological advances and developments require new control algorithms for the automation of nonlinear systems using PLCs [1]. Virtualization is a technology that lets us to save hardware, electricity and maintenance [2].

In [3] the use of the Hardware in the loop (HIL) technique allows the development and testing of controlled systems to manage complex machines and processes, likewise this technique enables replacing a physical part with software.

Ever since level systems are the most useful processes in the industry, as well as in the field of control and automation teaching, the implementation of level controllers for SISO and MIMO processes is essential. Hence, being very frequent in the industry, an analysis is required to increase the efficiency of the controllers [4]**.** In [5] the development of the mathematical model of a quadruple process of interconnected tanks is presented, from which a non-linear model was disposed and an analysis was carried out to adjust its parameters, to minimize the differences between the measurements. Experimental data and the predictions obtained by the model. Likewise, in [6] it is mentioned that the use of the mathematical model for the quadruple tank process, which was used to implement a controller in linear algebra. These models have been used frequently for the control of power plants, hydrographic processes, chemical processes and biotechnological industries.

To work out the control of a quadruple process of tanks, the use of classic controllers has been studied, one of the strategies was that [7] where a decentralized multivariable control with two PI controllers was designed, giving as a result a response that conforms the right specifications. There are investigations that make use of advanced controllers as presented in [8], where the study and design of a model-based predictive controller (MPC) was made to check and control the speed of a motor using the tool Matlab/Simulink concluding from the experimentation that the controller had better results than a self-adjusted PID controller, as well.

In [9] it is noted how the PLC is essential in industrial automation since they are very robust, but they have the limitation in view of computing performance, memory and deficiency when programming, which forces it currently searching new methods to implement more efficient and tunable control algorithms. Hence, in [10] the usage of the Structured Control Language (SCL) is explained, which has few studies given its complexity and low popularity in small and medium-sized industries, however, they are suitable for programs that require calculations of mathematical equations. Evenly, the research shows a clear guide for the use of the Matlab/Simulink PLC-Coder tool to export a mathematical function block to a programming language with the international standard IEC 61131 understandable by PLCs [11]. For industrial communication between hardware (PLC) and software (virtualized plant) the Industrial protocol Profinet is used.

This work provides a methodology for the design of the advanced MPC controller and implementation in a PLC S7-1200 programmable logic controller, providing a low-cost solution in automatic process control; considers the educational approach, it will help to fight the problem of training automation and control from students for using the process, control and techniques with simulated plants.

This article is organized as follows: Section 2 presents the virtual environment; Section 3 presents the mathematical model; Section 4 presents the design of the controllers; then, Section 5 contains the experimental results. Finally, the conclusions are set in Section 6.

2 Virtual Environment

This section illustrates the methodology used for the virtualization quadruple tank process, which is divided into four main stages: reference models; 3D modeling; programming and visualization; and Profinet communication with the PLC as shown in Fig. 1.

