ISSN:1991-8178

Australian Journal of Basic and Applied Sciences

Journal home page: www.ajbasweb.com

Design and modeling of fractional order PI controller for a coupled spherical tank MIMO system.

[1]D. Pradeepkannan and [2]Dr. S. Sathiyamoorthy

[1]*AssociateProfessor,Electronics and Instrumentation Engineering Department, K.L.N.College of Engineering Pottapalayam, Tamilnadu,India 630611.*
[2]*Professor, Electronics and Instrumentation Engineering Department, J.J.College of Engineering and Technology, Ammapettai, Tiruchirrappalli, Tamilnadu,India 600024.*

ARTICLE INFO

Article history:
Received 12 October 2014
Received in revised form 26 December 2014
Accepted 1 January 2015
Available online 27 February 2015

Keywords:
PID controller, ZN tuning, Fractional Order Controller, Spherical tank process, MIMO systems.

ABSTRACT

Conventional Proportional Integral (PI) controller is a well known controller used in most of the process Industries for controlling the process parameters at desired set values. As the process tanks are connected in an interacting Multi Input Multi Output (MIMO) mode, there exhibits a highly nonlinear dynamic behavior and time delay between tanks input and output. The ZN tuned PID controller parameters does not cope with all operating points as it exhibits different non linear characteristics. The recent advancement in fractional calculus leads the control Engineers to apply the fractional order calculus in control theory. One of the prime applications of fractional calculus is fractional order Proportional Integral (FOPI) controller. Fractional order controller differs from conventional integer order PI controller by the order of the integral term. The key challenge in designing fraction order PI controller is to determine the Integral order (α) and the conventional PI parameters such as K_p, τ_i.. This research paper proposes the design and modeling of Fractional order PI controller for a nonlinear coupled spherical tank process. The aim of this paper is to compare the control performance between the conventional PI and the fractional controller for a nonlinear process plant and to justify the superior performance of FOPI in terms of time domain specifications Robustness and Performance indices. Better enhanced controller performance was obtained for a FOPI controller than that of ZN tuned PI controller at various operating points.

To Cite This Article: D. Pradeepkannan and Dr. S. Sathiyamoorthy., Design and modeling of fractional order PI controller for a coupled spherical tank MIMO system.. ***Aust. J. Basic & Appl. Sci.,*** *9(5): 477-485, 2015*

INTRODUCTION

Proportional Integral Derivative Controller has been using in Industrial control applications for a long time. The reasons for their wide popularity lies in the simplicity of design and good performance which includes low percent over shoot and small settling time for slow process (Astrom, K.J. and T. Hagglund, 1995; Astrom, K.J. and T. Hagglund, 2001). According to the survey in 1989, 90 percentage of process industries uses the conventional PID controllers (Astrom, K.J. and T. Hagglund, 1984).The wide spread use of the PID controller in the Industry is due to their simplicity and ease of retuning online (Astrom, K.J., 1993). One of the most successful and oldest classical techniques is Zeigler Nichols method. It was put forward by John Ziegler and Nathaniel Nichols in 1942 and is still a simple, fairly effective PID tuning method. He proposed two methods, one is open loop step response method and the second is closed loop frequency response method. The Ziegler and Nichols first PID tuning method is the techniques made based on certain controller assumptions. Hence, there is always a requirement of further tuning; because the controller settings derived are rather aggressive and thus result in excessive overshoot and oscillatory response. Also the controller parameters are rather difficult to estimate in noisy environment. The second method is based on knowledge of the response to specific frequencies. The idea is that the controller settings can be based on the most critical frequency points for stability. This method is based on experimentally determining the point of marginal stability. This frequency can be found by increasing the proportional gain of the controller, until the process becomes marginally stable. These two parameters define one point in the Nyquist plot. The gain is called ultimate gain Ku and the time period Tp. The PID parameter setting is given in **(**Weng Khuen Ho, 1995; Ziegler, J.G. and N.B. Nichols, 1942).Fractional order calculus has gained

Corresponding Author: D. Pradeepkannan, Associate Professor, Electronics and Instrumentation Engineering Department, K.L.N.College of Engineering Pottapalayam,Tamilnadu,India 630611.

