Control of TITO Process using Internal Model Control Technique

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Abstract - **This paper presents an Internal Model Control technique for TITO process with different decoupling schemes and comparing the response with each other. A system which has multiple inputs & multiple outputs is called as MIMO system. In industries most of the systems are of MIMO type e.g. Chemical reactors, heat exchangers, distillation column. In this paper Binary distillation column has been taken as a TITO process and its reference model is taken from model given by Wood and Berry. Conventional and Inverted Decoupling schemes are used to reduce the interactions and by varying the single tuning parameter (λ) of Internal Model Control (IMC) technique the set-point is trying to achieve.**

Index Terms – TITO process, Binary Distillation Column, Conventional Decoupler, Inverted Decoupler, Internal Model Control, Disturbances.

1. INTRODUCTION

Distillation is a process in which a mixture consisting of two or more miscible components is separated out on the basis of their volatility or B.P. If a mixture of methanol and water undertakes distillation process, the higher volatile component (methanol) will vaporize rapidly than water under the same atmospheric pressure [1, 2]. There are 3 sections in distillation column Feed section, rectifying/enriching section, stripping/exhaust section. The internal column is used to enhance separation quality, it consists different types of trays like sieve tray, chimney tray, valve tray, bubble cap etc. and also has different packing like structural packing and random packing, they provide maximum surface area and maximize the heat & mass transfer between downward flowing liquid & vapor. The trays between the feed and top of vertical column is called rectifying section & vice-versa is stripping section. In rectifying section lighter components (more volatile) is removed and in stripping section the heavier component (less volatile) is removed. Firstly in preheater mixture is heated under pressure just below the B.P. the pressure in tower is kept lower than that of preheater, so when feed enters the tower it starts boiling, the vapors from boiling liquid which contains lighter component in feed, rises up in the tower the remaining liquid which contain primarily the heavier component in feed goes down the tower & collected to bottom some of the liquid is drawn off as a bottom product & some of it is given to re-boiler, which is connected to bottom of a tower [3, 4]. The re-boiler is mainly a heat exchanger which is considered to vaporize lighter components that remain in liquid from the bottom of the tower. Vapors from re-boiler, reenters the tower & rises up, these vapors & the heat they contain is called boil up, the hot boil up provides heat that needed for distillation, the vapor which rises up is gone to a condenser, the condenser cool & condense the vapors into liquid, a part of liquid is stored as overhead product & rest is pumped back into top of tower the reintroduced liquid is called external reflux , it is cooler than the liquid in the top of tower so vapor made of heavier fractions are condensed & liquid made of heavier fraction flows down the tower & called as internal reflux [4,5].

2. DISTILLATION COLUMN

The basic diagram is shown below. The temperature of distillation column decreases as materials moves higher in tower the steady decrease in temperature from top bottom to top is called as temperature gradient [6]. Here the controlled variable is mole fraction of top & bottom product manipulated variables are external reflux & boil up, and the disturbances are feed compositions & feed flow rate. The middle loop creates interactions between upper & lower loop, also in between manipulated variables & controlled output.

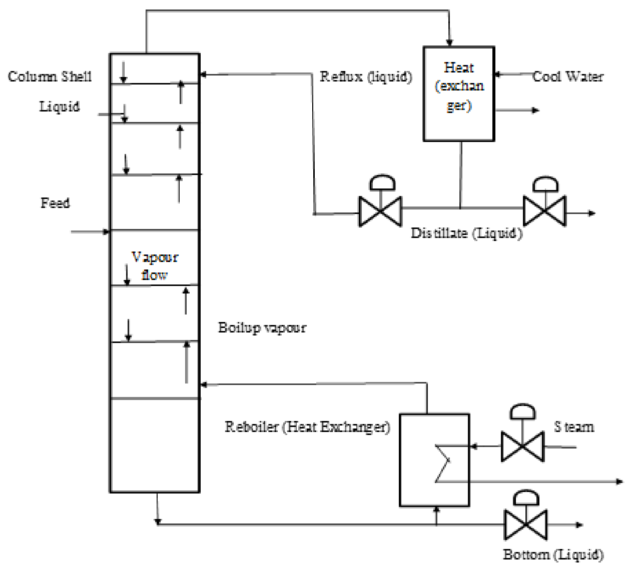

Fig. 1 Distillation Column

$$G(S)=\frac{K}{(\tau S+1)^n}e^{-DS}$$ Where n belongs to integer (2.1)

