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Comparasion of 1DoF IMC and 2DoF IMC Method to Control Shell Heavy Oil Fractionator(SHOF) Model

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Abstract— *Shell Heavy Oil Fractionator (SHOF) is a distillation column type used to separate crude oil into desired products based on the boiling point difference of each product. The design of control on SHOF has several constraints, it is caused by non-linearity of the process, mulrivariable interactions, long dead time, and disturbances. It needs the control method that make the system response track the set point and eliminate the disturbances. This research is designed comparasion of 1 DoF IMC and 2 DoF IMC method to controlling SHOF with 3x3 MIMO decentralized in the form of First Order Plus Dead Time (FOPDT). Filter parameter tuning on this controller using Rivera filter parameter tuning method. Interaction between subsystems is reduced by applying the Relative Gain Array method and decoupling. The designed controllers were simulated in the MATLAB/SIMULINK environment. From the simulation results it was proven that the 2 DoF IMC showed the better performance compared to 1 DoF IMC with IAE respectively value of 44,4454 at y_1, 19,2279 at y_2, and 0,1483 at y_3 on set point tracking test respectively, and IAE value 93,9574 at y_1, 40,0455 at y_2, and 0,0099at y_3 on disturbance rejection test.*

Keywords: Shell Heavy Oil Fractionator (SHOF), 1DoF IMC, 2DoF IMC, Rivera, decoupling

1. INTRODUCTION

Shell Heavy Oil Fractionator (SHOF) is a distillation column type used to separate crude oil into desired products based on the boiling point difference of each product. Heavy oil will be separated, boiled into steam and the steam is condensed, so the distillation result is obtained[1].The design of control on SHOF has several constraints, it is caused by non-linearity of the process, mulrivariable interactions, long dead time, and disturbances. It needs the control method that make the system response track the set point and eliminate the disturbances, so the output of the product composition as expected. Goal of this research is simulate and compare of Internal Model Control (IMC) 1DoF and IMC 2DoF control method to controlling SHOF with 3x3 decentralized MIMO system in the form of First Order Plus Dead Time (FOPDT). Filter parameter tuning on this controller using Rivera method [2][3]. Interaction between subsystems is reduced by applying the Relative Gain Array method and decoupling, so the system can be converted into three Single Input Single Output (SISO)[4]. Comparative analysis of the performance of the 1DoF IMC and 2DoF IMC method is based on evaluation of Integral of the Absolute Error (IAE) value..

2. METHODE

2.1 *Shell Heavy Oil Fractionator* (SHOF)

The fractionator column on SHOF is shown in Figure 1[1]. Based on the fractionator column as shown in Figure 1, heavy oil flowed through the bottom of the fractionator which had previously been heated, so it has been in the form of steam. Furthermore, inside the fractionator, heavy oil is processed to obtain three types of products which is flowed on the right side of the fractionator, divided into top, side, and bottom fractionators with unit flow is kmol / minute. Top poductand side product specifications are determined based on economic value and also operation or control,while the bottom product of the specification is not specified, but there are operational constraints on the temperature at the bottom of the column.

On the left side of the fractionator there are three reflux namely upper (upper reflux), middle (intermediate reflux), and bottom (bottom reflux)which serves to drain the heatresulting in the separation of the desired product.The lower reflux has an enthalpy regulator, whose purpose is to regulate heat transfer in the loop by regulating the formation of vapors[1]. Upper and middle reflux is used for heat removal at the top and the center of the fractional column. Both of these reflux are not controlled separately so that the mixed temperature is uncontrolled, both of these quantities can be regarded as disturbancesin the system [1].Manipulated input variables are top draw (u_1), side draw (u_2), and bottom reflux duty (u_3). The controlled output variables are top end point composition (y_1), side end point composition (y_2) and bottom reflux temperature (y_3). Intermediate reflux duty (d_1) and upper reflux duty (d_2) will be considered as input disturbance variables to the plant.

