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A Comparative study between MPC and PI controller to control vacuum distillation unit for producing LVGO, MVGO, and HVGO

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Abstract. This study describes the selection of controllers in the vacuum distillation unit (VDU) between a model predictive control (MPC) and a proportional-integral (PI) controller by comparing the integral square error (ISE) values. Design of VDU in this simulation is based on modified Metso Automation Inc. scheme. Controlled variables in this study are feed flow rate, feed temperature, top stage pressure, condenser level, bottom stage temperature, LVGO (light vacuum gas oil), MVGO (medium vacuum gas oil), and HVGO (heavy vacuum gas oil) flow rate. As a result, control performance improvements occurred as using MPC compared to PI controllers, when testing a set-point change, of feed flow rate control, feed temperature, top-stage pressure, bottom-stage temperature and flow rate of LVGO, MVGO, and HVGO, respectively, 36%, 6%, 92%, 53%, 90%, 96% and 88%. Only on condenser level control PI performs much better than the MPC. So PI controller is used for level condenser control. While for the test of disturbance rejection, by changing feed flow rate by 10%, there is improvement of control performance using MPC compared to PI controller on feed temperature control, top-stage pressure, bottom-stage temperature and flow rate LVGO, MVGO and HVGO 0.3%, 0.7%, 14%, 2.7%, 10.6% and 4.3%, respectively.

1. Introduction

Vacuum Distillation Unit (VDU) is a secondary process unit in refinery. This unit is very important for fractionating atmospheric residue/long residue, bottom product of Crude Distillation Unit (CDU), which has boiling point more than 350°C [1]. Generally, VDU operates in 25-65 mmHg. As the pressure of the columns is reduced, the component's boiling point will be decreased as well. So that, it doesn't need too high temperature to fractionate the atmospheric residue into lighter fraction.

The products of VDU are Light Vacuum Gas Oil (LVGO), Medium Vacuum Gas Oil (MVGO), and Heavy Vacuum Gas Oil (HVGO). These products can be processed further into gasoline and diesel product blending.

VDU has many variables that have a very prominent role to the stability of operation and product quality. Column temperature can stabilize the composition profile within the column. In the other words, temperature column gives indirect composition control [2]. As we know, column pressure affects boiling point of the component. Pressure fluctuations make control more difficult and reduce

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unit performance. In addition, pressure variations alter relative volatility and affects fractionation performance [3]. Feed flow rate and temperature will affect the vapor-liquid contact and influence the product's composition [4]. In order to maintain the stability of operation and reject any disturbances, proper controllers are needed.

There are some types of controller that are used in chemical industry, Proportional-Integral (PI) and Model Predictive Control (MPC) are two of them. PI is a controller that works by comparing the error value with the desired response and integrating it so that the difference becomes zero [5].

MPC predicts the future values of the process output using dynamic model and available measurement. The controller outputs are calculated so as to minimize the difference between the predicted process response and desired response [6]. MPC can improve control performance and stabilize unit operation by using optimization [7]. Furthermore, operational costs can be minimized due to more economic process operation [7].

This study focuses on VDU simulation and control to produce LVGO, MVGO, and HVGO. Controller that implemented are MPC and PI. In this study, will be compared the results of MPC and PI controller by calculating the ISE (integral square error) of MPC and PI, respectively, against set-point changes and disturbance. Disturbance that is conducted in this study is feed flow rate increasing by 10%.

2. Methodology

2.1. Simulation Environment

In this simulation, the feed that is going to be fractionated is atmospheric residue which flow rate is 118,021 bpd. The configuration of VDU simulation can be seen in figure 1. In this configuration, feed and products (side streams such as LVGO, MVGO, and HVGO) flow rate are adjusted by flow rate controller. Feed temperature is controlled by controlling heater duty Top stage pressure is controlled by manipulating vapor flow rate. The condenser level is controlled by controlling overhead condensate flow rate. The bottom stage temperature is controlled by manipulating reboiler duty.

