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Design of Fractional Order Controller for a MIMO Process

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Abstract

PID controller is a simple and versatile device used in process industries since 1940. There has been a fast development in the field of process control which results in advanced controllers like intelligent controllers. But the PID controller also has its own path in the sense that variety of modifications are introduced to improve the control performance. One among them is the application of fractional calculus in control theory. The controller is called fractional order controller with PID structure. The objective of this paper is to compare the performance of the Fractional order controller with three different tuning rules, for a MIMO process. Tuning formulas based on BLT, Gain shaping and Pole placement techniques are used for performance comparison. The Quadruple Tank Process is taken to study the performance of the controllers. Simulation is carried out through MATLAB SIMULINK software. Real time experimental results are also presented to validate the controller performance.

Keywords: Multi-loop, Quadruple tank process, Fractional Order Control, BLT Controller, Gain Shaping Controller, Pole Placement Controller.

1. Introduction

The range of real world control problem are increasing and hence the research is devoted in developing control strategy to meet the requirements. Fractional calculus and its applications to control theory is one of the dynamic field of research. Extending the concept of integer-order calculus to non-integer order is one of the development in the field of control theory. The so called Fractional order Proportional Integral Derivative controller ($PI^{\lambda}D^{\mu}$) may be designed both for Fractional-order as well as integer order systems.

The flexibility of tuning fractional order controller made it possible to develop a control strategy for a MIMO process. $PI^{\lambda}D^{\mu}$ controller has been introduced in [1]. Speed control of DC motor using fractional order controller was described in [2]. Optimization algorithms were implemented to tune FOPID controller in [3]. Real Time Implementation of Fractional Order Proportional-Integral Controller (PI^{λ}) for a liquid level system is presented in [4]. A new strategy to tune a fractional order controller for a temperature profile tracking was proposed in [5]. Drilling machines output controlled by FOPID controller using minimization technique was explained in [6].

The objective of this paper is to compare the performance of the tuning techniques with fractional order controller. BLT, Gain shaping and Pole placement techniques are used for comparison. The developed control strategy is implemented in the QTP which is a MIMO process with minimum phase as well as non-minimum phase characteristics. The performance evaluation is carried out through simulations as well as experiment. This paper is organized as follows: Section 2 presents the process description. Structure of Fractional Order Controller is presented in section 3. Simulation results and discussion are given in section 4 followed by conclusion in section 5.

2. Process Description

The quadruple tank process was designed to illustrate performance limitation due to zero location in multivariable control systems. It consists of four inter connected water tanks and two pumps. The quadruple tank process is shown in Fig.1. Its inputs are voltages to two pumps and the outputs are the water level in the lower two tanks. This process can easily be build by using two double-tank process, which are standard processes in many control laboratories [7],[8]. The setup is thus simple, but still the process can illustrate several interesting multivariable phenomena. The linearized model of the quadruple tank process has a multi-variable zero, which can be located in either the left are the right half-plane by changing a valve position. Both the location and the direction of a multivariable zero are important for control design. They have direct physical interpretation for quadruple tank process which makes the process suitable to use in control education.

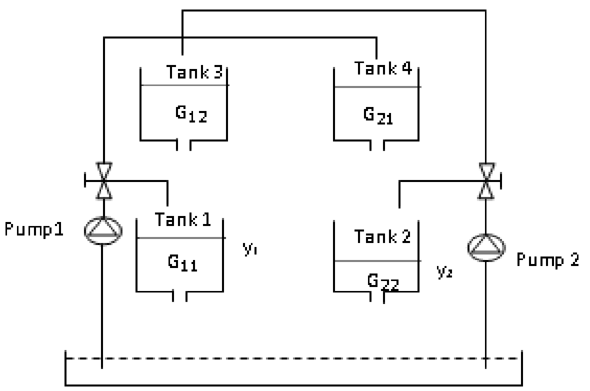

Fig.1. Schematic diagram of the quadruple-tank process

The transfer function model of the process can be experimentally found around the operating condition [9].
The Minimum Phase (G_(s)) transfer function model of the process is found to be

$$G_-(s) = \begin{bmatrix} \dfrac{3.06e^{-50s}}{(450s+1)} & \dfrac{2.353e^{-9s}}{(516s+1)} \\ \dfrac{1.6e^{-62.5s}}{(487.5s+1)} & \dfrac{4.4e^{-21.5s}}{(553.5s+1)} \end{bmatrix}$$