acceptance in the last couple of decades. J Liouville made the study of fractional calculus in 1832. In 1867 A.K. Grunwaled worked on the fractional operations. G.F.B. Riemann developed the theory of fractional integration in 1892. Fractional order mathematical phenomena allow us to describe and model a real object more accurately than the classical integer methods. Fractional order PID controllers are used in many control applications (Igor Podlubny, 1999). Schlegel Milos et.al (2006), performed a comparison between classical controller and fractional controller and summarized that the fractional order controller outperforms the classical controller. D Xue et.al(2006), implemented fractional order PID control in DC motor. Chuang Zhao, Xiangde Zhang, et.al (2008), implemented fractional order controller in position servo mechanism. Varsha Bhambhani et.al (2008) implemented fractional order controller in water level control. Hyo-Sung Ahn et.al (2008) implemented fractional order integral derivative controller for temperature profile control. Concepcion A. Monje et.al (2010), and Fabrizio Padula et.al (2011), devised methods for tuning and auto tuning of fractional order controller for industry level control. Venu Kishore Kadiyala et.al (2009) implemented fractional order controller for aerofin control. Fabrizio Padula, Antonio Visioli et.al (2011) devised the Tuning rules for optimal PID and fractional order PID controllers. A state space design method based on feedback pole placement can be viewed in (Dorcak, L., 2001). The control of liquid level is a basic problem in Process Industries such as Petro chemical plants, Chemical recovery of Fertilizer industry etc. It is essential for control system engineers to understand the behavior of non linear Spherical tank level control system and how the level control problems are solved. Several real time works are being carried out to control the level of the spherical tank such as Design of self tuning Fuzzy controllers for non linear systems, by RajniJain, N.Sivakumaran, et.al (2011). Model based Controller Design for a Spherical tank process by S.Nithya, N.Sivakumaran, et.al (2008), Soft Computing Based Controllers Implementation for Non Linear Process in Real Time by S.Nithya, N.Sivakumaran et.al (2010), Design of Controller using Simulated Annealing for a real time process' by S.M.Girirajkumar,N.Anantharaman et.al (2010), Experimental study of Fractional Order Proportional Integral Controller for water level Control carried out by Varsha Bhambani and Y.Q.Chen (2088), State Feedback with Intergal Controller for a Non-Linear spherical tank Process was done by PradeepKannan.D, S.Sathiyamoorthy (2012) etc. Almost all the above works are focused on design of a controller for a nonlinear SISO system. The problem of level control in a nonlinear coupled spherical tank MIMO process with variable area is quite cumbersome. The PID controllers have been used for several decades in industries for process control applications..The performance of PID controllers can be further improved by appropriate settings of fractional-I and fractional-D actions. This paper attempts to study the behavior of fractional PI controllers. Finding [α,kp,τ_i,] as an optimal solution to a given process thus calls for optimization on a three dimensional space. The performance of the FOPI controllers is better than its conventional PI. Thus fractional order PI controller can be applied for coupled nonlinear spherical tank process to control the level of the nonlinear tank by manipulating the inflow rate of the process tank by providing optimal values of parameters such as k_p,τ_i and α. so as to obtain a desired performance characteristics. The proposed design will find extensive application not only in non linear spherical tank process but also for other nonlinear process with simple fine tuning in the values of α. This paper is organized as follows. Section 2 explains about the mathematical modeling of the non-linear coupled spherical tank MIMO process. Section 3 describes the Experimental set up. Section 4 illustrates the simulation of ZN tuned PI controller and Section 5 illustrates the simulation of FOPI controller. Section 6 describes the Results obtained for servo and regulatory operation at various operating points of the tank for both the controllers. Finally the conclusion is given in section 7.

