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Enhancement of PID Controller Performance for a Quadruple Tank Process with Minimum and Non-Minimum Phase Behaviors

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Abstract

This paper analyses the Proportional-Integral-Derivative (PID) controller's performance for quadruple tank process. The selection of controlling the flow ratios in quadruple tank process act as Minimum and Non-minimum phase system. Its performance can be affected when system is shifted from minimum to non-minimum phase configuration and vice versa. This paper mainly focuses on searching the optimal controller structure by increasing the controllers' performance criteria. A comparative study on different controllers' structures responses are in the presence of peak overshoot. A simulation study of PID controller and Modified PID controller structures have been designed and to analyzed the different controllers' performance for the minimum and non-minimum phase system. The simulation results show that the PI-PD controller structure is provides enhanced performance for the set point tracking with nonappearance of peak overshoot.

Keywords: Quadruple tank process, PID controller and structure, Multivariable controller, Minimum and Non-minimum system

1. Introduction

Chemical process industries are strongly integrated process, that exhibit nonlinear behavior and complex dynamic properties. Many industrial controlled problems have more number of manipulated and controlled variables. It is common for industrial processes to have significant uncertainties, strong interaction of minimum and non-minimum phase behavior. The four tank multi variable system exhibits characteristics of interest in both control and research motivation. The quadruple-tank introduced by Johansson [1] has received a great attention because it presents interesting properties in the controller design and implementation. In this process, it can be shifted from minimum to non-minimum phase configuration and vice versa simply by changing a valve controlling the flow ratios γ_1 and γ_2 between lower and upper tanks. The linearized dynamics of the minimum and non-minimum phase system has a multivariable zero that is possible to move along the real axis either in left half-plane or right half plane by simply changing the valve controlling the flow ratios. The changing valve flow ration in quadruple tank process exhibits a sophisticated and simple way complex dynamics. Such dynamic characteristics include interactions; minimum and non-minimum phase systems require optimum controller operation.

Ali Abdullah and Mohamed Zribi [2] proposed that input-output feedback linearization controller for level control of a quadruple tank process. This proposed result indicated that the developed control schemes work well and are able to regulate the output of the process to its desired value and gave the best performance. Danica Rosinov and Matus Markech [3], reported that robust decentralized PID controller was designed for a nonlinear model of quadruple tank system with both minimum phase and non-minimum phase system configuration. This method has been proposed for LMI approach to the linearized state space model with polytopic uncertainties and both the approaches are compared and simulation results are presented. Kenichi Tamura and Hiromitsu Ohmori [4] discuss the auto-tuning of the expanded PID control for multi input and multi output (MIMO) linear system. The auto tuning is to give an adaptive law of time-varying PID parameter matrices and the closed-loop regulation system is asymptotically stabilized using the expanded PID control. In this paper a multivariable process is considered four interconnected water tanks with configuration of minimum phase and non-minimum phase system.

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Nomenclature

A	Cross-section of tank
a	Cross-section of the outlet hole of tank
h	Water level in tank
g	Acceleration of gravity
k	Flow corresponding to pump
F_{in}	Input flow of tank
F_{out}	Output flow of tank
A	Area of the tank
R	Output flow of tank
h_1	Liquid level inside tank 1
h_2	Liquid level inside tank 2
h_3	Liquid level inside tank 3
h_4	Liquid level inside tank 4
V	Volume of the tank
T_d	Dead time of input flow
g	gravitational constant
K_p	Proportional gain constant
K_i	Integral gain constant
K_d	Derivative gain constant
T_i	Integral time constant
T_d	Derivative time constant
u	Controller output
e	Error signal
y	Actual liquid level inside the tank
G	Process transfer function matrix

Greek Symbols

γ_1	Divides flow from pump 1 to the tanks 1 and 4
γ_2	Divides flow from pump 2 to the tanks 2 and 3

Abbreviations

PI	Proportional-Integral
PID	Proportional-Integral-Derivative
ZN	Ziegler-Nichols
FOPDT	First order plus dead time
MIMO	Multi-input and Multi-output

K Yamada [5] discussed that a designing method for modified PID control for minimum phase systems using the parameterization of all proper stabilizing controllers for linear minimum phase systems. The adequate controller structure is used system presents of minimum and non-minimum phase behavior that arises due to the multivariable nature of the problem. For this reason the quadruple tank has been used with different PID controller structure and to analyze the performance of the control techniques. Takaaki Hagiwara and Kou Yamada [6], this paper reported that a design method of modified PID controllers for MIMO plants. This paper deals that PID controller structure is the most widely used one in industrial applications. This method has been to guarantee the stability of PID control system in MIMO plants and the admissible sets of proportional, integrator and derivative parameters are used to guarantee the stability of PID control system.