The Non Minimum Phase ($G_+(s)$) transfer function model of the process is found to be

$$G_+s = \begin{bmatrix} \dfrac{2.083e^{-63s}}{(525s+1)} & \dfrac{4.32e^{-10s}}{920s+1)} \\ \dfrac{2.45e^{-20s}}{(550s+1)} & \dfrac{1.411e^{-75s}}{(262.5s+1)} \end{bmatrix}$$

3. Structure of Fractional Order Controller

The Fractional order controller ($PI^\lambda D^\mu$) [10] consists of an integrator of order λ and a differentiator of order μ. The transfer function of such a controller has the form

$$G_c(s) = \frac{U(s)}{E(s)} = K_P + K_I s^{-\lambda} + K_D s^{\mu} \quad (1)$$

(λ, μ >0)

where
$G_c(s)$ is the transfer function of the controller,
E(s) is an error, and
U(s) is controller output.

The $PI^\lambda D^\mu$-controller output in the time domain is given by

$$u(t) = K_P e(t) + K_I D^{-\lambda} e(t) + K_D D^{\mu} e(t) \quad (2)$$

λ=μ=1.The block diagram of Fractional order PID controller is shown in Fig.2. The values of given k_c, k_i
and k_d are selected using the three tuning techniques.

The parameters λ and μ are tuned to meet the requirements.

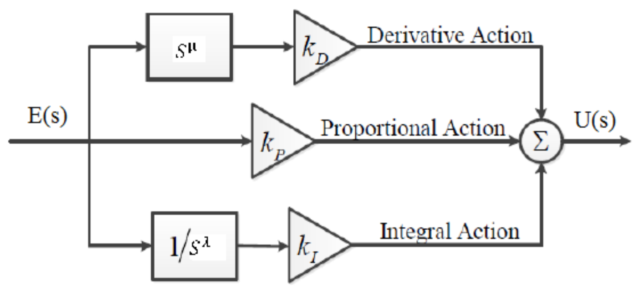

Fig.2. Fractional PID controller

The control strategy of both the minimum and non-minimum phase process with Fractional order controller is shown in Fig.3. and Fig.4. respectively.

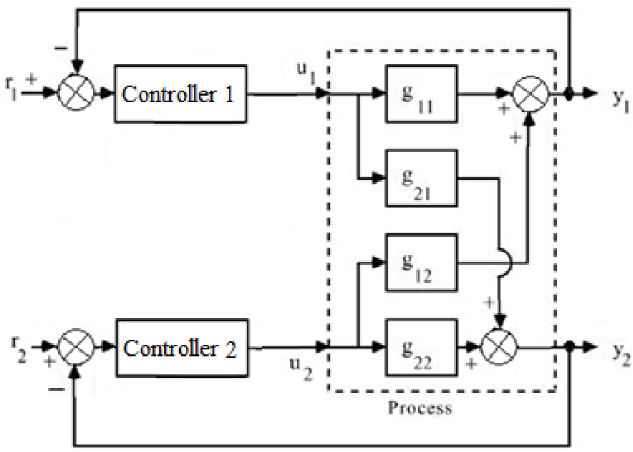

Fig.3. Structure of multi-loop Fractional order control strategy for minimum phase process

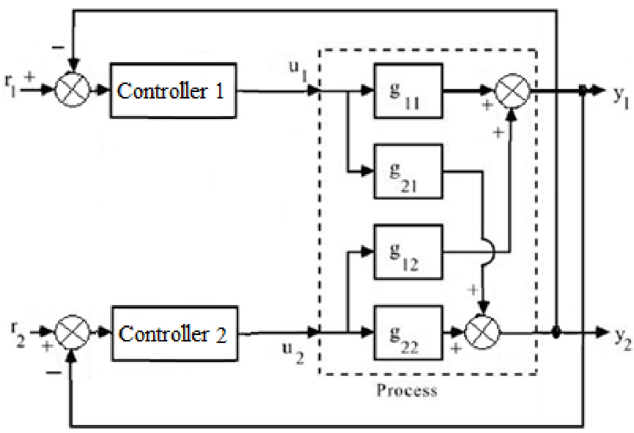

Fig.4. Structure of multi-loop Fractional order control strategy for non minimum phase process

4. Simulation Result and Discussion

Fractional order controller is designed and implemented using MATLAB SIMULINK software as well as in a real process using interfacing card. The servo and regulatory responses of the process (both minimum phase as well as non minimum phase characteristics) with fractional order PI controller tuned using BLT, Gain shaping and Pole placement technique [11], [12], [13] are presented from Fig.5. to Fig.16. The parameters of the controller are presented in Table.1. and Table.2. The performance of the process with all the three control strategies are evaluated using the performance indices namely settling time(t_s), maximum overshoot(M_p%),peak time (t_p),rise time(t_r) and Integral square error (ISE) are presented from Table.3. to Table.6.

