International Journal of Soft Computing 5 (4): 177-184, 2010
ISSN: 1816-9503

Control of Dead Time Systems Using Improved Tabu Search

Kanthaswamy Ganapathy and Jovitha Jerome
Department of Electrical and Electronics Engineering Coimbatore,
PSG College of Technology, Anna University, 641004, Tamilnadu, India

Abstract: This study introduces an approach to optimize the gains of a PID controller for a class of Time Delay Systems using directed tabu search algorithm. Metaheuristic applications to control theory have been a wide found topic of interest for research. Many research work have been done in choosing the proper choice of the parameters of the PID controller. The PID controller designed using the hybridized Tabu Search scheme guarantees boundedness of the closed loop system behaviour. In this study, attempt has been made to compare results of PID tuning obtained based on directed tabu search algorithm which is made continuous using Nelder Mead Method and adaptive random search algorithm. The algorithm used gives improved performance for an exhaustive class of dead time processes comparatively better than Luyben, Visioli, Chidambaram, Kookos and Syrcos.

Key words: Proportional Integral Derivative (PID), directed tabu search, time delay systems, Integral Square Error (ISE), metaheuristic application, India

INTRODUCTION

Recent years have found remarkable research in the area of meta heuristics and its application to engineering and design. Metaheuristic intelligence is applied to the areas of optimal control design using Genetic algorithm, Evolutionary algorithm, Memtic algorithm, Greedy Random Adaptive Search algorithm, Differential Evolution algorithm, Swarm Intelligence, Simulated Annealing, Ant Colony optimization and Tabu Search algorithm. These heuristic techniques are further improvised as part of research by effective optimization and faster convergence achieved by modification of the general algorithm.

Tabu search is a heuristic if used properly can promise efficient near optimal solutions. The original research on Tabu search was carried out by Glover (1989, 1990) and Hu (1992) modified the earliest Tabu search for application to constrained optimization problems. Cvijovic and Klinowski (1995, 2002) extended the Tabu search to functions with variables that may be continuous or discrete.

Battiti and Tecchiolli (1996) proposed the continuous Tabu search namely the Continuous Reactive Tabu Search. Al-Sultan and Al-Fawzan (1997) gave the hookes and jeeves-local search based modified form of Tabu search algorithm. The Enhanced Continuous Tabu Search given by Chelouah and Siarry (2000) performs diversified approach to locate the most promising solutions among the domain of possible solutions. The search further intensifies to locate the closest possible solution space. Hybrid forms of Tabu search involve combination of Tabu search with Local search techniques.

In this study, the method of directed Tabu search which is hybridized using local search technique of adaptive random search algorithm and Nelder Mead method is used to design PID controller for a class of Time delay systems. The role of the search technique is to stabilize the search especially in the vicinity of local minima.

There are three search procedures employed as part of the directed tabu search namely exploration, diversification and intensification. Exploration is based on Local search method of Nelder-Mead given by Nelder and Mead (1965), Ribeiro and Hansen (2002). Diversification of search to unvisited solution space is achieved using concept of visited regions list given by Hedar and Fukushima (2006).

This multi start approach aims to finally reach a global solution from the initial techniques of exploration and diversification through intensification making the Tabu search an intelligent search algorithm as given by Marti (2002) and Schoen (2002). The neighbourhood moves of the approximate solutions of the Tabu search is achieved using directed search technique adopted by Hedar and Fukushima (2006) through minimization of error for computing the PID controller gains. The resultant solution is used to tune various classes of time delay systems considered in the research by Kookos and

Corresponding Author: Kanthaswamy Ganapathy, Department of Electrical and Electronics Engineering Coimbatore, PSG College of Technology, Anna University, 641004, Tamilnadu, India

Syrcos (2005). The local search involved as part of exploration shall be modified using adaptive random search using approximate descent direction as given by Hedar and Fukushima (2004). The results of the direct search guided Tabu search PID scheme is compared with various methods proposed by (Tyreus and Luyben, 1992; Luyben, 1996, 2003), Visioli (2001), (Chidambaram and Sree, 2003; Chidambaram, 1998), (Marlin, 1995) and (Rotstein and Lewin, 1991) based on the response characteristics.