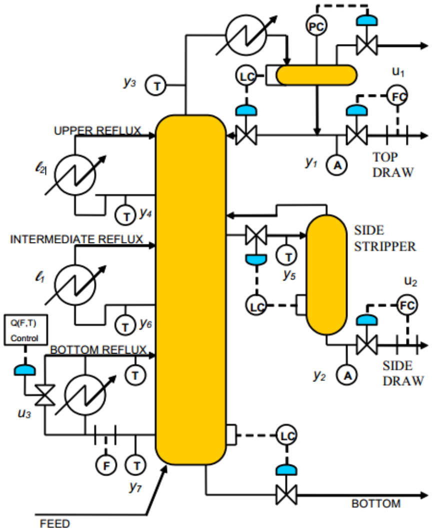


Figure 1. Shell Heavy Oil Fractionator column system

In this research, the transfer function of SHOF has shown by the equation (David M. Preet and Carlos E. Gracia) (1) [1].

$$\begin{bmatrix} Y_1 \\ Y_2 \\ Y_7 \end{bmatrix} = \begin{bmatrix} \frac{4.05e^{-27s}}{50s+1} & \frac{1.77e^{-28s}}{60s+1} & \frac{5.88^{-27s}}{50s+1} \\ \frac{5.39^{-18s}}{50s+1} & \frac{5.72^{-14s}}{60s+1} & \frac{6.90^{-15s}}{40s+1} \\ \frac{4.38^{-20s}}{33s+1} & \frac{4.42^{-22s}}{44s+1} & \frac{7.20}{19s+1} \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \\ U_3 \end{bmatrix} + \begin{bmatrix} \frac{1,20\, e^{-27s}}{45s+1} & \frac{1,44\, e^{-27s}}{40s+1} \\ \frac{1,52\, e^{-15s}}{25s+1} & \frac{1,83\, e^{-15s}}{20s+1} \\ \frac{1,14}{27s+1} & \frac{1,26}{32s+1} \end{bmatrix} \begin{bmatrix} d_1 \\ d_2 \end{bmatrix} \qquad (1)$$

The control objectives and Economic Objectives of the Shell Heavy Oil Fractionator (SHOF) are as follows[1][6][7]:

1. Maintain y_1 at specification $0,0 \ \pm 0,005$ at steady state
2. Maintain y_2 at specification $0,0 \ \pm 0,005$ steady state
3. Reject the disturbances entering the column from the upper d_1 and intermediate refluxes d_2 range between $-0,5$ dan $0,5$
4. Economic Objectives of SHOF is Maximize steam make in the steam generators (i.e. maximize heat removal) in the bottom circulating reflux u_3. Decreasing heat duty implies increasing the amount of heat removed.

Constraints of controlled SHOF are [1][6][7]:

1. Top draw and side draw have *hard bounds*:

$$-0,5 \ \leq u_1 \leq 0,5$$
$$-0,5 \ \leq u_2 \leq 0,5$$

2. Bottom re*flux duty* has *hard bound*:

$$-0,5 \ \leq u_3 \leq 0,5$$

3. y_1 dan y_2 must be maintenance between $-0,5$ dan $0,5$ during disturbance.
4. y_3 has minimum value $-0,5$.

2.2 MIMO Control System

2.2.1 Decentralized Mimo System

Decentralized control systems are widely used in the industrial world because of easily designed system structures, simplicity in hardware procurement, easy to perform the tuning parameters , and the system is flexible in operation and repair[8][9].

In practice for a MIMO system with n the number of controlled variables and n manipulated variables will produce n! possible configurations [5]. So the 3x3 MIMO system structure has 3! or six possible control configurations available. The MIMO decentralized system 1-1 / 2-2 / 3-3 is shown in Figure 2 [10].

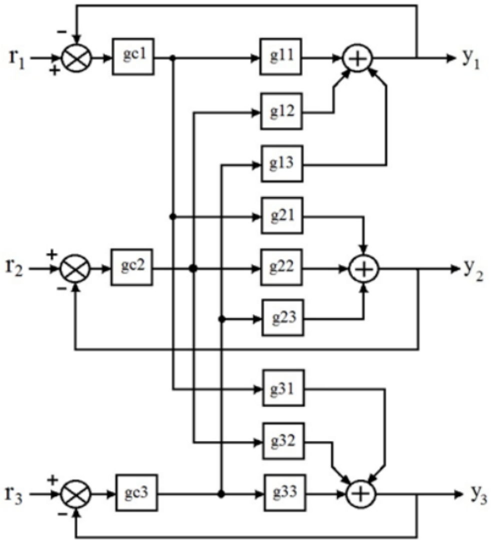


Figure 2. The 3x3 MIMO decentralized control structure.