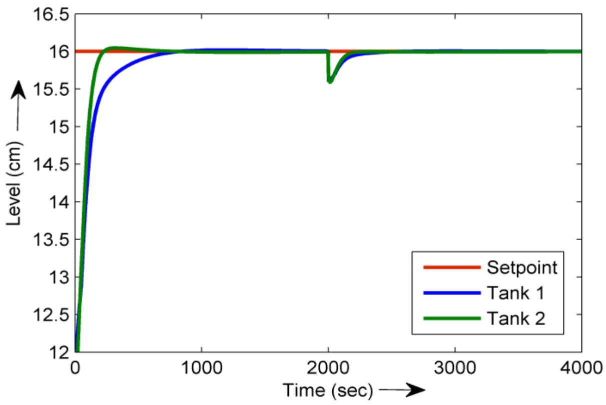

Fig .5.Servo and regulatory responses of the process (minimum phase characteristics) with BLT tuned Fractional order PI control strategy (simulation)

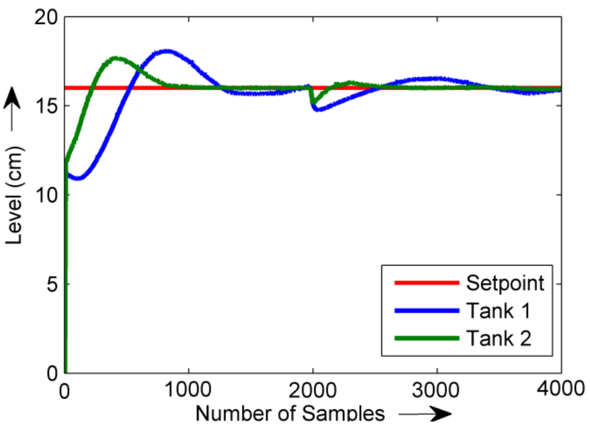

Fig. 6. Servo and regulatory responses of the process (minimum phase characteristics) with BLT tuned Fractional order PI control strategy (experiment)

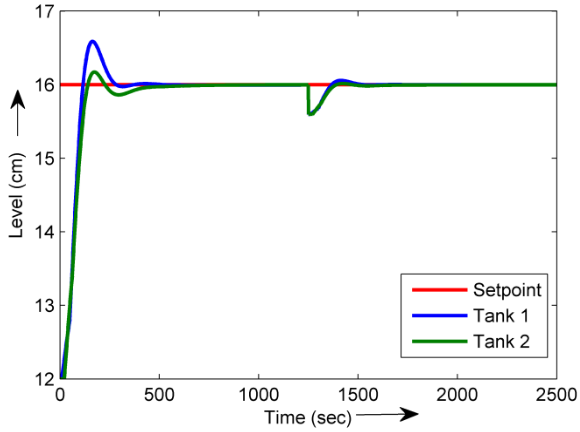

Fig.7. Servo and regulatory responses of the process (minimum phase characteristics) with Gain shaping tuned Fractional order PI control strategy (simulation)

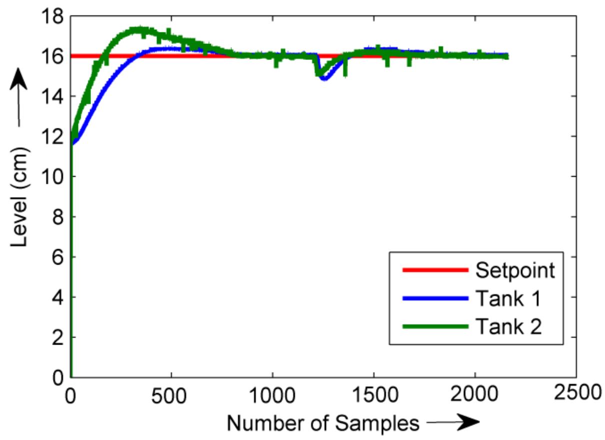

Fig .8. Servo and regulatory responses of the process (minimum phase characteristics) with Gain shaping tuned Fractional order PI control strategy (experiment)

