Design and Analysis of Different Tuning Strategies of PI Controller for Distillation Column

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Abstract: - This manuscript illustrates different tuning strategies of PI controller for highly interacting distillation column. The reduced order transfer function is introduced to dilute the complexity of multi loop control system. Initially the open loop transfer function is introduced to decompose multi loop control system. The Ziegler-Nichols, Tyreus-Luyben and Internal model control based PI controller performance is compared in terms of integral squared error, integral absolute error and integral absolute time error in real time pilot distillation column.

Key-Words: - Ziegler-Nichols, Tyreus-Luyben, Internal model control, Integral squared error, Distillation column

1 Introduction

Now a days all chemical process in Industries have more than one controller output to manipulate necessary input in order ensure perfect output response. Modelling a distillation column is a quiet challenging task due to interaction between two or more process variables. Lalu Seban et.al have used GOBF-ARMA model to design a model based predictive controller for distillation column [1]. In past decades different authors have proposed different techniques to model the distillation column depends on applications.

The designed value of PI controller ensures perfect control action for getting desired output. The Ziegler-Nichols tuning is widely accepted method and various authors illustrated effectiveness of Z-N method [2]. Ivan.D et al, have proposed Z-N method to tune PI controller[3]. The IMC based PI Controller provide best performance in series cascade unstable systems [4]. D.B Santhosh kumar et al. highlighted internal model control based PID Controller to control integrating system which has time delay [5][6].

2 Decoupler Design

Vanishing the effect of interaction between the two control loops is obtained by decoupler design. These design plays vital role in more interaction system. The decoupling is the process of changing transfer function matrix to diagonal matrix [7]. Among many ways, the feed forward cancelling in coupling items is widely accepted method to design a decoupler. The multiple input and multiple output (MIMO) process is represented by following equations.

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

$$E(S) = \begin{pmatrix} 1 & \frac{-g_{12}}{-g_{11}} \\ \frac{-g_{21}}{-g_{22}} & 1 \end{pmatrix} \tag{2}$$

3 Model Development

We have developed wood and berry model for a distillation column using open loop process reaction curve method. The model has been developed between input and different tray temperature. The tray temperature T1 and T5 consider as process variable. The open loop transfer function identified using some parameter setting given in table 1.

Where
T1 – Temperature at tray 1
T5 - Temperature at tray 5

$$G(s) = \begin{pmatrix} \frac{10.8e^{-8s}}{13.6s+1} & \frac{16.63e^{-3.98s}}{15s+1} \\ \frac{6.9e^{-4s}}{5.98s+1} & \frac{17.5e^{-3.65s}}{13.45s+1} \end{pmatrix} \tag{3}$$

The open loop reduced order transfer function obtained from real time distillation column are

$$g_{11}(s)=\frac{0.276e^{-3.4095s}}{0.681s+1} \quad (4)$$

$$g_{12}(s)=\frac{0.261e^{-2s}}{1.321s+1} \quad (5)$$

Table 1. Different transfer function for different temperature

Constant	Process Variable 1 (T1)	Process Variable 2 (T5)	Transfer function
PV 2	10%	10%	$\frac{10.8e^{-2s}}{13.6s+1}$
	60%	10%	$\frac{16.63e^{-2.9s}}{19s+1}$
PV 1	10%	10%	$\frac{5.9e^{-6s}}{8.93s+1}$
	10%	60%	$\frac{17.3e^{-2.8s}}{13.45s+1}$

4 Tuning Methods

The controller parameter values are identified by Z-N tuning rules, tyreus luyben rules and internal model control method. The ultimate gain and ultimate time period is identified by closed loop method under the condition of marginally oscillation for loop1 and loop2.

The relative gain array is used represent the effective model of the loop1 and loop2.

$$g_{ii}^{ef}=\frac{g_{ii}}{\Delta_{ii}} \quad (6)$$

The diagonal element of relative gain array is denoted by

$$\Delta_{ii}=[G(s)\otimes(G(s))^{-1}]^{T} \quad (7)$$

Where

T – Transpose of the matrix

$\otimes$ - Schur Product

The ratio of effective open loop transfer function (g_{ii}^{ef}) and open loop transfer function (g_{ii}) located in diagonal position of dynamic relative gain array (DRGA) [8].