In the installation of the controller, the considerations are the control objective, the desired set-point (SP) value and the independent variable that will affect the SP when the dynamic behavior of the vacuum distillation unit system is performed. There are two types of controller which are used in this study, MPC and PI. Furthermore, these two types of controllers will be compared to see which controller provide the best performance.

2.2. FOPDT (first-order plus dead time) Model

MPC and PI are types of controllers which performance is depend on the model that is used. In this study, model which is used is empirical model FOPDT (first-order plus dead time). FOPDT model can be obtained by doing model testing in each controller to get process reaction curve (PRC). The PRC can be seen in figure 2

The empirical model of FOPDT is shown by equation (1)

$$G_p(s) = \frac{K_p e^{-\theta s}}{\tau s + 1} \quad (1)$$

Where, K_p is process gain describing how far PV moves; τ , time constant that describe how fast the PV respond; θ is dead time describing how much delay occurs before the PV first begins to move.

2.3. Controller Tuning

Based on model that is obtained from the PRC, controller tuning is done to get optimal control. For PI controller, tuning parameter is conducted by calculating the parameter using Ziegler-Nichols method to get proportional gain (K_c) and integral time (T_i) [8]. Where, the following is Ziegler-Nichols

equation to calculate K_c and T_i for open loop [eq. (2) and (3)] and closed loop control [eq. (4) and (5)]:

$$K_c = \frac{0.9}{K_p} \left(\frac{\theta}{\tau} \right)^{-1} \quad (2)$$

$$T_i = 3.33\theta \quad (3)$$

$$K_c = \frac{Kcu}{2.2} \quad (4)$$

$$T_i = \frac{Tu}{1.2} \quad (5)$$

In the MPC controller the FOPDT model can be used directly. There are two ways how MPC uses this model. MPC uses this model to predict effect of past control moves on future outputs, P (prediction horizon) and using identical model to compute M (control horizon) moves [9].

2.4. Control Performance

The performance of the controller is tested by doing set-point tracking and disturbance rejection. The disturbances are the elevation of feed flow rate by 10%. Next is comparing the error value, ISE (integral square error), of the MPC and PI controllers to the set-point (SP) changes and also the disturbance to see which controller has more optimum performance. The smaller ISE values the better the performance of the controller. The equation of ISE can be seen as follow:

