CHEMICAL ENGINEERING TRANSACTIONS

VOL. 86, 2021

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Sauro Pierucci, Jiří Jaromír Klemeš

ISBN 978-88-95608-84-6; **ISSN** 2283-9216

DECOUPLED PID CONTROLLERS FOR TRACKING OPTIMUM SET POINT IN MULTIPLE-INPUT-MULTIPLE-OUTPUT (MIMO) SYSTEM OF ETHYLENE GLYCOL PRODUCTION

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Control of ethylene glycol (EG) production involves highly interacting parameters which disrupts and degrades controllers' performance. In this work, a validated model is used to attain and maintain the optimum EG flowrate and reactor temperature. Effective Relative Gain Analysis (ERGA) method is applied in determining the pairing of each manipulated (MV) and controlled variables (CV). The best pairing is identified as MV1-CV1/MV2-CV2. Sensitivity analysis are performed to identify the stability and controllability of the closed loop systems. The conditioned number (C) and Morari Resilience Index (MRI) calculated are 1.47 and 0.679, respectively. Decoupling method within Simulink Matlab environment is used to reduce/eliminate loop interactions for increased quality of Proportional-Integral (PI) controllers in controlling EG production. The results show that the decoupled PI controller (with proper/tight control boundary) shows significant improvement in control performance.

Keywords: Ethylene Glycol (EG), Multiple-Input-Multiple-Output (MIMO), Decoupler, Control, Effective Relative Gain Analysis (ERGA)

1. Introduction

EG plays an important role as organic intermediates for industries (Schwaar, 1997). It is categorized as an organic solvent (organic dio-lipid) (Brent et al., 1999). EG is colorless, odorless, viscous dihydroxy alcohol, clear and completely soluble in water. It is widely used in industries for electrolytic condensers, hydraulic brake fluid, and synthetic waxes and also as primal matter in the production of a broad range of products, including polyester fibers, fiberglass, and polyethylene terephthalate (Gulledge, 2020). Statistics show that EG production is rapidly increasing and the increase is expected to continue until 2030 (Garside, 2019).

In most production industries, multiple variables are present and frequently, these variables must be simultaneously controlled, in which the concept of MIMO is applied. When a process has multiple loops and the various control loops disturb each other, it may be necessary to use a reciprocal system that isolates the loops from each other and such a design is known as decoupling control. Decoupler has been a promising control technique due to its ability to significantly reduce loop interactions. Nevertheless, it should be pointed out that there are still cases in which decoupling may not be necessary even though decoupling is an important problem in the control of the MIMO process (Liu et al., 2019).

As for the EG production (hydrogenation) reactor, the EG production rate is directly linked to the reactor temperature and there are different control mechanisms for each of the parameters mentioned above. However, both parameters will be simultaneously bypassed, as long as the control mechanism is adjusted. This phenomenon is called loop interactions. The decoupling control strategy can reduce these interactions so that each control loop is almost theoretically independent of each other. Thus, a practical approach is necessary to identify the validity of the control strategy in this field.

Decoupling control has been employed in many sectors involving chemical engineering and manufacturing. Previous researches have shown significant impact of decoupler on various processes. It can be seen that, in 2012, the Tyreus-Luyben PI and PID methods were applied to the decoupling temperature control of a reactive distillation process for the production of ethyl acetate and water (by-product) from the esterification reaction between acetic acid and ethanol. With low oscillations and lower IAE and ISE values obtained, the Tyreus-Luyben PID method has been proven to be the best among the methods studied (Giwa, 2012). In 2014, a multivariable PID controllers based on decoupling control methodology was developed. It comprises of an integral action ideal decoupling control that aims to minimize interactions and zero error at the steady state condition (Garrido et al., 2014). A decoupling control using the inverted decoupling scheme is applied to the PI controller by introducing a system with decoupling elements in a cascade manner to decrease the occurrences of interaction between their strategic variables. The major advantage of applying decoupling control is the controller's parameters determination is simple since each loop is treated independently (Hamdy et al., 2016).

