International Journal of Pure and Applied Mathematics
Volume 118 No. 9 2018, 413-419
ISSN: 1311-8080 (printed version); ISSN: 1314-3395 (on-line version)
url: http://www.ijpam.eu
Special Issue
ijpam.eu

EXPERIMENTAL VALIDATION OF PI CONTROLLER BASED ON POLE PLACEMENT FOR A BATCH DISTILLATION COLUMN

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***Abstract*— The article presents the decentralized Proportional Integral (PI) controller which is designed and implemented with decoupler for a Batch Distillation Process. Decoupler is used to minimize the interaction combining it with decentralized control algorithm. In order to minimize the loop interaction between the loops, an ideal decoupling technique is implemented on a First Order Plus Dead Time (FOPDT) model. The PI controller is designed using Pole Placement technique. The simulation of Pole Placement technique has been adopted to study the main effect and the interaction effect of the Batch Distillation Column. The controller is designed and implemented on a Batch Distillation Column.**

Keywords— Decentralized PI controller, Decoupler, First Order Plus Dead Time, Pole Placement, TITO process, Interaction process, Real-time application.

I. INTRODUCTION

The Two Input Two Output (TITO) process system are commonly controlled using PI/PID controllers [1-2]. Control of TITO process is complex when compare to Single Input Single Output (SISO) process because of interactions among the loops. The decentralized control techniques results in less interaction, good stability, reliability, hardware simplicity, easy operation, good performance over its counterparts [3-6]. Centralized control system is having the limitation that, if one sub loop fails there is a risk system to perform poor or results with unstable response. Decoupler ensure that for an Multi Input Multi Output (MIMO) system, the above mentioned problem never occurs and has minimum interaction while pairing [7-8]. Decentralized PI controller has two major issues namely pairing problem and tuning problem [3]. The reduced loop interaction can be achieved by proper paring of manipulated variables and controlled variables [9-10]. The other methods which are used for controlling TITO systems are detuning, sequential loopshaping, relay auto tuning and independent loop method [11-13]. The article presents a decentralized PI control technique for effective control of the identified distillation column transfer function matrix [4].Pole Placement technique is used for tuning decoupled PI controller [14-16].

The article is extended in following sections: section II describes steps involved in the decoupler design procedures, section III dedicated to the controller design. Simulation and experimental result are presented and discussed in section IV, followed by conclusion is drawn in section V.

A. MOTIVATION

Decoupler ensure that MIMO system has minimum interaction while pairing of Input /Output (I/O). Decentralized PI controller provides good performance and stability margin.

II. DECOUPLER

To maximize the independent operation between two loops, the decentralized controller is designed using decoupler method. An additional controller is introduced along with PI decentralized controllers to compensate for any interaction [4]. In a TITO system the reboiler power rate and reflux flow rate are the two manipulated variables, and tray-1 and tray-5 are the controller variables [14]. The distillation process G(s) is with decoupler is shown in Figure1.

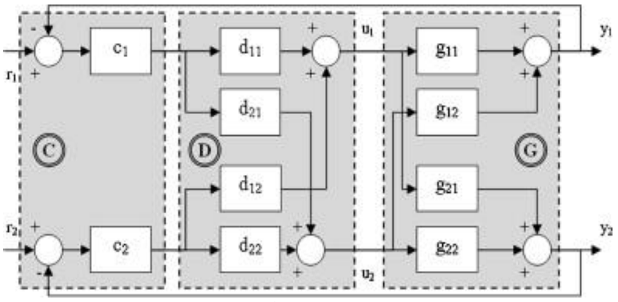

Fig 1. Block Diagram of TITO Process with Decoupler

Consider the system shown in Fig.1 and explained by Equation 1

$$G(s)=\begin{bmatrix} g_{11}(s)e^{-\tau_{11}s} & g_{12}(s)e^{-\tau_{12}s} \\ g_{21}(s)e^{-\tau_{21}s} & g_{22}(s)e^{-\tau_{22}s} \end{bmatrix} \quad (1)$$