$$\Delta_{11}(s)=(\frac{g_{11}(s)*g_{22}(s)}{g_{11}(s)*g_{22}(s)-g_{21}(s)g_{12}(s)} \quad (8)$$

$$g^{ef}{}_{11}(s)=g_{11}(s)-\frac{g_{12}(s)*g_{21}(s)}{g_{22}(s)} \quad (9)$$

$$g^{ef}{}_{22}(s)=g_{22}(s)-\frac{g_{12}(s)*g_{21}(s)}{g_{11}(s)} \quad (10)$$

The more number of orders in the effective transfer function $g^{ef}{}_{11}(s)$ and $g^{ef}{}_{22}(s)$ leads to complicate in controller design. The effective transfer function further reduce to first order plus dead time model to overcome the issues in controller design. The coefficient matching method is the best technique to obtain the FOPDT model.

$$g^{ef}{}_{11}(s)=a_{ii}+b_{ii}s+c_{ii}s^{2}+d_{ii}s^{3} \quad (11)$$

k=a_{ii} (12a)

$$\tau=\sqrt{(\frac{2c_{ii}}{d_{ii}}-(\frac{b_{ii}}{a_{ii}})^{2})} \quad (12b)$$

$$\theta=\sqrt{(\frac{2c_{ii}}{d_{ii}}-(\frac{b_{ii}}{a_{ii}})^{2})} \quad (12c)$$

The controller parameters of all individual loop tuned based IMC tuning rules.

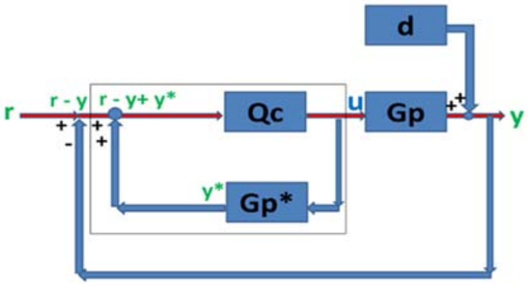

Fig 1. Structure of IMC

The model can be represented by following equation [9]

$$Gp*(S)=\frac{Kp*}{[Tp*S+1]} \quad (13)$$

$$k_{cj} = \frac{\tau}{k\lambda} \tag{14a}$$

$$\tau_j = \tau \tag{14b}$$

The PI controller parameters is tuned for different tuning method is given table.2.

Table 2. PI values for Different tuning strategies

Loop Number	Z-N Tuning Rules		T-L Tuning Rules		IMC	
	Kp	Ki	Kp	Ki	Kp	Ki
1	2.141	0.48	1.57	0.59	1.26	2
2	2.54	0.38	1.86	0.466	2.64	2

4 Result and Discussion

The performance of different tuning strategies is compared in various values of tray temperature T1 and T5 using MATLAB software. The IMC based PI controller is compared with Z-N method and T-L method in terms of various academic measures like integral absolute error (IAE), Integral squared error (ISE) and Integral time absolute error. The fig.2, fig.4, fig.6, fig.7 shows effectiveness of internal model control based PI controller on tray temperature T1 and fig.3 and fig.5 infers behavior of different controller with respect current process variables.

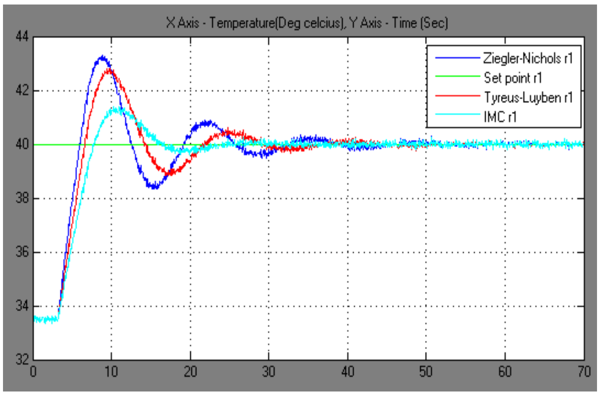

Fig 2. Output response using Ziegler-Nicols,Tyreus-Luyben and IMC based PI controller for tray1 temperature T1 = 40^0C

