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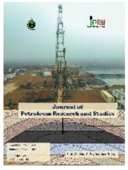

Separator Control of Tuba Degassing Using Model Predictive Control (MPC)

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Abstract

The Proportional-Integral-Derivative (PID) controller is widely used in the Basrah Oil Company (BOC) to control oil equipment, such as the inlet and outlet valves of separators in degassing sites. PID controllers are simple and do not require a full model of the equipment to be controlled. However, they can be difficult to tune, and the trial-and-error method used by BOC engineers can be risky and inefficient. Additionally, PID controllers are single-input and single-output, which limits their flexibility. Otherwise, Model Predictive Control (MPC) is a multi-input and multi-output (MIMO) controller that can be used to control complex systems with multiple interacting variables. MPC also requires a model of the system, but this model can be uncertain. In this paper, we use MPC to control the valves of a three-phase separator in the Tuba degassing station of the Tuba oil field in Basrah city. We use a Matlab program to derive a model of the separators' valves from collected data stored in the Distributed Control System (DCS) network control system. We compare the responses of the PID and MPC and show that the MPC performs better. We also estimate that using an MPC instead of PID controllers could improve annual gas production by 58.5% and oil production by 87.2% (equivalent to 31,800 barrels of oil). This would not only increase oil and gas production but also reduce gas flaring and oil-water mixing. Therefore, MPC is a promising alternative to PID controllers for controlling oil equipment to improve performance, reduce risks, and increase efficiency.

Keywords: PID, Model Predictive Controller (MPC), Three-Phase Separator, Control Valves.

السيطرة على عازلة في محطة عزل غاز الطوبة باستخدام المتحكم التنبئي (MPC)

الخلاصة:

يُستخدم متحكم التناسبية والتكاملية والتفاضلية (PID) على نطاق واسع في شركة نفط البصرة (BOC) للتحكم في المعدات النفطية، مثل صمامات الدخول والخروج لعازلات في محطات عزل الغاز. تتميز متحكمات PID ببساطتها وعدم حاجتها إلى نموذج ديناميكي كامل للمعدة المراد التحكم بها. ومع ذلك، قد يكون ضبط ومعايرة (Tuning) متغيرات المتحكم أمراً معقداً، كما أن طريقة التجربة والخطأ التي يتبعها مهندسو المواقع قد تكون محفوفة بالمخاطر وغير فعالة. إضافةً إلى ذلك، تُعد متحكمات PID أحادية المدخلات والمخرجات (SISO)، مما يحد من مرونتها التشغيلية.

في المقابل، يُعد التحكم التنبؤي بالنموذج (MPC) متحكماً متعدد المدخلات والمخرجات (MIMO)، ويمكن استخدامه للتحكم في الأنظمة المعقدة ذات المتغيرات المتبادلة المتعددة. ورغم أن متحكم MPC يتطلب وجود نموذج رياضي للنظام، إلا أنه قادر على التعامل مع عدم اليقين (Uncertainty) في هذا النموذج.

في هذه الورقة البحثية، نستخدم نظام التحكم التنبؤي بالنموذج (MPC) للتحكم في صمامات عازلة ثلاثي الأطوار في محطة عزل غاز الطوبة الواقعة ضمن حقل الطوبة النفطي في مدينة البصرة. وقد استعننا ببرنامج ماتلاب (Matlab) لاشتقاق نموذج رياضي لصمامات الفاصل اعتماداً على البيانات المجمعة والمخزنة في نظام التحكم الموزع (DCS).

ومن خلال مقارنة استجابة كل من متحكّمي PID وMPC، أظهرت النتائج تفوق نظام MPC. كما نُقَدِّر أن استخدام متحكم MPC بدلاً من متحكمات PID قد يؤدي إلى زيادة الإنتاج السنوي من الغاز بنسبة 58.5%، والنفط بنسبة 87.2% (ما يعادل 31,800 برميل نفط). ولن يقتصر هذا التحسين على زيادة إنتاج النفط والغاز فحسب، بل يسهم أيضاً في تقليل حرق الغاز وتخفيف حدة اختلاط النفط بالماء.

وبناءً على ذلك، يُشكل نظام MPC بديلاً واعداً لمتحكمات PID للتحكم في المعدات النفطية؛ بهدف رفع كفاءة الأداء، وتقليل المخاطر التشغيلية، وتعزيز الإنتاجية.

1. Introduction

The Tuba degassing station is a facility near the Al-Zubair district, located in southern Iraq. It is a station used for separating gas from oil with a capacity of 90,000 barrels per day. The station is fed from wells scattered in the Tuba oil field. The station consists of two banks, Bank A and Bank B, with auxiliary and main pumps connecting to the tanks. Bank A comprises four stages for dry oil separating, with two stages for testing and examining oil components. Bank B consists of three stages for wet oil separation. Currently, the Tuba degassing station relies only on Bank A to separate gas reaching 31.5 bar for the first separator, the second separator is at 9.1 bar, and the third separator separates gas at an equivalent of 5 bar. Lastly, the fourth separator at 2.5 bar. The main control room has modern control systems that are used to control all equipment in the Tuba degassing. The control system consists of the following:

1) Distributed Control System (DCS)/ Programmable Logic Controller (PLC)
2) Emergency Shutdown (ESD) System
3) Supervisory Control and Data Acquisition (SCADA).

In this research, data is collected from the first separator of Bank A to build a mathematical model (ordinary differential equation) for the purpose of implementing and applying Model Predictive Control (MPC) strategies instead of the current Proportional-Integral-Derivative controllers (PID), which is the main contribution of this work. Plenty of important research is presented in the literature that is used to improve the operation of separators. For instance, Yang *et al.* [1] propose a new PI design that uses several new control coefficients that are developed using three different cost-effective tuning methods. The simulation results show that all of these developments can significantly improve the system performance compared with the current control system, but the drawback of a new PI design is the consumption of resources. Bukhari *et al.* [2] propose a visualization tool for oil separator vessels that can be used to support decision-making for control. The tool uses tomographic imaging to provide a real-time image of the distribution of the three phases inside the separator. Sayda and Taylor [3] develop a mathematical model of a three-phase gravity separator and use it to design a model-based controller. The simulation results show that the model-based controller outperforms a conventional PI controller under a variety of operating conditions. [4] developed a dynamic simulator for three-phase gravity separators that is used to evaluate the performance of different level control methods. The simulator is validated with experimental data and is shown to be accurate and reliable by using a PI controller.

This paper illustrates advanced features of using MPC for enhancing productivity, leading to increased exports and reducing emissions resulting from burnt gas and crude oil mixed with gas and water. Recently, many Artificial Intelligence (AI) algorithms have firmly inserted to play an important role in the field of industrial control, such as deep neural networks, fuzzy systems, and adaptive dynamic programming [5]-[7]. Whereas, in this paper, MPC uses the AI algorithms to predict the optimal state and control trajectories of the control separator valves.

