Advanced Control Algorithms for a Horizontal Three-Phase Separator in a Hardware in the Loop Simulation Environment

Aimacaña Cueva, Lady Elizabeth y Gahui Auqui, Oscar Jonathan

Departamento de Eléctrica y Electrónica

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Ing. Llanos Proaño, Jacqueline del Rosario Ph.D

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L. Aimacaña-Cueva[1][0000−0002−6611−8453], O.Gahui-Auqui[1][0000−0002−6079−4696], J. Llanos-Proaño[1][0000−0002−6708−3897], D. Ortiz-Villalba[1][0000−0001−8090−6125].
leaimacana1@espe.edu.ec, ojgahui@espe.edu.ec, jdllanos1@espe.edu.ec, ddortiz5@espe.edu.ec.

[1]Universidad de las Fuerzas Armadas ESPE, Sangolqui, Ecuador

Abstract. The three-phase separator has a fundamental role in oil production, due to its multivariable and nonlinear characteristics, controlling it represents a major challenge. In the engineering training academy, having a real industrial process represents a significant cost, however, thanks to technological advances, providing a virtual industrial process is possible. In this research work, a hardware in the loop simulation (HIL) environment is proposed, which includes a three-phase horizontal separator, and its controllers implemented in a physical control device. The proposed system is flexible enough to perform different control algorithms and implement them in any control device. The design methodology of the proposed system includes three sections. In the first section, the nonlinear multivariable mathematical models of the industrial process are obtained. The second section corresponds to the development of the virtual environment, in which the 3D modeling of the industrial process is performed. In the third section, the control strategies are proposed, designed and implemented in a physical control device. To validate the applicability and performance of the variables to be controlled, two control strategies are implemented: a traditional proportional integral derivative (PID) control, and a multivariable model predictive control (MPC). Finally, a comparison of the implemented controllers performance is made for the controlled variables: water level $h(t)_w$, oil level $h(t)_l$ and separator pressure $P(t)$.

Keywords: Advanced control, hardware in the loop, multivariable dynamics, three-phase separator, PID, virtual laboratory.

1 Introduction

In an oil production industrial process, the separator has the function of separating in phases (water, oil, and gas), liquids from gas, and free water from oil [1]. There are different types of separators, vertical, horizontal, and spherical [1] [2], which can be two-phase or three-phase. The two-phase separators have the disadvantage that extra processes are needed to obtain oil, generating problems in the oil separation, which does not happen with the three-phase separators since they optimize the division process and improve the quality of the final product. Within the study of three-phase separators, concepts from hydrodynamics to thermodynamics and the law of energy conservation are involved [3]. From a point of view of process control, three-phase separators are much more efficient than two-phase. However, since it is a multivariable nonlinear system, the variables to be controlled are correlated with each other, this is a control challenge. Usually the control strategies for three-phase separators have been designed considering them as SISO systems when in fact their dynamics is multivariable, and also traditional linear controllers are used, so the performance of the industrial process is not as efficient in the transient state as expected, therefore it is proposed the development of multivariable and advanced control algorithms, in order to optimize the operation and performance of the separator.

There are several traditional controllers used for the three-phase separator, for example, the PID controller, whose purpose is to maintain a stable pressure inside the separator [4] [5]. As is the case of the research work in which a PID controller with Particle Swarm Optimization (PSO) tuning is chosen to improve the system response of the three-phase separator [4], however, the system is still considered as linear and single-variable when in fact the real dynamics of the industrial process is multivariable, which means that its variables are correlated.

Another of the controllers used is the PI controller in order to maintain the required water level, since this type of control works appropriately for first-order processes, as is the case of the water level and SISO systems [6]. Although the proposal shows a minimum error, in the transient state, an overshot is produced, this could be improved with the use of advanced controllers, such as model predictive control (MPC) with feedforward action that is applied to a three-phase separator [7], which is efficient, however, it does not consider the real dynamics of the system because it is modeling based on transfer functions; when in fact the system is highly nonlinear. On the other hand, advanced control techniques such as fuzzy control are used in the regulation of variables in the separator, the results show a higher efficiency and lower sensitivity to the effect of gases [8].

