Comparative analysis of different control techniques for a distillation column

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***Abstract*— This paper provides a comparative analysis of different control strategies used to control the top and bottom product of binary distillation column. Classical Wood and Berry model has been considered as the model of distillation column and the controller is designed considering a non-interacting process. Performance evaluation of different controllers such as internal model controller (IMC), lead-lag IMC, smith predictor IMC and feed forward IMC controller has been carried out in this paper. Set point regulation and disturbance rejection property of the controller is evaluated.**

***Keywords*— IMC, Distillation column, lead-lag IMC, smith predictor and feed forward IMC.**

I. Introduction

Distillation column is one of the most important unit operation involved in a chemical and a petro chemical industry. This is a liquid-liquid separation process which can be operated either in continuous system or batch system. Distillation column is used to separate binary or multi-mixture components. Using application or removal of heat, the distillation column exploits the differences in relative volatility of different fluid.

The main objectives of distillation column control can be stated as (a) to set stable operating condition for column operation, (b) to regulate the conditions in column so that the products always meet the required specification and (c) to achieve the above mentioned objectives in an effective manner by maximizing the yield of product and minimizing the energy consumption. A good amount of literature is available regarding modeling and control of distillation column. This section provides the summary of some of the papers.

Mathematical model of binary distillation column has been formulated in [1, 5]. Design of multi variable internal model controller for a full scale industrial distillation column has been reported in [3]. Internal model controller is a model based controller techniques which is widely used in many process control applications because using this technique different model uncertainties and modeling error can be accounted for. An overview of different internal model control technique is summarized in [2]. Different intelligent and adaptive controller algorithms are also used in distillation column. Model free adaptive control for binary distillation column has been reported in literature [4].

This paper provides a comparative analysis of different controllers used to control top product and bottom product of distillation column in a non-interacting manner. Different controllers are designed and the performance of the controller is evaluated based on steady state and transient state performance of the controller. Set point regulation and disturbance rejection property of the controller is evaluated using simulation.

This paper is organized as follows. Section II provides the basics of distillation column. Section III describes the controller design technique. Section IV provides simulation results and section V concludes the paper.

II. Distillation Column

A typical distillation column contains a vertical column where trays are used for component separation. Condenser is used to cool and condense the vapor from the top of the distillation column and Reboiler is used to provide heat for the necessary vaporization from the bottom of the column. Reflux drum is used to hold the condensed vapor to recycle the liquid reflux back from the top of the column. The distillation column contains one feed stream and two product streams. The feed molar concentration is x_F , top product concentration x_D and bottom concentration x_B. The schematic diagram of distillation column is shown in Fig. 1.

A. *Dynamic Model of distillation column*

The nonlinear model equation of distillation column can be represented as follows. The material balance on stage *i* can be represented as

$$\frac{dM_i}{dt} = L_{i+1} - L_i + V_{i-1} - V_i \qquad (1)$$

The material balance of light material in each stage can be represented as

$$\frac{dM_i x_i}{dt} = L_{i+1}x_{i+1} - L_i x_i + V_{i-1}y_{i-1} - V_i y_i \qquad (2)$$

The vapor composition y_i and liquid composition x_i is related using the following equation

$$y_i = \frac{\alpha x_i}{1+(\alpha-1)x_i} \quad (3)$$

The feed stage of distillation column can be represented as

$$\frac{dM_i}{dt} = L_{i+1} - L_i + V_{i-1} - V_i + F \quad (4)$$

$$\frac{d}{dt}(M_i x_i) = L_{i+1}x_{i+1} - L_i x_i + V_{i-1}y_{i-1} - V_i y_i + Fx_F \quad (5)$$