$$G(S)=\frac{K}{(\tau_1 S+1)(\tau_2 S+1)}e^{-DS} \quad (2.2)$$

Where τ_1, τ_2 & τ are constants

3. INTERNAL MODEL CONTROL SYSTEM

The block diagram of feedback control system is given in Fig. 2

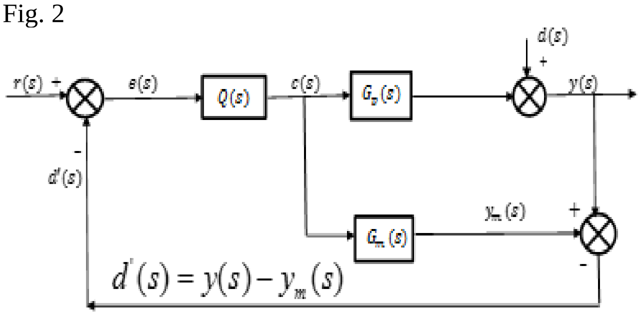

Fig. 2 Block diagram of IMC

where $Q(s)$ is the primary controller (IMC) transfer function, $G_P(s)$ is the process transfer function, $G_m(s)$ is the process model transfer function, $r(s)$ is set point, $e(s)$ is error $c(s)$ is manipulated variable, $d(s)$ is disturbance, $y_m(s)$ is model output and $y(s)$ is controlled variable (process output), $d^{'}(s)$ is estimated disturbances.

Internal Model Control Systems are categorized by a control system involving of the controller and of a simulation of the process, the internal model [7, 8]. IMC controller is an advance model based controller in which dynamics of model is also incorporated in its control law, it has one only one degree of freedom (λ). It tracks set point and also care about process- model mismatch & disturbance rejection, where as a general PID control is a model free controller and it only tries to tracks given set point and doesn't care about the above.

3.1 IMC strategy

There are three IMC strategies and these are as follows:

3.2 Model is accurate and has zero Disturbance

If the model is accurate then we have $G_m(s)=G_p(s)$ and there is no effect of disturbance $(d(s)=0)$ then according to Fig. 2 feedback signal becomes zero. Hence correlation between input and output is given by the expression which is given below

$$y(s)=G_P(s)Q(s)r(s) \quad (3.1)$$

This is corresponding to open loop control strategy proposal

3.3 Model is accurate and Disturbance effects the Process

If the model is accurate which gives $G_m(s)=G_P(s)$ and there is disturbance,

Hence, feedback signal is $d^{'}(s)=d(s)$ then output is given by

$$y(s)=G_P(s)Q(s)r(s)+\left(1-G_m(s)Q(s)\right)d(s) \quad (3.2)$$

3.4 Model Ambiguity & zero Disturbance

If there is zero disturbance $d(s)$ but model ambiguity $G_P(s)\neq G_m(s)$ occurs then the feedback signal is

$$d^{'}(s)=\left(G_P(s)-G_m(s)\right)u(s) \quad (3.3)$$

Hence process output

$$y(s)=\left[\frac{G_P(s)Q(s)}{1+Q(s)\left(G_P(s)-G_m(s)\right)}\right]r(s)+\left[\frac{1-G_m(s)Q(s)}{1+Q(s)\left(G_P(s)-G_m(s)\right)}\right]d(s) \quad (3.4)$$

3.5. Design Procedure of IMC

We discern that dynamic controller [9] gives faster reaction than the static controller so we use dynamic control by-law. Hence

$$Q(s)=\frac{1}{G_P(s)} \quad (3.5)$$

This is only applicable for stable process which has zero time delay. Now we have to attention on designing the IMC for time delay system. The controller strategy has been comprehensive to the following step.

Firstly we identify the process model & convert it into invertible (decent stuff) and non-invertible (useless stuff which is demarcated by time delays and right hand plane Zeroes) by applying all pass factorization or simple formulation [10]. Inverse the invertible portion of the process model and to mark appropriate we multiply it with the filter transfer function [11].

$$Q(s)=\frac{1}{G_m(s)}f(s) \quad (3.6)$$

Where $f(s)=\frac{1}{(\lambda s+1)^n}$ filter transfer function [11], n is a constant (1, 2, 3 …..).We choose it accordingly to make the controller proper or semi proper.