2. *Mathematical modeling:*

Consider the coupled Spherical tank process shown in Fig 1. The objective of the process is to control the level of the two tanks namely $h_a(t)$ and $h_b(t)$. The inlet water flow from the two pumps f_1 (t) and f_2 (t) are used as manipulated variables so as to keep the control variable at the desired set point. The level of the tank at any instant is measured by the combination of orifice and Differential pressure transmitters which are mounted on the respective tanks discharge line whose output is (4 -20)mA. This output are compared with the desired set point value of level one and level two which will be configured as (4 -20)mA. The error signal is amplified based on the controller specification. The controller outputs is used to vary the inflow rates $f_1(t)$ and $f_2(t)$ of the spherical tank so as to maintain the set point at desired level h_a and h_b of the tanks. Electro pneumatic converters are used to convert the controller outputs of (4 -20)mA in to a pneumatic signal of (3-15) psi so that the final control element will be able to throttle the inflow rates f_1 and f_2.

Using the law of Conservation of mass, the non linear plant equations are obtained.

For tank 1, $f_1 - f_3 - f_4 = (Ah)\ dh_a/dt \quad (1)$

For tank 2, $f_3 + f_2 - f_5 = (Ah)\ dh_b/dt \quad (2)$

$$f_3 = a\sqrt{}2g(h_a - h_b) \quad (3)$$

$f_4 = a\sqrt{2g(h_a - x_0)}$ (4)

and $f_5 = a\sqrt{2g(h_b - x_0)}$ (5)

Where, f_1 and f_2 are in flow rates to $tank_1$ and $tank_2$ respectively in (m^3/sec).f_4 and f_5 are outflow rate of tank 1 and tank 2 (m^3/sec). f_3 is the flow rate between the tanks in m^3/sec.Radius on the surface of the fluid varies according to the surface level of fluid in the tank. Let this radius be known as r_s. Therefore $r_{s1}^2 = \sqrt{2r_a h_a - h_a^2}$ and $r_{s2}^2 = \sqrt{2r_b h_b} - h_b^2$ Where r_a= radius of $tank_1$ in metres.

r_b= radius of $tank_2$ in metres.
$r_a = r_b = r = 0.5$metres
h_a = fluid level in $tank_1$ in metres.
h_b = fluid level in $tank_2$ in metres.
$a=\pi[x_0/2]^2$
x_0 = thickness of pipe 0.04 in metres.
h_{as} - steady state water level of tank 1 = 0.22m
h_{bs} - steady state water level of tank 2 = 0.21m.

The linearised plant transfer function in S domain are given as

$$G_{11}(s) = \frac{1.855s + 0.0881}{s^2 + 0.0794s + 0.0008} \quad (6)$$

$$G_{22}(s) = \frac{1.919s + 0.0612}{s^2 + 0.0794s + 0.0008} \quad (7)$$

$$G_{21}(s) = \frac{0.0489}{s^2 + 0.0794s + 0.0008} \quad (8)$$

and $G_{12}(s) = \dfrac{0.0492}{s^2 + .0794s + .0008}$. (9)

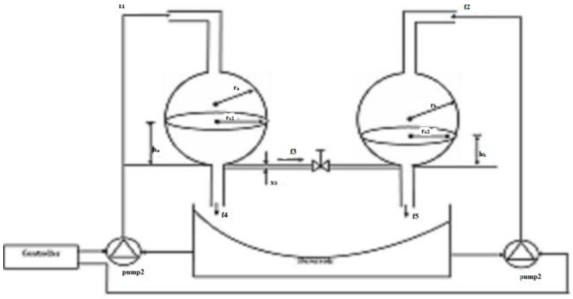

Fig. 1: Schematic diagram of Coupled Spherical Tank Process.

2.1 Black Box Modeling:

The first order system with dead time represented as a transfer function $G(s) = \dfrac{k_p e^{-t_d s}}{\tau_p s + 1}$ (10)

The output response to a step change in input is given by,

$$y(t) = \{k_p \Delta u(1 - exp(-(t-\theta)/\tau_p)) \quad \text{for } t \geq \theta \quad (11)$$

The measured output is in deviation variable form. The three process parameters K_p, τ_p, θ can be estimated by performing a single step test on process input. The process gain is found as simply the long term change in process output to the change in process input. The time delay is the amount of time, after the input change, before a significant output response is observed

2.2 Estimation of time constant by two point method:

Smith has obtained the parameters of FOPDT transverse function model by letting the response of actual system and that of the model to meet the two points which describe the parameter τ_p & t_d. Here, time that required for the process output to make 28.3% and 63.2% respectively are measured. The time constant and time delay can be estimated from the equation given below for both the transfer function, $\tau_p = \dfrac{(2t/3) - (t/3)}{0.7}, and t_d = t/3 - 0.4\tau_p$ (12)

Thus the obtained FOPDT models are given by

$$G_{11}(s) = \frac{110e^{-4.492s}}{81.58s + 1} \quad (13)$$

Similarly $G_{22}(s) = \dfrac{76.425e^{-8.79s}}{70.72s + 1}$ (14)

The parameters of PID and PI controllers as per Ziegler Nichols tuning method are determined.