2. Method

2.1. Horizontal Three-Phase Separator

The fluids produced from the wells consist of varying quantities of oil, water, natural gas, and sediment. The first step in oil and gas production involves separating these components from each other into their individual components by using separator vessels. Three-phase separators take advantage of gravity to separate the produced well fluid into three phases (gas, oil, and water). These separators are installed and constructed near the wellhead, and they are categorized into horizontal separators and vertical separators. In horizontal three-phase separators, the fluid enters the separator through a Flow Control Valve (FCV), which determines the amount of fluid entering the separator. Upon entry, the fluid immediately collides with an inlet deflector, as shown in Figure (1). This collision provides the sudden impact that initiates the initial separation of liquid and vapor. The liquids gather in the vessel, and due to density differences, the oil and emulsion form a layer above the water. A weir keeps the extracted oil isolated from the released water, while the Level Control Valve (LCV) maintains the oil level [3][4][8]. The pressure of accompanying gas is controlled by the Pressure Control Valve (PCV), which regulates the amount of pressure exiting from the separator and is released through the mist eliminator or extractor. In most cases, the accompanying water from the separation process is permanently discharged through an on-off valve by sending an open signal to a Solenoid Valve (or through a proportional valve, which can also provide complete opening or closing). Meanwhile, the FCV, LCV, and PCV valves are controlled via current/voltage signals coming from the control unit to the Positioner, which determines the percentage of the valve's opening and the valve's closing.

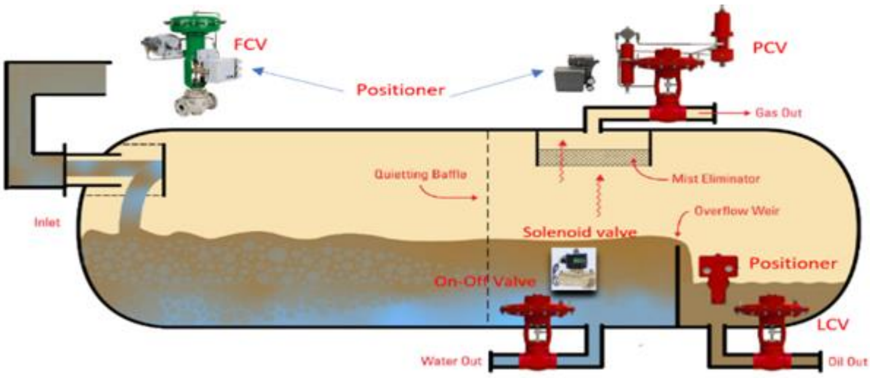

Fig. (1): Horizontal Three-Phase Separator

2.2. PID Controller

A PID controller is a control that is widely used in engineering and automation systems. The main function of a PID controller is to achieve an optimal control of a system based on the minimization of the difference (error) between the desired value and the actual value of the controlled variable (e.g., pressure, level, flow, … etc). The PID controller consists of the sum of three main components (Figure (2)) [9 - 11]:

Proportional Control (P): It is based on calculating the relative error value over time (e(t)) between the desired value (Set-Point - SP or Reference Value) and the actual value (Process Value - PV) of the controlled variable. Integral Control (I): It relies on accumulated error over time to generate an integrated control signal. Derivative Control (D): It is based on calculating the rate of change of the error and generates the derivative control signal.

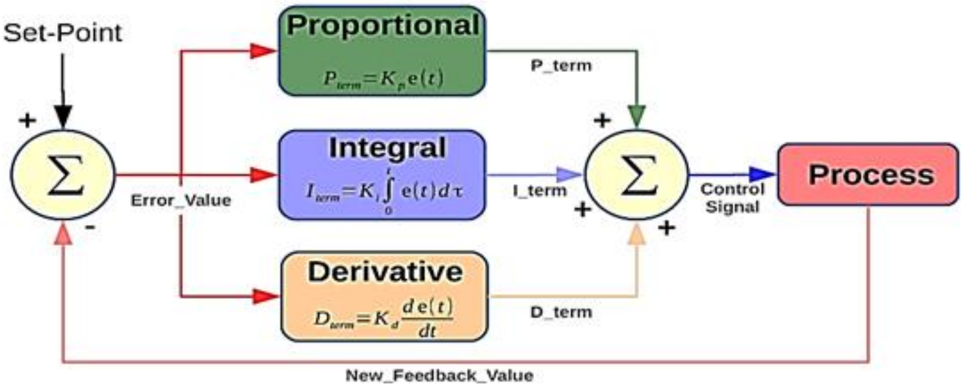

Fig. (2): Block diagram of PID controller [12]

The mathematical model of the three-phase separator valves has been derived using input and output data collected from the DCS of the first separator on bank A.

2.3. MPC

MPC is an advanced control strategy utilized in various industries, particularly in robotics, modern automotive systems, and synchronous processes. MPC predicts the future behaviour of a system based on a mathematical model, then employs techniques and algorithms aimed at minimizing relative error to achieve the desired optimal system behaviour. The algorithm of the MPC controller is achieved by the following conditions (Figure (3)) [12][13]:

1) Mathematical System Model: This model describes the system's dynamics, including its inputs, outputs, and internal states. The model can be derived based on physical laws or obtained through system identification techniques using input and output database.
2) Prediction Horizon: The length of the prediction horizon determines how far into the future the controller considers when making control decisions.
3) Cost Function: The cost function is used to assess the system's performance over the prediction horizon. It evaluates the reference trajectories, control objectives, and system constraints. MPC aims to achieve objectives such as minimizing tracking errors, energy consumption, or control effort.
4) Optimization Techniques: The primary task of optimization algorithms is to minimize the cost function and meeting the system constraints.
5) Control Action: The optimization algorithm is executed for the first step by calculating the minimum value of the cost function. This process is repeated for the next steps using updated information about the system's state until reaching the predefined control horizon value.

MPC can handle time-varying systems with or without constraints and uncertainties. MPC can also handle multi-variable systems with interactions between different variables (multiple-input and multiple-output, MIMO).

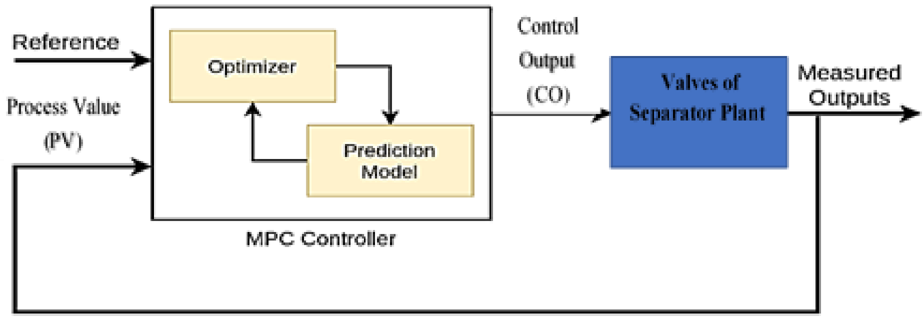

Fig. (3): Block diagram of MPC to control on Separator Valves

3. Results and Simulation

In this paper, the first separator on bank A is taken as a model for testing MPC. This is achieved by collecting input data for the valves for first separator as valve opening ratio ranging from 0% to 100%, whereas 0% indicates a fully closed valve and 100% indicates a fully open valve. This paper is studied how the controller impacts on the separator's operation. For instance, the PCV affects the gas pressure released from the first-stage unit, measured in bar, while the LCV valve controls the extracted oil level from the separator, measured in centimeter. On the other hand, the FCV valve influences the flow rate of incoming crude oil from the wells, measured in [kg.mole /hour], and is inhabited in the first-stage separator for few BOC's sites. Figure (4) illustrates a realistic depiction of the control of SCADA system, of the first-stage separator in Tuba degassing. Data was collected in Excel format and then imported into Matlab for processing and visualization. Approximately 10,000 seconds worth of data (2.7 hours) was collected. It is noteworthy that the separator's specifications include a design pressure of 40 bar and a volume of 92 cubic meters.