3.6 Calculation of tuning parameter of PI controller $K_{P,}K_i$ in terms of IMC tuning parameter (λ).

Let $G_{IMC}(S)$ is transfer function of IMC controller, $G_m(s)$ is transfer function of reference model of process, Q(S) is open loop gain of IMC controller, $G_P(s)$ is transfer function of a process, F(S) is filter transfer function. Now we find the expression of PI controller tuning parameter in terms of tuning parameter of IMC controller [12, 13].

$$G_{IMC} = \frac{Q(s)}{1 - G_m(s)Q(s)} \quad (3.7)$$

$$Q(s) = \frac{1}{G_m(s)} f(s) \quad (3.8)$$

$$G(s) = \frac{ke^{-ST_D}}{\tau s + 1} \quad (3.9)$$

e^{-ST_D} is non invertible term so we will neglect it [14].

$$f(s) = \frac{1}{(\lambda s + 1)^n} \quad (3.10)$$

$f(s)$ is used to make the transfer function $Q(s)$ at least semi proper, n is the order of plant here we take n=1, and λ is chosen in between 0.5 to 0.67 times dominant time constant [15].

$$Q(s) = \frac{\tau s + 1}{K} \times \frac{1}{\lambda s + 1} \quad (3.11)$$

$$G_{IMC} = \frac{\dfrac{\tau s + 1}{k(\lambda s + 1)}}{1 - \dfrac{k}{(\tau s + 1)} \times \dfrac{(\tau s + 1)}{k(\lambda s + 1)}} = \frac{\tau s + 1}{k\lambda s} \quad (3.12)$$

$$\Rightarrow \frac{\tau}{k\lambda} + \frac{1}{k\lambda s} \Rightarrow \frac{\tau}{k\lambda}\left(1 + \frac{1}{\tau s}\right) = k_P\left(1 + \frac{1}{\tau_i s}\right)$$

By comparing this result with transfer function of PI controller we get

$$k_P = \frac{\tau}{k\lambda} \; and, \tau_i = \tau \text{, So } k_i = \frac{1}{\tau_i} \quad (3.13)$$

4. DECOUPLER DESIGN

4.1 Conventional Decoupling

TITO is basically a coupled system, so we use decoupler to reduce the process & control loop interactions. We have designed a decoupler, the best input output pair is found by relative gain array method which is introduced by Bristol in 1966 [16]. After converting the TITO process into two SISO by using decoupler we uses nyquist criterion for finding stability. Consider a TITO process with Conventional Decoupler,

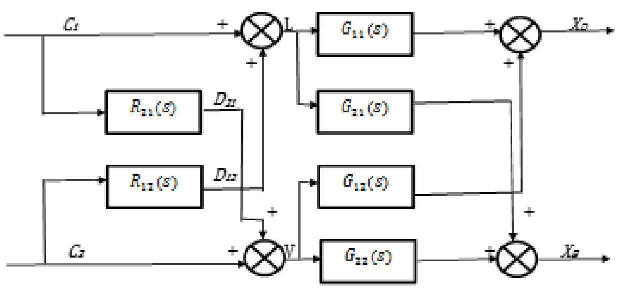

Fig 3. Conventional Decoupler

Decoupler transfer function matrix = $D(s)$

Output matrix = $X(s)$

Filter transfer functions = $f_1(s), f_2(s)$

Controller output matrix = $C(s)$

The relation between input and output matrix is given by

$$X(s) = G(s)D(s)C(s) \quad (4.1)$$

$$\text{Where } G(s) = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \quad (4.2)$$

$$D(s) = \begin{bmatrix} 1 & R_{12}(s) \\ R_{21}(s) & 1 \end{bmatrix} \quad (4.3)$$

Here we take $R_{11}(s) \,\&\, R_{22}(s) = 1$

$$X(s) = \begin{bmatrix} X_D(s) \\ X_B(s) \end{bmatrix} \& \, C(s) = \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} \quad (4.4)$$