For condenser, the nonlinear model can be represented as

$$\frac{dM_i}{dt} = V_{i-1} - L_i - D \quad (6)$$

$$\frac{d}{dt}(M_i x_i) = V_{i-1} - L_i x_i - Dx_i \quad (7)$$

The nonlinear model of the reboiler can be represented as

$$\frac{d}{dt}(M_i x_i) = L_{i+1}x_{i+1} - V_i y_i - Bx_i \quad (8)$$

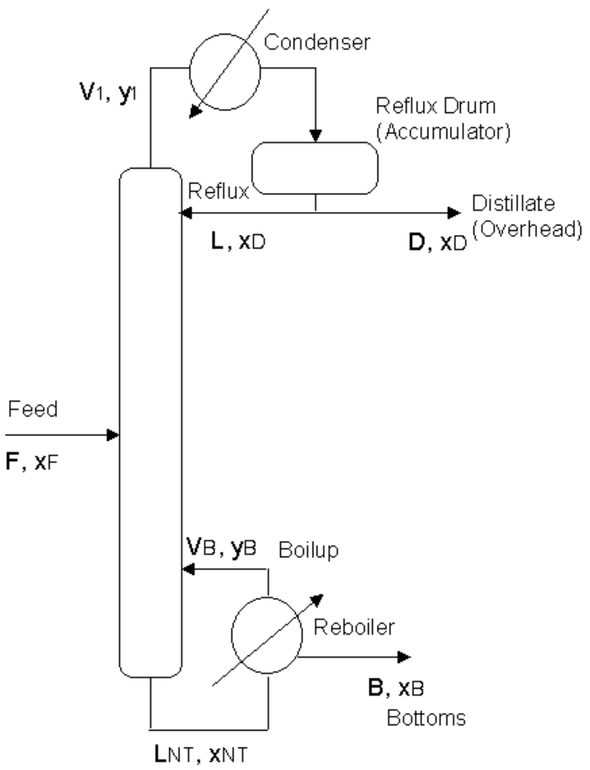


Fig.1. Schematic diagram of distillation column

TABLE I. NOMENCLATURE

Symbol	Description	Unit
F	Feed rate	Kmol/min
z_F	Feed composition	Mole fraction
Q_F	Fraction of liquid in bed	
D	Distillate product flow rate	Kmol/min
B	Bottom product flow rate	Kmol/min
Y_d	Distillate product composition	Mole fraction
X_b	Bottom product composition	Mole fraction
L	Reflux flow	Kmol/min
V	Boilup flow	Kmol/min
N	Number of stages	
i	Stage number	
L_i	Liquid flow from stage i	Kmol/min
V_i	Vapor flow from stage i	Kmol/min
x_i	Liquid composition of light material on stage i	Kmol/min
y_i	Vapor composition of light material on stage i	Kmol/min
M_i	Liquid holdup on stage i	Kmol
α	Relative volatility between light and heavy component	

III. CONTROLLER DESIGN

This section describes the design of different IMC (Internal Model Controller) for binary distillation column in non-interacting mode. IMC approach has the advantage that it allows model uncertainty and tradeoffs between performance and robustness to be considered in a more systematic fashion and it has only one tuning parameter unlike other controllers which have more tuning parameters. Fig. 2 shows the block diagram of classical IMC structure.

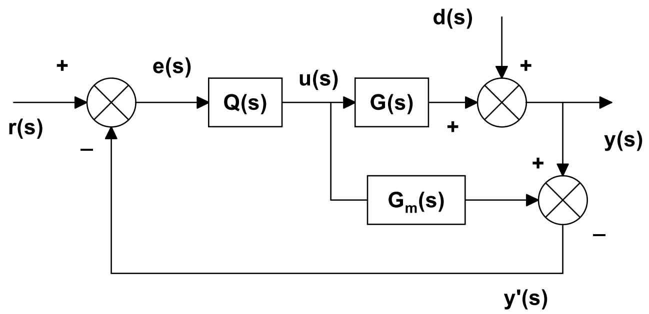


Fig.2. Block diagram of internal model controller

Here $G(s)$ is the process transfer function, $G_m(s)$ is the model, $Q(s)$ is the IMC. Here $Q(s) = \tilde{G}_{pm-}(s)\,f(s)$

Where $f(s) = \frac{1}{\lambda s + 1}$

Here $\tilde{G}_{pm-}(s)$ invertible part of plant model and λ is tuning parameter.