The objective of the work is to design and implement a different form of PID controller structure and robust control analysis for a multivariable four tank level control process. The designs are demonstrated on a quadruple tank level control process with two inputs and two outputs. The aim of this work is to analyze some different PID controller structure of multivariable control systems. The control methodologies are PI, PID,PI-D, I-PD and PI-PD controllers. The five control algorithms are comparatively analyzed and controller tuned parameters are determined by ZN method. The different forms of controller structures are used on the four-tank system and the performance is compared with reference to tracking and performance indices. All simulation results are simulated using the MATLAB software and comparing different controllers' performance. In this work the pairing of inputs and outputs, multivariable control loops, and the presence of PID controller structures are analyzed.

In this paper, the first chapter gives an introduction about the quadruple tank level control process. It consists of literature reviews on controller techniques in minimum and non-minimum phase system. Chapter two covers the description of multivariable four tank process. Chapter three and four deal with PID controller and different forms of PID controllers structures respectively. Chapter five focuses on the results analysis and discussion of the work. Chapter six includes the concludes the work.

2. Process Description

This section aims at description and analysis of two input - two output process from literature, which will be later used to demonstrate the different forms of PID controller structure. The quadruple tank process shown in Fig.1 consists of four cylindrical tanks and two pumps; these pumps are connected to valves for water distribution. The Pump 1 is used to flow water from the water reservoir to tanks 1 and 4, while pump 2 is used to flow water to tanks 2 and 3.

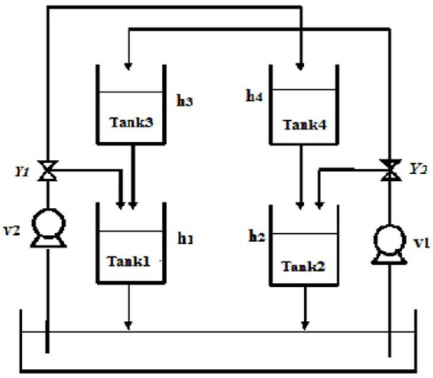

Fig.1 The quadruple tank process

The objective of this paper is to design control schemes and to control the level in the lower tanks using two pumps. The controlled outputs h1 and h2 are levels in lower tanks 1 and 2 respectively. The nonlinear model of the four tanks can be described by state equations.

$$\begin{aligned}
\frac{dh_1}{dt} &= -\frac{a_1}{A_1}\sqrt{2gh_1} + \frac{a_3}{A_1}\sqrt{2gh_3} + \frac{\gamma_1 k_1}{A_1} v_1 \\
\frac{dh_2}{dt} &= -\frac{a_2}{A_2}\sqrt{2gh_2} + \frac{a_4}{A_2}\sqrt{2gh_4} + \frac{\gamma_2 k_2}{A_2} v_2 \\
\frac{dh_3}{dt} &= -\frac{a_3}{A_3}\sqrt{2gh_3} + \frac{(1-\gamma_2) k_2}{A_3} v_2 \\
\frac{dh_4}{dt} &= -\frac{a_4}{A_3}\sqrt{2gh_4} + \frac{(1-\gamma_1) k_1}{A_4} v_1
\end{aligned} \tag{1}$$

Where, $k_i v_i$ is the flow corresponding to pump i, $\gamma_1 k_1 v_1$ - is the flow of tank 1, $\gamma_2 k_2 v_2$ - is the flow of tank 2, $(1-\gamma_1)k_1 v_1$ - is the flow of tank 4 and $(1-\gamma_2)k_2 v_2$ - is the flow of tank 2. The quadruple tank nonlinear model can be linearized around the working point given by the water levels in tanks $h_{10}, h_{20}, h_{30}, h_{40}$. The linearized state space model for quadruple tank process is,

