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Design and Implementation of Decentralized Pi Controller for Pilot Plant Binary Distillation Column

Vinayambika S. Bhat[1], I. Thirunavukkarasu[2*], S. Shanmuga Priya[3]

[1, 2] Dept. of Instrumentation and Control Engineering,
[3] Dept. of Chemical Engineering, Manipal Institute of Technology, Manipal University, Karnataka-India

Abstract : The article presents a decentralized Proportional Integral (PI) controller for a pilot plant binary distillation column and discusses, the basic theory of the decentralized control technique. The Relative Gain Array (RGA) approach is used for input output pairing. The PI controller is designed based on process parameters such as time constant and time delay of the process transfer function matrix. The algorithm is compared with cross- control technique, and the performance is evaluated with Integral Square Error (ISE) and Integral Absolute Error (IAE)criteria. The simulation technique has been adopted to study the main effect and the interaction effect of the plant model for the identified distillation column. Moreover, servo and regulatory response are evaluated. Further, the simulated results are validated in real- time environment for the identified Two Input Two Output (TITO) distillation column model.

Keywords : Pilot Plant, Decentralized PI Controller, Relative Gain Array, Integral Square Error, Integral Absolute Error.

I. Introduction

The Proportional Integral Derivative (PID) control technique is one of the commonly used control technique, which has the advantages of simple structure, reliability, easy operation, and tuning along with fairly good control performance over its counterparts[1-4].It is evident from the available academic literature that more than 95% of the process industry uses thePI/PID control technique[5].The academic literature discusses several PI/PID control schemes for single or multi Input/Output (I/O) processes[6]. The control of the Multiple Input Multiple Output (MIMO) system is challenging because of loop interaction, multiple delays,etc[7, 8]. The interactive MIMO systems can be controlled either by centralized or decentralized control techniques[9].Complex structure and lack of integrity are the major drawbacks of the centralized control technique[10].The decentralized PI/PID control technique is most widely used in multivariable process control industries. This is mainly due toits hardware simplicity, easy tuning, and capacity to satisfy the control objectives.However, the control structure performance is limited because of interaction between the loops[11].This is due to the existence of non-zero off diagonal elements in the process plant transfer function matrix. The academic literature highlights two major issues of the decentralized controller,namely, pairing problem (to identify which output should be controlled by which input) and tuning problem (to identify and tune individual controllers)[12].The reduced loop interaction can be achieved by proper pairing of manipulated and controlled variables[13].The Relative Gain Array (RGA)- based control configuration is most commonly used for loop interaction in MIMO process industries[14]. The RGA- based control technique uses steady state gain of the system to identify the interaction effects in the MIMO system[10]. Thus, the current research adopts the RGA approach to interpret the interaction effect of the pilot plant distillation column. Further, in the present work, the PI controller is designed based on process parameters (T and τ) along with the tuning parameters, δ_1 and δ_2.

The 'Distillation Process' is one of themost commonly used separation technique in the process industry[15, 16]. Effective control of the distillation process is necessary to reduce energy consumption in the process control industry[17, 18]. The article presents adecentralized PI control technique for effective control of the identified distillation column transfer function matrix[19].The closed loop responses of the distillation column model for both, setpointchange and load disturbance, are noted. Further, the result is compared with thecross-control scheme. The ISE and IAE values are listed to check the performance ability of both the control techniques.

The rest of the article is structured as follows: Section 2 briefly discusses the experimental setup of the pilot plant binary distillation column; the decentralized control scheme is discussed in section 3; andin section 4, the cross- controller algorithm iscompared with the decentralized control technique. The simulation and experimental result verification are discussed in section 5, followed by concluding remarks.

II. Brief Discussion on Experimental Setup

The objective of the distillation column is to separate the mixture of two or more components either by the application of heat or by the removal of heat[20, 21]. The application of the distillation column is found in many fields such as industrial distillation, azeotropic distillation, food processing,etc[22]. The laboratory setup of apilot plant binary distillation column used to separate isopropyl alcohol and water is shown in Fig (1). In the present setup, the reboiler is connected to the bottom of the column for the necessary separation. The condenser, connected at the top of the column, is usedto condensate the vapour. Later, the condensated vapour liquid is stored in the reflux drum. Both, there boiler and the condenser, act as heat exchanger. The DAQ card is used to acquire the temperature of the tray using MATLAB@2015 Simulink environment. The temperature at tray 3-T_3 (near the bottom of the column) reads higher temperature than the temperature at tray 6-T_6 (near the top of the column). The reboiler power rate and reflux flow rate are the two manipulated variables, whereas T_3 and T_6 are the two controlled variables in the present research work. The reboiler power rate is controlled with the help of Solid State Relay (SSR), and the reflux flow rate is controlled using theperistaltic pump connected atthe top of the column.