It has been shown that advanced controllers have a better performance than traditional PI or PID controllers in industrial processes with nonlineal and multivariable dynamics, for instance, the control of cycle-combined process [9] [10] or reactor multivariable with control of temperature and level [11]. However, in the industry, these controllers are unusually implemented, this is mainly because the control devices are mostly programmable logic controllers (PLC) that do not have simple tools to implement these strategies. On the other hand, the design of advanced control strategies requires knowledge and experience. Therefore, during the engineering learning in the area of process control, design and experimentation are required, considering real industrial processes, which are very expensive. For this reason, it has been useful and appropriate the fact of creating industrial processes or virtual laboratories, as they allow to have environments similar to real processes such as a two-phase separator [9], a virtual laboratory multivariable for temperature and level control [12], or a pressure process in order to implement advanced controllers [13]. However, these virtual industrial processes do not allow interaction with physical controllers, therefore, the hardware technique has been implemented, so the user can experiment with the virtualized process and with the physical control device.

In this research project, a hardware in the loop environment is designed for a horizontal three-phase separator which can be controlled from any physical control device, for instance, a programmable logic controller (PLC). In addition, traditional and advanced controllers are compared to validate the impact of advanced controllers in nonlinear multivariable industrial processes. The main contributions of this research work are: i) A hardware in the loop design methodology that can be replicated in other industrial processes. ii) A realistic nonlinear multivariable modelling of a three-phase separator. iii) The design of an advanced control strategy for the efficient operation of the three-phase separator. iv) A methodology to implement an advanced MPC control in a programmable logic controller (PLC) for industrial use.

2 Description and Mathematical Modeling of the Three-Phase Separator

In this section, the operation of the three-phase separator is described and analyzed. In addition, the description of the mathematical models is shown.

2.1 Description of the three-phase separator operation

To understand the behavior of the three-phase separator, the piping and instrumentation diagram (P&ID) for the horizontal three-phase separator is used (Fig. 1), where the instrumentation and process equipment are shown.

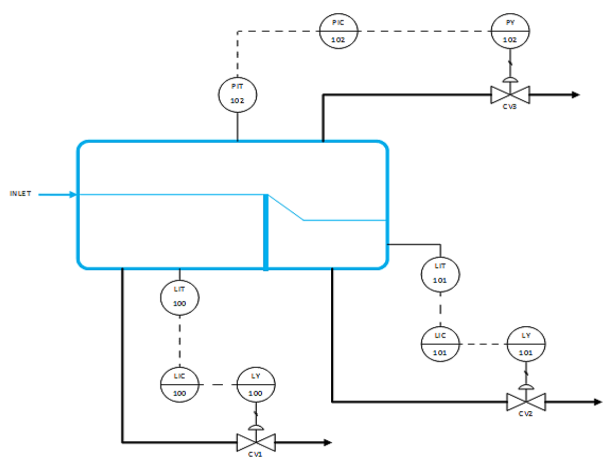

Fig. 1. Three-phase separator P&ID diagram.

In Fig. 1 there is a constant oil inlet (INLET), the separation process includes three control loops: 100, 101 and 102. The control loop 100 is responsible for controlling the water level and also requires a level indicator transmitter (LIT-100), whose signal enters to the level indicator controller (LIC-100), the output is connected to the actuator which is a control valve (CV1), and passes through an electric to a pneumatic signal converter, which in this case is a level relay (LY-100). The control loop 101 is responsible for controlling the oil level and requires a level indicator transmitter (LIT-101), whose signal enters to the level indicator controller (LIC-101), the output is connected to the actuator which is a control valve (CV2), and passes through an electrical to pneumatic signal converter, which in this case is a level relay (LY-101). The control loop 102 is responsible for controlling the pressure inside the separator and requires a pressure transmitter (PT-102), whose signal enters the pressure indicating controller (PIC-102), the output is connected to the actuator which is a control valve (CV3), and passes through an electrical to pneumatic signal converter, which in this case is a pressure relay (PY-102).

The operating principle of the three-phase separator is based on the separation by gravity action, this process starts when the inlet fluid stream, coming directly from the oil producing wells, then, this fluid enters to the separator, where the first stage occurs when the oil flow hits the flow diverter, where the separation of gas and liquids occurs due to the change of momentum and the difference of their densities [1]. It is important that the liquid collection section has the volume and time necessary to separate the oil and emulsion from the water. The layer of oil and emulsion that forms on top of the water is called the oil pad. The weir controls the level of the oil pad, and the interface controller controls the water level through the water outlet valve. Oil and emulsion flow over the weir and into the oil accumulation section, where their level is controlled by a level controller through the oil outlet valve [3] [1].