2.3 Decoupler design:

The effect of interactions in a MIMO system is minimized with the introduction of decoupler. Thus for the coupled non linear interacting spherical tank system, the decoupler are designed as given below.

$$D_{12}(s) = \frac{-0.0492}{1.8550s + 0.0881} \quad (15)$$

$$D_{21}(s) = \frac{-0.0489}{1.919s + 0.0612} \quad (16)$$

2.4 *Model validation:*

The FOPDT model obtained from two point method is given by equations 13 and 14 and the derived transfer function on substituting the dimensions of the spherical tank is given by equations 5,7,8 and 9. The open loop response for both the cases for a given step change in set point is obtained as follows**,**

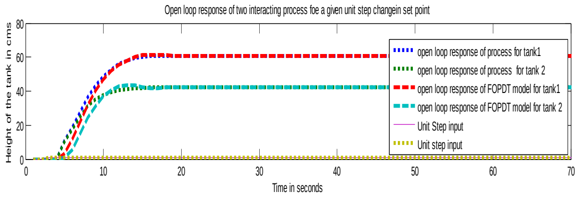

Fig. 2: open loop responses of processes and FOPDT models.

It is evident from the figure 2 that both the responses coincides and have similar time domain response. Hence FOPDT model approximation can be used for tuning the PI controller to obtain optimal values of controller parameters.

3. *Experimental Set Up Of Coupled Interacting Spherical Tank Process:*

The experimental set up of the Coupled spherical tank system is shown in figure 3. And the corresponding schematic block diagram is shown in figure 4.The spherical tanks are made up of SS316 material which has high corrosion resistance property and has a maximum height, radius of 0.5 meter. Water from the reservoir tank whose size of 1250 mm x 450 mm x 450 mm are pumped through a Kirloskar make 0.5 HP pumps having a discharge of 1500 litres per hour that flows through a Teleline make rotameter having a range (40 - 440) LPH to the spherical tank.

Fig. 3: Experimental set up of coupled spherical tank system.

The levels of the tank$_1$ and tank$_2$ at any instant are measured by the Rose mount make Differential pressure transmitters having a measurement range of (0-400) mm of water column corresponds to the output range of (4 -20)mA.

These outputs are compared with the desired set value of levels in tank$_1$ and tank$_2$ respectively which will be scaled in the control law as (4 -20)mA. The error signals are also in the range of (4-20)mA which is then amplified based on the controller specifications. These output are used to vary the inflow rate $f_1(t)$ and $f_2(t)$ of the spherical tank with the help of an ABB make Electro pneumatic converters which converts the output of (4 -20)mA in to a pneumatic signal of (3-15) psi so that the Equal percentage control valve will be able to throttle the inflow rates $f_1$and f_2 respectively. The controller parameters are determined for both ZN tuned PI Controller as well as FOPI controllers. The coupled spherical tank set up is interface to the real time controller NI Compact RIO 9024which is an 8 module chassis having an inbuilt FPGA real time controller with a data transfer baud rate of 400Mbps and with an accuracy of 200ppm.These values are applied to the PID controller block of LabVIEW program for a given step change in inflow rates f_1 and f_2, and the corresponding steady state response are obtained.