Based on previous researches mentioned, various decoupling techniques have been implemented to different kinds of processes. However, it is comprehended that so far the decoupler has not been developed, tested, and used in a hydrogenation reactor for the production of EG. Decoupler is superior compared to predictive control model in terms of implementation simplicity and cost, while showing exceptional results compared to PID in other industrial application. Thus, this work focuses on determining the applicability and implementation of decoupling control in the EG production reactor.

2. Methodology

2.1 Modelling

A reactor model used was based on the work of Yu and Chien (2017), with the addition of coolant flow (Prokop et al.,2020)., and it was simulated using ASPEN Plus V10. The reactor was simulated as a Plug Flow Reactor (PFR) model (Table 1). The optimized value of reactor temperature (CV1) and EG flowrate (CV2) were determined using multi-objective optimization method with a 'ε-constraint' approach. The MVs are also set as coolant flowrate (MV1) and hydrogen flowrate (MV2). The model is then linked to Simulink (Matlab) for control system development.

Table 1: Specification of ASPEN Plus PFR model

Feed Parameter	Quantity	Reactor Parameter	Quantity
Temperature (°C)	160	Temperature (°C)	210
Pressure (bar)	25	Pressure (bar)	25
Mole Flow (kmol/h)	7,059.97	Length (m)	5
DMO[a] (%)	0.0179	Diameter (m)	1
MeOH[b] (%)	0.2643	Bed Voidage	0.5
MG[c] (%)	0.0005	Particle Density (kg/m^{3})	980
H_2[d] (%)	0.7172		
CO[e] (%)	0.01		

[a]dimethyl oxide [b]methanol; [c]methyl glycolate; [d]hydrogen; [e]carbon monoxide.

2.2 MIMO process identification

This is a 2X2 MIMO process. A proper pairing is necessary to implement decoupling control. For this, the gain (K_P/G), the time constant/bandwidth (τ_P), and the time delay (θ) for each loop are calculated (Equation 1) using the process response curve, obtained by running the open loop simulation. Then, ERGA is performed using Equation 2 and 3 (Xiong et al., 2005).

$$K_P(G) = \frac{\Delta PV}{\Delta MV}\ , \tau_P = 0.632\ x\ T_{final}\ , \theta = T_{MVi} - T_{PVi} \quad (1)$$

$$E\ =\ G\,(0)\ X\ \Omega \quad (2)$$

$$\Phi\ =\ E\ X\ E^{-T} \quad (3)$$

Where: ΔPV is difference in process variable, ΔMV is difference in manipulated variable, T_{final} is settling time, E is effective gain, Ω is bandwidth, Φ is ERGA.

Sensitivity and controllability analyses are performed using Equation 4 and 5.

$$G = USV^T \quad (4)$$

$$C = \frac{Smax\,(G)}{Smin\,(G)} \quad (5)$$

Where: USV^T is singular value decomposition, C is conditioned number, $Smax$ is maximum singular value, and $Smin$ is minimum singular value (MRI)

2.3 Proportional-Integral (PI) control system

A PI control system for the EG production reactor is developed using Zeigler Nichols open loop method. The formula is indicated in Equation 6 (Altmann et al., 2005). The controllers' values are inserted in the PID block in Simulink (Figure 1). Auto tune method is selected as the tuning method for the controllers.