2.2 Mathematical modeling

The following parameters have been used for mathematical model (see Fig. 2), where: $F(t)_{w\_in}$ is the inlet water flow, $F(t)_{l\_in}$ is the inlet oil flow, $F(t)_{g\_in}$ is inlet gas flow, $F(t)_{w\_out}$ is the outlet water flow, $F(t)_{l\_out}$ is the outlet oil flow, $F(t)_{g\_out}$ is the outlet gas flow, C_w represents the liquid chamber length, C_l represents the oil chamber length, $h(t)_w$ represents the water level, $h(t)_t$ represents the water-oil interface level, $h(t)_l$ represents the oil level and $P(t)$ is the separator pressure.

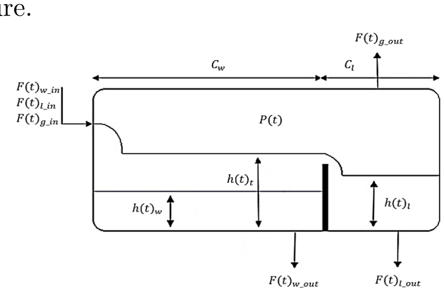

Fig. 2. Three-phase separator schematic diagram.

On the other hand, the differential equations that represent the dynamic model of a three-phase separator are given in terms such as $h(t)_w$, $h(t)_l$, $h(t)_t$ and $P(t)$. The differential equation to determine the water level inside the separator is given by equation 1

$$\frac{dh(t)_w}{dt} = \frac{F(t)_{w\_in} - F(t)_{w\_out}}{2C_w\sqrt{(D - h(t)_w)h(t)_w}} \tag{1}$$

Where D is the separator diameter. For the oil-water interface level model, the dynamics of $h(t)_t$ is defined and described by the differential equation 2:

$$\frac{dh(t)_t}{dt} = \frac{F(t)_{w\_in} + F(t)_{l\_in} - F(t)_{vert} - F(t)_{w\_out}}{2C_w\sqrt{(D - h(t)_t)h(t)_t}} \tag{2}$$

Where $F(t)_{vert}$, is the weir flow. For the oil level model, the dynamics of $h(t)_l$ is defined as shown in the following differential equation 3

$$\frac{dh(t)_l}{dt} = \frac{F(t)_{vert} - F(t)_{l\_out}}{2C_l\sqrt{(D - h(t)_l)h(t)_l}} \tag{3}$$

For pressure mathematical model, it is defined the dynamics of $P(t)$, described by the equation 4:

$$\frac{dP(t)}{dt} = \frac{P(t)[F(t)_{g\_in} + F(t)_{w\_in} + F(t)_{l\_in} - F(t)_{g\_out} - F(t)_{w\_out} - F(t)_{l\_out}]}{V_{3\phi} - V(t)_w - V(t)_l} \tag{4}$$

Where $V_{3\phi}$, is the total volume of the separator, $V(t)_w$, is the volume of the water chamber and $V(t)_l$ is the volume of the oil chamber. The total volume of the three-phase separator is defined by equation 5.

$$V_{3\phi} = \pi\left(\frac{D}{2}\right)^2 C \tag{5}$$

Where C is the total length of the three-phase separator.
For modeling the control of water, oil and gas outlet valves, an unidirectional flow is considered [14] [15]. The water flow outlet $F_{w_out}$is given by equation 6, which represents the valve that allows water level control.

$$F(t)_{w\_out} = 2.4 \times 10^{-4} k_w a(t)_w \sqrt{P(t) - P_a} \tag{6}$$

Where: k_w is the constant of the water level control valve, $a(t)_w$ is the water level control valve opening, $P(t)$ is the separator pressure and P_a is the pressure upstream of the valve.
Similarly, the oil outflow $F(t_{l\_out})$ is represented by equation 7 which represents the valve that allows oil level control.

$$F(t)_{l\_out} = 2.4 \times 10^{-4} k_l a(t)_l \sqrt{\frac{P(t) - P_a}{\frac{\rho_l}{\rho_{H2O\_15^\circ C}}}} \tag{7}$$

Where: k_l is the oil level control valve constant, $a(t)_l$ is the oil level control valve opening, ρ_l is the oil density and ρ_{H20} is the specific density of water at a temperature of $15,5°$C. Finally the gas flow is represented by equation 8.