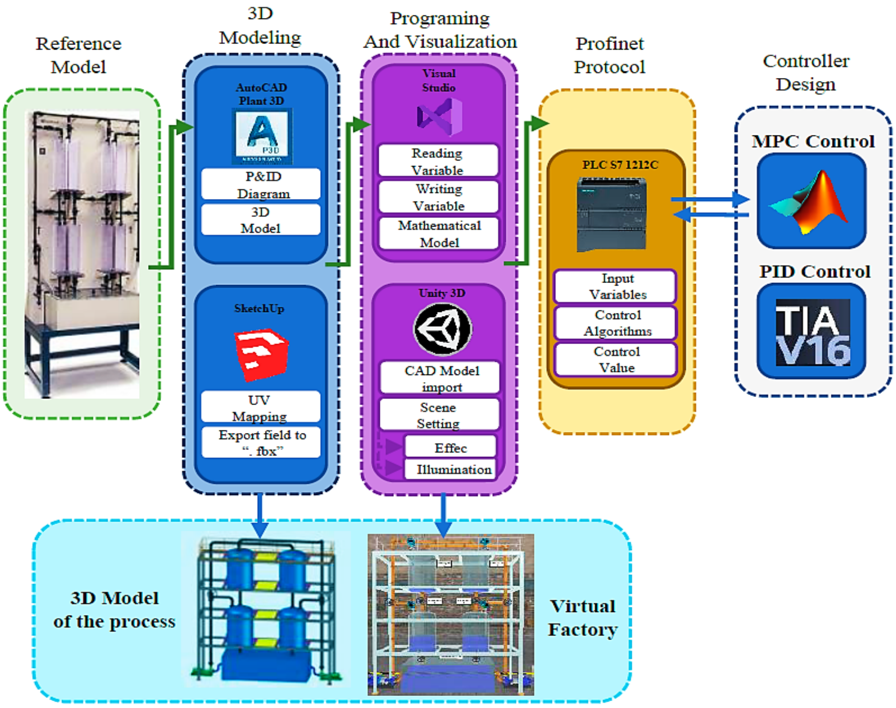


Fig. 1. Outline of the design of the virtual environment.

In the first stage, a reference model was looked for which considers features and aspects of a real industrial factory. In the second stage, called 3D modeling, the design of the quadruple tank process is worked out with AutoCAD Plant 3D software, where layers are defined to distribute the equipment and devices (tanks, flanges, pipes, structure, meshes) as well as the dimensions of the design, structures containing the tanks are created, valves and pumps are placed, the file created has the extension .dwg. To change the format, the native AutoCAD Plant 3D file must be opened in SketchUp software, which helps to get the file in extension fbx which is recognized by Unity 3D software.

In the Programming and virtualization of the 3D industrial environment, the different features of the process are incorporated, such as transmitters, frequency variators, control room, liquid filling, sounds and visual effects using the Unity 3D graphic engine and object-oriented programming in Visual Studio, enabling the virtualized plant having a greater resemblance to the real plant.

The last stage, Industrial communication with the PLC uses the Profinet protocol where the virtualized plant reads an IP address generated by the PLC to be able to write and read the data from the MPC and PID controller implemented in the PLC, this is how the system by means of the hardware in the loop (HIL) technique.

2.1 P&ID Diagram

The structure of the quadruple tank process is shown in Fig. 2, with a piping and instrumentation diagram.

The quadruple tank process starts with 2 centrifugal pumps controlled by means of a variable frequency Drive (VFD), which allow the transport of water from the reservoir tank to the 4 tanks using the 3-way valves (y_A, y_B), this process has two control loops which are located in TK_1 and TK_2 respectively, the same are composed of level indicator transmitters (LIT) that provides information to the multivariable controller (UIC) sending standard 4-20 mA signals thus achieving to execute control actions to the pumps (q_A, q_B), the TK_3 and TK_4 do not have control loops but they mainly show the water level and its standard signal.