So,

$$\begin{bmatrix} X_D(s) \\ X_B(s) \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \begin{bmatrix} 1 & R_{12}(s) \\ R_{21}(s) & 1 \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} \quad (4.5)$$

$$\begin{bmatrix} X_D(S) \\ X_B(s) \end{bmatrix} = \begin{bmatrix} G_{11}(s) + G_{12}(s)R_{21}(s) & G_{12}(s) + G_{11}(s)R_{12}(s) \\ G_{21}(s) + G_{22}(s)R(s) & G_{22}(s) + G_{21}(s)R_{12}(s) \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} \quad (4.6)$$

Decoupling of the TITO process requires the design of a transfer matrix $D(s)$ such that $G(s)D(s) = P(s)$ is a diagonal matrix [17]. Only then we can remove the interactions between upper and lower loop of TITO, for this we have to make following terms equal to zero,

$$G_{12}(s) + G_{11}(s)R_{12}(s) = 0 \quad (4.7)$$

$$G_{21}(s) + G_{22}(s)R_{21}(s) = 0 \quad (4.8)$$

Then we get,

$$R_{12}(s) = \frac{-G_{12}(s)}{G_{11}(s)} \quad (4.9)$$

$$R_{21}(s) = \frac{-G_{21}(s)}{G_{22}(s)} \quad (4.10)$$

By putting the values of $R_{12}(s) \,\&\, R_{21}(s)$ in equation of $D(s)$ we can easily find the decoupling matrix for any decoupler.

Now calculation of IMC controller transfer function for TITO process.

$$P(s) = G(s)D(s) = \begin{bmatrix} G(s) + G(s)R(s) & 0 \\ 0 & G(s) + G(s)R(s) \end{bmatrix} \quad (4.11)$$

$$\text{Or, } \; P(s) = \begin{bmatrix} G_{m11}(s) & 0 \\ 0 & G_{m22}(s) \end{bmatrix} \quad (4.12)$$

Now we can easily find transfer function of IMC controller $G_{c1}(s)\,\&\,G_{c2}(s)$ for upper and lower loop of TITO process by using formulae,

$$G_{c1}(s) = \frac{Q_1(s)}{1 - G_{m11}(s)Q_1(s)} \quad (4.13)$$

$$G_{c2}(s) = \frac{Q_2(s)}{1 - G_{m22}(s)Q_2(s)} \quad (4.14)$$

Where

$$Q_1(s) = \frac{1}{G_{m11}(s)} f_1(s) \quad (4.15)$$

$$Q_2(s) = \frac{1}{G_{m22}(s)} f_2(s) \quad (4.16)$$

4.2 Inverted Decoupling

Inverted decoupling is also a method to remove interactions, it gives more accurate result than conventional decoupling technique.

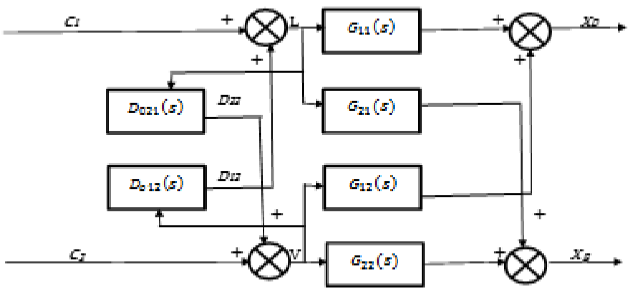

Fig. 4 Inverted Decoupler

Its decoupling transfer matrix is

$$D(s) = \begin{bmatrix} 1 & D_{12}(s) \\ D_{21}(s) & 1 \end{bmatrix} \quad (4.17)$$

The value of $D_{12}(s)\,\&\,D_{21}(s)$ are find by similar method as used for conventional decoupling, and we get the same results.

$$D_{12}(s) = \frac{-G_{12}(s)}{G_{11}(s)} \quad (4.18)$$

$$D_{21}(s) = \frac{-G_{21}(s)}{G_{22}(s)} \quad (4.19)$$

5. SIMULATION RESULTS OF WOOD AND BERRY DISTLLATION COLUMN

The transfer matrix of wood & berry distillation column is shown below its all transfer functions are FOPDT type.

$$G(S) = \begin{bmatrix} \dfrac{12.8}{16.7s+1}e^{-s} & \dfrac{-18.9}{21s+1}e^{-3s} \\ \dfrac{6.6}{10.9s+1}e^{-7s} & \dfrac{-19.4}{14.4s+1}e^{-3s} \end{bmatrix} \quad [18]$$

5.1 With Load disturbance & with Conventional Decoupler

I have taken a transfer matrix of a well-accepted reference model of a binary distillation column as a TITO process and by using different decoupling technique like conventional and inverted I have made simulation model, we also add two disturbances at a particular time of 150 sec in upper loop of TITO and at 75 sec in lower loop of TITO then I have recorded the responses by running the simulation model for different values of IMC tuning parameter (λ). I have shown the simulation graphs and tables for both top and bottom composition of binary distillation column below.