A. *Lead-lag IMC strategy*

Lead-Lag IMC is a modified IMC structure where a lead-lag filter is used along with IMC. Due to the presence of lead-lag compensator, the settling time and percentage overshoot of the transient response improves. The block diagram of lead-lag IMC is shown in Fig. 3.

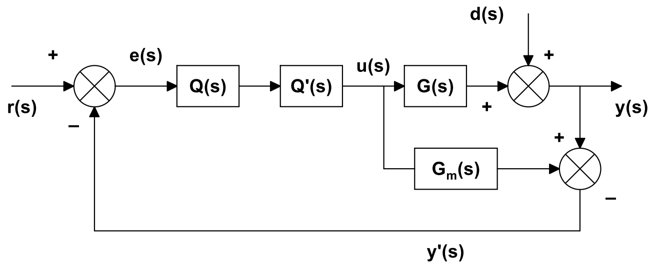


Fig.3. Block diagram of lead-lag IMC

$Q(s)$ is the internal model controller, $Q^{'}(s)$ is the lead-lag filter, $G(s)$ is the actual process, $G_m(s)$ is the process model and $d(s)$ is disturbance variable.

The lead-lag transfer function is given by $Q^{'}(s)=\dfrac{\alpha s+1}{\beta s+1}$

Generalized IMC transfer function is

$$Q(s)=\tilde{G}_{pm-}(s)\,f(s) \qquad (9)$$

In lead-lag IMC, there are three tuning parameters such as α,β,λ

B. Smith predictor IMC controller

Presence of time delays limits the performance of the system. The system response with time delays are very slow compared to the systems with no time delays. Smith predictor is a special control strategy used for time delay compensation. It is widely used in distillation columns for compensation of delays.

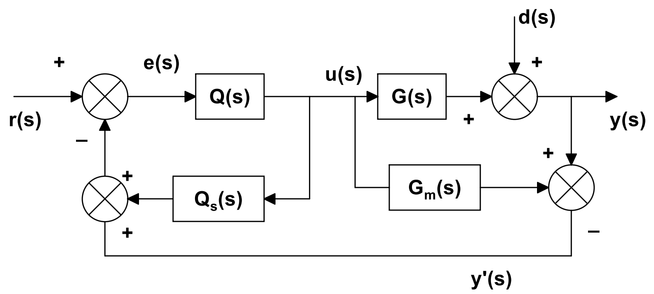


Fig.4. Block diagram of smith predictor IMC

Fig. 4 shows the block diagram of smith predictor IMC where $Q_s(s)$ is the smith predictor.

C. Feed-forward based IMC controller

If a specific knowledge about the disturbance is available then feed-forward controller is good choice for disturbance rejection purpose. For distillation column, feed-forward control strategy along with feedback control is used to reduce the disturbances. The block diagram of feed forward IMC is given in Fig. 5.