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} \frac{-1}{T_1} & \frac{A_3}{T_3 A_1} & 0 & 0 \\ 0 & \frac{-1}{T_3} & 0 & 0 \\ 0 & 0 & \frac{-1}{T_2} & \frac{A_4}{T_4 A_2} \\ 0 & 0 & 0 & \frac{-1}{T_4} \end{bmatrix} . \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} \frac{\gamma_1 k_1}{A_1} & 0 \\ 0 & \frac{(1-\gamma_2)k_2}{A_3} \\ 0 & \frac{\gamma_2 k_2}{A_1} \\ \frac{(1-\gamma_1)k_1}{A_4} & 0 \end{bmatrix} . \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \tag{2}$$

Where, $T_i = \frac{A_i}{a_i}\sqrt{\frac{2h_{i0}}{g}}, i = 1,2,3,4.$

The state variables corresponding to levels in tanks 2 and 3 have been interchanged in state vector so that subsystems respective to input u_1 from pump 1 (tanks 1 and 3) and u_2 from pump 2 (tanks 2 and 4) are more apparent. This decomposition in two subsystems is used for controller design. The respective transfer function matrix having inputs v1 and v2 and outputs h1 and h2 is,

$$G(s) = \begin{bmatrix} \frac{c_1\gamma_1}{T_1 s+1} & \frac{c_1(1-\gamma_2)}{(T_1 s+1)(T_3 s+1)} \\ \frac{c_2(1-\gamma_1)}{(T_2 s+1)(T_4 s+1)} & \frac{c_2\gamma_2}{T_2 s+1} \end{bmatrix} \quad (3)$$

Where, $c_i = \frac{T_i k_i}{A_i}\sqrt{\frac{2h_{i0}}{g}}, i = 1,2.$

The plant can be shifted from minimum to non-minimum phase configuration and vice versa simply by changing a valve controlling the flow ratios γ_1 and γ_2 between lower and upper tanks. The minimum-phase configuration corresponds to $1 < \gamma_1 + \gamma_2 < 2$ and the non-minimum phase one to $0 < \gamma_1 + \gamma_2 < 1$. The main aim of this work is to analyze both minimum and non-minimum phase MIMO systems on the same plant with the presence of PID controllers.

3. Conventional PID Controller

Many industrial processes see it complicated to describe system mathematically. However, it is known that many processes can be satisfied when controlling the process using the Proportional-Integral-Derivative (PID) controller provide that controller parameters are tuned well.

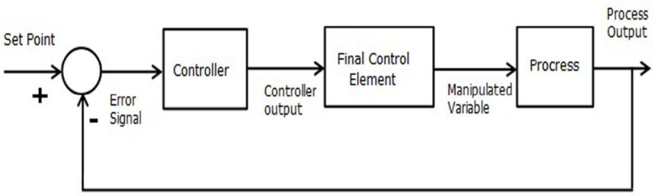

Fig. 2 A single loop system

In Fig. 2 shows that a single control or closed loop system, the output value of the process loop is measured and it is subtracted from the target value or set point. The difference is error signal and it is given to the controller. The controller takes the corrective action depending on the error signal. The controller is given the control signal to the control valve or correcting device. The control valve is to adjust the manipulated variable until the process output to reach the desired value or set point. The performance of the control loop depends on the gain, linearity and dynamics of all elements.

A continuous development of new control algorithms insure that the time of PID controller has not past and that this basic algorithm will have its part to play in process control applications. The modified structure of PID controller is used to improve the controller performance in process industry and it is designed from basic structure of PID controller.