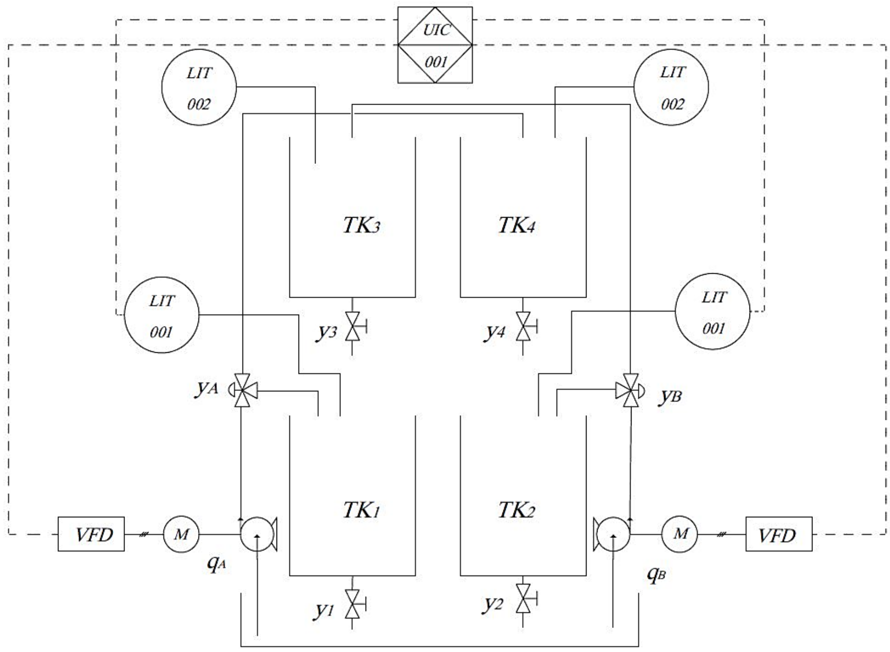


Fig. 2. P&ID diagram of the quadruple tank process

3 Mathematical Modelling

The mathematical model is based on some physical principles such as volumetric flow, mass balance equation, Torricelli's theorem and Bernoulli's principle [12]. The quadruple level tank process is shown in Fig. 2, consisting of four tanks *(TK_1,TK_2,TK_3,TK_4)* two centrifugal pumps (q_A, q_B) to control the flow of water between tanks, six manual valves ($y \in R$ [0 1]), which are distributed in two three-way valves and four liquid release valves.

A continuous and constant inlet flow is assumed, while Torricelli's theorem is used for the outlet of the tanks, which relates the fluid speed to the cross-sectional area and its flow rate is limited by the centrifugal pumps.

The amount of flow through any section of pipe 1 or 2 is constant, so it follows that

$$Q_o = A_i v_i$$

$$Q_{oi} = A_i \sqrt{2gh_i} \qquad \text{where} \quad i = 1,2,3,4 \tag{1}$$

Once the operating principles have been analyzed, a mathematical expression of 4 non-linear equations is arrived at, which represent the mathematical model of the quadruple tank process.

$$\begin{aligned}
A_1 \frac{dh_1}{dt} &= y_A k_A q_A + y_3 k_3 \sqrt{2gh_3} - y_1 k_1 \sqrt{2gh_1} \\
A_2 \frac{dh_2}{dt} &= y_B k_B q_B + y_4 k_4 \sqrt{2gh_4} - y_2 k_2 \sqrt{2gh_2} \\
A_3 \frac{dh_3}{dt} &= (1 - y_B) k_B q_B - y_3 k_3 \sqrt{2gh_3} \\
A_4 \frac{dh_4}{dt} &= (1 - y_A) k_A q_A - y_4 k_4 \sqrt{2gh_4}
\end{aligned} \tag{2}$$

Where:

A_1, A_2, A_3, A_4 : Area of thanks
$k_A, k_B, k_1, k_2, k_3, k_4$: Valve constants
$y_A, y_B, y_1, y_2, y_3, y_4$: Valve opening
h_1, h_2, h_3, h_4 : Tanks height

The mathematical model in Fig. 2 is expressed in the form of a matrix, with the corresponding values of the control valve openings as well as the load valve:

$$\begin{bmatrix} \dot{h}_1 \\ \dot{h}_2 \\ \dot{h}_3 \\ \dot{h}_4 \end{bmatrix} = \begin{bmatrix} -\frac{y_1 k_1 \sqrt{2gh_1}}{A_1} & 0 & \frac{y_3 k_3 \sqrt{2gh_3}}{A_1} & 0 \\ 0 & \frac{-y_2 k_2 \sqrt{2gh_2}}{A_2} & 0 & \frac{y_4 k_4 \sqrt{2gh_4}}{A_2} \\ 0 & 0 & -\frac{y_3 k_3 \sqrt{2gh_3}}{A_3} & 0 \\ 0 & 0 & 0 & -\frac{y_4 k_4 \sqrt{2gh_4}}{A_4} \end{bmatrix} + \begin{bmatrix} \frac{y_A k_A}{A_1} & 0 \\ 0 & \frac{y_B k_B}{A_2} \\ 0 & \frac{(1-y_B) k_B}{A_3} \\ \frac{(1-y_A) k_A}{A_4} & 0 \end{bmatrix} \begin{bmatrix} q_A \\ q_B \end{bmatrix} \tag{3}$$

Fig. 3 shows the validation of the performance of the mathematical model for the quadruple tank process.