5.1.1 Top Composition

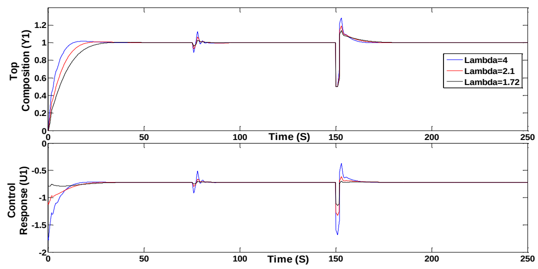

Fig 5 - Top Composition Response & Controller Response with Conventional Decoupler

Fig 5 shows top composition (Y1) and manipulated variable (U1) when we apply with load disturbance & with conventional decoupler. The load disturbance or interaction of loop 2 on loop 1 is minimized by conventional decoupler D21 here we want to observe the minimization of interaction parts that's why we keep the same values of lambda, proportional control action and integral control actions [19].

Table 1: Performance Indices (Top Composition)

lambda	k_P	k_i	IAE	ITAE	TV
4	0.326	0.019	9.516	413.4	0.129
2.1	0.604	0.030	7.909	561.8	0.403
1.72	0.760	0.045	10.10	795.7	0.700

Table above shows IAE and ITAE values for loop 1 for different types of lambda values. For different values of lambda, we get different values of proportional and integral control action values.

5.1.2 Bottom Composition

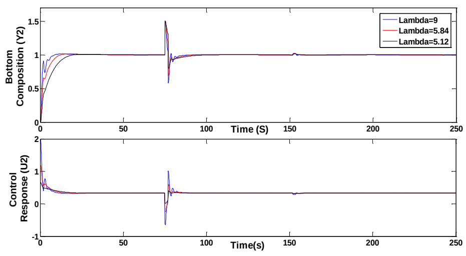

Fig 6- Bottom Composition Response & Controller Response with Conventional Decoupler

Fig 6. Shows top composition (Y2) and manipulated variable (U2) when we apply both load disturbances and conventional decoupler. The load disturbance or interaction of loop 1 on loop 2 is minimized by conventional decoupler D12. Here we observed that the interaction can be minimized by using conventional decoupler.
Here we want to observe the minimization of interaction parts that's why we keep the same values of lambda, proportional control action and integral control actions.

Table 2: Performance Indices (Bottom Composition)

lambda	k_P	k_i	IAE	ITAE	TV
9	-0.082	-0.006	18.09	466.7	0.0257
5.84	-0.127	-0.009	13.04	346.3	0.058
5.12	-0.125	-0.010	11.09	348.8	0.071

Table above shows IAE and ITAE values for loop 2 for different types of lambda values. For different values of lambda, we get different values of proportional and integral control action values [20]. We also find stability using Bode plot, that's why we also attached the values of gain margin and phase margin. The values of GM and PM shows the system stable.

- Lambda=4, Lambda=9 (Recommended by B. Wayne Bequette)
- Lambda=2.1, Lambda=5.84 (Recommended by Dale E. Seborg & Thomas F. Edgard)
- Lambda=1.72, Lambda=5.12 (Recommended by Morari & Zafirion)
- 1st Load Disturbance is +ve step of (0 to 0.5) at 75 sec & -ve step of (0 to 0.5) at 77 sec
- 2nd Load Disturbance is –ve step of (0 to 0.5) at 150 sec & +ve step of (0 to 0.5) at 152 sec

5.2 With Load disturbance & With Inverted Decoupler

5.2.1 Top Composition

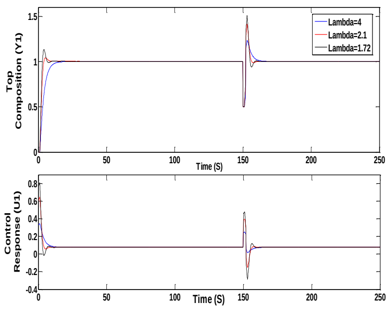

Fig 7 - Top Composition Response & Controller Response with Inverted Decoupler

Fig 7 shows the top composition (Y1) and controller response (U1) for loop 1 when inverted decoupler use. Inverted decoupler used to minimize of interactions between two loops. Inverted decoupler provides better response than conventional decoupler.
For Inverted decoupler we had chosen same values of lambda. So that we can compare both the responses.