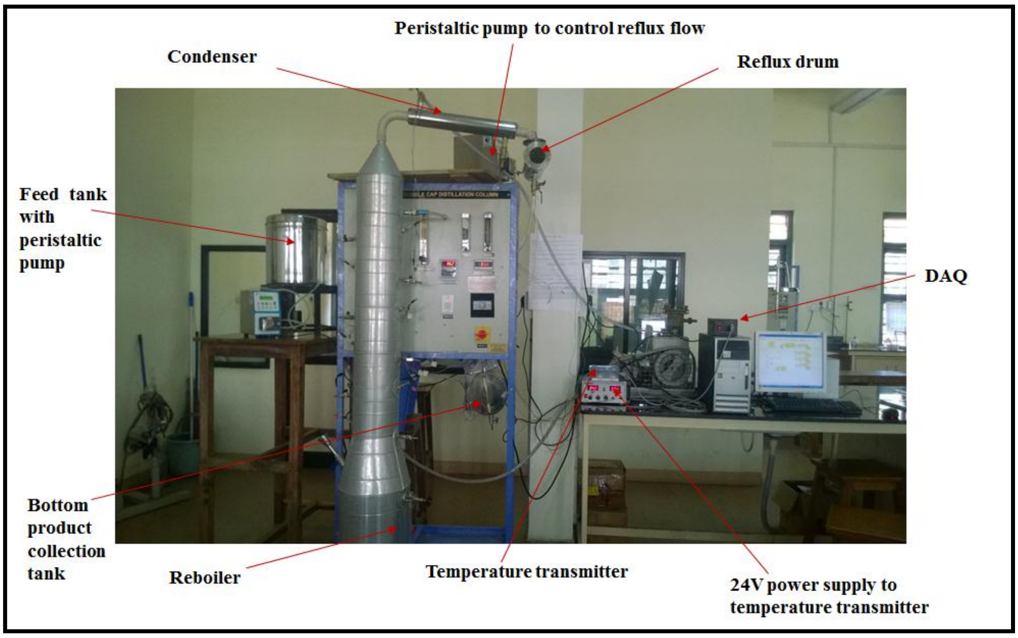

Fig. 1. Laboratory setup of binary distillation column

III. Decentralized Pi Controller

Consider the decentralized control structure of the TITO system as shown in Fig (2), where the process to be controlled has two inputs - u_1 and u_2, and two output variables –y_1 andy_2. The process transfer function matrix is given in Eq. (1).

$$y(s) = G_p(s)u(s) \quad (1)$$

Where, $y(s)=[y_1(s), y_2(s)]^T$ and $u(s)=[u_1(s), u_2(s)]^T$

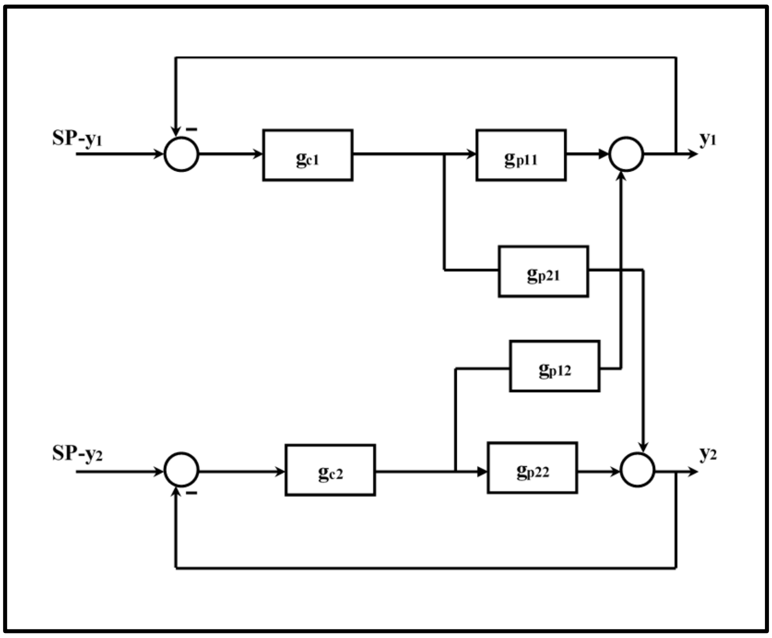

Fig. 2.Decentralised control structure for TITO system

$G_p(s)$ is the transfer function matrix of the process in Eq. (2).