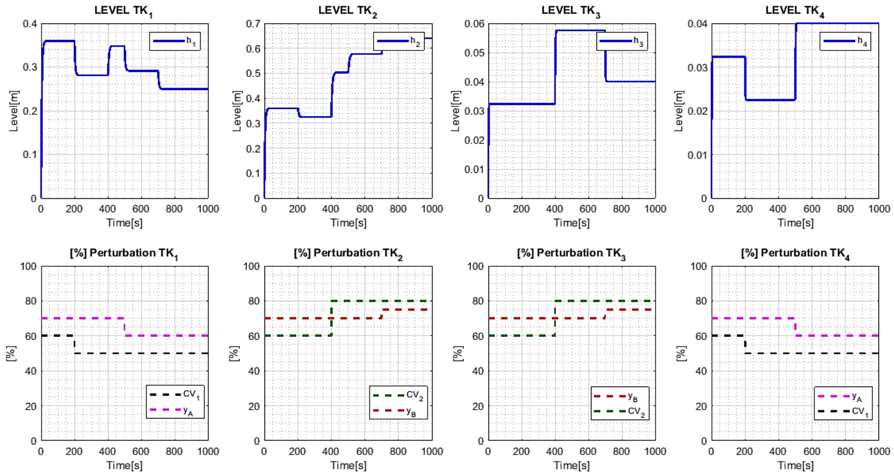


Fig. 3. Validation of the mathematical model.

For the validation of the mathematical model of the quadruple tank process, we start with initial conditions of level 0 $[m]$ for each tank, then:

At time 0 $[s]$ 3-way valves start with an initial value of $y_A = y_B = 70\%$ and control actions $CV_1 = CV_2 = 60\%$, which generates the tanks to increase their water level. Then at time 200 $[s]$ a decrease of CV_1 by 10% is generated, decreasing the level of TK_1, TK_2 and TK_4.

For the time 400 $[s]$ the value of CV_2 is increased by 20% so it is observed that the level of TK_1, TK_2 and TK_3 increases.

At 500 $[s]$ a perturbation of y_A with minus 10% is generated and it is observed that the level of TK_1 decreases and TK_4, TK_2 increases. Finally, at the time 700 $[s]$ a perturbation of y_B with plus 10% is generated and it is visualized that TK_2 increases and TK_1, TK_3 decreases.

4 Controller Design

This section presents the design of an advanced MPC controller and a classical PID controller for quadruple tank process control. Moreover, the performance of the control algorithms in the quadruple tank process is analyzed as well.

4.1 MPC Controller

Model-based predictive control (MPC) is an optimization strategy that uses a model of a process to foretell the effect of the control action on the quadruple tank process.

For the design of the MPC controller, the nonlinear model of the plant is included, creating a subsystem in Matlab/Simulink, where the inputs and outputs of the subsystem enter the MPC block of the controller. In this way, trial and error tests can be developed to find the right constants of the controller and it can be exported through the PLC encoder with the international standard IEC 61131 understandable by PLCs.

The target function applicable to MIMO systems explained in (4), searches to minimize the level error in tank 1 and tank 2, in addition to optimizing the abrupt control actions of the actuators (centrifugal pumps), this equation (4) serves for the simultaneous control of two process variables to determine the control actions.

$$\underset{u_1,u_2}{J(k)} = \sum_{i=N_w}^{N_p} \delta_1(k)\left[h_1(k+i|k) - hd_1(k+i|k)\right]^2 + \delta_2(k)\left[h_2(k+i|k) - hd_2(k+i|k)\right]^2$$
$$+\sum_{j=1}^{N_{c-1}} \lambda_1(k)\left[\Delta q_A(k+i-1)\right]^2 + \lambda_2(k)\left[\Delta q_B(k+i-1)\right] \quad (4)$$

Where:

$$\begin{aligned} \Delta q_{\min} \le \Delta q_A \le \Delta q_{\max} \\ \Delta q_{\min} \le \Delta q_B \le \Delta q_{\max} \end{aligned} \quad (5)$$

$$\begin{aligned} h_{\min} \le h_1 \le h_{\max} \\ h_{\min} \le h_2 \le h_{\max} \end{aligned} \quad (6)$$

Where N_w y N_p are the starting of the prediction horizon and the number of samples of the prediction horizon, N_c is the control horizon which should be less than the prediction horizon., $h_1(k+i|\,k)$ is the predicted level output of tank level 1, $h_2(k+i|\,k)$ is the predicted level output of tank level 2, $hd_1(k+i|\,k)$ is the desired value of tank level 1 and $hd_2(k+i|\,k)$ is the desired value of tank level 2.

