International Journal of Pure and Applied Mathematics
Volume 118 No. 22 2018, 1109-1115
ISSN: 1314-3395 (on-line version)
url: http://acadpubl.eu/hub
Special Issue
ijpam.eu

SMITH PREDICTOR BASED PI CONTROLLER DESIGN FOR A BATCH DISTILLATION COLUMN

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Abstract: The article presents a design and implementation of decentralized Proportional Integral (PI) controller with decoupler based on Smith Predictor for a Batch Distillation Column. Decoupler is used to minimize the interaction combining it with decentralized control algorithm. 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 Smith Predictor method. The simulation of Smith Predictor 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, Smith Predictor, TITO process, Interaction process, Real-time application.

1. Introduction

Two Input Two Output (TITO) systems are commonly controller using PI/PID controller [1-2]. TITO process control is challenging in comparison with Single Input Single Output (SISO) process due to interactions among the loops. To accomplish minimum interaction, robust stability, high reliability, hardware simplicity, easy operation, superior performance over its counterparts decentralized control techniques should be utilized [3-6]. The centralized control system might yield poor performance or unstable response if any one sub loop fails. Whereas, for Multi Input Multi Output (MIMO) system decoupler avoids above problem and ensures minimum interaction while pairing [7-8]. Having said that, decentralized PI controller commonly confronted with pairing and tuning problems [3]. The reduced loop interaction can be achieved by proper pairing of manipulated variables and controlled variables [9-10]. The other methods 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]. Decoupled PI controller technique is tuned by using Smith Predictor control technique [20].

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

2. Design of Decoupler

To reduce the loop interaction between 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 [4]. The given process G(s) is decoupled using decoupler.

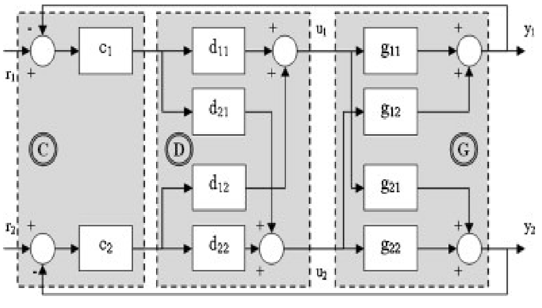

Figure 1. Block Diagram of TITO Process with Decoupler

Consider a TITO process is as given:

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

Let the interaction effect is eliminated by putting off-diagonal elements of G(s) have no RHP poles and diagonal elements of G(s) have no RHP zeros.

The decoupler matrix is:

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

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 $q_{ii}(s)$ are to be controlled through decentralized PI controllers.

3. Pi Controller Design Based on Smith Predictor

For the PI controller design, $q_1(s)$ and $q_2(s)$ approximate to First Order Plus Dead Time (FOPDT) model as shown:

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

Where k_p = gain constant, τ_d =time delay,

T =time constant, $i,n=1,2$

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:

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

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 plots of higher and reduced order model we calculate the value of ω_c, $\left|q_n(j\omega_c)\right|$ .This value is used for obtaining values of the cross over frequency and magnitude cross over frequency by using $q_1(s)$ and $q_2(s)$ [16].

The decentralized PI controller which is in the following form given below can be used for controlling TITO process:

$$G_c(s)=\begin{bmatrix} K_{11}(s) & 0 \\ 0 & K_{22}(s) \end{bmatrix} \quad (8)$$

Where $K_{11}(s)$ and $K_{22}(s)$ are PI controller type:

$$K_{PI}(s)=K_c\left[1+\frac{1}{\tau_i s}\right] \quad (9)$$

Where, K_c = proportional gain, T_i =integral time

The form of the control signal now comprises a PI controller acting on the reference error e(s) = r(s) - y(s) and the low pass filtering of the component of the control concerned with prediction. These rules could be used if a prior FOPDT model is determined. A PI controller of FOPDT Transfer Function model is obtained $l_n(s)$. **Smith Predictor method is used for tuning PI controllers [19]. Parameters for tuning PI controller are:**

$$K_P=\frac{\alpha}{k_p} \quad (10)$$

$$\tau_i=\frac{T}{\beta} \quad (11)$$

Smith Predictor analysis is used to reduce the parameters involved in the functions [19]. Let us assume the PI parameter α and β have been chosen as recommended, namely $\alpha=\beta=1$ for loop 1 and $\alpha=\beta=0.7$ for loop 2 to get better performance index while substituting any other values for α and β in Smith Predictive method will result in larger performance index. The PI parameter α and β is tuned so that the desirable performance of individual loops and the nominal system stability of the multi-loop system.

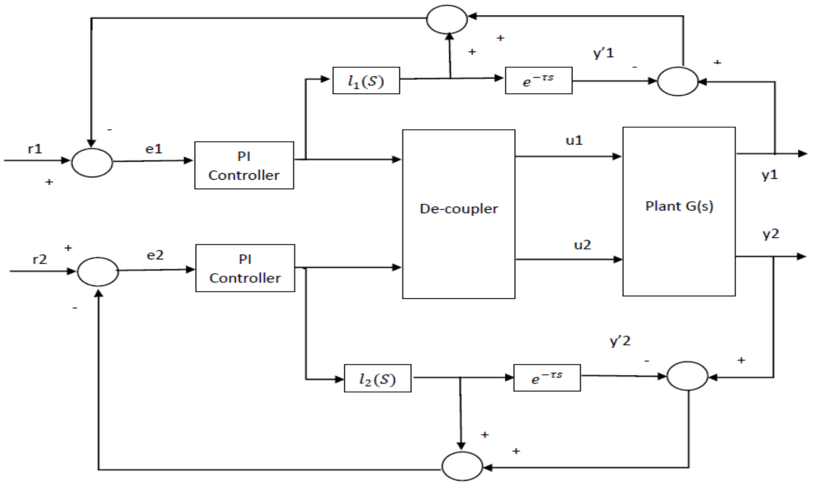

Figure 2. Smith Predictive PI Controller for MIMO system

4. 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 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 Smith Predictor techniques are given in table II [22][13] and performance analysis in table III [22].