2.2.2 Relative Gain Array (RGA)

RGA used to calculate the input-output interaction of the MIMO control system and determine the input and output pairs of decentralized MIMO system[11]. RGA on 3x3 system is formulated in equation 2[12].

$$RGA = K.\otimes (K^{-1})^T \qquad (2)$$

To determine the pairs of input and output variables of a multivariable process with *relative gain array* as in equation (3) we can use pairing rule as follows[13][4] :

- *Pairing rule* 1: Select the reconstituted pair, with a diagonal pair option, having an RGA matrix close to the identity when the frequency is at around the circumference of the closed loop bandwidth
- *Pairing rule* 2: Avoid (if possible) a negative pair on a steady state RGA element..

The result of RGA calculation on SHOF as follows.

$$RGA = \begin{bmatrix} 2{,}08 & -0{,}73 & -0{,}35 \\ 3{,}42 & 0{,}94 & -3{,}36 \\ -4{,}50 & 0{,}79 & 4{,}71 \end{bmatrix}$$

Based on pairing rule and RGA value calculation results, the configuration of SHOF is 1-1 / 2-2 / 3-3, where the top draw (u_1) will affect the top end point composition (y_1), side draw (u_2) will affect the side end point composition (y_2), and bottom reflux duty (u_3) will affect the bottom reflux temperature (y_3).

2.3 Controller Design of 1DoF IMC and 2DoF IMC

The 1DoF IMC structure with decoupling is shown in Figure 3[5].Based on Figure 3, the parameters in the 1DoF IMC structure are transfer control function set point tracking (q), process transfer function (G_p), transfer function of process model (G_{pm}), disturbance transfer function (G_d), *set point*controlled output variable (y_{sp}), controlled output variable (y), manipulated input variable/ *controller outpu t*(u), disturbance *input* variable (d), estimation variabel of disturbance input (de), and *decoupling variable* (D)[5].
2DoF IMC is a modern control method that can control the multivariable plant, following set point tracking and eliminate the disturbances. 2DoF IMC structure with decoupling is shown in Figure 4[5].

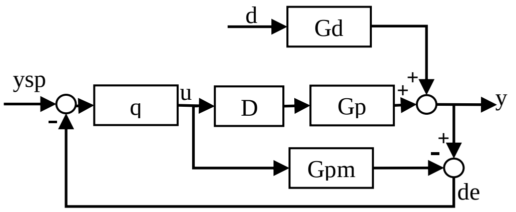


Figure3.The 1DoF IMC structure with decoupling

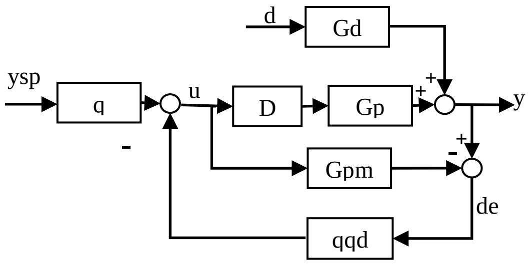


Figure4.The 2DoF IMC structure with decoupling

Based on Figure 4, the parameters in the 1DoF IMC structure are transfer control function set point tracking (q), process transfer function(G_p), transfer function of process model (G_{pm}), disturbance transfer function(G_d), *set point*controlled output variable(y_{sp}), controlled output variable(y), manipulated input variable/ *controller output*(u), disturbance *input* variable(d), estimation variabel of disturbance input(de), *decoupling variable* (D), and transfer control fuction of disturbance rejections (qq_d)[5].

The transfer function of SHOF is shown by the equation (1).