To stand the inequality constraints in the optimization function they were entered as the constraints of the quadruple tank process, equation 5 represents the percentage of the control variable that is input to the final control elements in charge of manipulating the level of both TK_1 and TK_2, the two have the maximum value is $\Delta q_{max} = 100\%$ and the minimum value is $\Delta q_{min} = 0\%$. Equation 6 is the inequality constraint for the tank level limits, in this case they are $h_{min} = 0[m]$ y $h_{max} = 1[m]$.

The values of δ_1, δ_2 (error weight) and the values of the constants λ (weight of the control actions variations) were determined by the trial-and-error method, which are presented in Table 1.

Table 1. MPC controller design parameters.

Parameters	Tank 1	Tank 2
Prediction horizon (N_w)	12	12
horizon control (N_c)	3	3
Rate weight – input (δ_1, δ_2)	6.5	6.5
weight – input (λ)	0.001	0.001
weight –output (λ)	0.9	0.85

The diagram in Fig. 4 represents the implementation of the MPC control loop for the level of TK_1 and TK_2.

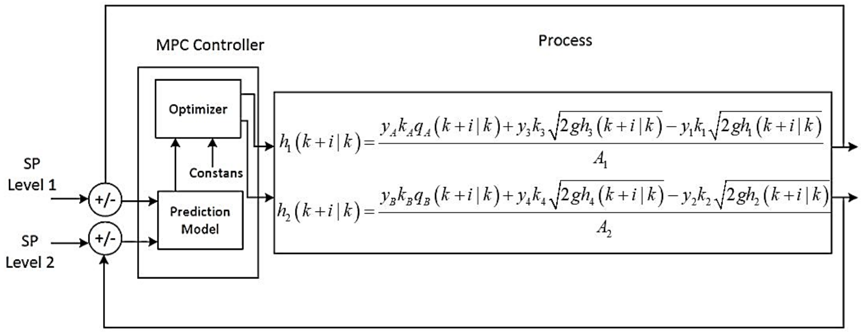


Fig. 4. Diagram of the implementation of the MPC control loops.

4.2 PID Controller

The Lambda tuning method was used to design the PID controller since it is robust and does not generate overshoot. Therefore, the dynamic model of the quadruple tank process must be determined. For de system, a first-order transfer function will be used, as shown in equation 7.

$$G(s)=\frac{k_p}{1+sT}e^{-sL} \quad (7)$$

Where k_p represents the static gain of the process, L is the dead time and T is the time constant. These parameters were calculated by obtaining a transfer function using the mathematical model of the quadruple tank process with the help of the linmode function of Matlab, it was possible to linearize the nonlinear model of the process and thus obtain the transfer function that represents the behavior of the quadruple tank process.

The transfer function representing the behavior of tank 1 and tank 2 are represented by equation 8.

$$G(s) = \frac{0.06015}{1+0.821s} e^{-0.01s} \quad (8)$$

PID controller tuning.

For the tuning of PID controllers, the aggressive lambda tuning method is used because of its high performance in the process industry. The closed-loop response time Tc1 is the design parameter, which will be set Tc1=T as denoted in [13].

The parameters describing the Lambda tuning constants are listed in Table 2. For this purpose, the constants K_p, T_i, T_d are calculated.

Table 2. Values of the constants for the PID controller with Lambda tuning.

Constants	Tank 1	Tank 2
k_p	16.62	16.62
T_i	0.78 *seg*	0.78 *seg*
T_d	0 *seg*	0 *seg*

The diagram in Fig. 5 shows the implementation of the PID level control loops for TK_1 and TK_2.

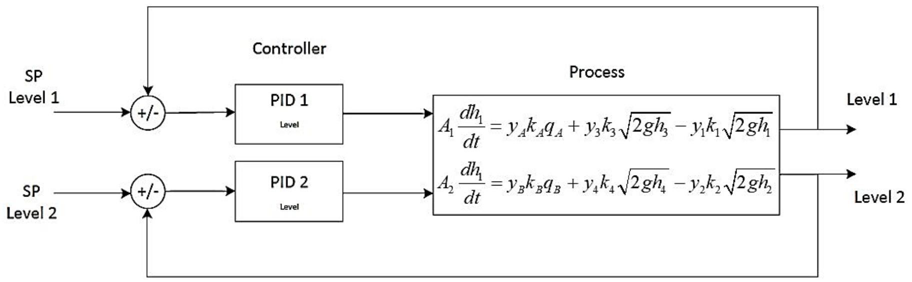


Fig. 5. Diagram of the implementation of the control loops.