3.1 The basic PI and PID controller

A PID controller consists of simple three terms controller. The letters are P, I and D stand for proportional, integral and derivative terms respectively. The characteristics of each terms, are used to obtain a desired response. Eqn. 4 and Eqn. 5 show P and PI controllers' expressions respectively. The proportional control action or signal is proportional to the error signal, the control signal will be,

$$u(t) = K_p\, e(t) \quad (4)$$

The proportional plus integral controller action or signal occurs in the following way,

$$u(t) = K_p\left(e(t) + \frac{1}{T_i}\int e(t)\,dt\right) \quad (5)$$

The proportional plus integral plus derivative controller action or signal in the following way,

$$u(t) = K_p\left(e(t) + \frac{1}{T_i}\int e(t)\,dt + T_d\frac{d\,e(t)}{dt}\right) \quad (6)$$

The integral and derivative constants are obtained using the below relations,

The integral gain or constant (K_i) = $\dfrac{K_p}{T_i}$

The Derivative gain or constant (K_d) = $K_p T_d$

Where, K_p - is proportional gain or constant

T_i and T_d - are integral time and derivative time constants respectively.

4. The Modified PID Controller Structures

The simple PID controller structure can be widely used in industrial control applications [7, 8]. The performance characteristics of a closed loop responses are rise-time, peak over shoot, settling time and steady state error. The PID controller parameters are affecting these performances characteristics of a control loop response. Recently, the performance of the closed loop system can be improved using the modified PID control structure [9, 10]. All the practical plants include the main problem that is designing of robust stabilizing modified PID controllers for any plant with uncertainty is important [11]. To overcome this problem, Yamada et. al. [12], gave a design method for robust stabilizing modified PID controllers to make the closed-loop system stable for any plant with uncertainty. The proportional term adjusts the speed of response of the system, the integral term adjusts the steady state error of the system and the derivative term adjusts the degree of stability of the system [13]. The modifications of PID controllers are derived from the basic form of PID controller. Typical structures are shown as follows.

4.1 The PI-D Controller Structure

The structure of PI-D controller, the proportional and integral action are in the form of serial compensation and the derivative action will be included in the parallel compensation. The error signal will be transferred through PI controller and derivative action is connected to process-output. The control signal for PI-D controller structure is,

$$u(t) = K_p\left(e(t) + \frac{1}{T_i}\int e(t)\,dt\right) - K_p\left(\frac{d\,y(t)}{dt}\right)T_d \tag{7}$$

4.2 The I-PD form of PID Controller

The error signal will be connected to integral controller, the proportional and derivative elements that are connected to process-output. The modified I-PD structure is shown in Eqn. 8. The I-PD controller structure improves the performance of the controller by avoiding the effect of proportional kick [12, 13]. The control signal for I-PD controller structure is,

$$u(t) = K_p\left(\frac{1}{T_i}\int e(t)\,dt\right) - K_p\left(y(t) + T_d\frac{d\,y(t)}{dt}\right) \tag{8}$$

4.3 The PI-PD Controller Structure

The error and the process output signals are connected to proportional plus integral (PI) and proportional plus derivative (PD) controllers respectively. The results for the process control examples are indicative of vastly improved time-domain performance and reduction in controller variance in the case of PI-PD controller, when compared to the more traditional PID controller [14]. The below equation is control signal for PI-PD controller structure,

$$u(t) = K_p\left(e(t) + \frac{1}{T_i}\int e(t)\,dt\right) - K_p\left(y(t) + T_d\frac{d\,y(t)}{dt}\right) \tag{9}$$

5. Simulation Results and Discussion

The Eqn.1, relates the rate of change of liquid height (h_1, h_2, h_3, h_4) and relates the difference between inlet flow and outlet flow. Using this equation, the simulation model of four tank system was developed. The simulation parameters are tabulated in Table I, given below and by using these parameters we obtain the open loop response.

Table I. The nominal values for simulation parameters

S.No.	*Description*	*Values*
1.	Area of the tank A_1,A_3	28 cm^2
2.	Area of the tank A_2,A_4	32 cm^2
3.	Area of the outlet pipes a_1,a_3	0.071 cm^2
4.	Area of the outlet pipes a_2,a_4	0.057 cm^2
5.	Gravitational constant g	9.81

For quadruple tank system, we consider the uncertainty to be a change of valve position γ_1 and γ_2 between lower and upper tanks; uncertainty domain is specified by three working points. In Minimum phase region three operating points are selected with different values of γ_1 and γ_2. The nominal parameters are tabulated below

Table II. Operating parameters of minimum phase

Parameter	Nominal Values		
	Operating Point 1	Operating Point 2	Operating Point 3
h_{10}, h_{20}	12.34,12.77	12.24,12.81	12.23,12.55
h_{30}, h_{40}	2.09,1.92	0.64,0.35	0.23,0.03
k_1, k_2	3.33,3.35	3.33,3.35	3.33,3.35
γ_1, γ_2	0.65,0.55	0.85,0.75	0.95,0.85
v_1, v_2	3,3	3,3	3,3

The Eqn.7, relates the rate of change of liquid height the difference between inlet flow and outlet flow of each tanks. Nominal parameters are used to develop the quadruple tank minimum phase system. The open loop response of the minimum phase system with three operating region is shown below.