$$ISE = \int_0^{\infty} (e)^2 dt \quad (6)$$

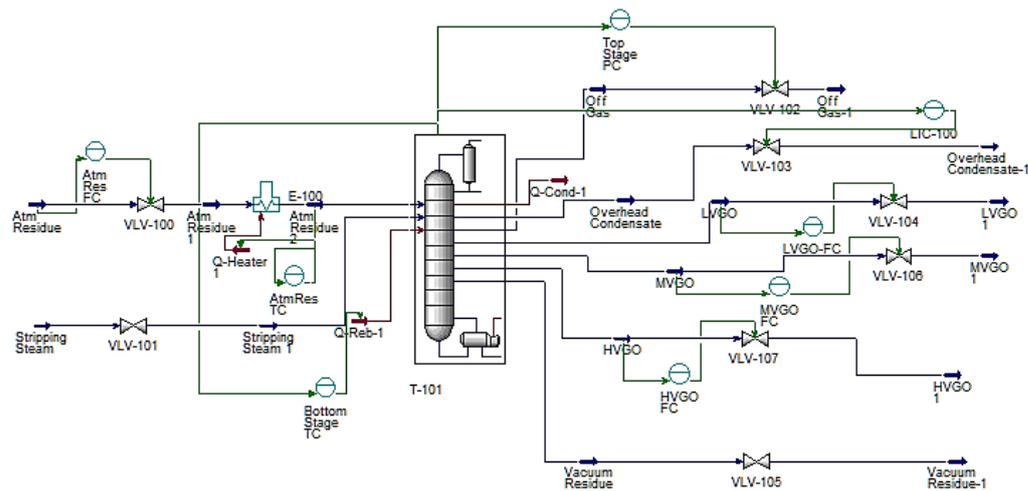


Figure 1. Configuration of VDU simulation

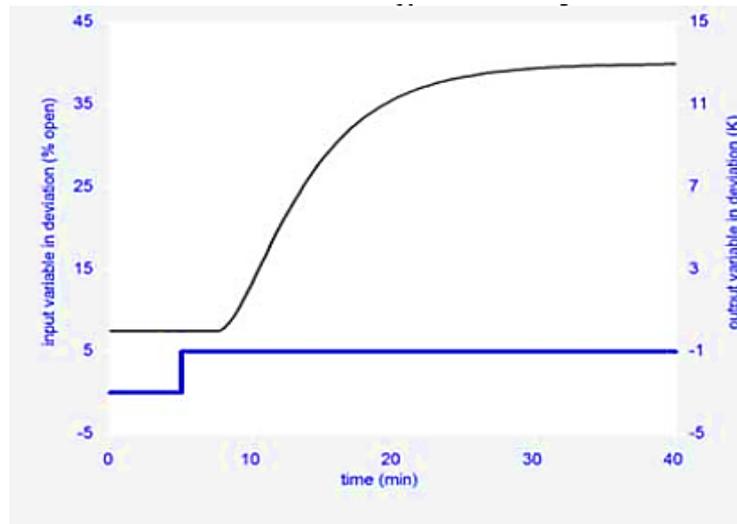
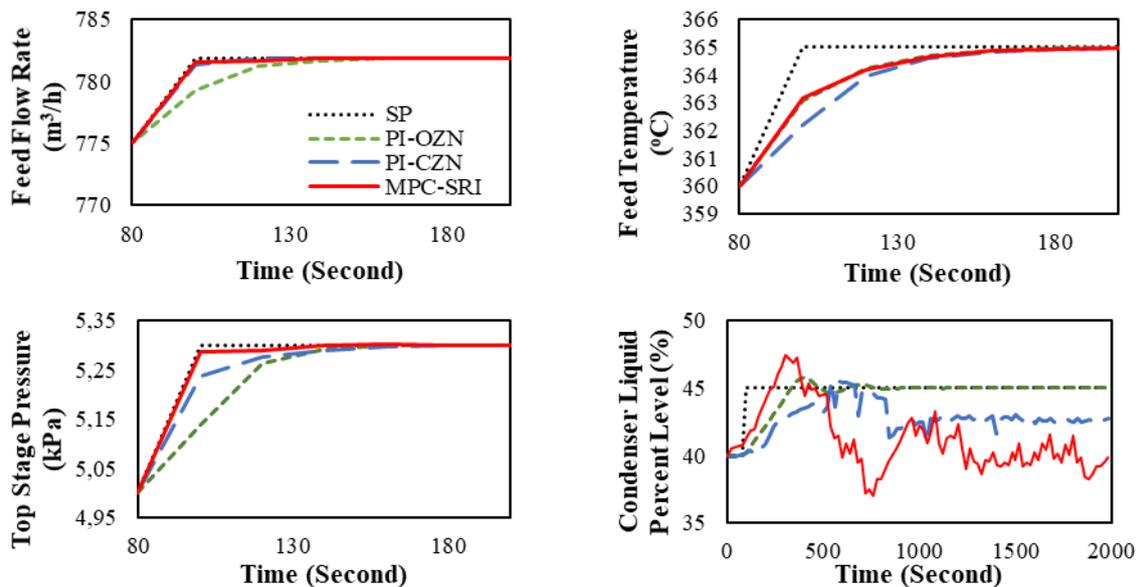


Figure 2. Example of PRC.

3. Result and Discussion

3.1. Set-point Tracking

In this study, set-point (SP) tracking is conducted in order to see the response of the controllers because of SP change. In this test, will be seen how quick MPC is able to respond the SP change compared to PI. The response of the controller due to change of SP of each variable in this test can be seen in figure 3.