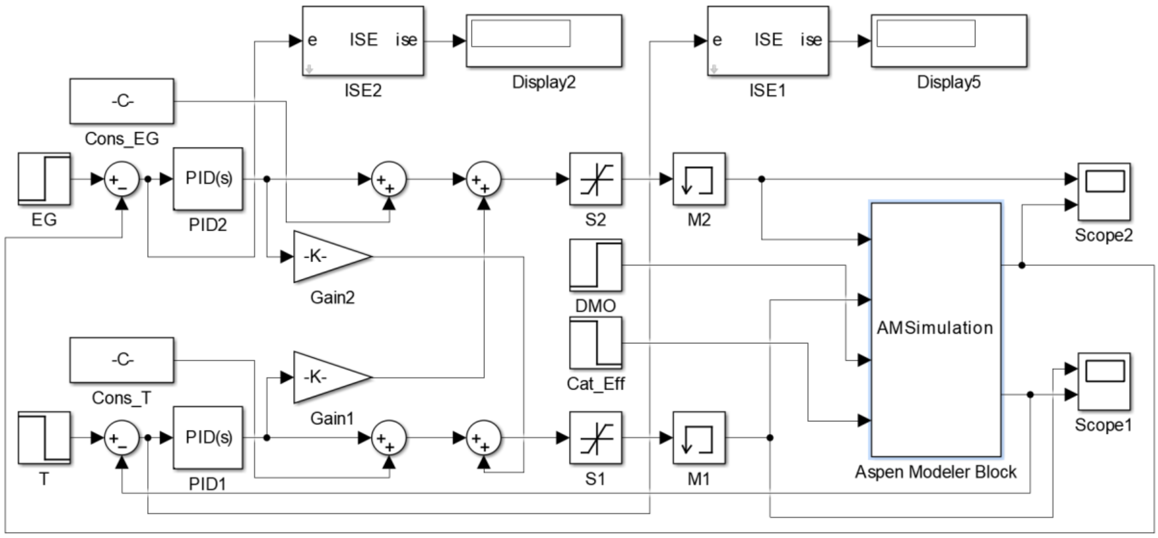

Figure 1: Simulink model of decoupled PI controller for EG MIMO process

$$K_c = 0.9\ x\ \frac{K_P}{\tau_P\ x\ \theta}\ , \tau_i = 0.3\ x\ \theta \quad (6)$$

Where: K_c is controller gain, τ_i is controller time constant.

2.4 Decoupled PI controller

The decoupler values are calculated using Equation 7. The values are placed in a separate block after the PID block in Simulink.

$$D_{12} = \frac{G_{12}}{G_{11}}\ , D_{21} = \frac{G_{21}}{G_{11}} \quad (7)$$

Where: D_{12} is decoupler MV2/CV1, D_{21} is decoupler MV1/CV2.

3. Result and Discussion

From the developed model, 4 set points for each CV were selected as the points of comparison between PID and decoupler. With this, it is ensured that the controller tested covers various aspects in terms of controllers' reliability towards stability, controllability, and efficiency.

3.1 MIMO system

The ERGA is calculated using Equation 2 and 3, and the gains are demonstrated in Table 2. The value is shown in Equation 8.

Table 2: Gain (K_P/G), time constant/bandwidth (τ_P), and time delay (θ)

	MV1/CV1	MV1/CV2	MV2/CV1	MV2/CV2
K_P/G	-0.04	0.01	0.04	-0.02
τ_P	0.60	0.30	0.50	0.30
θ	0.01	0.01	0.01	0.01

$$ERGA = \begin{bmatrix} 0.84 & 0.16 \\ 0.16 & 0.84 \end{bmatrix} \quad (8)$$

It is confirmed that pairing MV1/CV1 and MV2/CV2 is more effective when applying both PI and decoupling control, since 0.84 is nearer to 1 compared to 0.16. The value of 0.84 also indicates that, by applying this pairing, a lesser degree of interaction can be achieved (Wang et al., 2008).

The sensitivity analysis performed using Equation 4 and 5 result in C of 1.47, which is near 1. It demonstrates that the model is well conditioned and less sensitive to the effects of process model mismatch (PMM) (Jin et al., 2012). However, the MRI gives the value of 0.679, which is below to 1, so the process is difficult to control and poor control performance is expected (Jin et al., 2012).

3.2 PI controller

Since this is a 2X2 MIMO process, there is a total of four interactions. Table 2 shows the gain (K_P/G), time constant/bandwidth (τ_P), and time delay (θ) for each interaction. Using the data obtained from Table 2, the PI values for controller 1 and 2 are calculated using Equation 6 and tuned. The data used are only MV1/CV1 and MV2/CV2 for the controller calculation, referring to ERGA pairing results in Equation 8. The P and I value for controller 1 are -20 and -22, for controller 2 are -17.5 and -28, respectively.

3.3 Decoupler

Referring to Equation 7, the decoupler values are: D_{12} is 1.09 and D_{21} is 0.57.