$$F(t)_{g\_out} = 2.88 \times 10^{-4} k_g a(t)_g \sqrt{\frac{(P(t) - P_a)(P(t) + P_b)}{\frac{\rho(t)_g}{\rho_{H2O\_15°C}}}} \tag{8}$$

Where: k_g is the gas control valve constant, $a(t)_g$ is the gas flow control valve opening, P_b is the upstream pressure and $\rho(t)_g$ is the gas density, which is given by equation 9, where M_g is the molecular weight of the gas, T is the temperature inside the separator and R is the gas constant.

$$\rho(t)_g = \frac{P(t) M_g}{RT} \tag{9}$$

The mathematical model represents the real dynamics of the process and it is necessary for the virtual process as it is part of the hardware in the loop environment.

3 Hardware in the loop system design for three-phase horizontal separator

The HIL technique is a simulation of the required system or process in real time. The real signals of the controller are connected to a test system using a computer in which there is a virtual representation of the process designed in Unity 3D software, which is used to develop 2D and 3D projects, as well as control applications, allowing the creation of solutions in industrial areas, such as training, simulation and immersive experiences in these environments. In this section, the scheme of the HIL environment and the methodology for the implementation of controllers of a three-phase separator are described. (see Fig. 3).

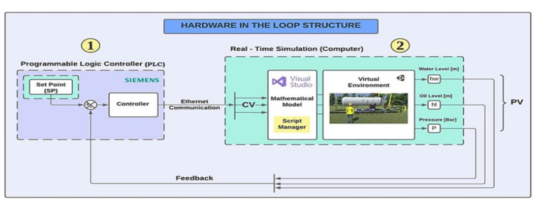

Fig. 3. Hardware in the Loop system for a three-phase separator.

The HIL system shown in Fig. 3 consists of two sections, section 1 corresponds to the Programmable Logic Controller block, where the control algorithm is implemented, it could be PID, MPC and others, using the most appropriate software depending on the type of control device to be used, for instance the TIA portal software for Siemens S7 family, and then load it into the control device, in this case, the PLC S7-1500. It is also important to emphasize that you can use any control device. On the other hand, section 2 refers to the virtualized industrial process; the connection between section 1 and section 2 is via Ethernet communication. From section 1, the control values (CV) are sent to the three-phase separator control valves. The mathematical models obtained in section 2.2 are incorporated into the virtual process by means of Visual Studio scripts in order to interact with the virtual environment developed in the Unity 3D software. The three-phase separator sends the process variables (PV), which are feedbacked to the control device, thus closing the control loop.

On the other hand, the methodology used for the virtualization of the three-phase separator starts from a piping and instrumentation diagram (P&ID) of an industrial process, in this case, the three-phase separator (see Fig. 1), the next step is the computer aided modeling (CAD) using Autocad Plant 3D software, where the measuring instruments involved in the three-phase separator are designed. Then, the previously created .fbx files are imported to the Unity 3D software, placing all necessary elements to make the virtual environment as realistic as possible. The models implemented in Visual Studio work jointly with the process designed in Unity 3D, at the same time this process works with the physical control device, thus, the Hardware in the Loop environment is conformed.

4 Three-phase separator control algorithms design

After the virtual process is designed and validated, it is linked to the controllers, so this section describes the development of the control algorithms.

4.1 Traditional PID control strategy design

The control law is given by the following equation [10]

$$u(t) = K\left[e(t) + \frac{1}{T_i}\int_0^t e(t)\mathrm{d}t + T\frac{de(t)}{dt}\right] \tag{10}$$

Where $u(t)$ is the control value, K is the gain, T_i is the integral time and T_d is the differential time. To design this control, the Lambda tuning method was used, which uses Pole-zero cancellation to achieve the response in a closed-loop control system [16]. Three PID control loops are implemented in the three-phase separator, one for each variable, as shown in the closed loop diagram (Fig. 4).

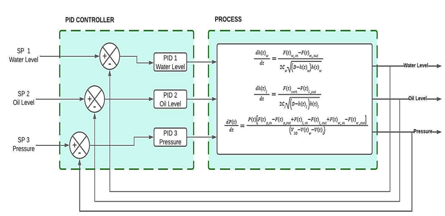

Fig. 4. PID control loop for the horizontal three-phase separator.