5 Experimental Results

This section presents the implementation of the HIL technique for the virtualization and control of the quadruple process of tank in Fig.2, the virtual environment consists of industrial equipment and instruments as shown in Table 3. The mathematical model of the plant is located in the computer that is characterized by having a Windows 10 operating system, Intel Core i7 Processor, 12 GB Ram memory, fifth generation and 2 GB video card. The control algorithms are found in a programmable logic controller (PLC S7-1200 CPU 1212 AC/DC/RL), while the industrial communication between the process and the controller is developed through the Profinet protocol.

Table 3. Industrial equipment and instruments

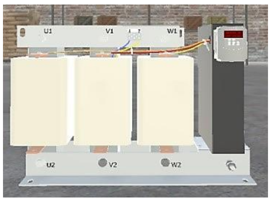
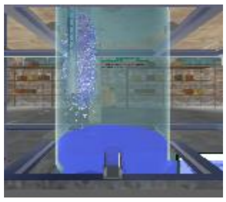
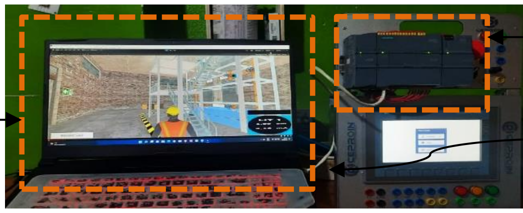
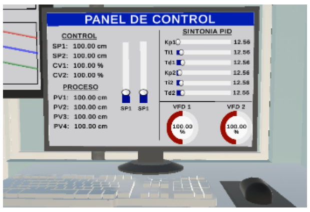
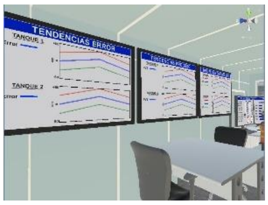
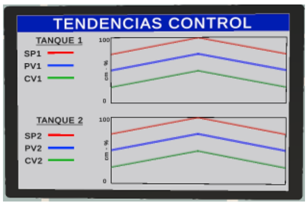
Centrifugal pump	Manual valve	Factory
		
Level transmitters (LIT)	Variable Frequency Drive	Tank (*TK*)
		
Hardware In the loop (HIL)		
		

Table 4 shows the virtual environment carried out in the Unity 3D graphic engine for the user to interact with the plant, this environment consists of a control room (to control the process through the computer peripherals) which contains monitors (to observe the evolution of the variables in the HMI) and the avatar to move through the virtualized process. The development of the virtual environment contains effects to give more realism to the quadruple tank process, such as: visual effects, surround sounds and the filling in the tanks.

Table 4. Control Room quadruple tanks

Perturbations and alarms	Control Panel	Control Room
		
Process trends	**Quadruple tanks process**	**Avatar**
		

5.1 PID and MPC Controller Performance

Fig. 6 illustrates the performance of the advanced control algorithm MPC and classical PID for different setpoint values, and in Table 5 you can see the values of the simulation parameters placed in the Unity 3D graphics engine.

Table 5. Parameters of the quadruple-tank.

Parameters	Value	Unit	Description
$h_{\max}$	1	m	Maximum level in all tanks
$h_{\min}$	0.01	m	Minimum level in all tanks
$q_{\max}$	3.1	V	Maximum voltage in q_A and q_B
$q_{\min}$	0	V	Minimum voltage in q_A and q_B
K_1, K_2, K_3, K_4	0.033	m^2/Vs	Discharge constant in all valves
K_A, K_B	0.0314	m^2/Vs	Discharge constant in 3-way valve
y_1, y_2, y_3, y_4	0.5	-	Parameter in all valves
y_A, y_B	0.7	-	Parameter of the 3-way valve

The process starts with $SP1 = SP2 = 0.5[m]$, the evolution of the level with the MPC controller is fast and does not present overshoot. From $220[s]$ a set point change of $SP1 = 0.4[m]$ and $SP2 = 1[m]$ is observed, the difference between the controllers is noticeable as the PID controller reaches its set point slower compared to the MPC controller. Finally, at time $450[s]$ another set point change occurs, from $SP1 = 1[m]$ and $SP2 = 0.2[m]$ in which the controllers have very similar PV responses, although the MPC controller reaches the desired value earlier, in Table 6 and Table 7 the settling time and the overshoot of the tanks level are shown.