Value of process transfer function (G_p), disturbance transfer function (G_d), transfer function of process model (G_{pm}), and transfer control function set point tracking*(q(s))*on 2DoF IMCis the same as 1DoF IMC.

process transfer function (G_p)in FOPDT form can be written using equation (3)[1][7].

$$G_p(s) = \begin{bmatrix} G_{p11}(s) & G_{p12}(s) & G_{p13}(s) \\ G_{p21}(s) & G_{p22}(s) & G_{p23}(s) \\ G_{p31}(s) & G_{p32}(s) & G_{p33}(s) \end{bmatrix} = \begin{bmatrix} \frac{4{,}05e^{-27s}}{50s+1} & \frac{1{,}77e^{-28s}}{60s+1} & \frac{5{,}88e^{-27s}}{50s+1} \\ \frac{5{,}39e^{-18s}}{50s+1} & \frac{5{,}72e^{-14s}}{60s+1} & \frac{6{,}90e^{-15s}}{40s+1} \\ \frac{4{,}38e^{-20s}}{33s+1} & \frac{4{,}42e^{-22s}}{44s+1} & \frac{7{,}20}{19s+1} \end{bmatrix} \qquad (3)$$

disturbance transfer function(G_d)in FOPDT form can be written using equation (4)[1][7].

$$G_d = \begin{bmatrix} G_{d11} & G_{d12} \\ G_{d21} & G_{d22} \\ G_{d31} & G_{d32} \end{bmatrix} = \begin{bmatrix} \frac{1{,}20\, e^{-27s}}{45s+1} & \frac{1{,}44\, e^{-27s}}{40s+1} \\ \frac{1{,}52\, e^{-15s}}{25s+1} & \frac{1{,}83\, e^{-15s}}{20s+1} \\ \frac{1{,}14}{27s+1} & \frac{1{,}26}{32s+1} \end{bmatrix} \qquad (4)$$

Transfer function of process model(G_{pm})in FOPDT form can be written using equation (5)[16].

$$\mathrm{G_{pm}} = \mathrm{diag.}\left[\mathrm{G_{p11}} \quad \mathrm{G_{p22}} \quad \mathrm{G_{p33}}\right] = \begin{bmatrix} \frac{4.05e^{-27s}}{50s+1} & 0 & 0 \\ 0 & \frac{5.72e^{-14s}}{60s+1} & 0 \\ 0 & 0 & \frac{7.20}{19s+1} \end{bmatrix} \qquad (5)$$

Transfer function of process model $(\mathrm{G_{pm}})$can be divided into two parts, the part that can be converted$(\mathrm{G_{pm}}^{-})$and non-convertible parts$(\mathrm{G_{pm}}^{+})$, which can be written by equations (6), (7) and (8)[17].

$$\mathrm{G_{pm11}} = \mathrm{G_{pm11}}^{-}.\mathrm{G_{pm11}}^{+} = \frac{4.05}{50s+1}.\frac{1-\frac{27\mathrm{s}}{2}}{1+\frac{27\mathrm{s}}{2}} \qquad (6)$$

$$\mathrm{G_{pm22}} = \mathrm{G_{pm22}}^{-}.\mathrm{G_{pm22}}^{+} = \frac{5{,}72}{60s+1}.\frac{1-\frac{14\mathrm{s}}{2}}{1+\frac{14\mathrm{s}}{2}} \qquad (7)$$

$$\mathrm{G_{pm33}} = \mathrm{G_{pm22}}^{-}.\mathrm{G_{pm22}}^{+} = \frac{7.20}{19s+1} \qquad (8)$$

Transfer control function set point tracking*(q(s))*on 1DoF IMC can be designed using equation (9)[16].

$$\mathrm{q(s)} = \mathrm{diag.}\left[q_1(s) \quad q_2(s) \quad q_3(s)\right] = \begin{bmatrix} \mathrm{inv.}(\mathrm{G_{pm11}}^{-}).\mathrm{f_1} & 0 & 0 \\ 0 & \mathrm{inv.}(\mathrm{G_{pm22}}^{-}).\mathrm{f_2} & 0 \\ 0 & 0 & \mathrm{inv.}(\mathrm{G_{pm22}}^{-}).\mathrm{f_3} \end{bmatrix} \qquad (9)$$

$$\mathrm{f} = \frac{1}{\tau_c s+1} \qquad (10)$$

According to equation (6) to equation (10) the set point tracking control function (q)) can be written by equation (11), (12), and (13).