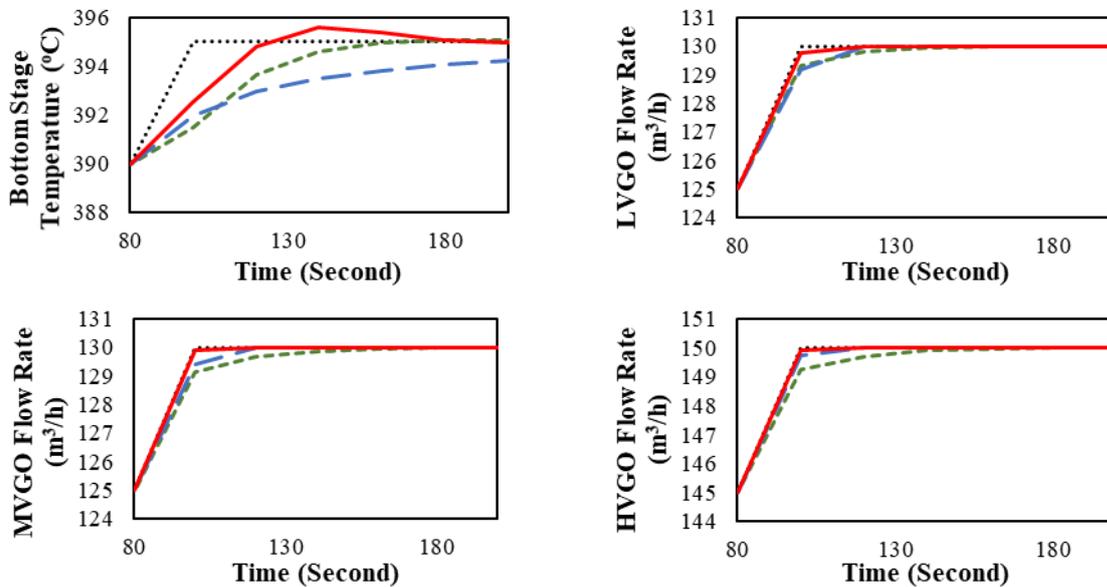


Figure 3. Response of MPC and PI control due to SP change.

The results shown in figure 3 indicate that, generally, MPC can provide better response due to SP change than PI controller. Although MPC is effective, it is not good for level control [7] as it can be seen in figure 3. So that, PI controller is used for level control of condenser. To find error value of each controller, the ISE value is computed by using equation (4). The result of the calculation is shown in table 1 below

Table 1. ISE of each controlled variable in MPC and PI controller because of SP change.

No.	Controlled Variable	ISE		
		PI	PI (Closed Loop)	MPC
1	Feed Flow Rate	134.6	4.2	2.7
2	Feed Temperature	90	181	84
3	Top Stage Pressure	0.552	0.092	0.007
4	Condenser Level	2129	11069	37840
5	Bottom Stage Temperature	282	385	131
6	LVGO Flow Rate	10.2	13	1.1
7	MVGO Flow Rate	18.29	6.98	0.28
8	HVGO Flow Rate	13.79	1.33	0.16

3.2. Disturbances Rejection

Figure 4 shows the response both MPC and PI controller due to the presence of disturbance.