PID CONTROLLER DESIGN

The PID controller is given by Eq. 1 as follows:

$$G(s) = K_P + \frac{K_I}{s} + K_D.s \tag{1}$$

Where:

$$K_P = k_c,\ \ K_I = \frac{k_c}{T_i},\ \ K_D = k_c.T_d$$

Under the case of unconstrained optimization of PID controller the cost function is chosen as ISE index given in Eq. 2:

$$J = \min \sum_{K_P, K_I, K_D} \left| e^2 \right| \tag{2}$$

Under the case of constrained optimization of PID controller the cost function shall be chosen as ISE index given in Eq. 3:

$$\begin{aligned} &\min_{K_P, K_I, K_D} J,\ \ \text{s.t},\ \ g(e) < 1, \\ &K_P, K_I, K_D \in s \end{aligned} \tag{3}$$

Where:

K_P = Proportional controller gain
K_I = Integral controller gain
K_D = Derivative controller gain
k_c = Controller gain
J = Integral Square Error (ISE)
e = Error signal
T_i = Integral time constant/Reset time
T_d = Derivative time constant
g (e) = Process output

DIRECTED SEARCH TABU SEARCH ALGORITHM

The algorithm given by Hedar and Fukushima (2006) is realized for design of PID controller as follows:

Initialization: Choose positive integers l_{main}, l_{main}, l_{inner} and l_{ineer} as loop parameters. Choose initial solution for the PID gains as $(K_{P_0}, K_{I_0}, K_{D_0})^{(0)}$ and set the Tabu list and Visited regions list to be empty.

Main loop

Exploration and diversification search: Set the main loop j = 0:l_{mein} until l_{main} consecutive iterations fail to seek improved solution or j>l_{main}.

Inner loop

Exploration aearch (nelder-mead aearch/adaptive pattern search): Set the main loop k = 0:l_{inner} until l_{inner} consecutive iterations fail to seek improved solution or k>l_{inner}.

Search directions: If current value $(K_{P_k}, K_{I_k}, K_{D_k})^{(j)}$ lies in the Semi-Tabu region then construct step size and search directions as follows: Let the trial point (K_P, K_i, K_D) lie in the Semi-TRs and with centres t_1.....t_v Compute the Centroid $\bar{t}$ of the semi Tabu region's centres and the maximum distance between (K_P, K_I, K_D) and the centres i.e.,:

$$t = \frac{1}{v}\sum_{i=1}^{v} t_i \tag{4}$$

$$d_{max} = \max_{i=1,2,..v} \{ \| [K_P, K_I, K_D] - t_i \| \} \tag{5}$$

Construct neighbourhood search directions that are parallel to the coordinate axes but point towards the direction x-t_i where, x = (K_P, K_I, K_D). The neighbourhood trial points are generated along these search directions with a suitable step size β>0.

Neighbourhood search: Generate n neighbourhood trial points:

$$y_i = [K_{P_k}, K_{I_k}, K_{D_k}]^{(j)} + \Delta_i d_i, i = 1,2....n \tag{6}$$

Where:

$$y_i = [K_{P_{k+1}}, K_{I_{k+1}}, K_{D_{k+1}}]^{(j)}$$

Whenever better improved solution is found set the new obtained move as better.

Local search (nelder-mead search)/adaptive pattern search): In case of Nelder-Mead based local search apply Nelder-Mead local search method to obtain improved solution from the obtained y_{n+1} and if improved solution is obtained, set q = 1. Else; set q = 0 and:

$$[K_{P_{k+1}}, K_{I_{k+1}}, K_{D_{k+1}}]^{(j)} = \arg \min_{i=1,2,....n+q} \{ f(y_i) \} \tag{7}$$