$$\mathrm{q_1(s)} = \frac{50\mathrm{s}+1}{4.05(\tau_{c1}\mathrm{s}+1)} \qquad (11)$$

$$\mathrm{q_2(s)} = \frac{60\mathrm{s}+1}{5.72(\tau_{c2}\mathrm{s}+1)} \qquad (12)$$

$$\mathrm{q_3(s)} = \frac{19\mathrm{s}+1}{7.20(\tau_{c3}\mathrm{s}+1)} \qquad (13)$$

transfer control fuction of disturbance rejections$(\mathrm{qq_d})$on 2DoF IMC can be designed using equation (14)and (15)[18].

$$\mathrm{qq_d(s)} = \mathrm{diag.}\left[qq_{\mathrm{d1}} \quad qq_{\mathrm{d2}} \quad \mathrm{qq_{d3}}\right] = \begin{bmatrix} qqd_1(\mathrm{s}).\frac{\propto_1 \mathrm{s}+1}{\tau_{c1}\mathrm{s}+1} & 0 & 0 \\ 0 & qqd_2(\mathrm{s}).\frac{\propto_2 \mathrm{s}+1}{\tau_{c2}\mathrm{s}+1} & 0 \\ 0 & 0 & qqd_3(\mathrm{s}).\frac{\propto_3 \mathrm{s}+1}{\tau_{c3}\mathrm{s}+1} \end{bmatrix} \qquad (14)$$

$$\propto = \frac{\left(1-\frac{\tau_c}{\tau}\right)^2 - e^{\frac{\theta}{\tau}}}{-e^{\frac{\theta}{\tau}}}.\tau \qquad (15)$$

Value of parameter filter (τ_c) of Rivera tuning on IMC controller ontransfer control function set point tracking$(\mathrm{q(s)})$and transfer fuction of disturbance rejections$(\mathrm{qq_d}(s))$shown by equation (16)[2][3].

$$\textbf{Rivera} = \tau_c > 0{,}8\theta \qquad (16)$$

Based on θ and τ values in transfer function of process model$\mathrm{G_{pm11}}$, $\mathrm{G_{pm22}}$ dan $\mathrm{G_{pm33}}$, requirements of parameter filter(τ_c) of Rivera in equation(16), so value of parameter filter tuning(τ_c) of Rivera in transfer function set point tracking$(\mathrm{q(s)})$and transfer fuction of disturbance rejections$(\mathrm{qq_d}(s))$shown by Table1.
Substitute the tuning values of the filter parameters$(\tau_{c1}, \tau_{c2}, \tau_{c3})$shown in Table 2 into equations (13), (14), and (15) so that transfer function of set point tracking $(q(s))$shown by Table 2.

Table1. Value of Rivera filter parameters tuning

Filter IMC Parameter	Tuning Value		
	τ_{c1}	τ_{c2}	τ_{c2}
Rivera	25	23	0,1

Table 2. Transfer function of *set point tracking* $(q(s))$based on *tuning* parameter filter value(τ_c)

Method	Trnasfer Function of *Set point Tracking*		
	$q_1(s)$	$q_2(s)$	$q_3(s)$
Rivera	$\frac{50s+1}{101{,}25s+4{,}05}$	$\frac{60s+1}{131{,}56s+5{,}72}$	$\frac{19s+1}{0{,}72s+7{,}2}$

Substitute the tuning values of the filter parameters$(\tau_{c1},\tau_{c2},\tau_{c3})$ on Table 1, transfer function offset point tracking(q_1,q_2,q_3)on Table 2, dead time value$(\theta)$and time constant(τ) on transfer function of process model G_{pm11},G_{pm22}, dan G_{pm33}into equation (16)and equation (17), so transfer fuction of disturbance rejections(qq_d)can shown by Table 3.