$$G_p(s) = \begin{bmatrix} g_{p11} & g_{p12} \\ g_{p21} & g_{p22} \end{bmatrix} \quad (2)$$

Where, the transfer function is in the First Order Plus Time Delay (FOPTD)form. The RGA technique is well-established for the design of MIMO control systems. In this technique, multivariable process interactions are reduced by pairing correct controlled and manipulated variables. This process of precise pairing also results in good performance and stability margins. Thus, the RGA approach will select the control loop pairing with minimum interaction[23, 24]. The RGA is determined by steady state gain matrix of the plant transfer function, which is shown in Eq. (3). Thus, the present work employs RGA techniqueto interpret the interaction effects.

i.e., $RGA = G_p(s=0) * \left[(G_p(s=0))^T \right]^{-1}$ (3)

In general, the decentralized controller matrix structure is given by Eq. (4).

$$G_c(s) = \begin{bmatrix} g_{c11} & 0 \\ 0 & g_{c22} \end{bmatrix} \quad (4)$$

In Eq. (4),g_{c11} and g_{c22} is designed based on the process parameters of g_{p11} and g_{p11},respectively. δ_1 and δ_2 are the tuning parameters[23]. The recommended range of δ_1 and δ_2 are in the range of 0-2. Thus, in PI controller$k_c = \delta_1 (T/\tau)$ and $\tau_I=\delta_2\tau$, here, T and τ are time constants and time delay of the respective plant transfer function in the transfer function matrix form of the TITO system.

IV. Cross- Controller

It is difficult to attain satisfactory control performance of the interactions between the variables in theMIMO system. But, such cases can be effectively handled by imposing a decoupled network in order to cancel the interaction effect in the process. This would results as a single loop control system. Thus, an additional controller is introduced along with the PI decentralized controllers to compensate for any interactions. In a MIMO system, controller variables relating to the manipulated variables through the diagonal matrix is called a decoupled system. Thus, the controller added to the decentralized control configuration is called cross- controller/ decoupler[23].The cross- controllerstructure for TITO system is shown in Fig(3).

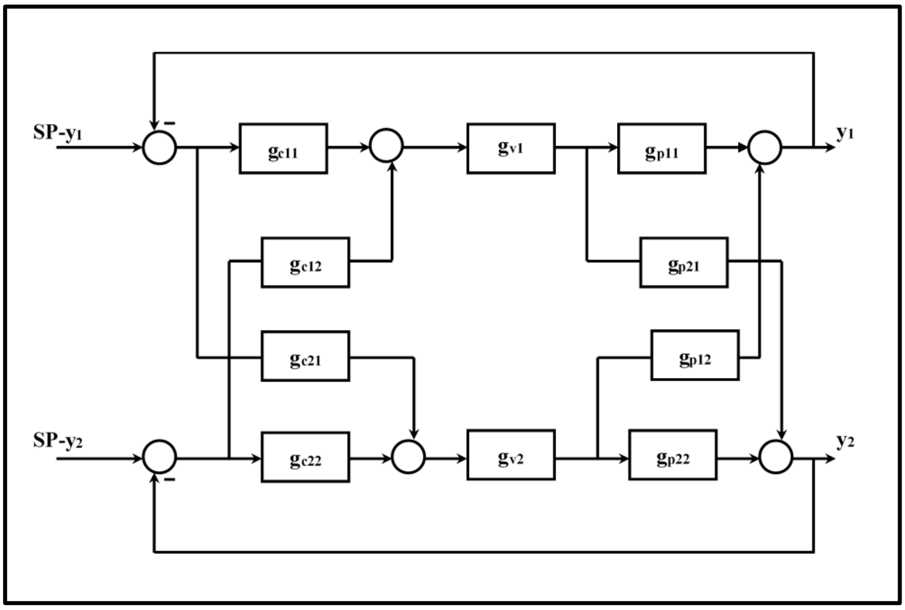

Fig. 3.Cross- control structure for TITO system

The TITO plant structure as given in Eq. (2) is considered here by ignoring the time delay. In Fig (3), the controller and decoupler structure for the system is as shown in Eq. (5) and Eq. (6).