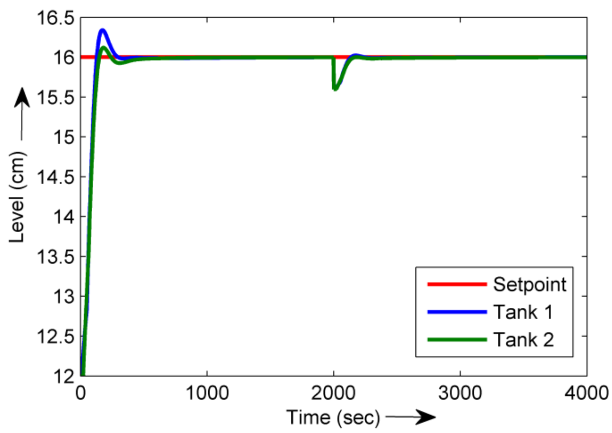

Fig .9. Servo and regulatory responses of the process (minimum phase characteristics) with Pole placement tuned Fractional order PI control strategy (simulation)

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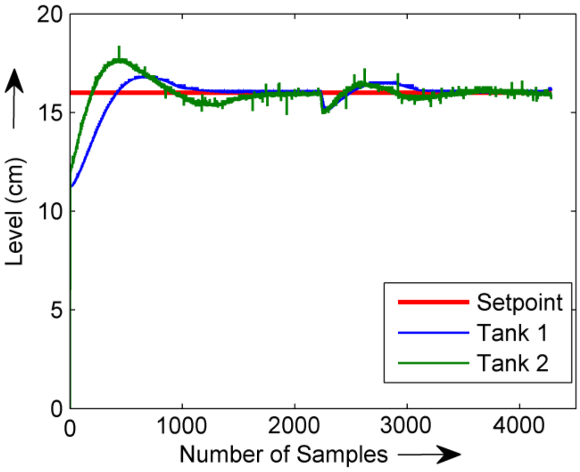

Fig.10. Servo and regulatory responses of the process (minimum phase characteristics) with Pole placement tuned Fractional order PI control strategy (experiment)

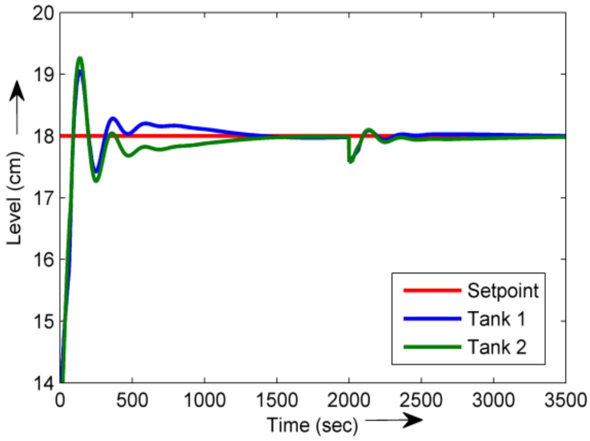

Fig.11. Servo and regulatory responses of the process (Non-minimum phase characteristics) with BLT tuned Fractional order PI control strategy (simulation)

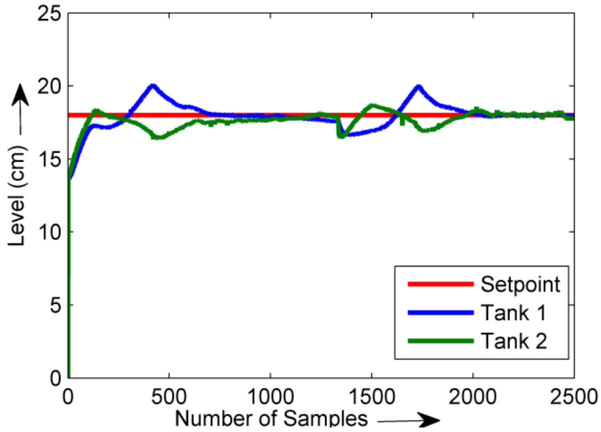

Fig.12. Servo and regulatory responses of the process (Non-minimum phase characteristics) with BLT tuned Fractional order PI control strategy (experiment)