Tabel 3. Transfer function of*disturbance rejections*$(qq_d(s))$based on tuning Rivera filter parameters(τ_c)

Method	Transfer Function of
qq_{d1}	$\frac{2135{,}7823s^2+92{,}7156s+1}{2531{,}25s^2+202{,}5s+4{,}05}$
qq_{d2}	$\frac{2515{,}9032s^2+101{,}932s+1}{3025{,}88s^2+263{,}12s+5{,}72}$
qq_{d3}	$\frac{3{,}79s^2+19{,}1995s+1}{0{,}072s^2+1{,}44s+7{,}2}$

The main purpose of decoupling is to reduce or eliminate the interaction effects between closed loops. This decoupling control method was developed by Zalkind and Luyben [13]. In the Internal Model Control (IMC) structure, decoupler (D) is placed between the model transfer function (G_{pm}) and the plant transfer fuction(G_p)[5][15].

For the SHOF system, the order used belongs to the high order. Therefore, to calculate the decoupling elements in this system, each transfer function G (s) is approximated by each of K gain value and ignores the effect of time delay [13].

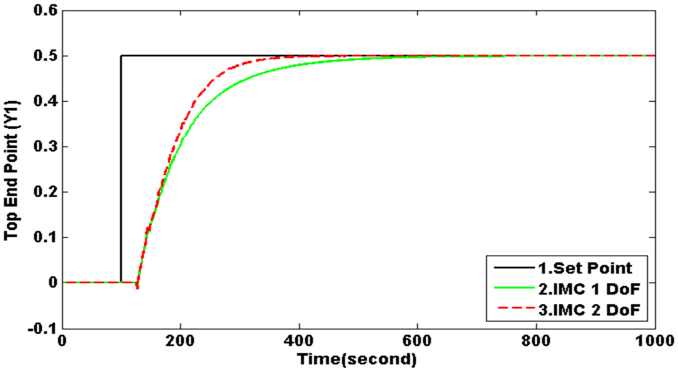
From the equation of each input and output variables pair, the following decouplers are obtained :

$$D_{11}=D_{22}=D_{33}=1$$
$$D_{12}=\frac{K_{32}\cdot K_{13}-K_{12}\cdot K_{33}}{K_{11}\cdot K_{33}-K_{31}\cdot K_{13}}=\frac{13{,}246}{3{,}406}=3{,}8893587033$$
$$D_{13}=\frac{K_{23}\cdot K_{12}-K_{13}\cdot K_{22}}{K_{11}\cdot K_{22}-K_{21}\cdot K_{12}}=-\frac{21{,}421}{13{,}626}=-1{,}5720733614$$
$$D_{21}=\frac{K_{31}\cdot K_{23}-K_{21}\cdot K_{33}}{K_{22}\cdot K_{33}-K_{32}\cdot K_{23}}=-\frac{8{,}586}{10{,}686}=0{,}8034811903$$
$$D_{23}=\frac{K_{23}\cdot K_{11}-K_{13}\cdot K_{21}}{K_{12}\cdot K_{21}-K_{22}\cdot K_{11}}=\frac{-3{,}7482}{-13{,}6257}=0{,}275083115$$
$$D_{31}=\frac{K_{31}\cdot K_{22}-K_{21}\cdot K_{32}}{K_{23}\cdot K_{32}-K_{33}\cdot K_{22}}=-\frac{1{,}2298}{10{,}686}=-0{,}1150851582$$
$$D_{32}=\frac{K_{32}\cdot K_{11}-K_{12}\cdot K_{31}}{K_{13}\cdot K_{31}-K_{33}\cdot K_{11}}=-\frac{10{,}1484}{3{,}4056}=-2{,}9799154334$$