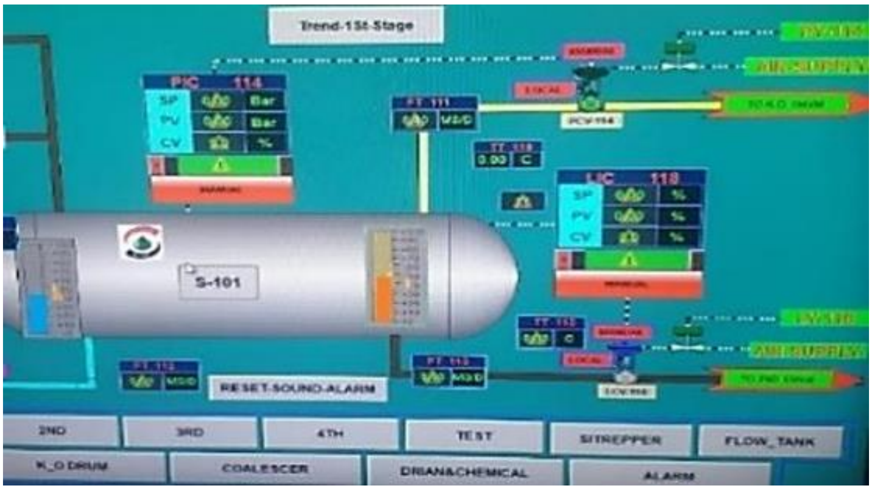

Fig. (4): SCADA System in Operator Workstation PC of the first separator for Tuba degassing.

Figure (5) illustrates the operation of the inlet valves (FCV) and the outlet valves (PCV and LCV). That display the Set-Point values (SP) that the operator adjusts through the Operator Workstation PC containing the control and display program and the actual values (PV) are received from sensors for oil level, gas pressure, and liquid flow entering the separator. Figure (5) demonstrates how the valves interact and influence each other during operation. Changes in the SP value of a specific valve is led to effects on the other valves to compensate for the change. These valves are individually controlled using PID controllers. Each valve has its own dedicated PID controller, independent of the other valve's controller. This signal is the output from the controller, as clarified in Figure (3), and is sent to the dedicated Positioner for each valve.

3.1. Modelling the Control Valves of the Separator

The mathematical model for the control valves is deduced by using data measured for both the control output (CO) and the PV of the valves. There are various linear and nonlinear models available to represent the mathematical model [9], including: Transfer Function (TF), polynomial, state-space, and Hammerstein-Wiener models.

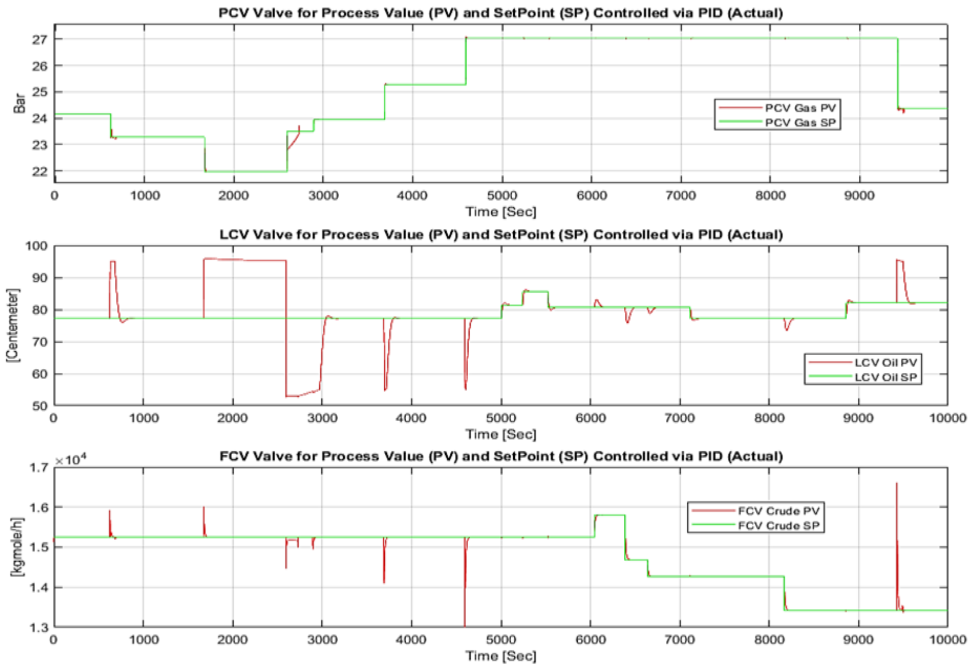

Fig. (5): SP and PV for PCV, LCV, and FCV controlled by a PID controller

Since TF has linear behavior does not consume a lot of PC resources and TF is existed in PLC/DCS platform, TF is chosen as the model. The Levenberg-Marquradt algorithm [14] is employed to calculate the TFs' confections with 1200 iterations to execute the algorithm for fitting, or the algorithm terminates if the likelihood of optimization improvement becomes less than 10^{-6}. In this paper, a limitation bounded time of data (included sudden changes in the signal) is used to build models for all valves (PCV, LCV and FCV).

3.1.1. PCV Valve

A portion of input and output data was extracted, which is taken from the time interval 4692 to 4630 second (Figure (6)), starting from 1 instead of 4692 for ease of illustrations and discussions. The derivative TF of the PCV valve is as in Equation (1), consisting of one zero and two poles, forming a stable transfer function, as shown in Figure (7), because all poles are oriented towards the left side, or more precisely, the S-plane root locus does not extend beyond the right side of the diagram [15].

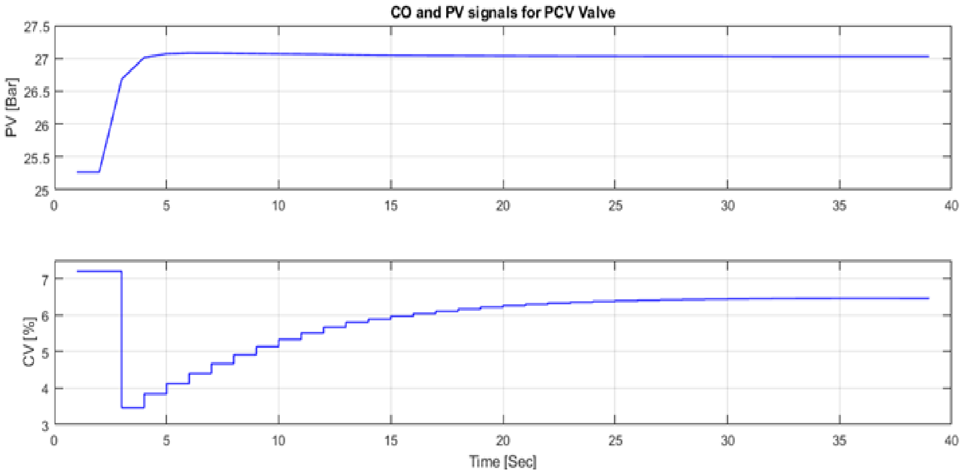

Fig. (6): Measured pressure over time for PCV, including the valve opening ratio (CO) and PV

$$PCV_{TF} = \frac{1.002\ s + 0.1681}{s^3 + 3.742\ s^2 + 0.8207\ s\ +\ 0.04027} \quad \ldots (1)$$

Figure (8) illustrates the alignment between the actual measured data from control devices and the mathematical model data concerning the Mean Squared Error (MSE), which amounts to 6.9×10^{-6}, corresponding to a 98.57% match.