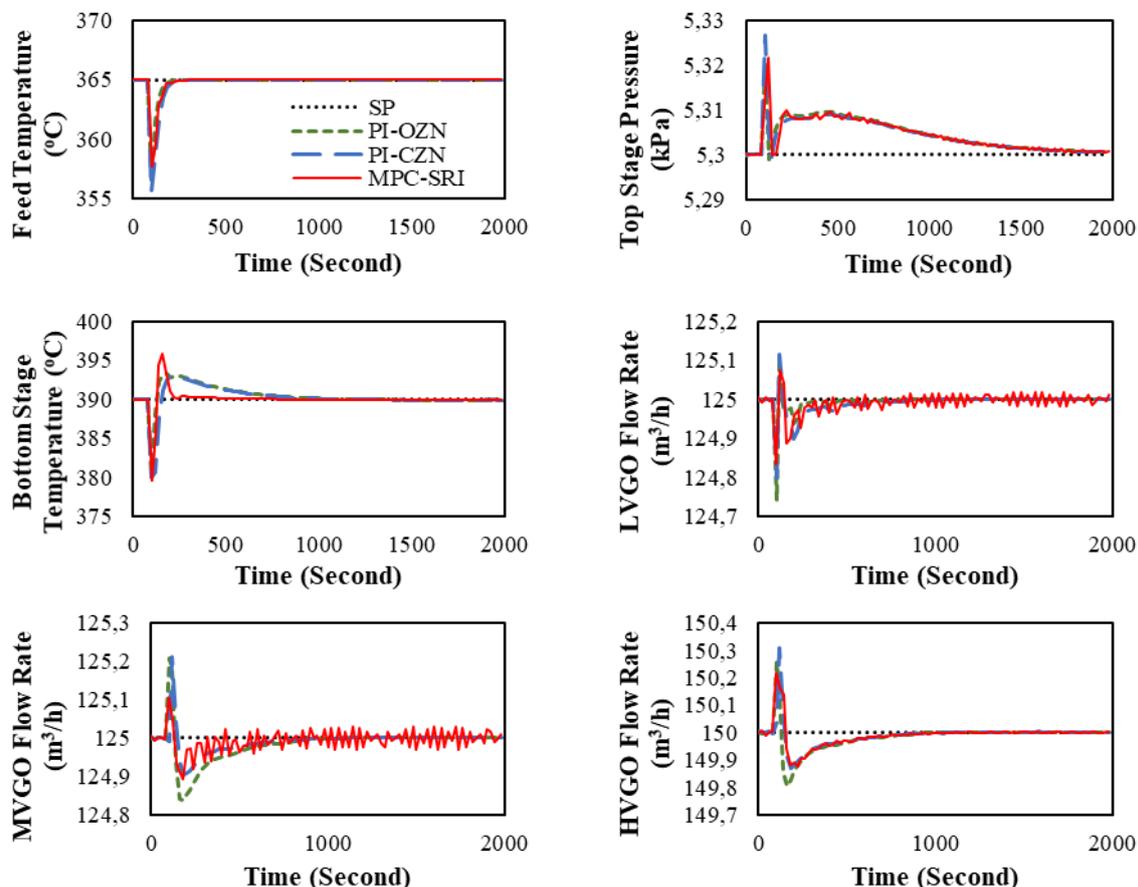


Figure 4. Response of MPC and PI control due to disturbance.

Increased feed flow rate, will cause the temperature of feed and bottom stage drop. Furthermore, higher feed flow rate will lead higher vapor flow rate within the column as well, and will affect the performance of the column and flow rate of the products as shown in figure 4. However, in spite of MPC has better response for maintaining the operation remain stable than PI, because of the presence of disturbance, it only provides slight improvement. The ISE value in disturbance rejection test is shown in table 2 as follow:

Table 2. ISE of each controlled variable in MPC and PI controller because of disturbance.

No.	Controlled Variable	ISE		
		PI	PI (Closed Loop)	MPC
1	Feed Temperature	1731	2883	1726
2	Top Stage Pressure	0.065	0.064	0.063
3	Bottom Stage Temperature	4501	5748	3870
4	LVGO Flow Rate	1.71	1.76	1.67
5	MVGO Flow Rate	4.759	1.995	1.783
6	HVGO Flow Rate	5.387	3.950	3.781

4. Conclusion

In general, MPC can improve control performance because it provide better response than PI when dealing with SP change and disturbance. As a result, control performance improvements occurred as using MPC compared to PI controllers. When testing a set-point change, MPC provide improvement of feed flow rate control, feed temperature, top-stage pressure, bottom-stage temperature and flow rate of LVGO, MVGO, and HVGO, respectively, 36%, 6%, 92%, 53%, 90%, 96% and 88% compared to PI. Only condenser level control that PI performance is much better than the MPC. So, for controlling condenser level in this study, PI controller is used. While for the test of disturbance rejection, by changing feed flow rate by 10%, there is improvement of control performance using MPC compared to PI controller on feed temperature control, top-stage pressure, bottom-stage temperature and flow rate LVGO, MVGO and HVGO 0.3%, 0.7%, 14%, 2.7%, 10.6% and 4.3%, respectively.

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