4.*Zn Tuned Pi Controller:*

The controller parameters are determined for both ZN tuned PI and PID Controllers. The values of kp, ki, kd for ZN tuned PID controller G_{c1} are found to be 0.1602, 0.031, 0.21and for ZN tuned PI controller G_{c1} are found to be 0.12, 0.0137 respectively. Similarly the values of kp, ki, kd for ZN tuned PID Controller G_{c2} are found to be 0.1058, 0.0064, 0.4372 respectively and for ZN tuned PI controller G_{c2} are found to be 0.0793,0.0029 respectively. As dynamics of the process are large, changes in the control variable over a small interval of time are constant and the derivative term does not contribute more in the performance of the controller output hence, in this work the Conventional PI controller is chosen for the analysis against the FO PI controller.

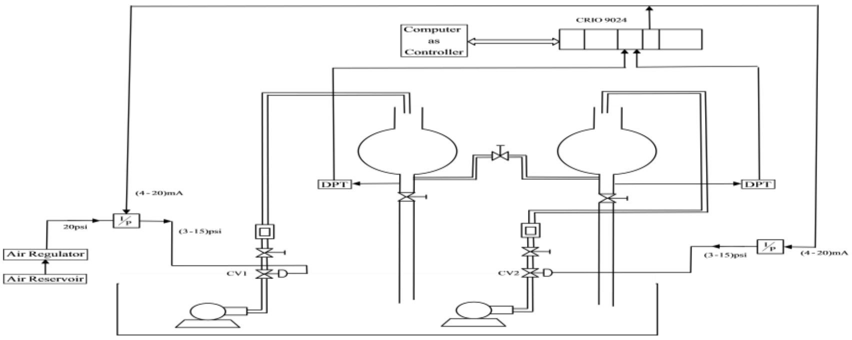

Fig. 4: Schematic block diagram of coupled spherical tank system.

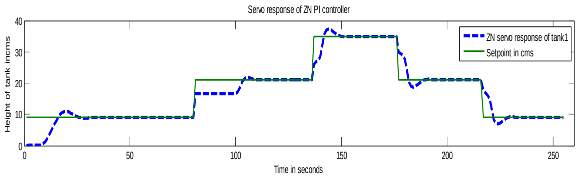

Fig. 5: Servo Response of ZN tuned PI controller for a set point of 10,22,36cms of water column of $tank_1$.

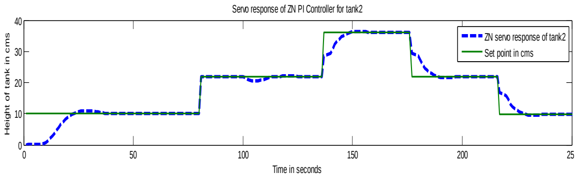

Fig. 6: Servo Response of ZN tuned PI controller for a set point of 9, 21, 35cms of water column of $tank_2$.

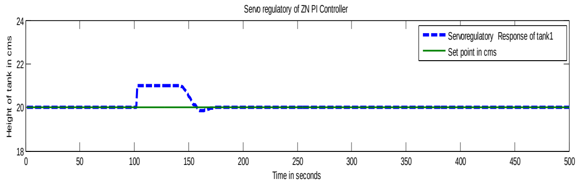

Fig. 7: Servo Regulatory response of ZN tuned PI controller for a set point of 20cms of water column of $tank_1$.

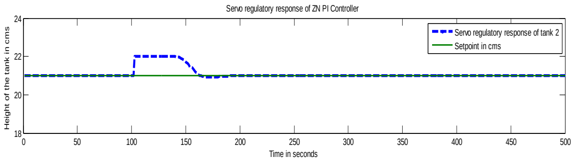

Fig. 8: Servo Regulatory response of ZN tuned PI controller for a set point of 20cms of water column of tank2.

The figure 7 shows the servo regulatory response of ZN tuned PI Controller for a set point of 20cms of water column and a disturbance is being applied after 100seconds.It is evident from the response that the controller effectively rejects the disturbance and track the set point after 180seconds.

The figure 8 shows the servo regulatory response of ZN tuned PI Controller for a set point of

20cms of water column and a disturbance is being applied after 100seconds. It is evident from the response that the controller effectively rejects the disturbance and tracks the set point after 180seconds.