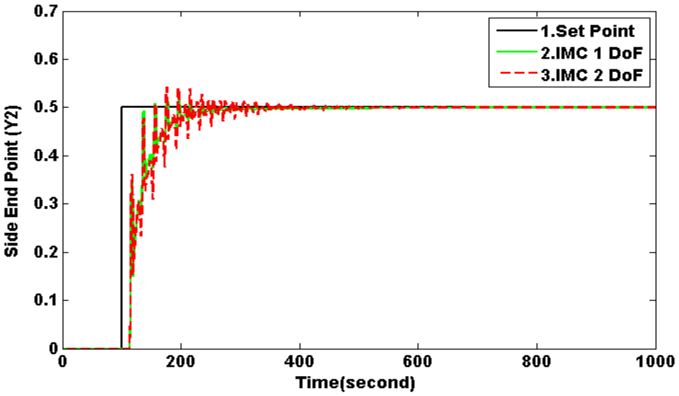
3. RESULTS AND ANALYSIS

3.1 *Set Point Tracking Testing*

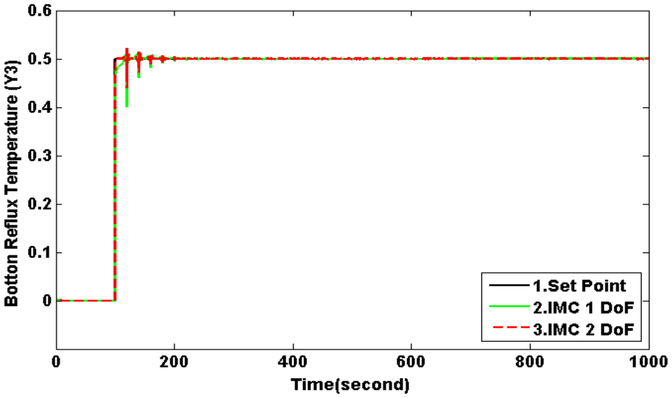
In this section, set point y_1, y_2, dan y_3 were raised respectively by 0,5. The simulation runs within 1000 seconds. Test resultset point tracking of SHOF control with 1DoF IMC and 2DoF IMC is shown in Figure 5



(a) Response of Top End Point Composition(y_1).



(b) Response of Side End Point Composition(y_2).



(c) Response of Bottom Reflux Temperature(y_3).

Figure 5. set point trackingy_1+0,5, y_2+0,5, dan y_3+0,5

Based on the graph of the system response in Figure 5, it can be seen that the 1DoF IMC and 2DoF IMC controller used to control the multivariable SHOF system can follow the set point changes on y_1, y_2, dan y_3 that change at the same time and can achieve stability.

1DoF and 2DoF IMC performance comparison analysis use Rivera's tuning method of set point increase of y_1, y_2, dan y_3 respectively of +0.5 based on IAE shown by Table 4. Base on IAE value on Table 5, 2DoF IMC Control Method has a smaller IAE value compared to 1DoF IMC. 2DoF IMC IAE values respectively 44,4454 at y_1, 19,2279 at y_2, and 0,1483 at y_3. 1DoF IMC IAE values respectively 53,9622 at y_1, 17,4733 at y_2, dan 0,53 aty_3.

Table 4. IAE Value on *set point tracking Test*

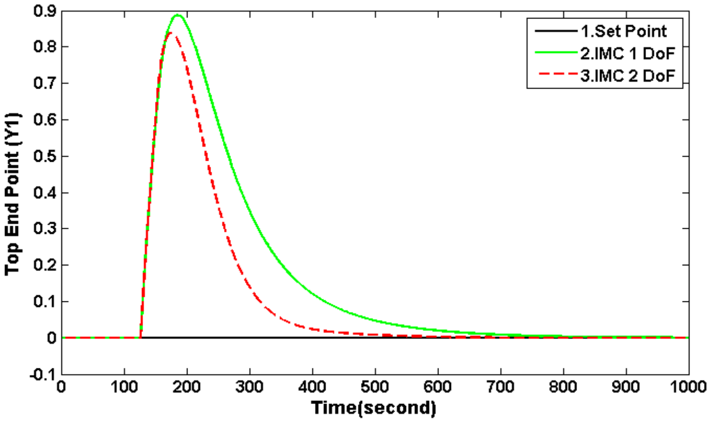
Control Method	**IAE** $\mathbf{d_1 + 0,5, dan\ d_2 + 0,5}$ $\mathbf{when y_1 + 0,5, y_2 + 0,5, dan\ y_3 + 0,5}$ y_1	y_2	y_3
1DoF IMC	53,9622	17,4733	0,53
2DoF IMC	**44,4454**	**19,2279**	**0,1483**