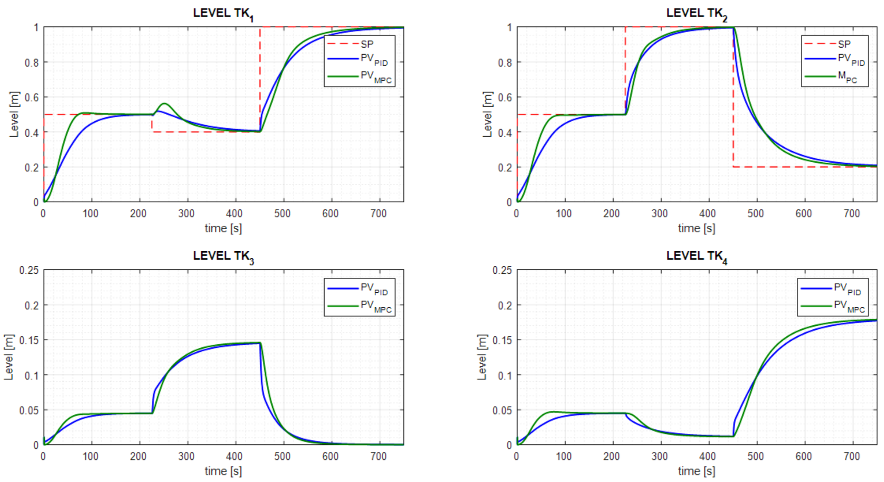


Fig. 6. Execution of classic PID control and advanced MPC.

Table 6. Controller Response Analysis in Tank 1

	Controllers	Set Point 0.5m		Set Point 0.4m		Set Point 1.0m	
		OS (%)	T_S (s)	*OS* (%)	T_S (s)	*OS* (%)	T_S (s)
TK_1	MPC	0.9	120	0	140	0	210
	PID	0	200	0	195	0	250

Table 7. Controller Response Analysis in Tank 2

	Controllers	Set Point 0.5m		Set Point 1m		Set Point 0.2m	
		OS (%)	T_S (s)	*OS* (%)	T_S (s)	*OS* (%)	T_S (s)
TK2	MPC	0	100	0	145	0	230
	PID	0	255	0	175	0	285

Fig. 7 shows the plant response to changes in the set point "SP". The simulation of the virtualized process indicates that the error tends to reduce to zero asymptotically, with the advanced MPC control being faster than the classical PID control.

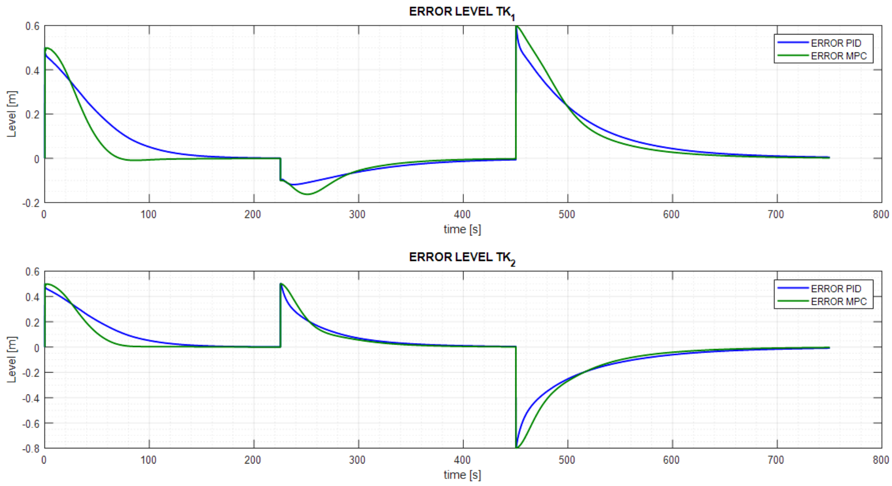


Fig. 7. MPC and PID controllers error.