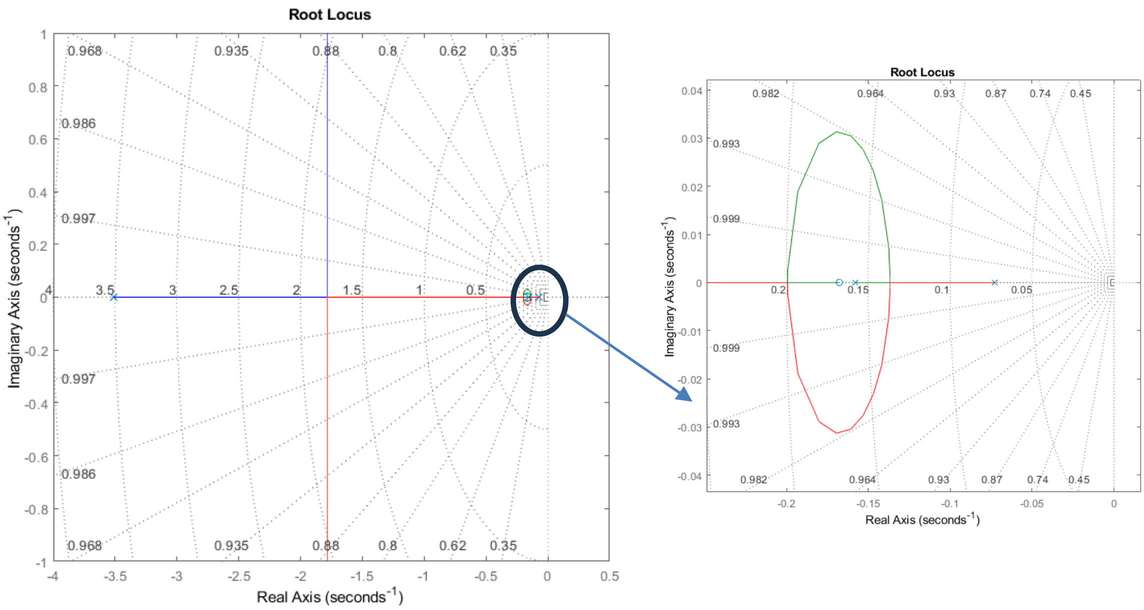

Fig. (7): Root Locus plot of the TF of the PCV.

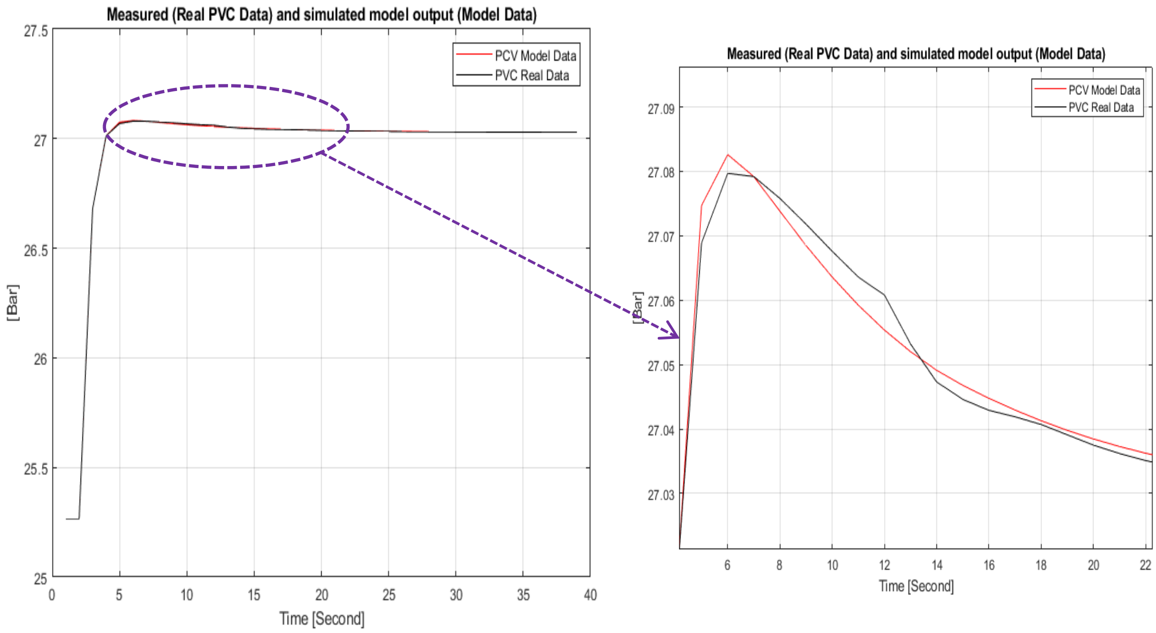

Fig. (8): A zoomed-in section of the derivative data curve alongside the real data over time for the PCV.

The input and output data for the valve are collected over the period from 8850 to 9050 seconds due to the variations in the desired valve values, as depicted in Figure (9a). In this context, the derivative transfer function for the LCV valve is as given in Equation 2:

$$LCV_{TF} = \frac{-96.74\, s + 0.1269}{s^3 + 197.6\, s^2 + 0.0001481\, \mathrm{s} \; + \; 0.02925} \quad \text{... (2)}$$

However, it's a non-stable function as illustrated in Figure (9b), which holds for various periods of change in the data for the separator's level valve. Despite the MSE not exceeding 0.0002228 with a matching rate of no less than 98.88%, the transfer function's instability remains. To address this, two solutions is considered. The first one is to add poles and zeros as a compensatory function (lead/lag compensator) to shift the root locus plot towards the stable region (essentially adding a PD compensator to minimize the instability region, not converting the function to fully stabilizing). The second solution is to increase the number of zeros in the valve's transfer function to eliminate the poles causing instability. In this study, the second approach is taken. More zeros are added, and the coefficients for the new transfer function were recalculated to stabilize TF (Equation (3)). However, this function is less accurate (MSE=0.0368) with a matching rate of 85.78%, which is an acceptable ratio for use in predictive controllers due to its stability, and gives system states of the TF approximate to reality with better tuning over time.

$$LCV_{TF} = \frac{2.848\, s^3 + 0.9836\, s^2 + 0.1648\, s + 0.005014}{s^3 + 0.362\, s^2 + 0.04132\, s + 0.001159} \quad \ldots (3)$$