$$G_c(s) = \begin{bmatrix} g_{c11} & g_{c12} \\ g_{c21} & g_{c22} \end{bmatrix} (5)$$

$$G_v(s) = \begin{bmatrix} g_{v1} & 0 \\ 0 & g_{v2} \end{bmatrix} (6)$$

Thus, the controller structure of the cross- controller to yield a completely decoupled system is given by Eq. (7).

$$G_{dc}(s) = (G_p \times G_v) \times G_c \,(7)$$

The interaction effect is eliminated by putting off-diagonal elements to zero in Eq. (7)and the same is shown in Eq. (8).

$$G_{dc}(s) = \begin{bmatrix} g_{dc11} & 0 \\ 0 & g_{dc22} \end{bmatrix} (8)$$

Where, $g_{dc11}(s) = g_{p11} g_{v1} g_{c11} + g_{p12} g_{v2} g_{c21} (9)$

$$g_{dc22}(s) = g_{p21} g_{v1} g_{c12} + g_{p22} g_{v2} g_{c22} (10)$$

Further, $g_{c12}(s)$ and $g_{c21}(s)$ obtained from Eq. (7)by putting off- diagonal elements to zero, is given by Eqs. (11) and (12), respectively.

$$g_{c12}(s) = -\frac{g_{p12} g_{v2} g_{c22}}{g_{p11} g_{v1}} \,(11)$$

$$g_{c21}(s) = -\frac{g_{p21} g_{v1} g_{c11}}{g_{p22} g_{v2}} \quad (12)$$

Where $g_{v1}=g_{v2}=1$, $g_{c11}=k_1$, and $g_{c22}=k_2$ is of the PI control structure,and designed as discussed in section 3.

V. Simulation and Experimental Validation

The distillation column model presented[19] is considered here to design a decentralized PI control algorithm. The TITO distillation column plant transfer function matrix is given byEq. (13).

$$G_p(s) = \begin{bmatrix} \dfrac{-0.16e^{-0.01s}}{0.01s+1} & \dfrac{0.6e^{-1.19s}}{0.05s+1} \\ \dfrac{-0.04e^{-0.01s}}{0.02s+1} & \dfrac{0.49e^{-0.47s}}{0.19s+1} \end{bmatrix} (13)$$

The steady state gain matrix of Eq. (13) is given by

$$G_p(s=0) = \begin{bmatrix} -0.16 & 0.6 \\ -0.04 & 0.49 \end{bmatrix} (14)$$

The RGA of Eq. (14) is obtained using Eq. (3) as shown in Eq. (15).

$$RGA = \begin{bmatrix} 1.4412 & -0.4412 \\ -0.4412 & 1.4412 \end{bmatrix} (15)$$

This implies that the diagonal controller effect is more in comparison with the off-diagonal controller. The most commonly used decentralized control structure, given in Eq. (4), is utilized in the present research. $\delta_1=0.1$ and $\delta_2=1.5$ along with process parameters such as time delay and time constant lead to controller valueg_{c11}. Further, the tuning value of $\delta_1=1$ and $\delta_2=1.6$along with process parameters represent controller value g_{c22}.i.e to find $g_{c11}(s)$:

$$k_p = \delta_1\left(\frac{T}{\tau}\right) = 0.1\left(\frac{0.01}{0.01}\right) = 0.1,$$

and $\tau_I = \delta_2 \tau = 1.5 \times 0.01 = 0.015$, i.e, $k_I = \dfrac{k_p}{\tau_I} = 0.1/0.015 = 6.67$

Similarly, to find $g_{c22}(s)$: $k_p = \delta_1\left(\dfrac{T}{\tau}\right) = 1\left(\dfrac{0.19}{0.47}\right) = 0.4$,

and $\tau_I = \delta_2 \tau = 1.6 \times 0.47 = 0.752$ i.e, $k_I = \dfrac{k_P}{\tau_I} = 0.4/0.752 = 0.53$