4.2 Model Predictive Control MPC design

The advanced control law includes an objective function, constraints, a prediction horizon and a control horizon. The MPC control law includes predictive models that are responsible for predicting the behavior of a future controlled variable over a prediction horizon when applying control actions [17] [18]. The predictive control based on MPC models includes an objective function that minimizes the errors of water level $h(t)_w$, oil level $h(t)_l$ and pressure $P(t)$ in the separator. Also, it minimizes the abrupt control actions to increase the life of the actuators as shown in Fig. 5.

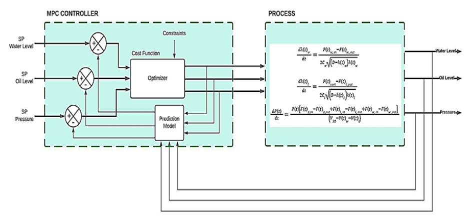

Fig. 5. MPC control loop for the horizontal three-phase separator.

The objective function $J(k)$ defined in equation 11 is responsible for minimizing the errors, where the first term $[\hat{h}_w(k+i \mid k) - h_{wd}(k+i \mid k)]^2$ is the squared error between the desired value and predicted value of level for minimizing water level errors, $\delta_1(k)$ is the weight for the first control objective, The second and third control objectives are similar to the first term for the oil level and pressure, followed by the variations of the control values, which must be minimal to protect the actuator, therefore the objective function includes $[\Delta u_1(k+i-1)]^2$, which is the variation of the quadratic control value for the water level control valve, $\lambda_1(k)$ is the weight for the control objectives, in the same way for $[\Delta u_2(k+i-1)]^2$, $[\Delta u_3(k+i-1)]^2$, and their respective weights $\lambda_2(k)$, $\lambda_3(k)$.

$$\begin{gathered} J(k) = \sum_{i=N_w}^{N_p} \delta_1(k) \left[\hat{h}_w(k+i \mid k) - h_{wd}(k+i \mid k)\right]^2 + .. \\ \delta_2(k) \left[\hat{h}_l(k+i \mid k) - h_{ld}(k+i \mid k)\right]^2 + \delta_2(k) \left[\hat{P}(k+i \mid k) - P_d(k+i \mid k)\right]^2 + \\ \sum_{i=0}^{N_{c-1}} \lambda_1(k) \left[\Delta u_1(k+i-1)\right]^2 + \lambda_2(k) \left[\Delta u_2(k+i-1)\right]^2 + .. \\ \lambda_3(k) \left[\Delta u_3(k+i-1)\right]^2 \end{gathered} \tag{11}$$

Furthermore, $\hat{h}_w(k+i \mid k)$ is the water level predicted output, $\hat{h}_l(k+i \mid k)$ is the oil level predicted output, $\hat{P}(k+i \mid k)$ is the pressure predicted output, $h_{wd}(k+i \mid k)$ is the desired value of water level, $h_{ld}(k+i \mid k)$ is the desired value of oil level, $Pd(k+i \mid k)$ is the desired value of pressure, and finally we have the variations of the control actions $\Delta u_n(k+i-1)$ corresponding to the three control valves.

The optimization problem is subject to inequality constraints, through an upper limit and a lower limit, for water level: $h_{wmin} \leq h(t)_w \leq h_{wmax}$, for oil level: $h_{lmin} \leq h(t)_l \leq h_{lmax}$ and finally for pressure: $P_{min} \leq P \leq P_{max}$. In addition, the constraints of the control value variations are included by setting maximum limits and minimum limits. The restriction of maximum (Δu_{max}) and minimum (Δu_{min}) limits of control value for water level control valve are shown in this way: $\Delta u_{min} \leq \Delta u_1 \leq \Delta u_{max}$, and in the same way for Δu_2, and Δu_3 for the other variables.