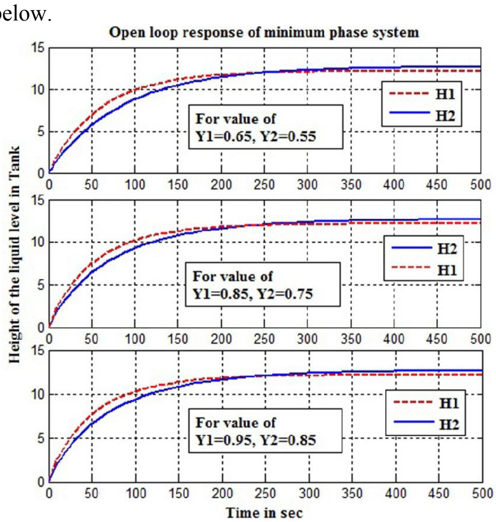

Fig. 3 The step response of minimum phase system

The model and control of the process are studied at two operating points, G_- at which the system exhibits minimum phase characteristics and G_+ at which the system exhibits non-minimum characteristics. The chosen operating points correspond to the values are specified in the Table 2. The transfer function model of the process can be analytically found around the operating condition as shown in the Table 2. The transfer function model of the process is found at three operating points.

$$G_{-1}(s) = \begin{bmatrix} \dfrac{0.76}{(63s+1)} & \dfrac{0.52}{(63s+1)(25s+1)} \\ \dfrac{0.53}{(91s+1)(35s+1)} & \dfrac{0.84}{(91s+1)} \end{bmatrix}$$

$$G_{-2}(s) = \begin{bmatrix} \dfrac{0.99}{(62s+1)} & \dfrac{0.29}{(62s+1)(14s+1)} \\ \dfrac{0.22}{(91s+1)(15s+1)} & \dfrac{1.14}{(91s+1)} \end{bmatrix}$$

$$G_{-3}(s) = \begin{bmatrix} \dfrac{1.10}{(62s+1)} & \dfrac{0.17}{(62s+1)(8s+1)} \\ \dfrac{0.07}{(91s+1)(4s+1)} & \dfrac{1.27}{(91s+1)} \end{bmatrix}$$

In Non-Minimum phase region three operating points are selected with different values of γ_1 and γ_2. The nominal parameters are tabulated below.

Table III. Operating parameters of non-minimum phase

Parameter	*Nominal Values*		
	Operating Point 1	*Operating Point 2*	*Operating Point 3*
h_{10}, h_{20}	8.662,18.975	12.242,12.808	12.228,12.546
h_{30}, h_{40}	6.108,11.088	0.638,0.352	0.229,0.025
k_1, k_2	3.14,3.29	3.14,3.29	3.14,3.29
γ_1, γ_2	0.15,0.25	0.25,0.35	0.35,0.45
v_1, v_2	3.15,3.15	3.15,3.15	3.15,3.15

The Eqn.1, relates the rate of change of liquid height to the difference between inlet flow and outlet flow of each tank. Using this equation and above nominal parameters are used to developed the quadruple tank non-minimum phase system. The open loop response of the minimum phase system with three operating region is shown below.