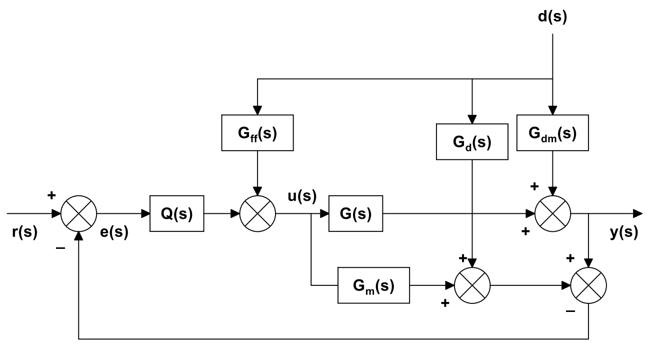


Fig.5. Block diagram of feed forward IMC

Feed-forward controller transfer function is given by

$$G_{ff}(s)=-\frac{G_{dm}(s)}{G_{pm}(s)}$$

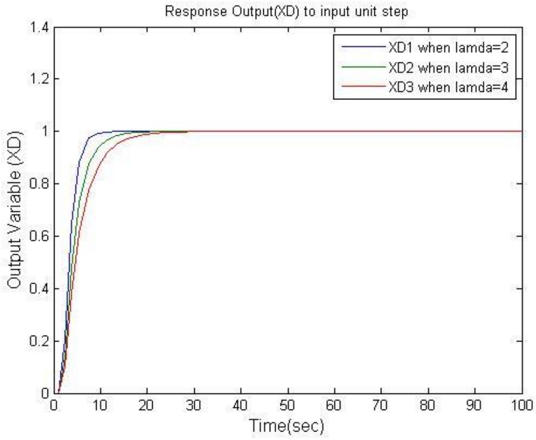
Where $G_{dm}(S)$ is disturbance model and $G_{pm}(S)$ is plant model. Here we considered both disturbance model and plant model are same as disturbance and process transfer functions.

IV. Simulation Results

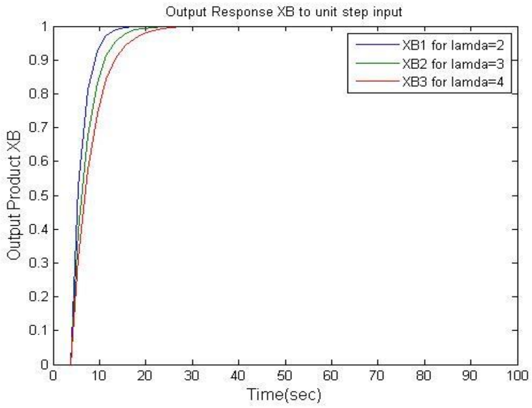
This section deals with simulated results of distillation column. Wood and Berry model of distillation column is considered which distillates ethanol from water. Wood and Berry model can be represented as

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} \dfrac{12.8e^{-s}}{16.7s+1} & \dfrac{-18.6e^{-3s}}{21s+1} \\ \dfrac{6.6e^{-7s}}{10.9s+1} & \dfrac{-19.4e^{-3s}}{14.4s+1} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} + \begin{bmatrix} \dfrac{3.8e^{-8s}}{14.9s+1} \\ \dfrac{4.9e^{-3.4s}}{13.2s+1} \end{bmatrix} d \qquad (10)$$

A controller has 2 specific objectives for a regulatory process control applications i.e set point regulation and disturbance rejection. This paper evaluates the controller performance using the above mentioned criteria. Fig. 6(a) shows the set point regulation of distillation composition in a distillation column. The set point regulation is achieved using internal model controller. Fig. 6(b) illustrates the set point regulation of bottom composition in a distillation column. Fig. 7(a) shows the disturbance rejection property of distillation composition in a distillation column. Fig. 7(b) illustrates the disturbance rejection property of bottom composition in a distillation column.

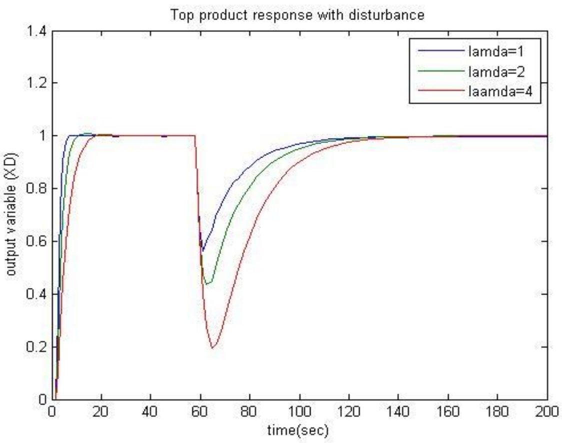


(a)