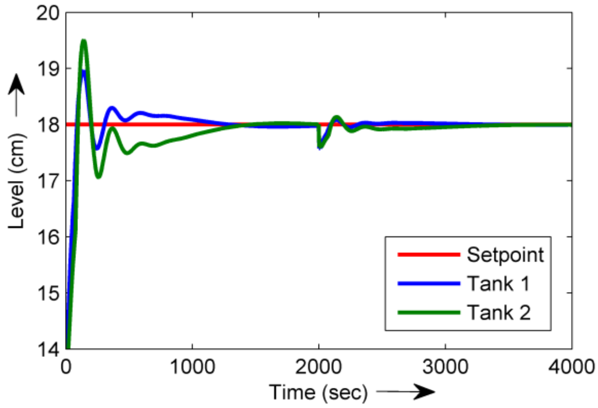

Fig.13. Servo and regulatory responses of the process (Non-minimum phase characteristics) with Gain shaping tuned Fractional order PI control strategy (simulation)

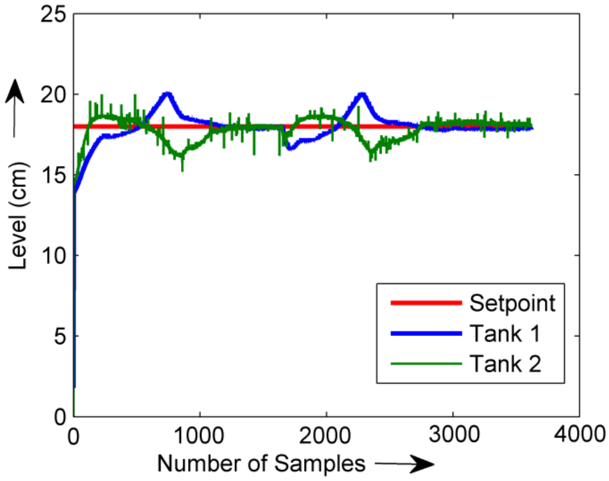

Fig.14. Servo and regulatory responses of the process (Non-minimum phase characteristics) with Gain shaping tuned Fractional order PI control strategy (experiment)

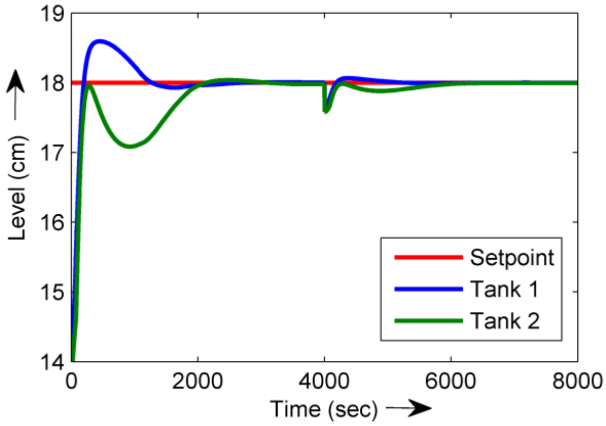

Fig .15. Servo and regulatory responses of the process (Non-minimum phase characteristics) with Pole placement tuned Fractional order PI control strategy (simulation)

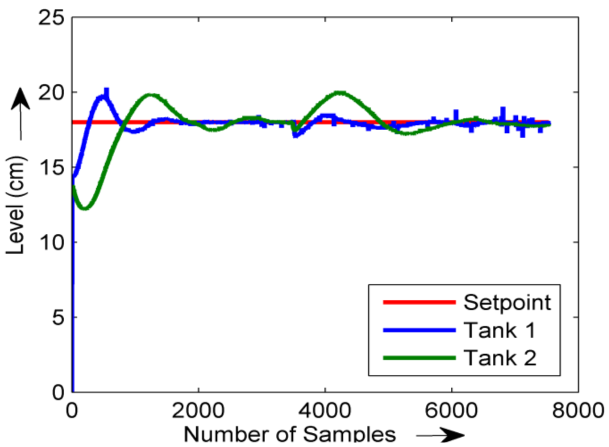

Fig.16. Servo and regulatory responses of the process (Non-minimum phase characteristics) with Pole placement tuned Fractional order PI control strategy (experiment)

TABLE.1. Controller parameters for the minimum phase process

Controller	BLT Controller Parameters		
	k_c	t_i	λ
Loop1	0.6456	682.6	1.1
Loop2	1.2843	293.5	0.85
Controller	**Gain shaping Controller Parameters**		
	k_c	t_i	λ
Loop1	1.635	553.5	1.04
Loop2	1.135	450	0.95
Controller	**Pole placement Controller Parameters**		
	k_c	t_i	λ
Loop1	1.42	149	0.8
Loop2	1.16	154	0.76