The maximum independency between loops is enhanced by having the off-diagonal elements of the process equation without RHP poles and diagonal elements without RHP zeros. The matrix for decoupling is as follows:

$$D(s)=\begin{bmatrix} v_1(s) & d_{12}(s)v_2(s) \\ d_{21}(s)v_1(s) & v_2(s) \end{bmatrix} \quad (2)$$

Where

$$v_1(s)=\begin{cases} 1, & \tau_{21}\geq\tau_{22} \\ e^{(\tau_{21}-\tau_{22})} & \tau_{21}\leq\tau_{22} \end{cases}$$

$$v_2(s)=\begin{cases} 1, & \tau_{12}\geq\tau_{11} \\ e^{(\tau_{12}-\tau_{11})} & \tau_{12}\leq\tau_{11} \end{cases}$$

$$d_{12}(s)=\frac{-g_{12}(s)}{-g_{11}(s)}e^{-(\tau_{12}-\tau_{11})s}$$

$$d_{21}(s)=\frac{-g_{21}(s)}{-g_{22}(s)}e^{-(\tau_{21}-\tau_{22})s} \quad (3)$$

As shown in Equation (4), $Q(s)$ is a diagonal matrix:

$$Q(s)=G(s)*D(s) \quad (4)$$

The decoupled elements $q_i(s)$ are used for controlling the decentralized PI controllers.

III. DESIGN OF POLE PLACEMENT CONTROLLER

In the tuning process of PI controller, $q_1(s)$ and $q_2(s)$ were approximated to FOPDT model as given below:

$$l_i=\frac{k_p e^{-\tau_d s}}{Ts+1} \quad (5)$$

Where k_p = gain of the process, τ_d = delay time in the process, T =time constant of the system, and $i,n=1,2$

We find k_p by using q_n in the diagonal matrix as shown:

$$k_p=q_n(0)$$

Calculate time constant T by using:

$$T=\frac{\sqrt{\left(\frac{q_n(0)}{|q_n(j\omega_c)|}\right)^2-1}}{\omega_c} \quad (6)$$

Then using time delay in the controller as shown:

$$\tau_d=\frac{\pi-\tan^{-1}(T\omega_c)}{\omega_c} \quad (7)$$

Where,

q_n =diagonal element of $Q(s)$

ω_c =crossover frequency

By using bode diagrms of reduced and higher order models, the value of $\omega_c, |q_n(j\omega_c)|$ where calculated. This value is used for obtaining the values of gain cross over frequency and magnitude cross over frequency by using $q_1(s)$ and $q_2(s)$ [18].

If the control system designed specification are provided by time domain specifications of step response in closed loop, the overshoot can be modified using preferred damping ratio [14].

$$T_s=T_{ii}\left(4.5+7.5\frac{\tau_{ii}}{T_{ii}}\right)\left(\frac{0.35}{\xi}+0.5\right) \quad (8)$$

For the FOPDT model of TITO system, the Pole Placement PI controller setting are given by:

$$\omega_{ni}=\frac{4}{\xi T_s} \quad (9)$$

Where ξ =damping ratio,

ξ range is 0.7 to 1 mostly 0.707 is used [14].

Calculate dominant poles:

$$\theta_{1,2}=-p\pm qi \quad (10)$$

Consider the desired characteristics equation given below:

$$s^2+2\xi\omega_n s+\omega_n^2=0 \quad (11)$$

The first order Taylor series approximation is used for obtaining the dead time value.

$$e^{-\tau_{ii}s} \tilde{=} \frac{1}{\tau_{ii}s+1}$$

Dead time approximated FOPDT model is given as follows:

$$G_{T,ii}^{FO}(s) = \frac{b_0}{s^2 + a_1 s + a_0} \qquad (12)$$

Where,

$$b_0 = \frac{K_{P,ii}}{(T_{ii} * \tau_{ii})}$$

$$a_1 = \frac{(T_{ii} + \tau_{ii})}{(T_{ii} * \tau_{ii})}$$

$$a_0 = \frac{1}{(T_{ii} * \tau_{ii})}$$

Let us assume the PI parameter K_P=1.866 for loop 1 and K_P=-1.249 for loop 2 to get better performance index while substituting any other values for K_P in pole placement method will result in larger performance index. The controller gain K_P is tuned for required performance of each loops and system stability for muti loop interactive system.