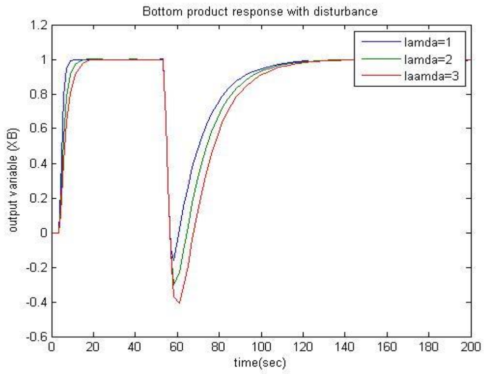


(b)

Fig.6. (a) Set point regulation of X_d (b) Set point regulation of X_b using internal model controller

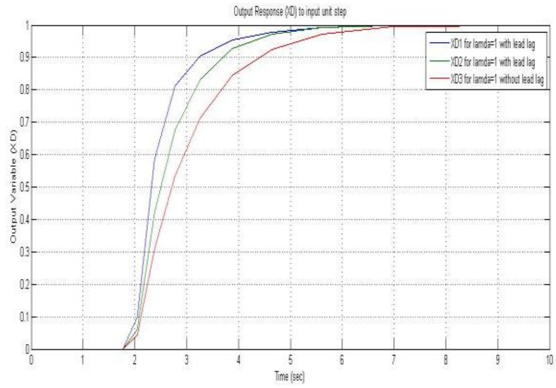


(a)

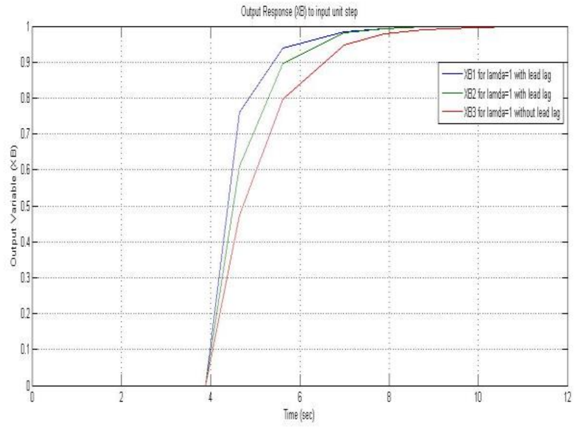


(b)

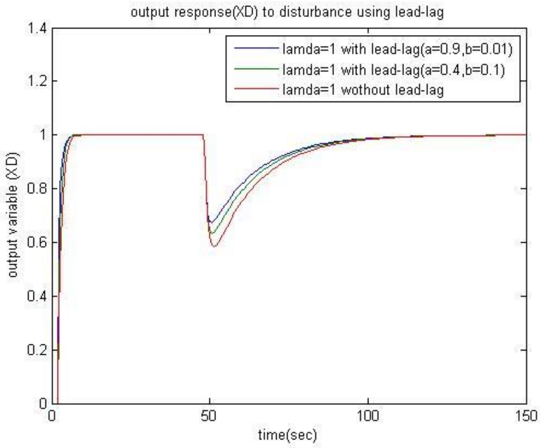
Fig.7. (a) Disturbance rejection of X_d (b) Disturbance rejection of X_b using internal model controller



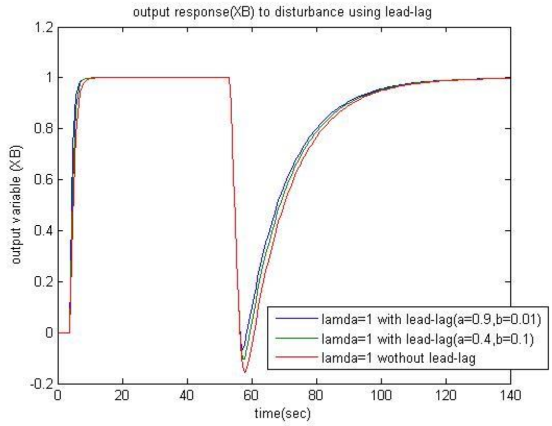
(a)