Table 1. Frequency Response Specification 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 2. Smith Predictive PI Controller Parameter for Top Tray and Bottom Tray Composition

Parameters	**Loop-1**	**Loop-2**
K_C	4.3478	-2.4138
T_i	1.35	1.05

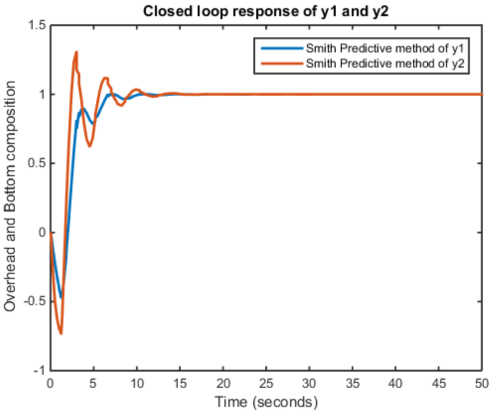

Figure 3. Closed loop servo response with r1=1 and r2=1

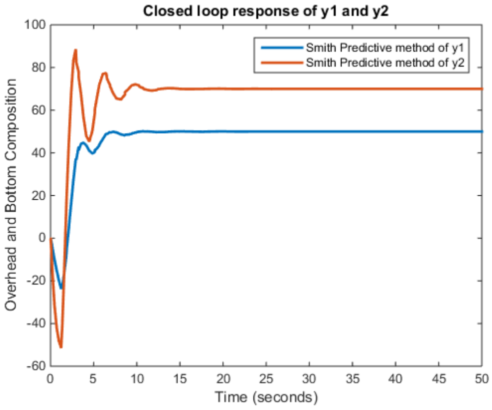

Figure 4. Closed loop servo response with r1=50 and r2=70

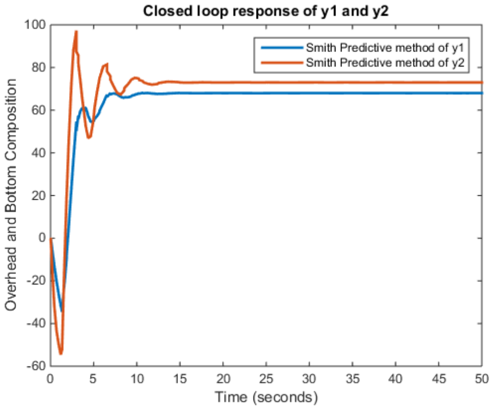

Figure 5. Closed loop Servo response with r1=68 and r2=73

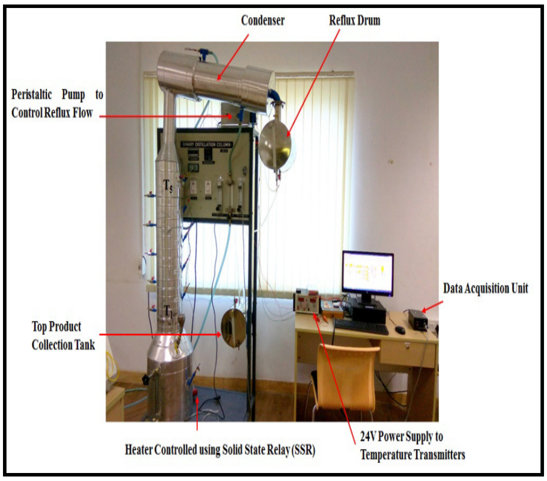

Figure 6. Laboratory Setup of Binary Distillation Column

Experimental Setup of Binary Distillation Column is shown in Fig. 6 and the mathematical model of the system is given and studies. The real time output is given soon.

Table 3. 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 [26]	45.22	24.527	1516.6	297.97
SMITH PREDICTOR	3.65	2.355	6.572	1.877

5. Conclusion

Design of decentralized PI controller with decoupler is done here. The controller designed are 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 established. In addition, the closed loop servo response with different set points for a Distillation Column model are determined.

A decentralized PI controller is designed for the transfer function model of Distillation Column. The result shows that 1-1 and 2-2 pairing of the manipulated and controlled variables. The performance index of 4 different controllers are NDT, SMIC, Pole Placement and Smith Predictor algorithm are compared. The

Smith Predictor algorithm results in better closed loop response with lesser overshoot and settling time. The closed loop servo response of Smith Predictor is better than all other controllers, which has been proved along with the performance index calculation tabulated in table IV.

6. 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 real-time experimental facility for carrying out the post-graduation project.

7. 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
τ_{cii} : 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
NDT : Non Dimensional Tuning
SIMC : Simplified Internal Model Control

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