Fractional Order Pi Controller:

The fractional-order controller will be represented by fractional-order PI^{α} controller with transfer function given by the following expression.

$$\mathrm{Gfopi}(s) = \frac{u(s)}{e(s)} = K_c[1 + \frac{1}{\tau_i S^{\alpha}}] \qquad (17)$$

Where α is an arbitrary real numbers, K_p is amplification (gain), τ_i is integration constant. Taking α =1, a classical PI controller is obtained. The PI^{α} controller is more flexible and gives an opportunity to better adjust the dynamics of control system. It is compact and simple but the analog realization of fractional order system is very difficult and challenging. The fraction order PI, PID controller can be realized with FAMCON tool box, N integer tool box in matlab. Determination of optimal values of $K_{p,}K_{i,,}\alpha$, for a FOPI controller is done by a minimum search algorithm Keeping the objective function as minimization of integral square error. The values of kp, ki, α for FOPI controller G_{c1} are found to be 0.8147, 0.9058, 0.127 and similarly the values of kp, ki, α for FOPI Controller G_{c2} are found to be 0.9134, 0.6324, 0.0975 respectively.

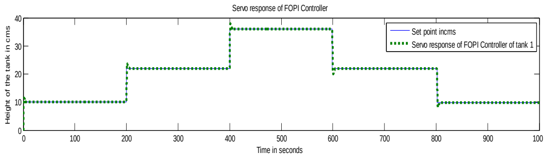

Fig. 9: Servo Response of FOPI controller for a set point of 10, 22, 36cms of water column of tank 1.

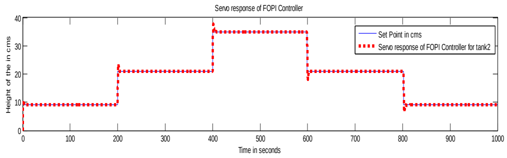

Fig. 10: ServoResponse of FOPI controller for a set point of 9, 21, 35cms of water column of tank 2.

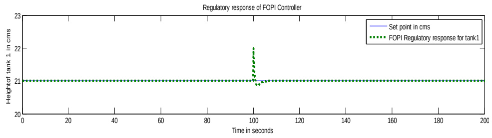

Fig. 11: Servo Regulatory response of FOPI controller for a set point of 22cms of water column of tank 1.

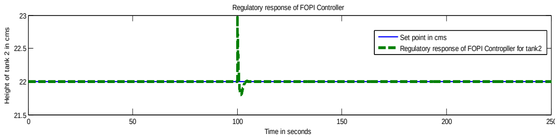

Fig. 12: Servo Regulatory response of FOPI controller for a set point of 21cms of water column of tank 2.

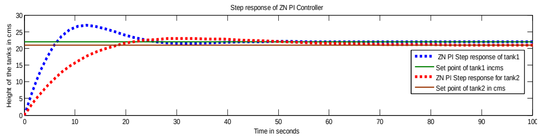

Fig. 13: Step Response of ZN PI controller for a set point of 22, 21cms of water column of tank 1 and tank2.

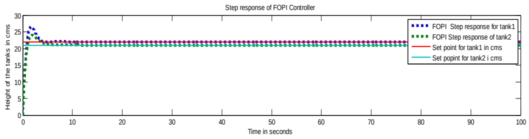

Fig. 14: Step response of FOPI controller for a set point of 22, 21cms of water column of tank 1 and tank2.

The figure 11 shows the servo regulatory response of FOPI Controller for a set point of 22cms of water column and a disturbance is being applied after 100seconds.It is evident from the response that the controller effectively rejects the disturbance and track the set point after 110seconds.

The figure 12 shows the servo regulatory response of FOPI Controller for a set point of 21cms of water column and a disturbance is being applied after 100seconds. It is evident from the response that the controller effectively rejects the disturbance and tracks the set point after 110seconds.

Further Robustness analysis has been done for both the ZN tuned PI controller as well as FOPI Controller. A 10 percent change in process parameters such as k_p t_d and t_i are applied and the corresponding FOPDT model are determined as

$$G_{11}(s) = \frac{121e^{-4.043s}}{89.738s+1} \text{ and } G_{22}(s) = \frac{84.0675e^{-7.911s}}{77.79s+1} \qquad (12)$$

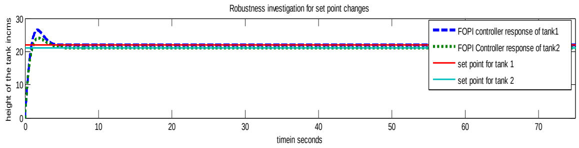

Fig. 15: Robust Response of FOPI controller for a set point of,22, 21cms of water column of tank 1 and tank2.