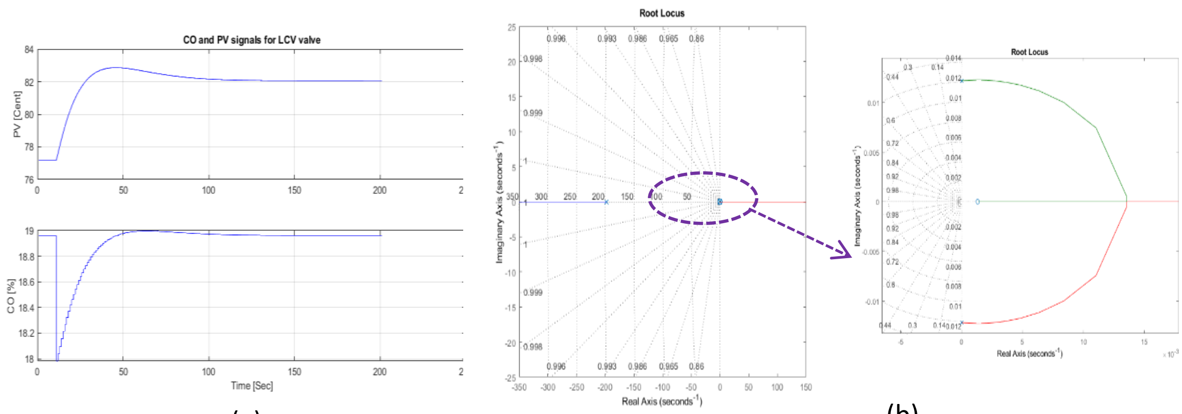

Fig. (9): (a) Measurement data in centimeters over time for the LCV valve, including CO and PV. (b) Root Locus plot of the TF associated with the LCV

Figure (10) illustrates the alignment between actual measured data from control devices and the modeled data for both stable transfer functions (3 zeros with 3 poles) and unstable transfer functions (3 poles and 1 zero). In this research, the unstable function was taken into account along with the predictive control MPC. That is one of the advantages of predictive control is compensating for the instability of the transfer function. However, it's preferable for the system entering the MPC to be stable.

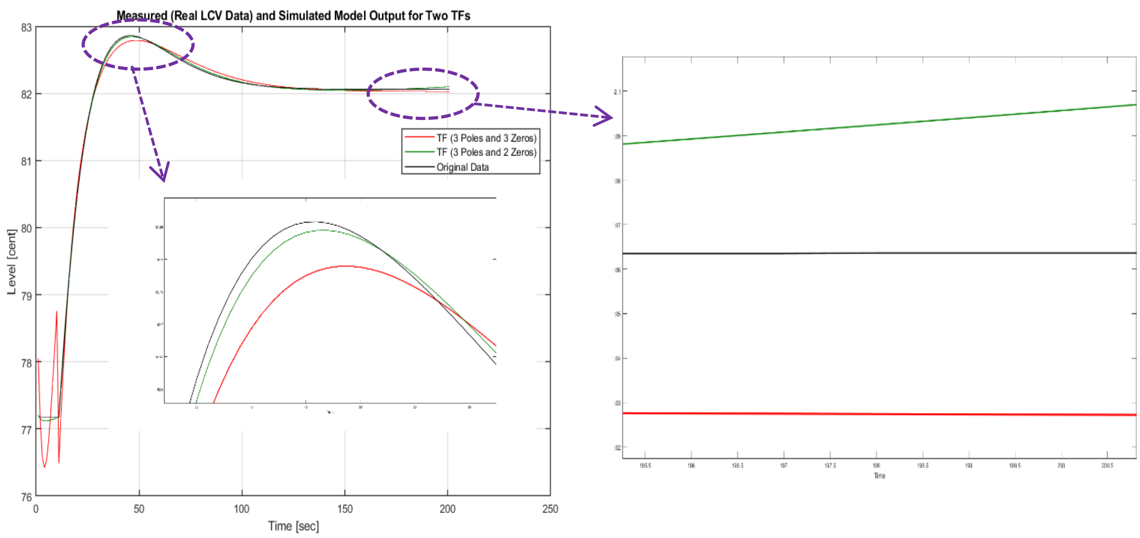

Fig. (10): Plot of derivative data along with actual data over time for LCV valve, with a zoom-in portion of the plot.

3.1.2. FCV Valve

The input and output data for the FCV valve were collected over the period from 8100 to 8260 seconds due to significant variations in the desired valve values, as shown in Figure (11a). The representation begins from 1 as of 8100 for ease of discussion and presentation. The derivative transfer function for the FCV valve is given by Equation (4):

$$FCV_{TF} = \frac{1710\,s + 100.7}{s^3 + 3.45\,s^2 + 9.26\,\mathrm{s} + 0.5337} \qquad \dots (4)$$

The derivative TF for the LCV valve, as given by Equation 4, consists of one zero and three poles. This equation forms a stable TF, as depicted in Figure (11b), since all poles are in the left half-plane.

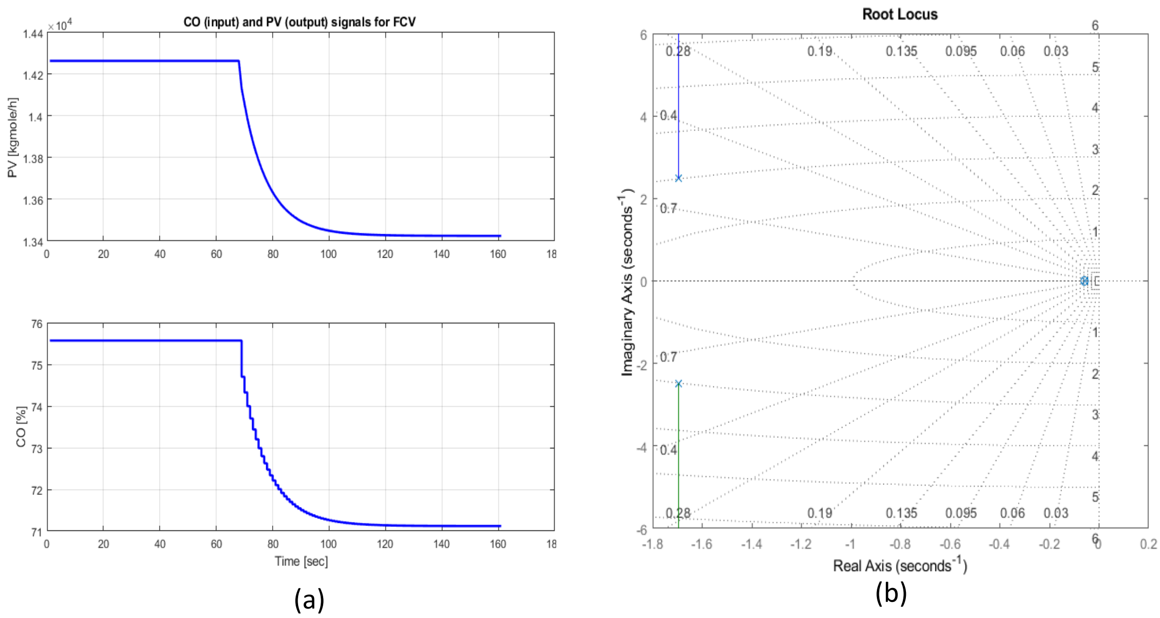

Fig. (11): (a) Measured data in kg.mole/hour for FCV, including CO and PV.
(b): Root Locus plot of the TF associated with the FCV.