The characteristic equation of the system with unity feedback in closed loop is given by:

$$K_{ii}(s) G_{Tii}^{FO}(s) + 1 = 0 \qquad (13)$$

In the proposed controller design, the controller parameters K_P and K_I are tuned in such a way that the dominant complex conjugate poles are moved to the right of closed loop poles.

In above expression, $\theta_1 = -p + qi$ in equation 13,

$$\left(K_P + \frac{K_I}{(-p+qi)}\right)\left(G_{T,ii}^{FO}(-p+qi)\right) = -1 \qquad (14)$$

Separating real and imaginary parts of equation 14,

$$K_I = \frac{(p^2+q^2)(K_P - 2pZ_1)}{2p} \qquad (15)$$

Where,

$$Z_1 = \frac{1}{2p}\mathrm{Re}\,al\left\{\frac{-1}{G_{T,ii}^{FO}(-p+qi)}\right\} + \frac{1}{2q}\mathrm{Im}\,ag\left\{\frac{-1}{G_{T,ii}^{FO}(-p+qi)}\right\}$$

$$PI = \left[K_P + \frac{(p^2+q^2)(K_P - 2pZ_1)}{2ps}\right] \qquad (16)$$

$$G_{T,ii}^{FO}(s) = \begin{bmatrix} \dfrac{b_0}{s^2 + a_1 s + a_0} & 0 \\ 0 & \dfrac{b_0}{s^2 + a_1 s + a_0} \end{bmatrix}$$

IV. SIMULATION AND EXPERIMENTAL RESULTS

The designed PI controllers are simulated on a pilot plant Batch Distillation Column. The performance indices are tabulated along with the Smith Predictor method and Pole Placement techniques for comparison and analysis [15].

EXAMPLE

The mathematical model is identified by Vinaya and Arasu for a Batch Distillation Column is considered for simulation studies and implemented in real-time system [4]. The process transfer function model is:

$$G(s) = \begin{bmatrix} \dfrac{-0.13e^{-0.03s}}{1.14s+1} & \dfrac{0.18e^{-0.03s}}{0.64s+1} \\ \dfrac{-0.34e^{-1.22s}}{1.23s+1} & \dfrac{0.18e^{-0.03s}}{0.32s+1} \end{bmatrix}$$

The Decoupler matrix is designed by:

$$D(s) = \begin{bmatrix} 1 & \dfrac{1.3846(1.14s+1)}{0.64s+1} \\ \dfrac{1.888(0.32s+1)e^{-1.19s}}{1.23s+1} & 1 \end{bmatrix}$$

The resulting diagonal subsystem are:

$$q_1(s) = \frac{-0.13e^{-0.03s}}{1.14s+1} + \frac{0.3398(0.32s+1)e^{-1.22s}}{(0.64s+1)(1.23s+1)}$$

and

$$q_2(s) = \frac{0.18e^{-0.03s}}{0.32s+1} - \frac{0.47076(1.14s+1)e^{-1.22s}}{(1.23s+1)(0.64s+1)}$$

The FOPDT model of $l_1(s)$ and $l_2(s)$ are:

$$l_1(s) = \frac{0.21e^{-2s}}{1.35s+1}$$

and

$$l_2(s) = \frac{-0.29e^{-1.545s}}{0.735s+1}$$

The controller values designed using Pole Placement control techniques are provided in Table II [22][13] and performance analysis in Table III.