Which is the ISE index given by:

$$\varphi = \min \sum_{KpKiKd} | e^2 |$$

Where e is the error signal. Incase of adaptive pattern search based local search, use Approximate Descent Direction method (ADD) given by (Hedar and Fukushima, 2004) to compute the descent direction v as given by Eq. 8:

$$v = \sum_{i=1}^{n} w_i u_i \tag{8}$$

Where:

$$w_i = \frac{\Delta f_i}{\sum_{j=1}^{n} \Delta f_j}, i = 1, 2....n$$

$$u_i = -\frac{(y_i - x)}{\| y_i - x \|}, i = 1, 2....n$$

$$\Delta f_i = f(y_i) - f(x), i = 1, 2....n$$

Choose step sizes α_1 and α_2 to generate trial points to generate:

$$[K_{P_{k+1}}, K_{I_{k+1}}, K_{D_{k+1}}] = [K_{P_k}, K_{I_k}, K_{D_k}]^{(j)} + \frac{\alpha_i v_i}{\| v_i \|}, i = 1, 2 \tag{9}$$

Set $$[K_{P_{k+1}}, K_{I_{k+1}}, K_{D_{k+1}}]^{(j)} = \arg \min_{i=1,2,....n+2} \{f(y_i)\} \tag{10}$$

Parameter update: Let $(K_{P_0}, K_{I_0}, K_{D_0})$ replace the element with smallest membership value in the Tabu list and re-rank the Tabu list elements using and increment the inner loop count k = k+1. Update the Visited Regions Tabu (VRT) List.

Diversification: Generate the trial point $(K_{P_0}, K_{I_0}, K_{D_0})^{(j+1)}$ as follows. Randomly generate trial point (K_P, K_I, K_D) in the search domain and compute the search distance:

$$d_{max} = \| [K_P, K_I, K_D] - \varsigma_i \| / (1 + \Phi(\varphi_i)); \quad i = 1,2....M \tag{11}$$

Where, ζ_I is the centre of the visited region. The function $\Phi(\varphi) = \gamma (1-e^{(-\gamma(\varphi-1))})$, γ is a random constant. The Visited Region List (VRL) is given by:

$$VRL = \{\varphi_i, \varsigma_i, \rho_i\}_{i=1}^{M} \tag{12}$$

Where:
M = The number of all visited regions
ρ_i = The radius of the visited region

If: $$\min_1 \le i \le M \frac{d_i}{e_i} \ge 1$$

then accept (K_P, K_I, K_D) otherwise again repeat the diversification starting from generating trial point (K_P, K_I, K_D) in the search domain and compute the search distance. Update the Tabu list and the Visited Region Tabu. Increment the outer loop count j = j+1.

Intensification search: Start with another local search method namely the Kelly's modification of the Nelder Mead method to improve the present obtained solution of (K_P, K_I, K_D).

CASE STUDIES

The response for unit step set point change was simulated for the case studies having different time-delay/ Lag ratios. The computation was performed using a Core 2 duo processor based, 2 Ghz/3 gigabyte computer with computational time in the range same as that of Kookos and Syrcos (2005) having values in the order of few seconds to estimate the optimal values of the controller gains. The controller configuration used in most of the simulation was Smith PID configuration given by Chidambaram and Sree (2003) except for some cases.

Control of Integrating Processes with Time Delay (IPTD)

Example 1: Integrating processes with time delay are most commonly modeled among industrial processes. For example, processes involving level exhibit the integrating behavior. They are found in distillation columns, boiler controls and several industrial applications. The transfer function of an integrating process with time delay is given by Eq. 13 as:

$$g(s) = \frac{k_p}{s} e^{-ds} \tag{13}$$

The PID controller tunings for this model have been given by a number of researchers. With reference to initial research done on Integrating sytems with delay by Kookos and Syrcos (2005), Chidambaram and Sree (2003), Chidambaram (1998), Tyreus and Luyben (1992) and Luyben (1996), consider the industrial example of level control in a distillation column having the open loop transfer function as in Eq. 14 with parameters k_P = 0.0506 and k_d = 6 sec.

$$g(s) = \frac{0.0506}{s} e^{-6s} \tag{14}$$

The directed tabu search optimization was carried out for minimization of the ISE and the tuning parameters achieved by the directed tabu search based controller using Smith PID given by Chidambaram and Sree (2003) configuration is compared with other methods as shown in Table 1. Figure 1 compares the closed loop performance

of the directed tabu search based smith PID controller and the tunings proposed by Tyreus and Luyben (1992), Visioli (2001), Chidambaram (1998) and Chidambaram and Sree (2003). In Fig. 1, the unit step set point response for the directed tabu search based controller configuration results in a more or less dead beat response compared to the other schemes. The comparison of the tuning factors and the value of the performance index, ISE is shown in Table 1.