Figure (12) illustrates the actual measured single from control devices (flow sensor) and the modeled signal after control via the valve opening ratio signal (Fig. (11a)), with a matching percentage of 96.86%.

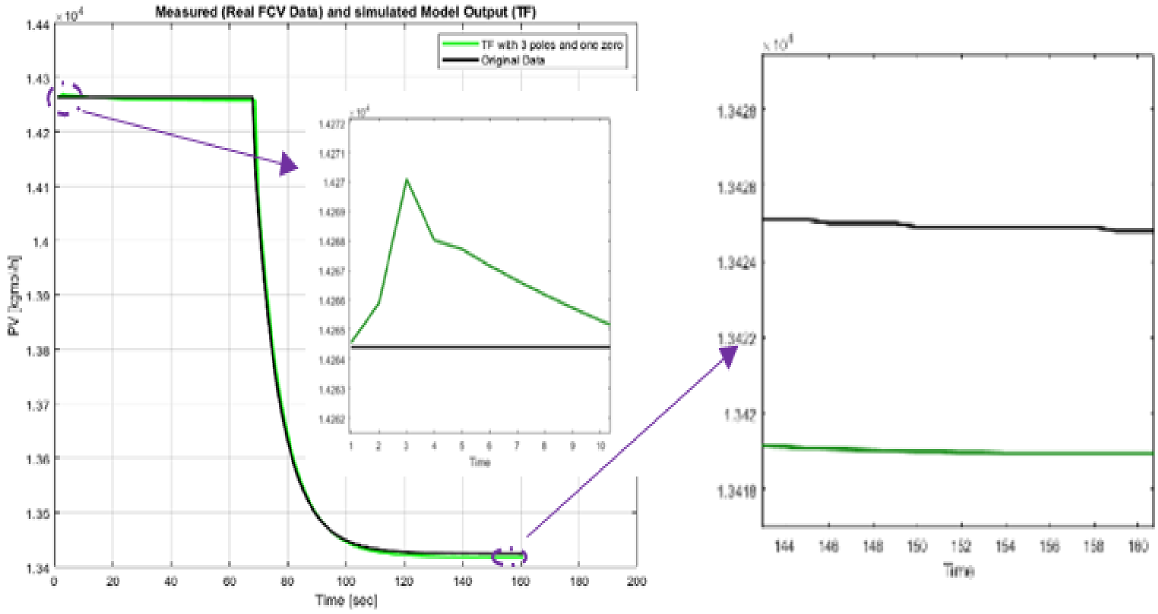

Fig. (12): Derivative data along with actual data over time for FCV, with a zoom-in portion.

3.1.3. Utilizing Predictive MPC Controller for Separator Valve Control

Predictive controllers are employed to control the first separator valves after deriving their mathematical models (Where in practical applications, these valves are typically controlled using PID controllers). This is achieved by constructing a simulation using MATLAB/Simulink software, as illustrated in Figure (13). Fifty prediction steps were taken for the Prediction Horizon with 0.01 of a sample time, along with twelve control steps for the Control Horizon. To demonstrate the robustness and efficacy of the MPC controller, diverse signals were introduced (sawtooth signal, pulses, and sine wave). This is depicted in Figure (14). In order to compare the MPC controller with the currently used PID controller in the separator systems, both controllers are compared for the same input type, which was previously taken, and the MSE is calculated for each valve.

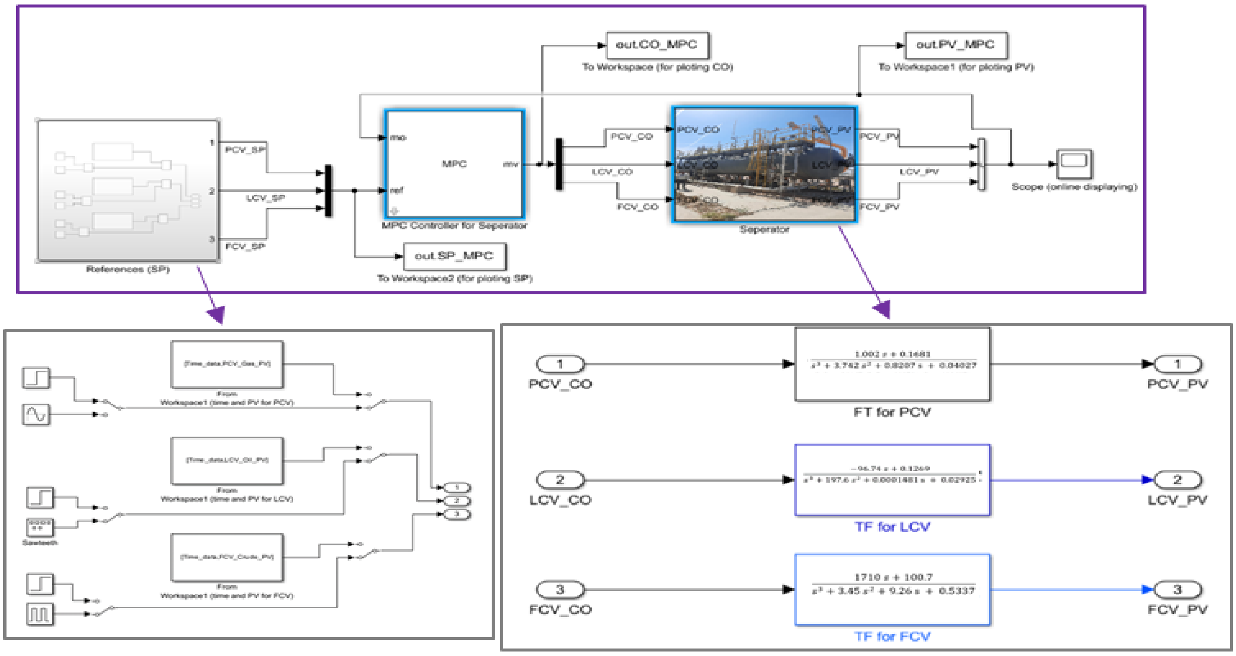

Fig. (13): MATLAB simulation for the mathematical model of the valves with MPC and the required input signals.