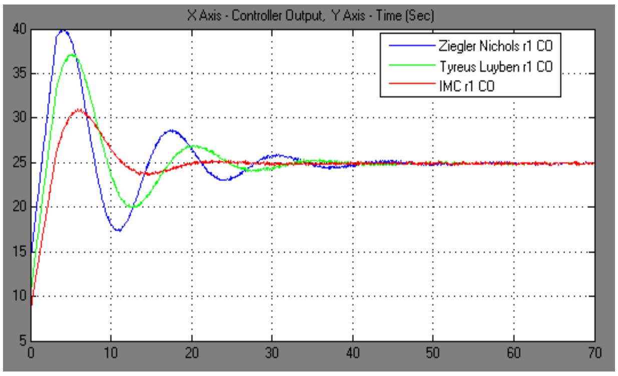

Fig 3. Controller output of Ziegler-Nicols,Tyreus-Luyben and IMC based PI controller for tray1 temperature T1 = 40 ^{0}C

Table 3. Servo Performance analysis for tray temperature T1=40^0C

Controller	Overshoot	Settling time	ISE	IAE	ITAE
Z-N method	3.2	50	12.73	6.2	92.4
T-L Method	2.8	45	8.14	6	90.1
IMC	1.2	25	1.49	1.5	19

The Z-N Tuning rules initially have very fast response and settled gradually with much oscillation at 50th second. The T-L based PI controller has some aggressive action and settled at 45th sec. oscillation in the tray temperature leads to uncertainty in the process variable which leads to more integral squared error, integral absolute error and integral time absolute error and settling time. Initially the IMC based PI controller has average speed of response and settled in 25th second which shows effective control action on tray temperature T1.

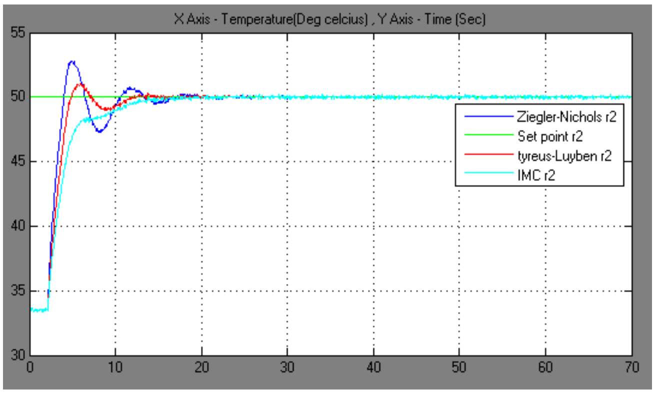

Fig 4. Output response using Ziegler-Nicols,Tyreus-Luyben and IMC based PI controller for tray5 temperature T5 = 50^0C

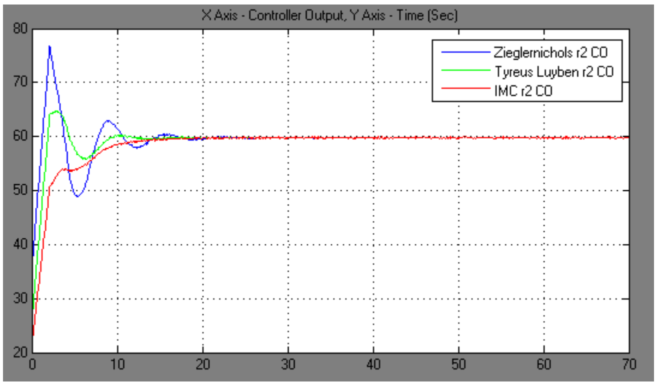

Fig 5. Controller output of Ziegler-Nicols,Tyreus-Luyben and IMC based PI controller for tray5 temperature T5 = 50^0C

Table 4. Servo Performance analysis for tray temperature T1=50^0C

Controller	Overshoot	Settling time	ISE	IAE	ITAE
Z-N method	2.5	25	13.31	6.3	49.9
T-L Method	1.2	17	5.24	1.4	18.4
IMC	Nil	18	1.04	1.2	13

The ISE, IAE, ITAE are very small when the IMC takes control action on tray temperature on T5. It shows that, The IMC based PI controller provide effective control action in tray2 temperature T5 than tray temperature T1

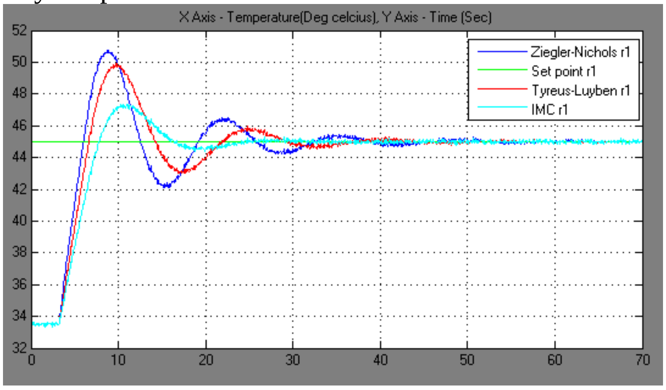

Fig 6. Output response using Ziegler-Nicols,Tyreus-Luyben and IMC based PI controller for tray1 temperature T1 = 45^0C