Thus, the decentralized PI controller for Eq. (13) is given by Eq. (16).

$$G_c(s) = \begin{bmatrix} -0.1 - \dfrac{6.67}{s} & 0 \\ 0 & 0.4 + \dfrac{0.53}{s} \end{bmatrix} (16)$$

The controller design based on cross- control technique is given by

$$G_{dc}(s) = \begin{bmatrix} \dfrac{k_1(-0.000067s^2 - 0.000133s - 0.1108)}{(0.00001s^3 + 0.001s^2 + 0.012s + 1)} & 0 \\ 0 & \dfrac{k_2(0.00021s^2 + 0.00041s + 0.34)}{(0.00019s^3 + 0.00138s^2 + 0.192s + 1)} \end{bmatrix} (17)$$

Where, k_1 and k_2 are designed similar to the decentralized PI control technique, given in Eq. (16) without the negative sign.
i.e to find k_1:

$$k_p = \delta_1\left(\frac{T}{\tau}\right) = 0.1\left(\frac{0.01}{0.01}\right) = 0.1,$$

and $\tau_I = \delta_2\tau = 0.8\times0.01 = 0.008$, i.e, $k_I = \frac{k_p}{\tau_I} = 0.1/0.008 = 12.5$

Similarly, to find k_2: $k_p = \delta_1\left(\frac{T}{\tau}\right) = 1\left(\frac{0.19}{0.47}\right) = 0.4$,

and $\tau_I = \delta_2\tau = 1\times0.47 = 0.47$ i.e, $k_I = \frac{k_P}{\tau_I} = 0.4/0.47 = 0.85$

Thus, in Eq. (17), $k_1 = 0.1 + \frac{12.5}{s}$ and $k_2 = 0.4 + \frac{0.85}{s}$.

Good performance and stable response is achieved by proper tuning of the controller. The controller designed in the present work gives satisfactory closed loop response for set point change and load disturbance. The dynamic performance criteria such IAE and ISE are evaluated to verify the performance of the designed controller[4]. Further, IAE and ISE are based on the process response. The ISE is used to suppress small errors, whereas IAE is used to suppress larger errors[22].Table 1 summarizes the performance analysis of both the controllersused in the current research work. Moreover, from Table 1, it is evident that the decentralized controller gives asignificantly stable response with less IAE and ISE values.

Table 1. Performance analysis

Type			**Main effect**		**Interaction effect**	
			y_{11}	**y_{22}**	**y_{12}**	**y_{21}**
PI	Decentralized	IAE	1.166	5.741	1.745	1.302
		ISE	0.3187	2.508	0.2102	0.08803
	Cross controller	IAE	5.463	10.48	8.187	2.383
		ISE	1.67	4.604	1.93	0.1323

Both controller techniques attain closed loop stable responses in closed loop simulation. Further, the decentralized PI closed loop response is fast with less settling time as shown in Figs (4) and (5). The Figs (6) and (7) represent the closed loop simulation response of decentralized and cross- control technique, considering tray temperature as setpoint. The decentralized PI and cross- controller is implemented on a pilot plant distillation column, and its response is shown in Fig (8) and Fig (9) respectively.

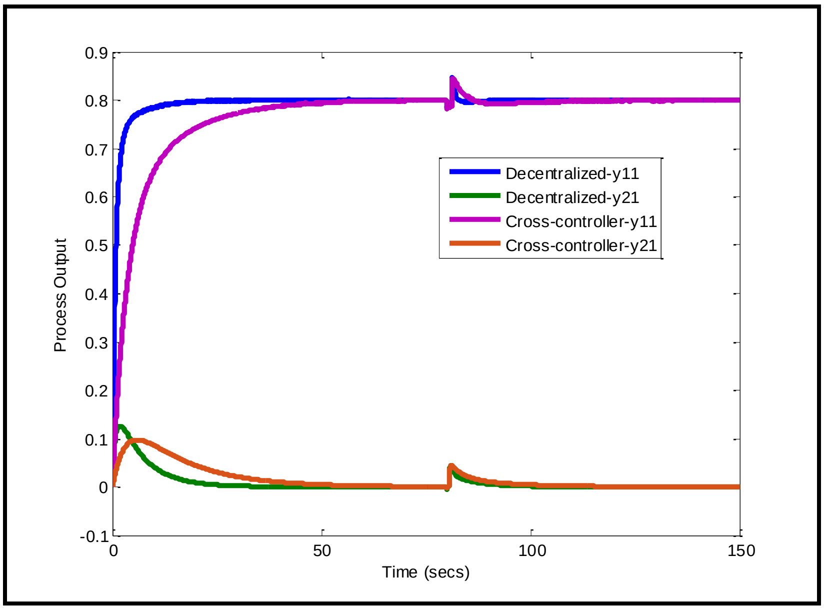

Fig. 4. Closed loop response for setpoint change and load disturbance with SP-y_1=0.8 and SP-y_2=0