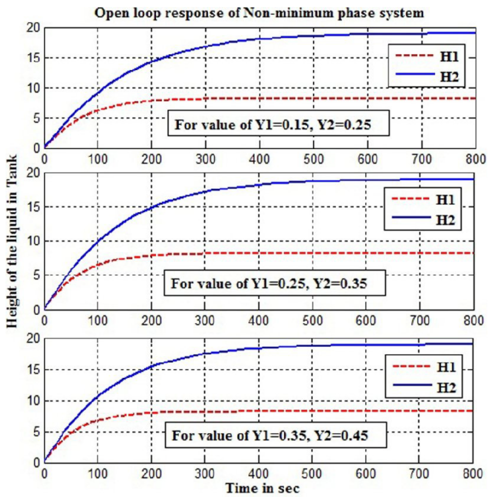

Fig. 4 The step response of non-minimum phase system

The transfer function model of the non-minimum phase system can be analytically found around the operating condition as shown in the Table 3. The transfer function model of the process is found at three operating points.

$$G_{+1}(s) = \begin{bmatrix} \dfrac{0.11}{(52s+1)} & \dfrac{0.58}{(52s+1)(44s+1)} \\ \dfrac{1.89}{(110s+1)(84s+1)} & \dfrac{0.55}{(110s+1)} \end{bmatrix}$$

$$G_{+2}(s) = \begin{bmatrix} \dfrac{0.26}{(51s+1)} & \dfrac{0.41}{(51s+1)(32s+1)} \\ \dfrac{1.47}{(111s+1)(64s+1)} & \dfrac{1.02}{(111s+1)} \end{bmatrix}$$

$$G_{+3}(s) = \begin{bmatrix} \dfrac{0.19}{(52s+1)} & \dfrac{0.50}{(52s+1)(38s+1)} \\ \dfrac{1.68}{(110s+1)(74s+1)} & \dfrac{0.78}{(110s+1)} \end{bmatrix}$$

The Ziegler-Nichols open loop method [16] is used for tuning the controller P, PI and PID controller parameters. The tuning controller parameters are used in different PID structures and to obtain the simulated responses. The closed loop responses for the presence of PID controller and different controller structures are show in Fig. 4 to Fig. 10.The controller tuning parameters is found by using the ZN method. The quadruple four tank level control process is considered the multivariable control system [17]. In this work the controlled variable is tank 1 and tank 2 liquid levels. Liquid level control in tank 1 is first loop (Loop 1) and tank is loop 2. The proportional, integral and derivative (PID) controller parameters for the minimum phase system are given below in Table 4. The controller parameters of loop1 and loop 2 for three operating points are considered as controller tuning. The controllers are designed around the operating point ($h_{10}, h_{20}, h_{30}, h_{40}$) and their tuning constants are tabulated. Step responses of the closed loops PID controllers are shown here and the simulated results are also shown using the three different operations.

Table IV. Controller parameters for Minimum phase system

Parameters	*Loop1*			*Loop2*		
	K_P	K_I	K_D	K_P	K_I	K_D
Operating Point 1	15.78	1.253	49.73	14.28	0.784	64.99
Operating Point 2	12.12	0.97	37.57	10.52	0.57	47.89
Operating Point 3	10.90	0.87	33.81	9.448	0.524	42.51

Implementing the control method mentioned in this paper, control system is compared with the classical common method Ziegler – Nichols and comparing the simulation results. The simulation of minimum phase system with tuned PID type controller and simulated response are shown in Fig.5. The responses of PI-D controller for minimum phase systems are shown in Fig. 6. When PI-D is used, a step reference at the end results having overshoot at both levels (h_1, h_2).