(b)



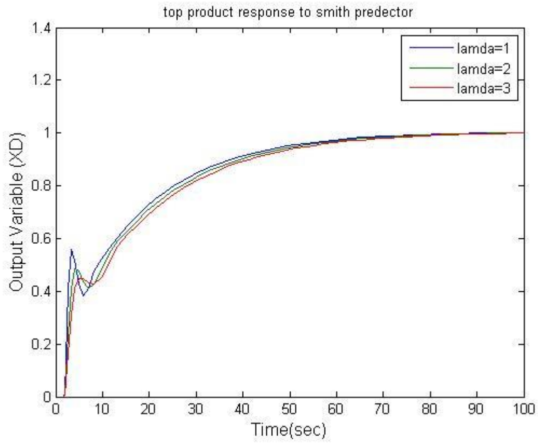
(c)



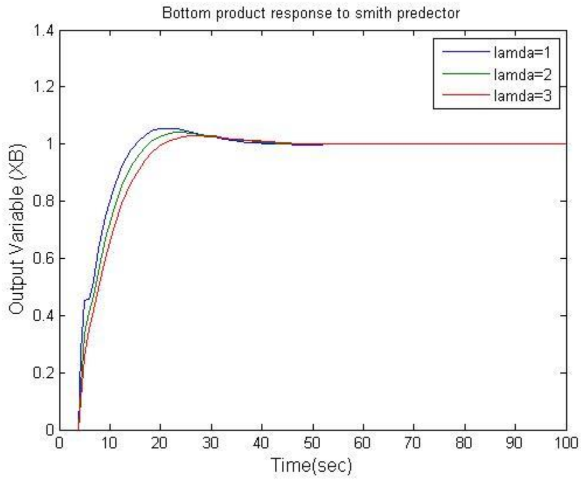
(d)

Fig.8. (a) Set point regulation of X_d (b) set point regulation of X_b using lead-lag internal model controller (c) Disturbance rejection of X_d (d) Disturbance rejection of X_b using lead-lag IMC.

Fig. 8(c) and Fig. 8(d) shows the disturbance rejection of top and bottom products composition using lead lag based IMC. Above results shows that the recovery time of the controller is less for lead-lag based IMC compared to general IMC controller. The controller along with lead-lag network is reducing disturbances effectively compared to normal IMC controller.



(a)



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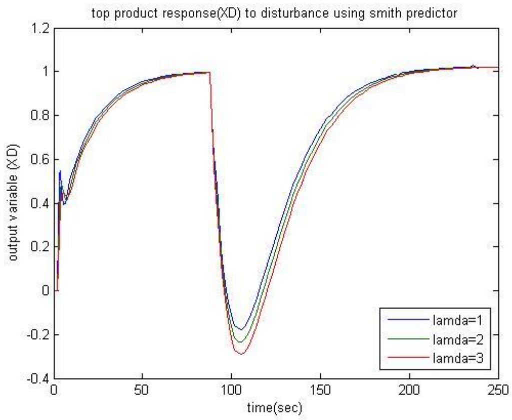
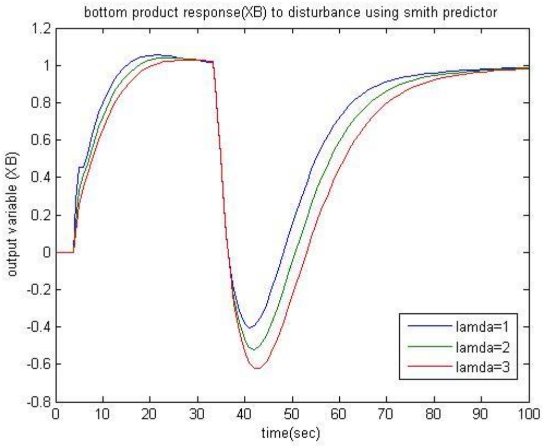
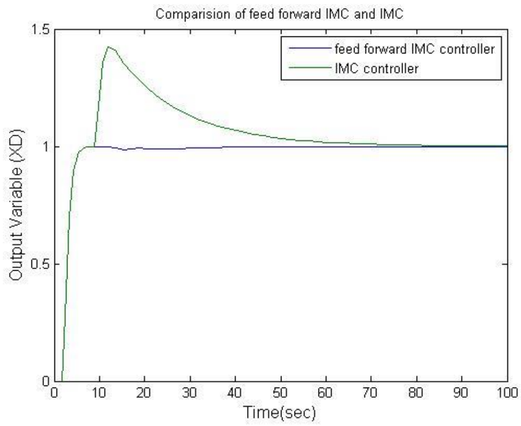