Example 2: Consider the second example of level control process given by Chen and Fruehauf referred by Kookos and Syrcos (2005) in a distillation column having the open loop transfer function as given in Eq. 15:

$$g(s) = \frac{0.2}{s} e^{-7.4s} \tag{15}$$

Table 1: Comparison of the tuning parameters and performance indices for closed loop response of IPDT system, example 1

Method	K_P	K_I	K_D	ISE (φ)
Luyben (1996)	2.563	0.0455	9.130	8.2763
Visioli (2001)	4.5	0.5033	15.93	14.1482
Chidambaram (1998), Chidambaram and Sree (2003)	4.066	0.1504	10.979	9.1920
DTS Smith PID	100.5738	107.2608	0	0.2902
	18.0862	3.7089	6.2874	0.6019

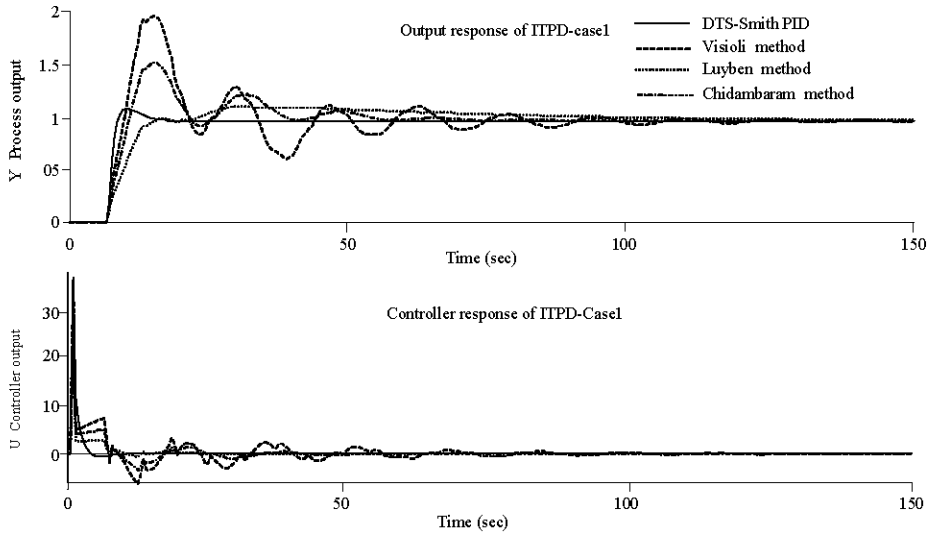

Fig. 1: Closed loop response of the closed loop IPDT system example 1

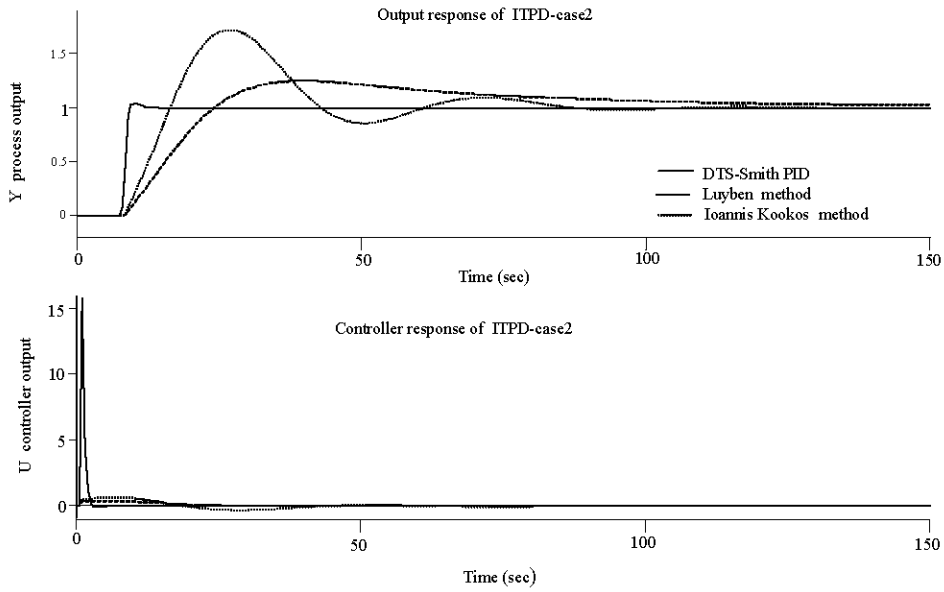

Fig. 2: Unit set point response of the closed loop IPDT system-example 1

Table 2: Comparison of the tuning parameters and performance indices for unit step set point response of the closed loop IPDT system, example 2

Method	K_P	K_I	K_D	ISE (φ)
Luyben (1992, 1996)	0.3300	0.0051	0	21.7991
Kookos and Syrcos (2005)	0.5530	0.0178	0	17.0434
DTS Smith PID1	14.1674	6.3422	0	0.2074
DTS Smith PID2	25.4497	27.1363	0	0.2904

Table 3: Comparison of the tuning parameters and performance indices for unit step setpoint response of the system with inverse response and time delay

Method	K_P	K_I	K_D	ISE (φ)
Kookos and Syrcos (2005)	0.3560	0.1540	0.0000	5.7742
DTS PID	0.5041	0.1952	0.1952	5.5076

with parameters k_P = 0.2 and K_d = 7.4 sec. The system response for unit step set point change were simulated for a time of t = 150 sec. The comparison of the tuning factors and the values of the performance index, ISE obtained are shown in Table 2.

Figure 2 shows the closed loop performance of the directed tabu search based method and the tunings proposed by Kookos and Syrcos (2005) and Tyreus and Luyben (1992). The obtained tunings were used to compute the performance indices given by Eq. 2. The directed tabu search optimization was carried out for minimization of the ISE and the tuning parameters achieved by the directed tabu search based Smith PID method is compared with other methods as shown in Table 2.