3.4 Comparison of decoupled and non-decoupled PID

The simulation is performed for PI and decoupler; using different decoupling approach, which is full decoupler (DF), partial bottom decoupler (DPB), and partial top decoupler (DPT) (Sulaiman & Ahmad, 2019). The simulations' difference is presented in the form of set point tracking curves (Figure 2 and Figure 3), and error was calculated using Integral Square Error (ISE) (Table 4).

The PID controller gives a relatively good response in terms of overshoot and settling time for both CV1 and CV2 (Figure 2 and 3), with non-excessive MV movements. On the other hand, the interactions between CV1 and CV2 are quite high. For the DF controller, the decoupler does not work as intended, which results in the amplification of the controllers parameters and, subsequently, leads to high overshoots, long settling time and large MV movements (Zhang et al., 2019). For the DPB controller, an optimal CV1 response is obtained, but at the cost of poor CV2 performance. The DPT controller excels at both: set point tracking efficiency and minimizing loop interactions with the least MV movement. However, for CV1 at 120 s, the interaction is absurdly high due to the movement of CV2 that opposes the optimal set point on a large scale, which explains that the controller is sensitive to CV2 changes (Albertos & Sala, 2004).

The DF controller is at a disadvantage compared to the PI controller (Table 4). The ISE for CV1 and CV2 of the DF controller is greater than the PI controller. This occurs when both decouplers are implemented, the degree of sensitivity to the PMM increases, which causes a high ISE value (Lee et al., 2005). As for the DPB controller, CV1 shows an excellent ISE value, but with a lower CV2 response compared to the PI controller. Ultimately, this is due to the effects of partial decoupling, which increases the outputs of the CV1 controller, but at the same time degrades the outputs of the CV2 controller. For the DPT controller, the ISE value is the worst among the three decoupled controllers. However, for the second step change of the CV2, the error is 57.6 and 558.3 for CV1 and CV2, respectively. As mentioned, the controller is sensitive to large and drastic changes in CV2 due to the controllers being partially decoupled (Albertos & Sala, 2004). This shows that, when deleting the step, the DPT controller is the best for the CV1 and CV2 responses compared to other controllers. Thus, with the appropriate limit settings (small/low control limit), exceptional control of the decoupled controller (DPT) is expected.

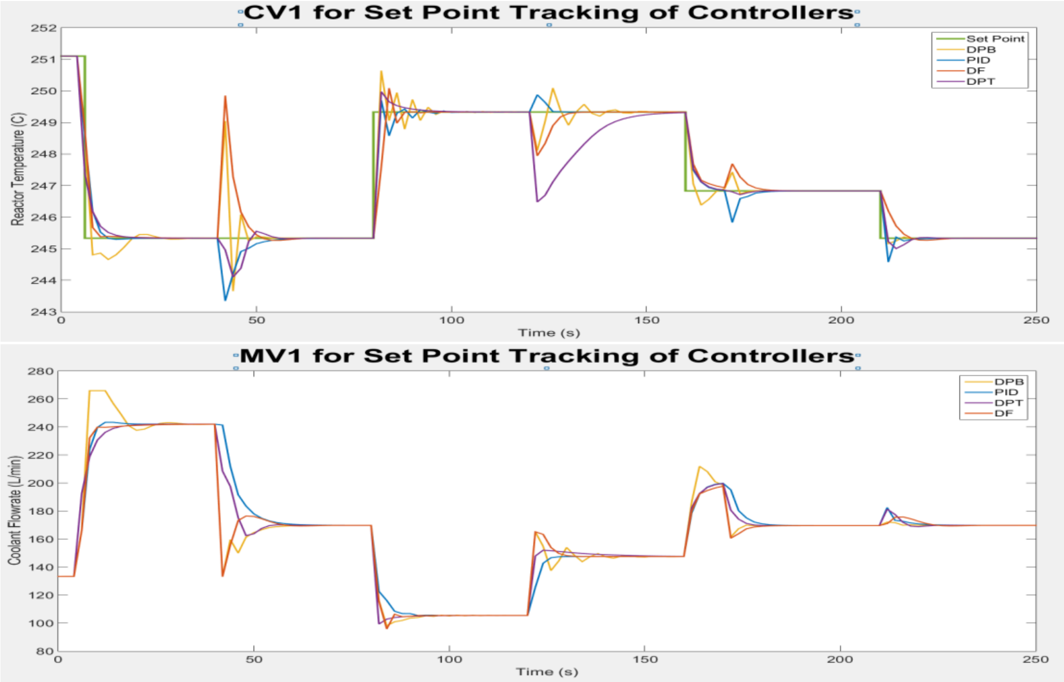

Figure 2: CV1 and MV1 response towards set point change.