The constraints values are: $\Delta u_{min} = 0$, and $\Delta u_{max} = 1$; the water level limits are: $h_{w\_min} = 0[m]$ and $h_{w\_max} = 1.2[m]$, the oil level constraints are given by $h_{l\_min} = 0[m]$ and $h_{l\_max} = 1.2[m]$, and the pressure constraints are given by $P_{min} = 7[bar]$ and $P_{max} = 20[bar]$. On the other hand, the values corresponding to the weights of the process variables are the following: water level weight at $\delta_1 = 1$, oil level weight at $\delta_2 = 1.8$ and pressure weight at $\delta_3 = 0.4$. Finally, control actions weights are: $\lambda_1 = 0.005$, $\lambda_2 = 0.1$ and $\lambda_3 = 0.1$. In addition the other parameters required by the MPC control are control and prediction horizon, these are given by N_p, which have the same samples for water level, oil level and pressure. For prediction horizon a value of $N_w = 15$ was considered and for control horizon a value of $N_c = 3$ every 0.1 seconds was considered.

On the other hand, if it is required to implement this controller (MPC) in a PLC device, this does not have a toolbox or tools that allow us to implement directly. However, in this work, the following methodology used in order to advanced controllers can be implemented in PLC devices that are widely used in the industry: i) Implement the nonlinear process model by using Simulink toolbox ii) Design the MPC controller using the Matlab Simulink toolbox iii) Transform the MPC controller designed in Simulink to a structured code by using the PLC Coder tool in order to generate the control block, which is compatible with TIA portal software.

5 Analysis Results

This section analyzes the control strategies applied to the three-phase separator in a Hardware in the Loop simulation environment.

5.1 Virtual environment of the Hardware in the Loop system

After implementing the HIL strategy, the following results were obtained regarding the virtual environment of three-phase separator and the interaction with the programmable logic controller (PLC).

Fig. 6 shows the three-phase separator virtual environment that is similar to a real process, it has the respective instrumentation components, monitoring and control area and the multivariable nonlinear process dynamics animation.

Fig. 6. Three-phase separator virtual environment.

Regarding the monitoring and control area (Fig.7), there are six screens distributed for the three control variables, which are: water level, oil level and pressure, in which the different parameters of the designed controllers can be observed, such as: set point, process variable, control value, disturbances and trends where the evolution of the PID and MPC controller is shown.

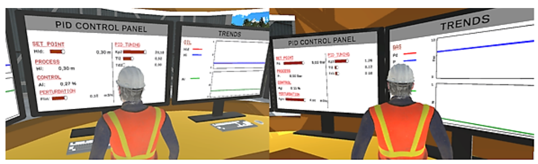

Fig. 7. Monitoring and Control Area.

Fig.8 shows the implementation of the hardware in the loop strategy, thus, the connection of the physical controller (PLC) where the designed controllers are implemented, with the virtualized process through Ethernet communication to validate the control algorithms is presented.

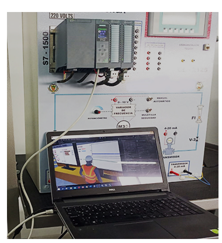

Fig. 8. Connection between the physical controller and the virtualized process.

In order to be able to communicate between the devices, it is necessary to know the Internet Protocol (IP) address of the programmable logic controller (PLC SIEMENS S7-1500) in order to create a link port between the virtualized process and the controller, which allows sending and receiving data to observe the nonlinear and multivariable dynamics of the process when a control action is applied.

5.2 Performance and comparative analysis between the strategies control proposed for the three-phase horizontal separator

The parameters used in the virtualized three-phase separator are: (see section 2.2): $C = 8m$, $D = 3m$, $k_w = 410$, $k_l = 1024$, $k_g = 120$, $P_a = 6bar$, $P_b = 6bar$, $\rho_l = 850kg/L$, $\rho_{H2O} = 999,19kg/L$, $Mg = 0.029kg/mol$, $C_l = 3m$, $C_w = 5m$, $g = 9.81m/s^2$, $R = (0.08314474barL)/(mol°K)$, $T = 303.15°K$, $V = 56,6m^3$. In addition, the initial conditions for the three variables to be controlled are: water level $h(t)_w = 0.1m$, oil level $h(t)_l = 0.1m$, oil-water interface level $h(t)t = 1.5m$, initial condition of pressure $P = 8bares$ and the inlet flows, water flow $F(t)_w = 0.1m^3/s$, oil flow $F(t)_l = 0.1m^3/s$ and finally the gas flow $F(t)_g = 8m^3/s$.

Fig. 9a, shows the analysis of the water level variable, where the water level control in relation to a set point (red), the evolution of PID controller and its respective control value (green) and finally, the evolution of MPC controller and its respective control value (blue) are presented.