Table I. Frequency Response characteristics for a Batch Distillation Column

Parameters	$q_1(s)$	$l_1(s)$	$q_2(s)$	$l_2(s)$
Gain (dB)	0.21	0.21	-0.29	-0.29
Crossover frequency	1.0846	1.0849	0.02	0.01
Magnitude at cross over frequency	0.1182	0.1184	0.2903	0.2900

Table II. Pole Placement PI Controller Parameter for Top Tray Composition and Bottom Tray Composition

Parameters	**Loop-1**	**Loop-2**
K_C	1.866	-1.249
T_i	0.7914	0.7466

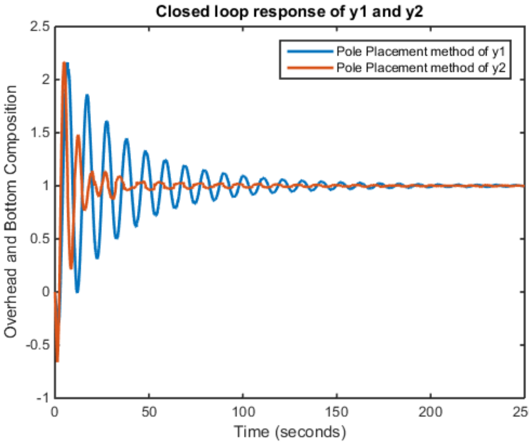

Fig. 2. Servo response in closed loop with SP-r1=1 and SP-r2=1

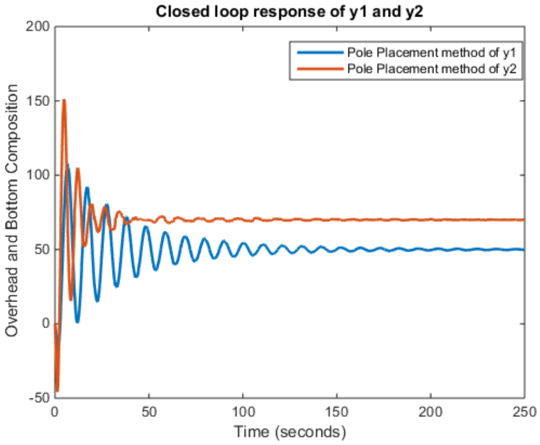

Fig 3. Servo response with closed loop SP-r1=50 and SP-r2=70

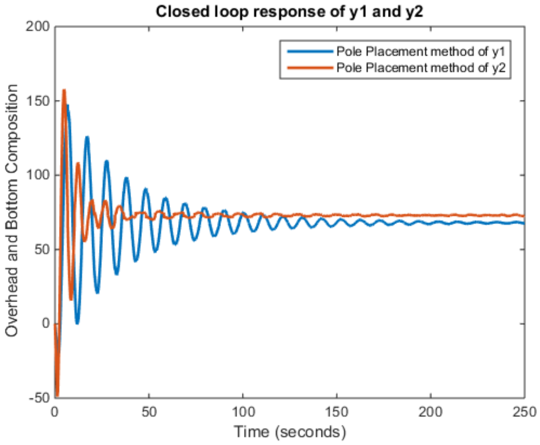

Fig. 4. Servo response with closed loop SP-r1=68 and SP-r2=73

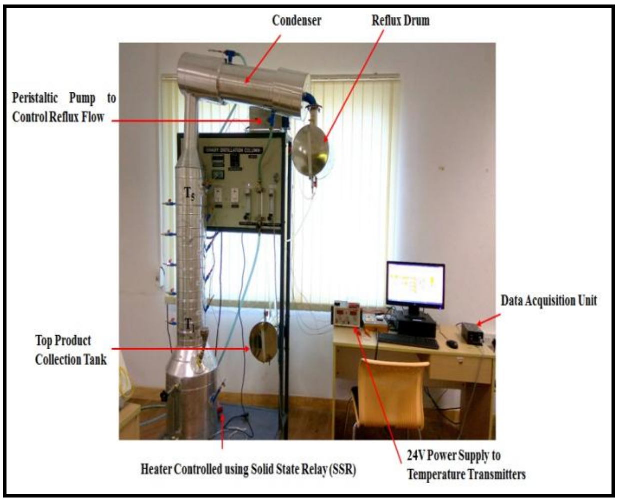

Fig. 5. Laboratory Setup of Binary Distillation Column

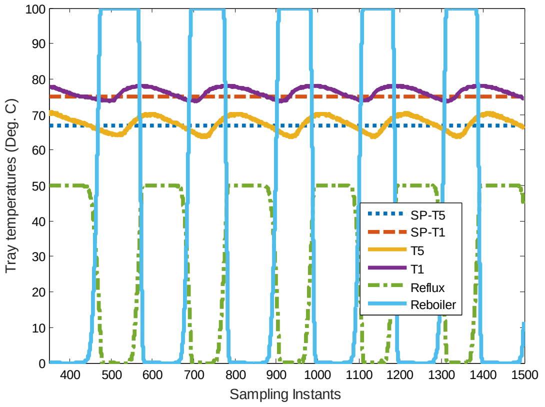

Fig. 6. Experimental validation of Pole Placement PI controller for a Batch Distillation Column

Fig. 6 shows the real-time implementation of the PI controller designed based on Pole Placement. Tray-5 is given 67 Deg. Cel as setpoint to track. The Tray-1 is given a setpoint change to track which starts from 75 Deg. Cel. Both the manipulated variables are also shown in the figure with respective captions.

Table III. Performance Analysis of Different Controllers

CONTROLLERS	IAE	ISE	ITAE	ISTE
NDT [23]	8.3	7.986	18.184	11.849
SIMC [23]	9.089	8.185	23.48	13.426
POLE PLACEMENT	45.22	24.527	1516.6	297.97

V. CONCLUSION

In this article the suitable decoupler and a decentralized PI controller is designed for a distillation process. The designed controller is validated in simulation and real-time. The frequency response specifications for two controllers along with controller parameters such as K_c and T_i are given in Table II. Fig. 2, Fig. 3 and Fig. 4 shows the closed loop servo response with different set points for a Distillation Column model.