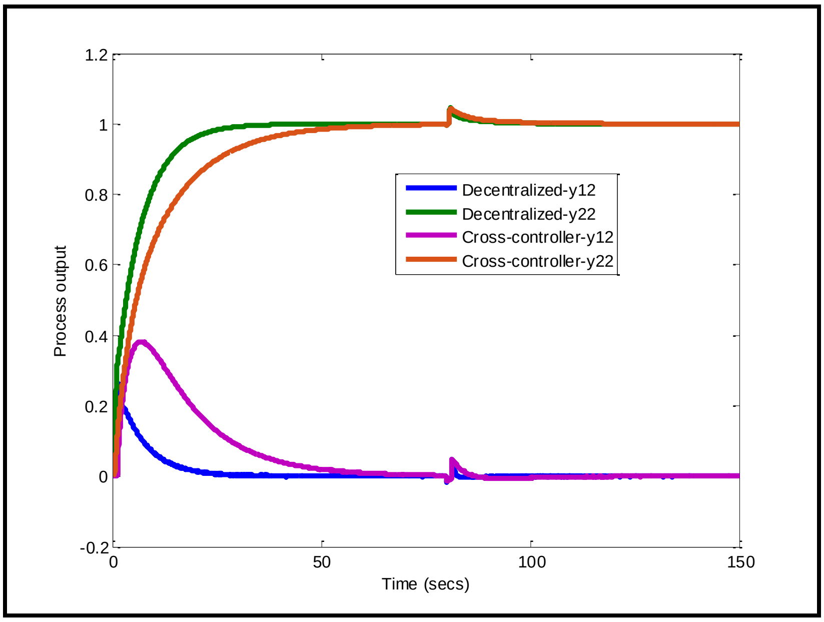

Fig. 5. Closed loop response for setpoint change and load disturbance with SP-y_1=0 and SP-y_2=1

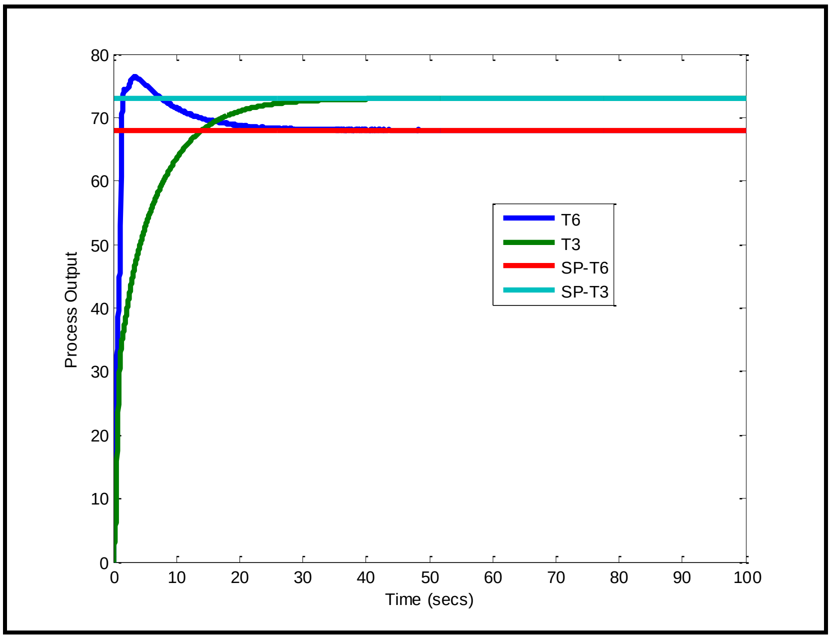

Fig. 6. Closed loop simulation response for decentralized control technique with SP-y_1=68 and SP-y_2=73