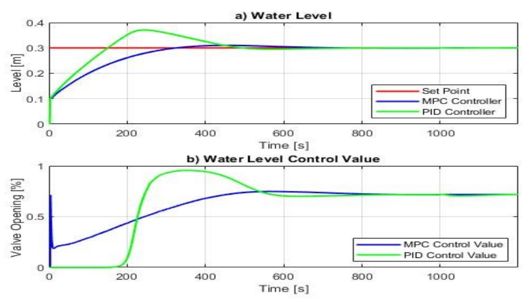

Fig. 9. a) Water level response, PID controller (green), MPC controller (blue). b) PID control value (green), and MPC control value (blue).

For the water level control, there is a constant set point value at 0.3m (Fig. 9.a), where the response for PID controller shows a overshoot at 233s and it presents a slight oscillation until 750s, where the controller reaches its settling time and remains constant from that time, the control error at steady state is within the tolerable range of 1%. On the other hand, the MPC controller does not present an overshoot, and has a settling time of 626s, from this time the errors in the steady state are within the tolerable range of 1%.

Regarding the control values (Fig. 9b), it can be observed that with PID controller, the water control valve starts to act from 200s and tends to open at 90% of its total value and at 800s it maintains a constant opening of 75%. In contrast, with MPC controller, the control valve starts to act from 0s, and tends to open at 75% of its total value and from 800s it maintains a constant opening of 75%, showing a smoother response for the actuators.

Table 1 compares the results of the control parameters such as overshoot, settling time and steady-state error of PID and MPC controllers implemented in the three-phase separator.

Fig. 10a, shows the analysis of three-phase separator oil level variable, where the oil level control in relation to a set point (red), the evolution of the PID controller and its respective control value (green) and finally, the evolution of the MPC controller and its respective control value (blue) are presented.

Table 1. Performance of the control algorithms in relation to the water level variable.

Parameters	PID Controller	MPC Controlle
	Water Level	Water Level
Overshoot [%]	20	0
Settling time [s]	750	625
Steady-state error [m]	2.9×10^{-4}	1.17×10^{-5}

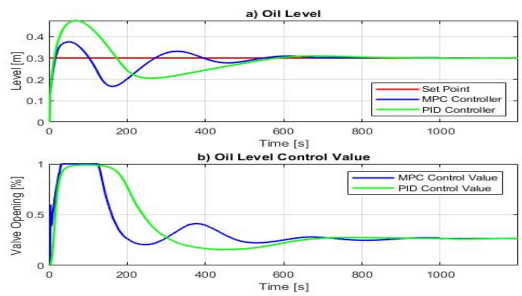

Fig. 10. a) Oil level response, PID controller (green), MPC controller (blue). b) PID control value (green), and MPC control action (blue)

For the oil level control, a constant set point value of 0.3m was taken (Fig. 10a). The PID controller has a overshoot at 66s and it presents an oscillation until 890s, when the controller reaches its settling time, the control error in steady state is within the tolerable range of 1%. On the other hand, the MPC controller presents a overshoot at 47s, oscillating up to 675s. The time where the controller reaches its settling time and from that its steady-state control error is within the range is a tolerable value of 1%.

Regarding the control values (Fig.10b), it can be observed that with the PID controller, the oil level control valve starts to act from 0s. It tends to open to 98% of its total value and at 900s maintains a constant opening of 25%. In contrast, with the MPC controller, the control valve starts to act from 0s, and tends to open completely and from 800s maintains a constant opening of 25%, presenting a smoother response for the actuators.

Table. 2 compares the results of the control parameters such as overshoot, settling time and steady-state error of PID and MPC controllers.

Fig. 11a, shows the analysis of Variable Pressure of the three-phase separator, where the pressure control in relation to a set point (red), the evolution of the PID controller and its respective control value (green) and finally, the evolution of the MPC controller and its respective control avalue (blue) are presented.

Table 2. Performance of control algorithms in relation to the oil level variable

Parameters	PID Controller	MPC Controlle
	Water Level	Water Level
Overshoot [%]	56.6	16.6
Settling time [s]	890	675
Steady-state error [m]	26.6×10^{-4}	6.7×10^{-4}

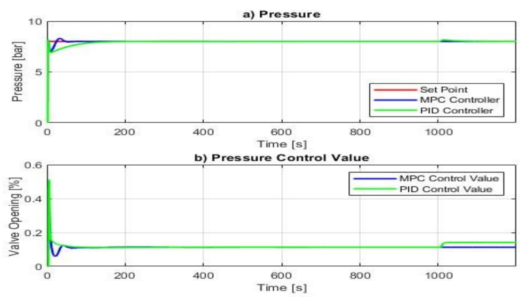

Fig. 11. a) Pressure response, PID controller (green), MPC controller (blue). b) PID control value (green), and MPC control action (blue).