Table 3: Performance Indices (Top Composition)

lambda	k_P	k_i	IAE	ITAE	TV
4	0.326	0.019	5.986	301.4	0.108
2.1	0.604	0.037	4.389	289.4	0.237
1.72	0.760	0.045	4.353	307.2	0.339

Table above shows IAE and ITAE values for loop 1 for different types of lambda values. For different values of lambda, we get different values of proportional and integral control action values.

5.2.2 Bottom Composition

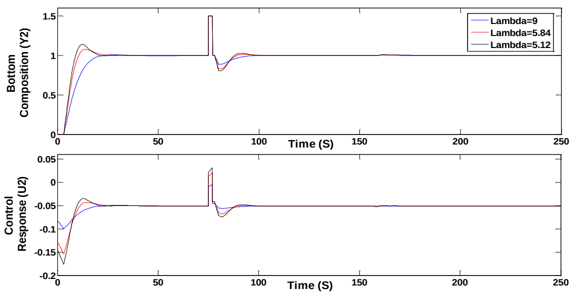

Fig. 8 - Bottom Composition Response & Controller Response with Inverted Decoupler

Fig.8 shows the top composition (Y2) and controller response (U2) for loop 2 when inverted decoupler use. Inverted decoupler used to minimize of interactions between two loops.
Inverted decoupler provides better response than conventional decoupler.
For Inverted decoupler we had chosen same values of lambda. So that we can compare both the responses.

Table 4: Performance Indices (Bottom Composition)

lambda	k_P	k_i	IAE	ITAE	TV
9	-0.082	-0.006	11.18	241.8	0.025
5.84	-0.127	-0.009	9.19	224.9	0.045
5.12	-0.145	-0.010	9.146	234.1	0.055

Table above shows IAE and ITAE values for loop 2 for different types of lambda values. For different values of lambda, we get different values of proportional and integral control action values. We also found the stability using Bode plot, that's why we also attached the values of gain margin and phase margin. The values of GM and PM shows the system is stable [21].

- Lambda=4, Lambda=9 (Recommended by B. Wayne Bequette)

- Lambda=2.1, Lambda=5.84 (Recommended by Dale E. Seborg & Thomas F. Edgard)
- Lambda=1.72, Lambda=5.12 (Recommended by Morari & Zafirion)
- 1st Load Disturbance is +ve step of (0 to 0.5) at 75 sec & -ve step of (0 to 0.5) at 77 sec
- 2nd Load Disturbance is –ve step of (0 to 0.5) at 150 sec & +ve step of (0 to 0.5) at 152 sec

6. CONCLUSION

PID controller has 3 degree of freedom (k_p, k_i & k_d) for TITO system it becomes 6 (including both PID) so it is difficult to synchronise all the parameters at the same time, also it is model free controller means it doesn't care about process- model mismatch & disturbance rejection it only tries to track given set point - for its solution we use IMC controller which is an advance model based controller in which dynamics of model is also incorporated in its control law, it has one only one degree of freedom (λ), and it also solves the above problem [21]. Moreover using IMCs, rise time will be decreased, faster response and disturbance compensation and able to compensate the model uncertainty. We also observed from the graph if the values of lambda is high (that means if the values of proportional control action and integral control action low) then the overshoot of the response will be low but rise time will be high and oscillation will be less. But if the value of lambda is low (that means if the value of proportional control action and integral control action high) then the overshoot of the response will be high but rise time will be low and oscillation will be more. We also observed from the graph that inverted decoupler is better than the conventional decoupler. When we use inverted decoupler then it can eliminate the interaction between two loops completely. It is an advantage of inverted decoupler over conventional decoupler.

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