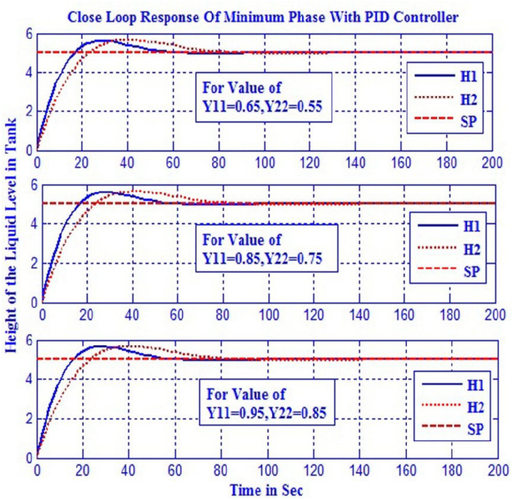

Fig.5 Servo response of minimum phase system with PID controller

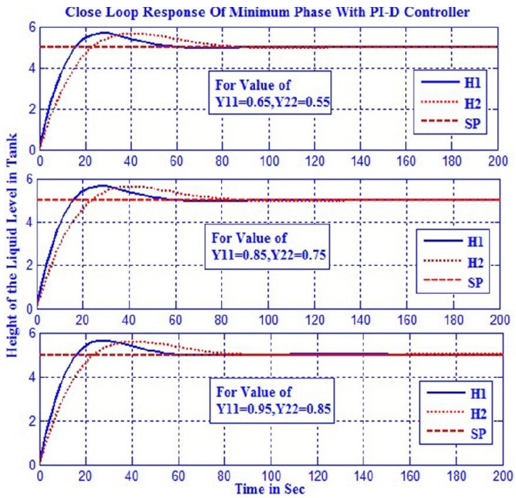

Fig.6 Servo response of minimum phase system with PI-D controller

The controller response of I-PD controller for minimum phase system set point trajectory responses are shown in Fig. 7. In this response, the I-PD controller tuning parameters are well tuned and provide a slight overshoot. The results are shown in Fig. 8 for modified form of PI-PD controller. From step references, it is observed that the PID structures possess an overshoot expect PI-PD controller. The servo response of PI-PD controller input to force the system output to a non-overshoot step response.

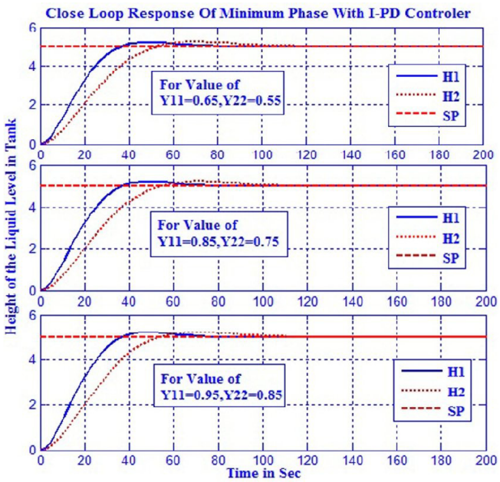

Fig.7 Servo response of minimum phase system with I-PD controller

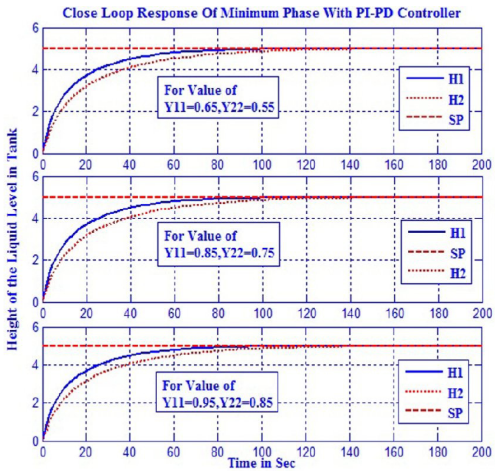

Fig.8 Servo response of minimum phase system with PI-PD controller

The PID controller tuning parameters for the non-minimum phase system are tabulated below. The controller parameters of loop1 and loop 2 for three operating points are considered as controller tuning.

Table V. Controller parameters for Non-Minimum phase system

Parameters	***Loop1***			***Loop2***		
	K_P	K_I	K_D	K_P	K_I	K_D
Operating Point 1	109.07	10.48	283.63	21.18	0.962	116.49
Operating Point 2	63.15	6.10	164.19	15.38	0.69	84.59
Operating Point 3	46.15	4.52	117.68	11.76	0.52	65.29

The simulation of non-minimum phase system with tuned PID type controller and simulated response are shown in Fig.9 to Fig. 12. From this simulation response, it is shown that PID, PI-D and I-PD controller response have overshoot. The process with PI-D controller is shown in the Fig. 10 and depicts the output of the process. It is observed that PI-D controllers presented overshoot in response.