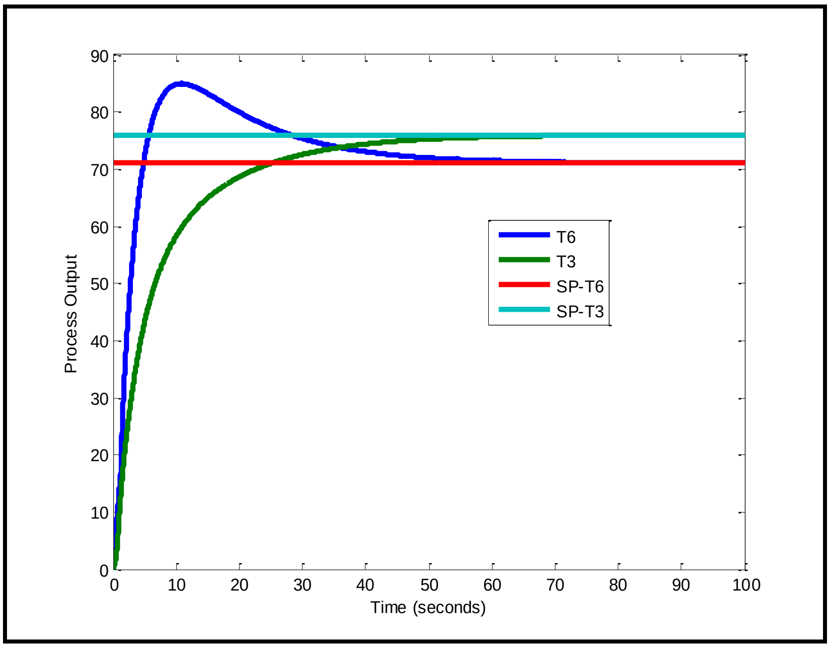

Fig.7. Closed loop simulation response for cross- control technique with SP-y_1=71and SP-y_2=76

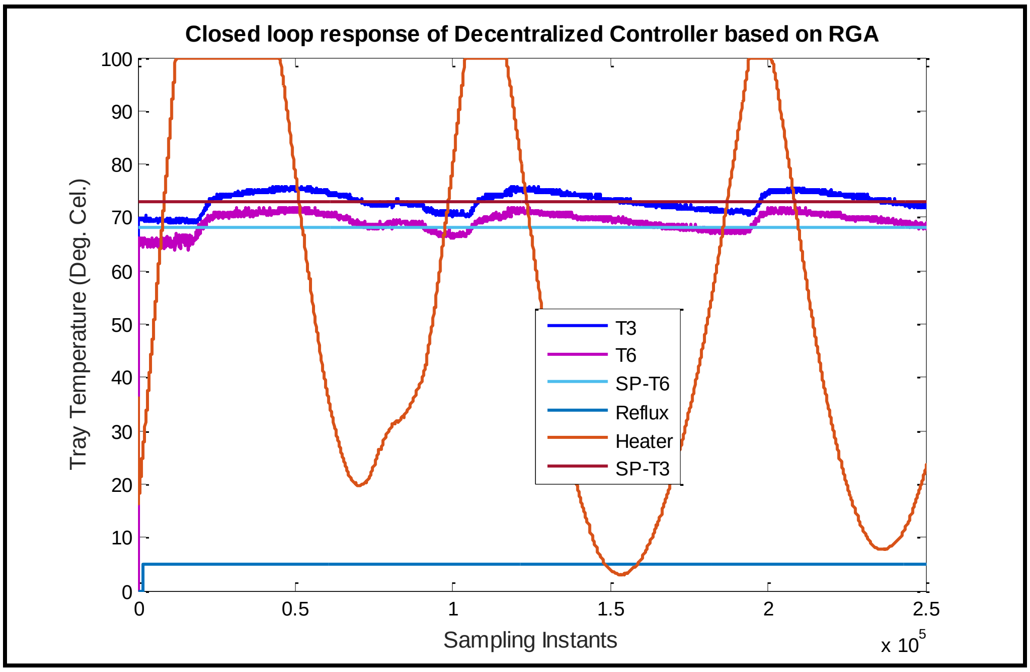

Fig.8. Implementation of decentralized PI controller on pilot plant binary distillation column for the setpoint tracking of 68 Deg. Cel for Tray-T_6 and 73 Deg. Cel for Tray-T_3