In Fig. 8, changes were carried out in the 3-way valves, valves that in-flow throughout the process, thus affecting the level of the tank to be controlled by increasing or decreasing its level according to the change in valve opening. As can be seen at time 250[*s*], the opening of valve y_A is increased to 75% causing the level of TK_1 to increase and the level of TK_2 to decrease, now by decreasing in the time 500[*s*] y_B to 65% a decrease in the level of TK_2 is observed and the level increases in TK_1, in time 750[s] the value of y_A decreases to 70% causing the level in TK_1 to decrease and the level in TK_2 to increase, Finally increasing the valve y_B to 70% in time 1000[s] causes a level increase in TK_2 and level in TK_1 to decrease.

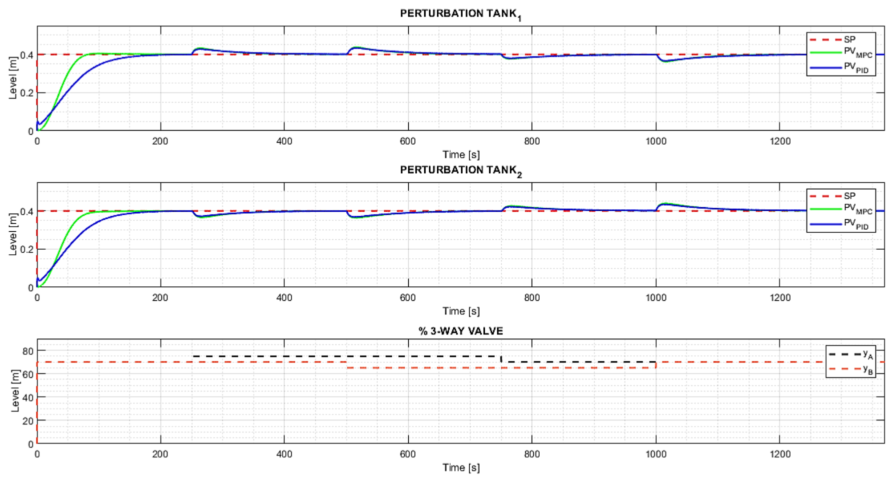


Fig. 8. Perturbation in the quadruple tank process.

6 Conclusions

In this work, the achievement of the mathematical model of the quadruple process of tanks has been shown, which has allowed the implementation of the MPC and PID controller, in addition to obtaining the transfer function, a correct tuning for the PID controller was carried out.

For the design of the MPC controller, the use of mathematical software (Matlab/Simulink) was necessary, since it allowed exporting and loading the function block (SCL language) to a programming language understandable by PLCs, while for the design of the controller PID, the Tia Portal V16 software was needed to place the tuning constants in the PID block.

The design and connection of the industrial devices and equipment in Unity 3D were worked out with the use of standard instrumentation, to give users a real environment of the quadruple process of tank and managing to control the variables through a panel located in a control room. The Profinet protocol of the PLC S7-1200 CPU 1212 AC/DC/RL allowed the communication between the PLC and the virtualized plant, achieving the sending and receiving of data for the correct operation of the control algorithms that act in the process.

To demonstrate the efficiency of the proposed algorithms, 2 tests were developed, the first one where no perturbations were considered and only the response of the controllers to set point changes was analyzed, and the second where there is a constant set point and perturbation are performed in the (y_A, y_B) valves. The design parameters that were chosen for the MPC control algorithm in tank 1 and tank 2 presented faster settling times, better reaction to perturbations and set point changes compared to the PID controller. Nevertheless, both controllers were adjusted to the user's requirements.

Finally, it was observed that the quadruple tank process being an interacting process has several restrictions at the time of the design of the controllers, one of them and the most important are the initial conditions (y_A, y_B) after many tests it was determined that: the value of the valves (y_A, y_B) cannot be less than 50 %, the range of variation between the valves is between 60 % - 80 %. With a value greater than 80% of the 3-way valves the coupling factor is reduced in the liquid ingress in tanks 3 and 4 tends to be eliminated.

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