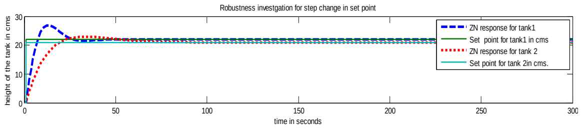

Fig. 16: Robust Response of ZNPI controller for a set point of,22, 21cms of water column of tank 1 and tank2.

The figures 15 and 16 show that the robustness response of ZNPI controller as well as FOPI controller for a step change in set point of both the tanks 1and 2 respectively. It is evident that the FOPI controller is robust enough to track the set point variation in spite of process parameters variation.

RESULTS AND DISCUSSION

An step response of ZN tuned PI controller and FOPI controller are obtained for servo problem and servo regulatory problem and their performance characteristics are compared in terms of time domain specifications such as rise time, peak time, peak over shoot, steady state value etc and performance indices such as ISE and IAE. The table shows the time domain specification and the corresponding performance indices for both the designed controllers. It is evident from the table that the ZN tuned PI controller output could track the set point at an operating point of 22cms,21cms of water column for both tank 1 and tank2 with a settling time of 38.62and 69.54seconds and with 21.8% and 9.22 % overshoots. It is evident from the table that the FOPI controller output could track the set point at various operating points such as 22,10cmsfor tank 1 and 21, 9cms of water column for tank2 with settling time of 4.89 and 6.19 seconds. Further there exist a drastic reduction in performance Indices ISE and IAE in FOPI Controller, maximum peak overshoot is nominal as that of ZN tuned PI controller.

Table 1: shows the servo response at various operating points with time domain specification of FOPI controllers against conventional PI controller at various height of the spherical tank such as 22,21,and 10,9 cms.

Type of controller	Set Point h_a in cm	Set Point h_b in cm	Rise time in sec	Settling time in sec	Max Peak over shoot in %	Steady state values
ZN PID	22	-	4.49	38.62	21.8	22.01
ZN PID	-	21	11.93	69.54	9.21	20.01
ZN PID	10		3.71	22.0	14.95	9.99
ZN PID		09	8.08	43.0	8.32	8.99
FOPI	22	-	0.68	4.9	20.2	21.99
FOPI	-	21	0.73	6.19	14.45	20.99
FOPI	10	-	0.461	4.56	11.77	9.99
FOPI	-	09	0.482	4.68	8.41	8.99

Conclusion:

FOPI controller can cope up with tank non-linear characteristics at various operating points such as 22, 21.10,9 centimeters of water column in the coupled spherical tank. Conventional controller based on Ziegler Nichols tuning response is outperformed by Fractional order PI controller with less overshoot and lesser settling time, peak time, when subjected to servo and regulatory operations. Further the FOPI controller proves itself that it is robust enough for changes in process variables and keeps track the set points. Further the controller can be tuned by other soft computing techniques and implemented in real time so as to compare their performances. Tuning FOPI controller can also be applied for other non linear processes such as continuous stirred tank reactor, fermentation process etc to obtain better controller performance characteristics.

Table 2: shows the servo response at various operating points with performance indices such as ISE and IAE of FOPID controllers against conventional PID controllers at various height of the spherical tank such as 22,21, and 10,9 cms.

Type of controller	Set Point h_a in cm	Set Point h_b in cm	ISE	IAE
ZN PID	22	-	46.06	47.96
ZN PID	-	21	37.85	43.46
ZN PID	10		94.86	107.6
ZN PID		09	94.83	107.4
FOPI	22	-	20.83	22.77
FOPI	-	21	20.61	21.56
FOPI	10	-	9.46	9.76
FOPI	-	09	9.32	9.04

ACKNOWLEDGMENT

This work was supported by department of electronics and Instrumentation engineering and research and development unit of K.L.N. College of Engineering, Pottapalayam, Sivagangai district, Tamilnadu, India.

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