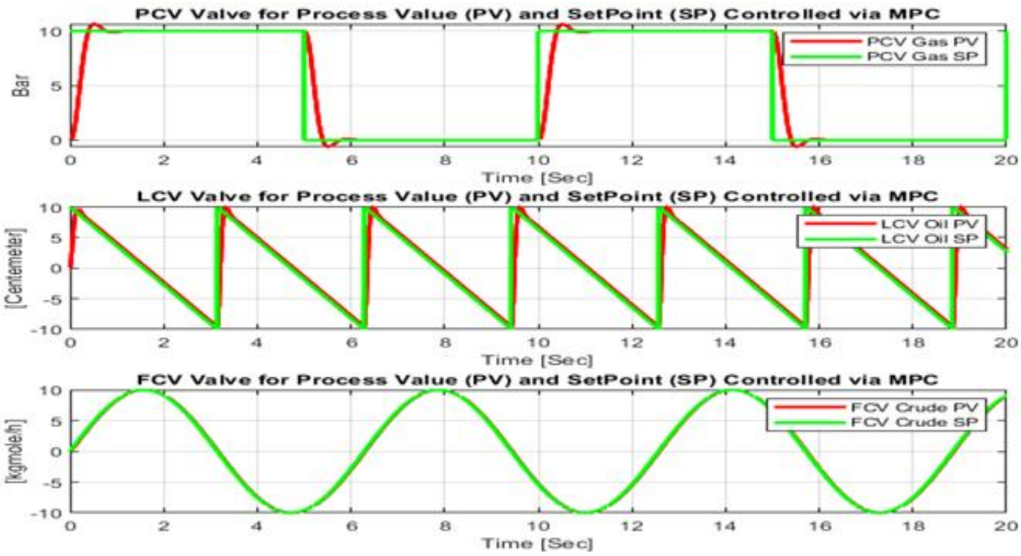

Fig. (14): Input a Pulse Wave to PCV, a Sawtooth Wave to LCV, and a Sine Wave to FCV, all with signal magnitude value of 10.

To conduct a fair comparison, only the valve transition time and the valve response during this time are considered for both the current PID controller and the designed MPC controller. Figure (15) illustrates the input to the PCV valve from second 1000 to second 5000, showing intentional variations introduced by operators. Figure (15) demonstrates the strong capability of the MPC controller compared to the PID controller, and the MSE is calculated for both controllers. The

MSE for the PID controller is 0.0089, while for the MPC controller, it is 9.2448×10^{-5}, indicating an improvement percentage of 98.96% according to equation number (5).

$$\text{Percentage Decreasing} = \frac{\text{Final Value} - \text{Starting Value}}{|\text{Starting Value}|} \times 100 \quad \ldots.(5)$$

Figure (16) illustrates the input of the LCV valve from second 5000 to second 6000, showcasing intentional changes made by the operators. Additionally, Figure (16) demonstrates the comparative capabilities of the MPC controller and the PID controller. The MSE was calculated for both controllers, revealing that the MSE for the PID controller is 0.2887, while for the MPC controller it is 8.177×10^{-4}. This indicates an improvement rate of 99.7168% according to Equation (5).

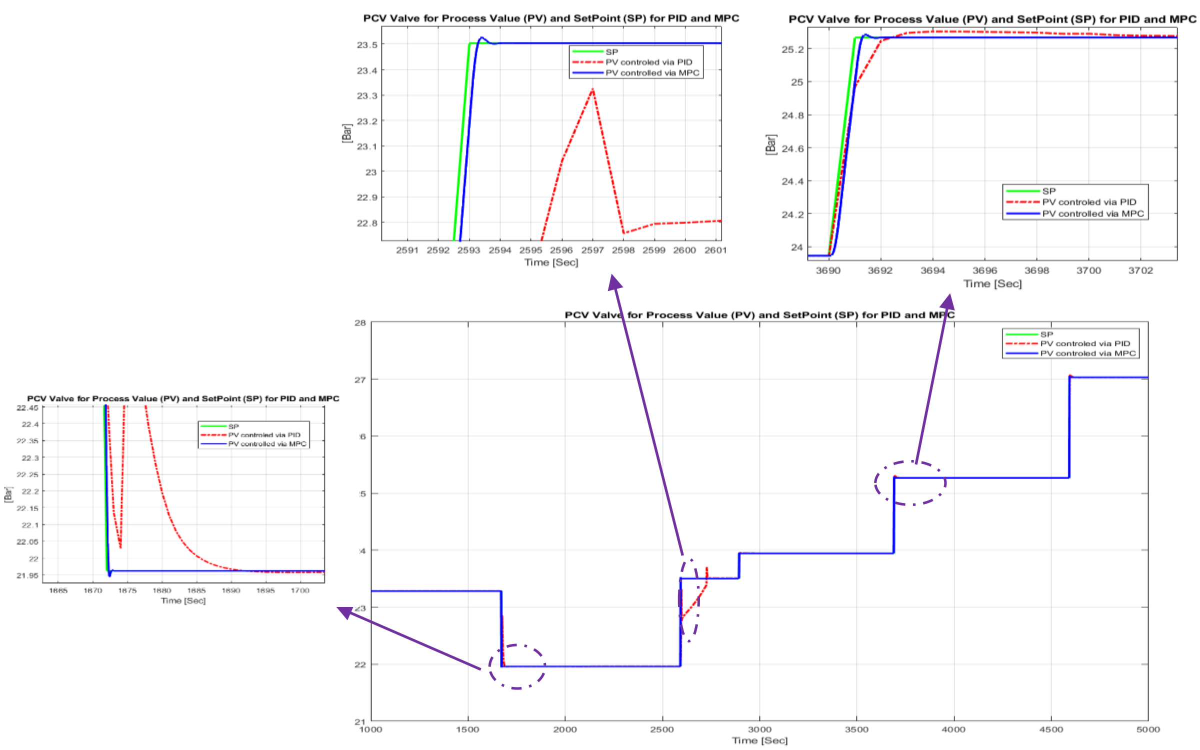

Fig. (15): Input of SP to the PCV from second 1000 to 5000, to comparing PID controller with MPC.

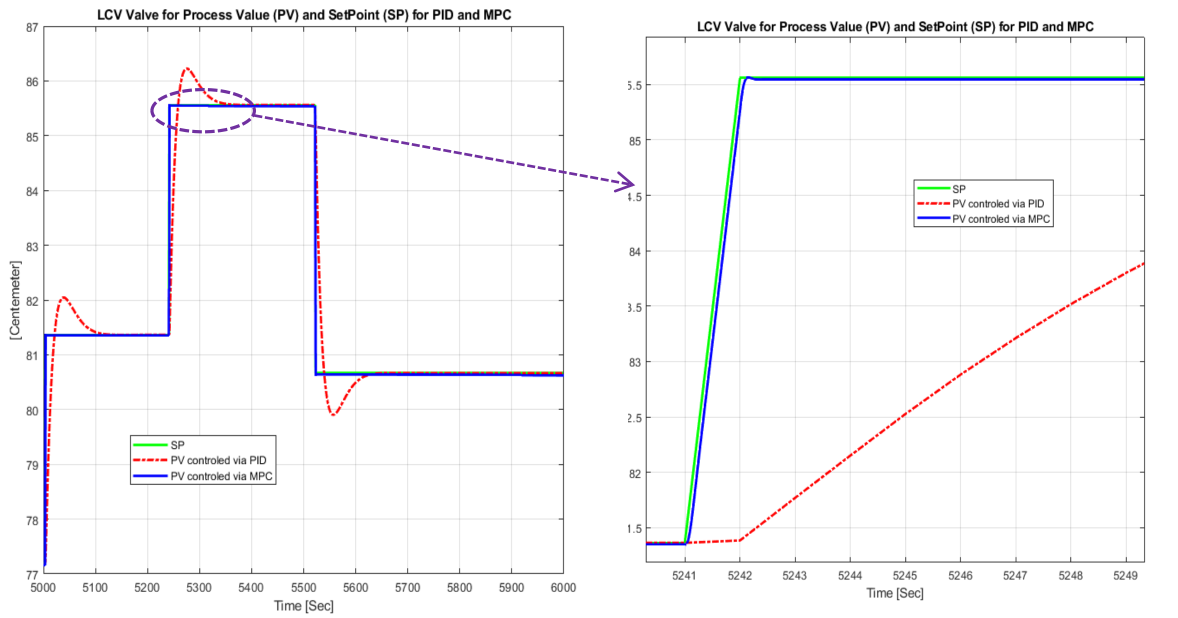

Fig. (16): Input of actual SP to the LCV from second 5000 to 6000, to comparing PID controller with MPC.