Table 5. Servo Performance analysis for tray temperature T1=45^0C

Controller	Overshoot	Settling time	ISE	IAE	ITAE
Z-N method	5.6	55	44.5	10.9	155.1
T-L Method	5	50	29.21	8.5	129.2
IMC	2	25	4.94	2.6	30.7

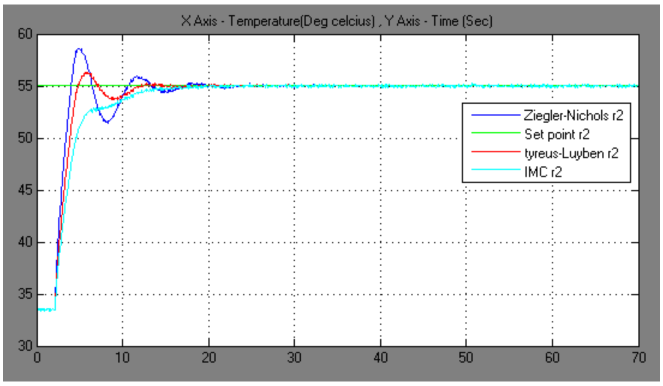

Fig7. Output response using Ziegler-Nicols,Tyreus-Luyben and IMC based PI controller for tray5 temperature T5 = 55^0C

Table 6. Servo Performance analysis for tray temperature T1=55^0C

Controller	Overshoot	Settling time	ISE	IAE	ITAE
Z-N method	3.5	25	34.35	9.8	74.9
T-L Method	1.4	15	2.89	2.5	21.2
IMC	Nil	18	2.60	2.1	17.6

Table 7. Total values of performance index

Tuning Method	ISE			IAE			ITAE		
	T1=40^0C	T2=50^0C	Total ISE	T1=40^0C	T2=50^0C	Total IAE	T1=40^0C	T2=50^0C	Total ITAE
Z-N Method	12.73	13.31	26.04	6.2	6.3	12.5	92.4	49.9	142.3
T-L Method	8.14	5.24	13.38	6	1.4	7.4	90.1	18.4	108.5
IMC Based PI	1.49	1.04	2.53	1.5	1.2	2.7	19	13	32

. **Table 8.** Total values of performance index

Tuning Method	ISE			IAE			ITAE		
	T1=45^{0}C	T2=55^{0}C	Total ISE	T1=45^{0}C	T2=55^{0}C	Total IAE	T1=45^{0}C	T2=55^{0}C	Total ITAE
Z-N Method	44.5	34.35	78.85	10.9	9.8	20.7	155.1	74.9	230
T-L Method	29.21	2.89	32.1	8.5	2.5	11	129.2	21.2	150.4
IMC Based PI	4.94	2.60	7.54	2.6	2.1	4.7	30.7	17.6	48.3

5 Conclusion

This work highlighted the effectuality the IMC based PI controller to control the tray temperature T1 and T5. The MATLAB software is used to design and analyze the controller for different set point in distillation column. The simulated result shows that, IMC based PI controller provides best control action than other controller. The Low value of overshoot, settling time, ISE, IAE, ITAE ensures best control action on tray temperature T1 and T5.

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Future Work

The different tuning strategies can be implemented for non square matrix. Further we can control the pressure of distillation column in effective manner.

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Nomenclature

e(t)	Error signal
y(s)	Process output
u(s)	Process input
K	Process gain
$G_p(s)$	Process
$G_p^*(s)$	Model of the process
G(S)	General transfer function
E(S)	Decoupler matrix

Greek Symbols

τ	Time constant
$\otimes$	Schur Product

Subscripts

IMC	Internal model control
ISE	Integral squared error
IAE	Integral absolute error
Z-N	Ziegler Nichols
T-L	Tyreus Luyben
P	Proportional
I	Integral
MIMO	Multiple input and multiple output
PV	Process variable
Kp	Proportional gain
Ki	Integral gain