3.2 Disturbance Rejection Testing

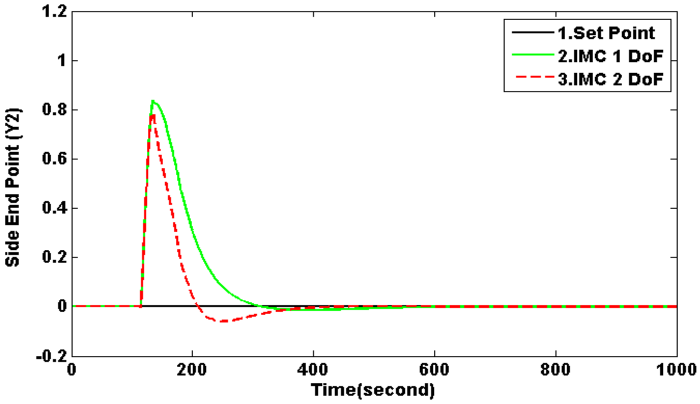
In this section, the system was given disturbance of Intermediate reflux duty (d1) and upper reflux duty (d2) each of +0,5.The simulation runs within 1000 seconds.The results of the SHOF control test with 1 DoF IMC and 2DoF IMC with disturbance are shown in Figure 6.

The system response graph of Figure 6 shows that the 1DoF IMC and 2DoF IMC controllers can reduce the disturbance, *Intermediate reflux duty* (d1) and upper reflux duty (d2), then return the top end point composition response (y_1), side end point composition response, and bottom reflux temperatur at the specified set point(y_3).

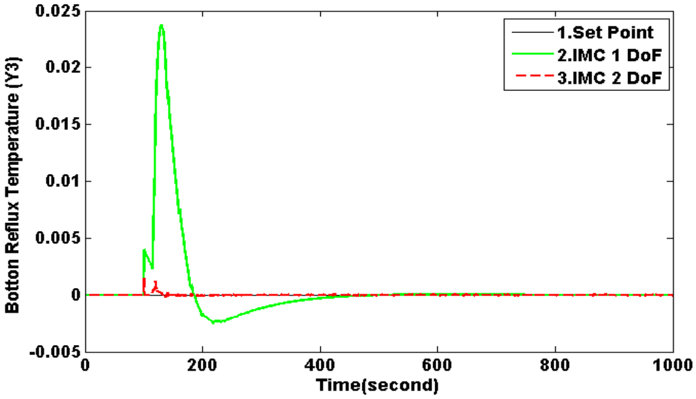
Comparison of 1DoF IMC and 2DoF IMC performance with Rivera tuning on disturbance input of *Intermediate reflux duty* (d_1)dan*upper reflux duty* (d_2 of each +0,5 based on IAE is shown by Table 5.



(a) Response of Top End Point Composition(y_1).



(b) Response of Side End Point Composition(y_2).



(c) Response of Bottom Reflux Temperature(y_3).

Figure 6. Disturbance rejection testingd_1+0,5 dan d_2+0,5, when*set point*y_1+0,5, y_2+0,5, andy_3+0,5

Tablel 5. IAE Value of Disturbance Rejectiorn Testing

Control Method	**IAE** $\mathbf{d_1 + 0,5,\ and d_2 + 0,5}$ $\mathbf{when y_1 + 0,5,\ y_2 + 0,5,\ dan\ y_3 + 0,5}$ y_1	y_2	y_3
1DoF IMC	142,4342	62,0389	1,1231
2DoF IMC	**93,9574**	**40,0455**	**0,0099**

According to Table 5, the 2DoF IMC control method has the smallest IAE value compared to 1DoF IMC. The IAE value on 2 DoF IMC are 93,9574 at y_1, 40,0455 at y_2, and 0,0099 at y_3. The IAE value on 1DoF IMC are 142,4342 at y_1, 62.0389 at y_2, and 1,1231 at y_3.

4. CONCLUSION

Based on test, it can be concluded that the 2 DoF IMC controller used in SHOF is able to following set point tracking and eliminate the disturbances. On testing with step input without disturbance, the best of settling time value is achieved using 2DoF IMC controller , with respective values of 442,0999 in response to y_1 , 345,0340 in response to y_2 and 153.2749 in response to y_3. On Disturbance Rejection Testing, 2DoF IMC shows the best performance compared to 1DoF IMC with IAE value respectively 44,4454 at y_1,19,2279 at y_2, and 0,1483 at y_3 on set point tracking test, and IAE value 93,9574 at y_1, 40,0455 at y_2, and 0,0099 at aty_3 on disturbance rejection test.

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