For the separator pressure control, a constant set point value of 8 bar is used (Fig. 11a). Where the PID controller presents a overshoot at 25s, and a settling time of 188s, from this time there is an steady-state control error within the tolerable range of 1%. While the MPC controller presents a maximum overshoot at 30s, and stabilizes at 55s, from that instant, there is a steady state control error within the tolerable range of 1%.

Regarding the control values (Fig.11b), it can be observed that with the PID controller, the pressure control valve starts to act from 0s and tends to open at 55% of its total value and at 900s maintains a constant opening of 17%. In contrast, with the MPC controller, the control valve starts to act from 0s and tends to open 19% and from 800s maintains a constant opening of 12%, showing a smoother response for the actuators.

Table.3 compares the results of the control parameters such as overshoot, settling time and steady state error of PID and MPC controllers. Regarding the controllers robustness analysis against to disturbances, a disturbance by means of a gas flow (Fg(t)) at the inlet has been subjected. Fig. 12 shows an enlargement in the graph of disturbance and what it causes to the controlled variables.

Table 3. Performance of the control algorithms in relation to the pressure variable.

Parameters	PID Controller	MPC Controlle
	Water Level	Water Level
Overshoot [%]	1.25	3.75
Settling time [s]	188	55
Steady-state error [m]	3.1×10^{-3}	5.91×10^{-4}

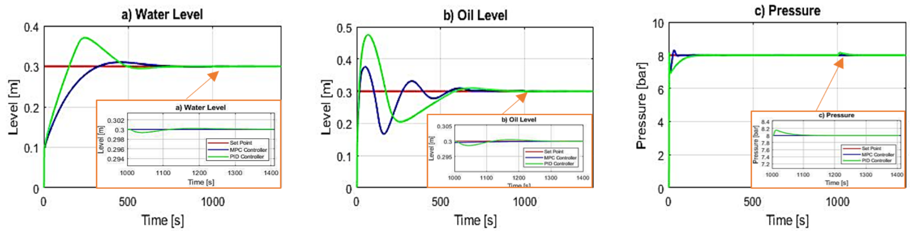

Fig. 12. Process subjected to a disturbance.

A gas flow disturbance has been subjected at 1000s (Fig. 12) where the behavior of PID and MPC controllers can be observed. The MPC controller is not affected and remains at the set point, while the PID controller does show variations when the disturbance occurs. Since the implemented process has multivariable nonlinear models, when a disturbance is made in one of the controlled variables, this disturbance affects the other variables, thus validating the multivariable characteristic of the designed controller.

6 Conclusions

The HIL strategy design methodology allows obtaining an immersive virtual environment of the three-phase separator process, which worked together with the control algorithms designed and implemented in a physical control device, significantly reducing the cost of working with real processes from the academic point of view.

From the nonlinear multivariable mathematical models of the three-phase separator, it was possible to obtain a virtual environment similar to the real industrial process with similar dynamics in the virtualized system. In addition, different controls algorithms can be applied, for instance, lineal controllers or more complex multivariable and nonlinear controllers.

The MPC controller has a better performance as it has an average overshoot of 6.78% among the three variables compared to the PID controller whose average overshoot is 25.95%. It also has a lower settling time than the traditional controller and a minimum steady-state error. Therefore the MPC controller has a better response in nonlinear and multivariable processes.

Regarding the control value, it is observed that with the MPC controller, the control valves have a better response because their control value is smoother compared to the control values of the PID controller, which are a little more abrupt. Thus, by implementing the MPC controller, longer life of the actuators can be achieved.

Regarding the disturbance analysis, it is determined that the MPC controller does not show variations and remains at the set point, which is not the case with the PID controller when the disturbance occurs.

The proposed HIL system is flexible enough and allows not only to connect the PLC control device but any other device as it would only change the programming of the control algorithms depending on the language that handles the controller device. Moreover, it is flexible to implement any control algorithm, including advanced controllers.

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