(c)

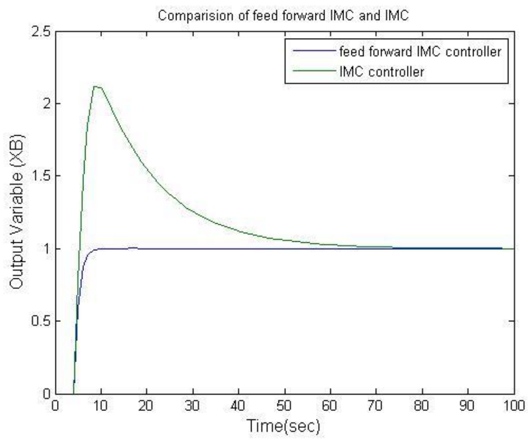


(d)

Fig.9. (a) Set point regulation of X_d (b) set point regulation of X_b using lead-lag internal model controller (c) Disturbance rejection of X_d (d) Disturbance rejection of X_b using smith predictor IMC.



(a)



(b)

Fig.10. (a) Set point regulation of X_d (b) set point regulation of X_b using feed forward internal model controller

From the transient response, it is evident that feed forward IMC controller performs better than rest of the controllers during disturbance at top and bottom product composition and lead-lag IMC provides better response in set point regulation scenario.

TABLE II. TRANSIENT PERFORMANCE OF CONTROLLER DURING SET POINT REGULATION

	Parameters	IMC	Lead-lag IMC	Smith predictor IMC
Top product	Rise time	1.6989	3.5304	47.3329
	Settling time	4.2582	3.5304	47.3329
Bottom product	Rise time	6.9238	5.316	22.2408
	Settling time	6.9238	5.316	22.2408

TABLE II. TRANSIENT PERFORMANCE OF CONTROLLER DURING TOP PRODUCT DISTURBANCE

	Rise time (sec)	Settling time (sec)	% overshoot
IMC	44.2397	44.2397	41.8019
Lead-lag IMC	39.956	39.956	32.48
Smith predictor IMC	49.6694	49.6694	53.4135
Feed-forward IMC	1.6989	4.2582	0

TABLE III. TRANSIENT PERFORMANCE OF CONTROLLER DURING BOTTOM PRODUCT DISTURBANCE

	Rise time	Settling time	% overshoot
IMC	51.1273	51.1273	114.28
Lead-lag IMC	49.15	49.15	105.2
Smith predictor IMC	46.7621	46.7621	134
Feed-forward IMC	3.9422	6.0953	0

V. CONCLUSION

This paper provides a comparative analysis of different control algorithm used to control distillate composition and bottom composition in a non-interactive scenario. Four different controllers such as internal model controller, lead lag IMC, feed-forward IMC and smith predictor IMC are evaluated. The steady state and transient state performance of these control techniques are evaluated using MATLAB-Simulink simulation platform.

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