TABLE.2. Controller parameters for the Non-minimum phase process

Controller	BLT Controller Parameters		
	k_c	t_i	λ
Loop1	3.598	209.79	0.85
Loop2	2.232	249.75	0.7
Controller	**Gain shaping Controller Parameters**		
	k_c	t_i	λ
Loop1	2.4	262.5	0.82
Loop2	3.543	525	0.88
Controller	**Pole placement Controller Parameters**		
	k_c	t_i	λ
Loop1	0.65	143.7	0.8
Loop2	1.205	78.7	0.8

TABLE.3. Performance comparison of the minimum phase process with fractional order PI control strategy (simulation)

Controller	BLT Controller				
	t_s(sec)	M_p(%)	t_p(sec)	t_r(sec)	ISE
Loop1	690	0	0	836	1069
Loop2	450	1.15	315	227.3	914.6
Controller	**Gain shaping Controller**				
	t_s(sec)	M_p(%)	t_p(sec)	t_r(sec)	ISE
Loop1	264	14.7	163	116.2	886.3
Loop2	464	4.28	172	140.4	920.6
Controller	**Pole Placement Controller**				
	t_s(sec)	M_p(%)	t_p(sec)	t_r(sec)	ISE
Loop1	270	8.5	173	128.8	884.2
Loop2	435	2.96	181	149	914.3

TABLE.4. Performance comparison of the minimum phase process with fractional order PI control strategy (experiment)

Controller	BLT Controller				
	t_s(sec)	M_p(%)	t_p(sec)	t_r(sec)	ISE
Loop1	1895	51.25	780	520	9870
Loop2	1060	41.25	370	220	1612
Controller	**Gain shaping Controller**				
	t_s(sec)	M_p(%)	t_p(sec)	t_r(sec)	ISE
Loop1	900	8.5	440	385	2167
Loop2	820	31.75	300	165	1553
Controller	**Pole Placement Controller**				
	t_s(sec)	M_p(%)	t_p(sec)	t_r(sec)	ISE
Loop1	1300	19.5	630	400	3709
Loop2	1820	41.5	420	195	2254

TABLE.5.Performance comparison of the non-minimum phase process with fractional order PI control strategy (simulation)

Controller	BLT Controller				
	t_s(sec)	M_p(%)	t_p(sec)	t_r(sec)	ISE
Loop1	1240	26.52	140	92.5	826.2
Loop2	1400	31.67	139	91	791.1
Controller	**Gain shaping Controller**				
	t_s(sec)	M_p(%)	t_p(sec)	t_r(sec)	ISE
Loop1	1160	23.94	140	87	1080
Loop2	1326	37.61	141	95	615.6
Controller	**Pole Placement Controller**				
	t_s(sec)	M_p(%)	t_p(sec)	t_r(sec)	ISE
Loop1	2068	14.85	445	199	2141
Loop2	2600	0	0	2130	1236

TABLE.6. Performance comparison of the non-minimum phase process with fractional order PI control strategy (experiment)

Controller	BLT Controller				
	t_s(sec)	M_p(%)	t_p(sec)	t_r(sec)	ISE
Loop1	750	50.5	416	295	1656
Loop2	1200	8	138	118	1346
Controller	Gain shaping Controller				
	t_s(sec)	M_p(%)	t_p(sec)	t_r(sec)	ISE
Loop1	1150	51.5	735	530	2254
Loop2	1270	16.25	200	120	1613
Controller	Pole Placement Controller				
	t_s(sec)	M_p(%)	t_p(sec)	t_r(sec)	ISE
Loop1	1900	42.5	470	275	2781
Loop2	3110	45.75	1200	845	1e+004

5. Conclusion

In this paper an attempt is made to study and compare the performance of the Fractional order Pi controller with BLT, gain shaping and pole placement techniques as tuning techniques. The developed control strategies are implemented in quadruple tank process to analyse the performance. The quadruple tank process is a MIMO process with minimum phase and non-minimum phase characteristics. Therefore multi-loop control structure is used for implementation and the results are presented. It is observed from the results that for minimum phase system the control strategies with Gain shaping and Pole placement techniques performing better than the control strategy using BLT tuning technique. The control strategies with BLT and Gain shaping tuning techniques are giving better performance compared with Pole placement tuning technique for non-minimum phase system. These results reveals the flexibility in tuning the Fractional order controller irrespective of the tuning rules.

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