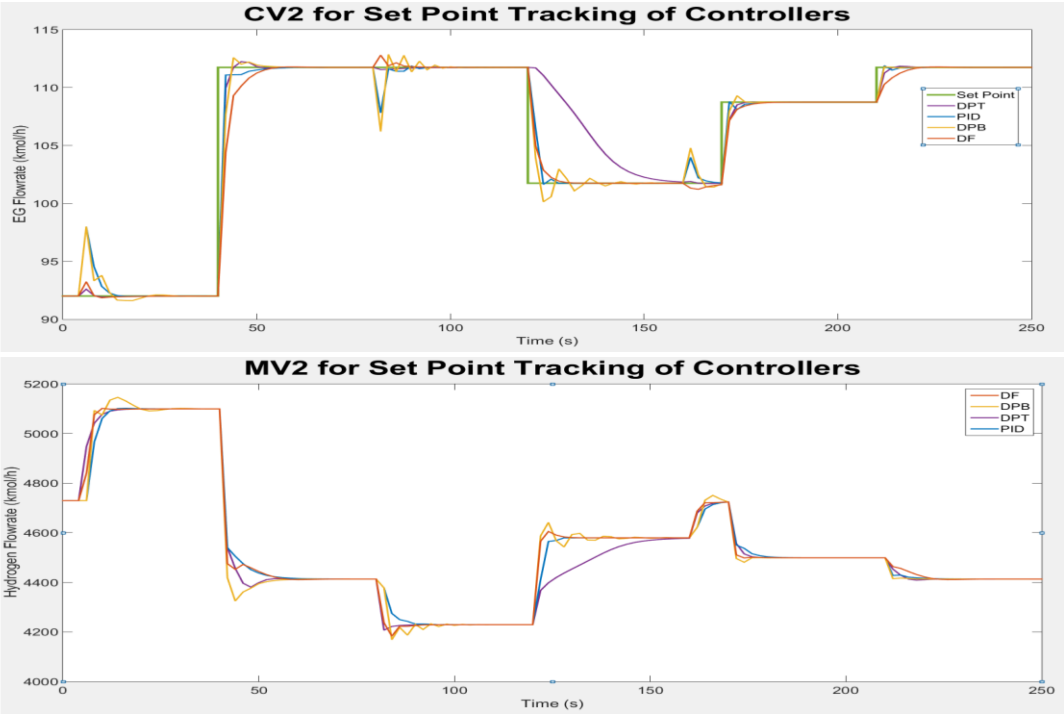

Figure 3: CV2 and MV2 response towards set point change.

Table 4: Controllers' ISE result

Type	DF	DPB	DPT	PI
CV1	141.9	86.2	144.5	104.4
CV2	735.4	793.9	1176.0	728.9

4. Conclusions

In conclusion, the model developed presented results as needed. The parameters selected for the controller test reflect the reliability of the controllers in relation to stability, controllability, and efficiency. A lower degree of loop interaction is achieved with the ERGA implementation. The sensitivity analysis shows that the model is well conditioned, with an acceptable degree of sensitivity to the effects of (PMM), but it is difficult to control and poor control performance is expected. The PI controllers and decouplers were successfully developed. The DPT controller offers the best control (excluding the CV2 second step) for CV1 and CV2 responses compared to other controllers. The decoupled controller (DPT) can produce a relatively higher control with small/low control limit. The possible future developments are the application and implementation of advance process control in order to further enhance the performance, reliability, stability, controllability, accuracy and consistency of the EG production system.

Acknowledgments

The financial support from Universiti Sains Malaysia through Research University Grant (RUI) 203.PJKIMIA.8014146 is greatly acknowledged.

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