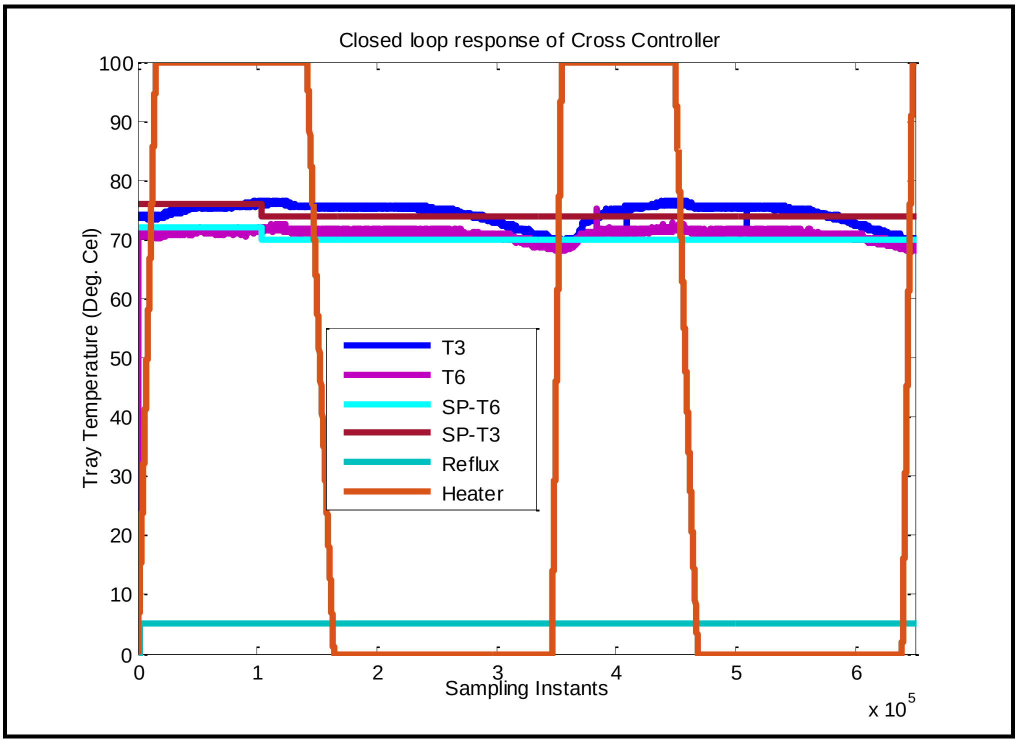

Fig.9. Implementation of cross controller on pilot plant binary distillation column for the setpoint tracking of 71 Deg. Cel for Tray-T_6 and 76 Deg. Cel for Tray-T_3

VI. Conclusions

The article presents a decentralized PI control technique for a pilot plant distillation column transfer function matrix. The control structure configuration is identified through the RGA approach. The results show that, the RGA value signified the 1-1 and 2-2 pairing of the manipulated and controlled variables. Also, the closed loop responsesettles fast,in the presence of load disturbance. The IAE and ISE values were used to validate the performance effect of the 'Decentralized' and 'Cross-controller' techniques. The results of this comparison depict that, the decentralized PI control technique results in significantly improved performance.Further, duringresearch work it was observed that significantly improved response is achievedwith both the control techniques. In addition, the simulation responses of the decentralized PI control technique on a pilot plant binary distillation column were validated through real-time experimental results.

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Nomenclatures and Abbreviations

δ_1, δ_2	:	Tuning parameters
T_3	:	Temperature of Tray-3, near the bottom of the column in Degree Celsius
T_6	:	Temperature of Tray-6, near the top of the column in Degree Celsius
k_c	:	Proportional gain
τ_I	:	Integral gain
T	:	Time constant in hours
τ	:	Time delay in hours
PI	:	Proportional-Integral
RGA	:	Relative Gain Array
ISE	:	Integral Square Error
IAE	:	Integral Absolute Error
TITO	:	Two Input Two Output
I/O	:	Input/Output
PID	:	Proportional-Integral-Derivative
MIMO	:	Multi Input Multi Output
DAQ	:	Data AcQuisition
SSR	:	Solid State Relay
SP	:	Setpoint

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