Figure (17) illustrates the input to the FCV valve from second 6000 to second 7000, showing intentional variations introduced by operators. Also demonstrates the capability of the MPC controller compared to the PID controller, and the MSE is calculated for both controllers. The MSE for the PID controller is 5893.9065, while for the MPC controller, it is 0.6059.

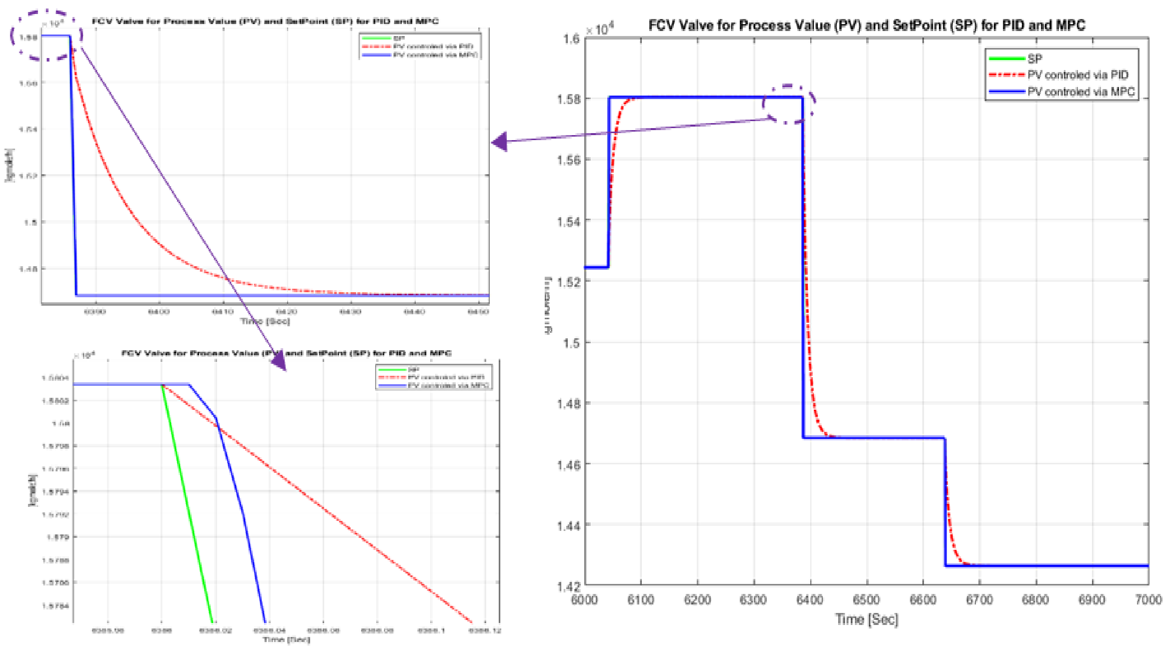

Fig. (17): Input of actual SP to the FCV valve from second 6000 to 7000, to comparing the PID controller with the MPC controller

3.2. The economic feasibility and implementation requirements.

The fundamental principle for determining the economic feasibility of this project revolves around the accuracy, speed, and stability of the valve's response to the operator's commands. In other words, if the operator intends to set the gas pressure for the separator at a specific value - the SP - the speed, accuracy, and stability of the valve's (PCV) response to this request is evaluated by making the actual gas value (PV) approach the desired value (SP), while maintaining the actual value (PV) steady, regardless of any external factors' influence (sensor signal noise, control devices, friction, fluid flow, etc.). This comparison is calculated through the absolute difference between the desired value and the actual value, known as the absolute error. An increase in the absolute error leads to wastage of gas or associated isolating oil, potentially leading to increased gas combustion and a higher ratio of oil mixed with water discharged from the separator. In essence, an accumulation of higher absolute errors results in increased environmental and financial losses. Therefore, this study calculates the economic feasibility by comparing the absolute error of each controller (PID and MPC) along with the response of all separator valves (PCV, LCV, FCV) over a duration of 1000 seconds. The absolute error for both PID and MPC controllers across all separator valves clearly demonstrates the performance advantage of MPC. The absolute error values over the 1000 seconds (16.667 hours) are tabulated in Table (1).

Table (1): Cumulative absolute error for (PCV, LCV, FCV) using both controllers over 16.667 hours.

	PCV [Bar]	LCV [m^3]	FCV [kg.mole/hour]
PID	**461.4150**	**43483.5244**	**860691.3361**
MPC	**191.6695**	**5565.1052**	**2061.4876**
Improvement	**%58.4606**	**%87.2019**	

Table (2) illustrates the cumulative absolute error percentage over the course of a year, taking into consideration the conversion of oil level from centimetres to cubic meters (volume).

Table (2): Loss values for (PCV, LCV, FCV), both controllers over one year, along with the improvement ratios for gas pressure and separated oil volume

	PCV[Bar]	LCV[Centimeter]	FCV [kg.mole/hour]
PID	0.8779	179.8534	39.2200
MPC	0.3647	23.0178	16375.8002

This is achieved by approximate calculation from a semi-circular shape (side of the separator weir and the other sides along with the base) to a rectangular shape, with a length of 5 meters (weir location) and a height representing the cumulative error percentage, not exceeding 2 meters (the difference between the highest level of the weir, which is 2.205 meters - High-high level, and the lowest level, which is 0.27 meters - Low-low level). The width is 2.3 meters (width of the separator). In order to calculate the cumulative absolute error percentage for a year, you need to extract the value for one hour (values from Table (1) divided by 16.667) and then multiply it by the number of hours in a year. The improvement ratio for the separated oil quantity amounts to 37,918.4 m^3 (the production difference between both controllers as shown in Table (2)), equivalent to 31,800 barrels annually (barrel of crude oil - bbl). Similarly, for the accompanying gas with an 8-inch pipe (the gas exiting the separator), with a pressure difference of 269.7 bar (production difference between the controllers), annually. For the practical implementation of this project, control systems for the separators must be modern (DCS as well as PLC). This research opens horizons for realistic implementation of deep and reinforcement learning [16][17] in the oil and gas industrial fields.

4. Conclusions

PID controllers are widely used in oil separator valves due to their simplicity and familiarity. However, PID controllers are limited in their ability to adapt to changes in the valve's equation or external conditions. This research utilizes an MPC and mathematical models derived from data collected from separator valves in the Tuba degassing process for oil separator valves. The MPC's performance was evaluated using Matlab/Simulink software and compared to the PID controller, revealing a significant advantage of 87.2% for annual oil separation and 58.5% for annual gas separation. The MPC controller is also compatible with most existing control systems, making it a feasible upgrade for many companies. The improved performance of the MPC controller can lead to reduced burnt gas quantities; minimized oil mixed with gas during combustion, and decreased oil content mixed with water coming out of the separator.

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