The result analysis shows that 1-1 and 2-2 pairing of the manipulated and controlled variables. The performance indices of 3 different controllers namely, NDT, SIMC and Pole Placement algorithm are compared. The NDT algorithm results in better closed loop response with lesser overshoot and settling time. The closed loop servo response of NDT is better than all other controllers, which has been proved along with the performance index calculation tabulated in table IV.

VI. ACKNOWLEDGMENT

Santhosh Kumar P L would like to acknowledge the MAHE, Manipal, for permitting to do a collaborate project. Vinayambika S Bhat would like to thank Mangalore Institute of Technology and Engineering (MITE) for sponsoring the PhD programme. Also, the authors would like to thank Department of Instrumentation and Control Engineering, Manipal Institute of Technology, MAHE, Manipal, for providing the the real-time experimental facility for carrying out the post-graduation project.

VII. NOMENCLATURES AND ABBREVIATIONS

T : Time constant in hours
τ : Time delay in hours
K_P : Process gain
τ_d : Delay times
Q_n : Diagonal elements of Q(s)
ω_c : Crossover frequency
K_C : Proportional gain
T_i : Integral gain
PI : Proportional-Integral
$TITO$: Two Input Two Output
$MIMO$: Multi Input Multi Output
T_1 : Temperature of Tray-1, near the bottom of the column in Degree Celsius
T_5 : Temperature of Tray-5, near the top of the column in Degree Celsius
θ_{ii} : Time delay
τ_{ci} : Closed loop time constant
$FOPDT$: First Order Plus Dead Time
SP : Setpoint
PID : Proportional-Integral- Derivative
ξ : Damping Ratio
p : Real poles
q : Imaginary poles

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