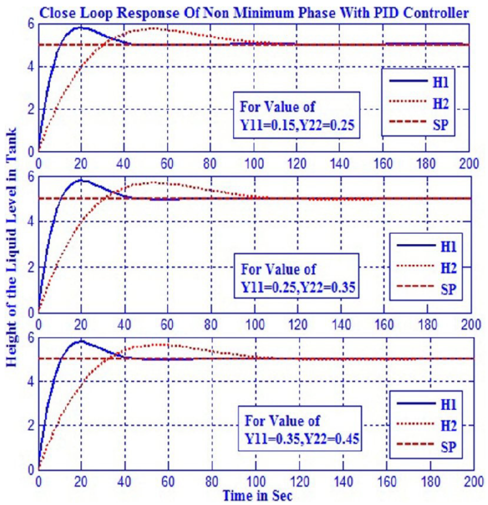

Fig.9 Servo response of non-minimum phase system with PID controller

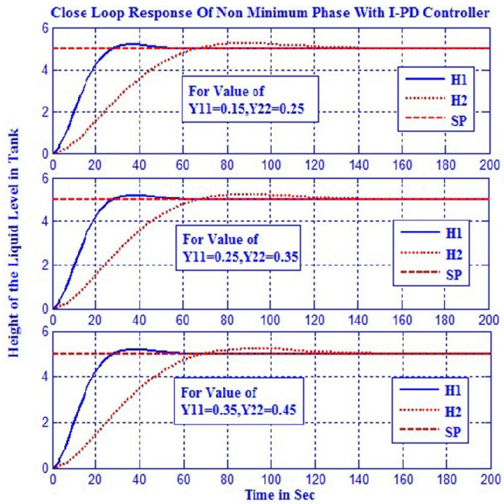

Fig.10 Servo response of non-minimum phase system with I-PD controller

Fig. 11 provides the plots of the servo response of the I-PD controller. By using I-PD controller there is minimizing overshoot effect to the output response as compared to PI-D controller response. By using the PI-PD controller structure for non-minimum phase system, the response for the step input is shown in Fig. 12. We see that the output has no overshoot and also speed of the desired response is more.

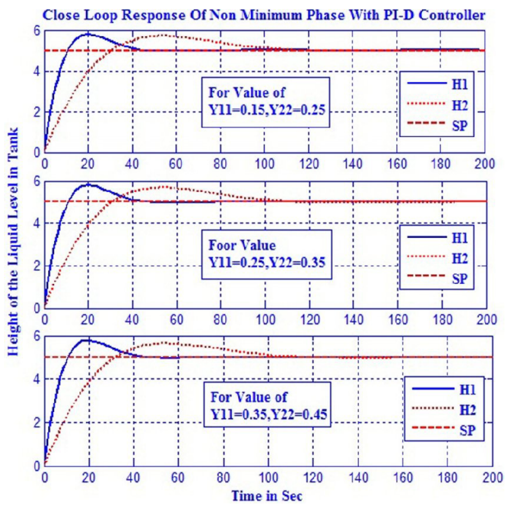

Fig.11 Servo response of non-minimum phase system with PI-D controller

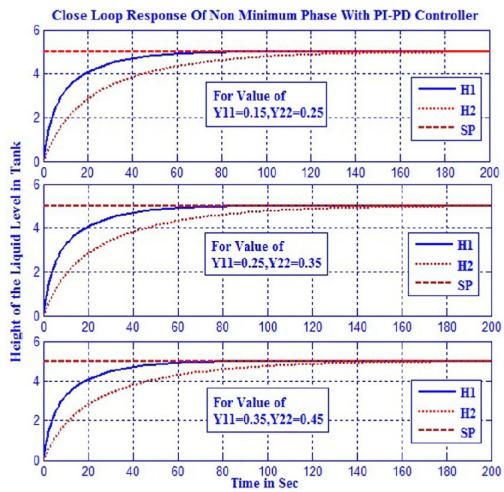

Fig.12 Servo response of non-minimum phase system with PI-PD controller

6. Conclusions

In this paper, we designed different modified PID controllers and applied to the four tank system with minimum phase and non-minimum phase system. MATLAB simulations show that PI-PD controller results in a quicker response with a no overshoot than the conventional PID, PI-D and I-PD controllers. It has a strong ability to adapt to the significant change of controlling flow ratio in quadruple tank level process. To summarize, the PI-PD controller has been proved to be an effective method in the level control in both minimum and non-minimum phase system.

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