Control of an unstable process: Chemical reactors and complex systems have unstable steady state. Number of researchers have proposed methods for tuning unstable processes with time delay as given by (Kookos and Syrcos, 2005). Consider the following open loop system as given by Eq. 16 with initial tunings proposed by Kookos and Syrcos (2005).

$$g(s) = \frac{e^{-0.5s}}{(5s-1)(2s+1)(0.5s+1)} \tag{16}$$

The comparison of the tuning factors and the value of the performance index, ISE are shown in Table 3. Figure 3 compares the closed loop performance of the DTS based PID/Smith PID and the tunings proposed by (Kookos and Syrcos, 2005).

The DTS based PID/Smith PID shows a comparatively better response to that of Kookos with reduced error index.

Table 4: Comparison of the tuning parameters and performance indices for integrating process with inverse response and time delay

Method	K_P	K_I	K_D	ISE (φ)
Kookos and Syrcos (2005)	1.1170	0.17670	0.0000	2.9751
Luyben (2003)	0.8540	0.03713	0.0000	2.4801
DTS Smith PID	1.4544	0.00340	0.6426	1.5389

Control of Integrating Process with Time Delay and Inverse response (IPTD and IV): Consider the general form of transfer function of an integrating process with time delay and inverse response given in Eq. 17 having a right half plane zero at $1/\tau_z$ delay d and a pole at zero (Table 4).

$$g(s) = k_p \frac{1-\tau_z s}{s(\tau_P s+1)} e^{-ds} \tag{17}$$

Kookos and Syrcos (2005) and Luyben (1996) have proposed PID controller setting for a integrating process with time delay and inverse response. Consider an IPTD and IV system having transfer function of form given in Eq. 18:

$$g(s) = 0.457 \frac{1-0.418s}{s(1.06s+1)} e^{-0.1s} \tag{18}$$

Figure 4 compares the closed loop performance of the DTS based PID/Smith PID and the tunings proposed by Kookos and Syrcos (2005). The DTS based PID/Smith PID shows a comparatively similar response to that of Kookos with closeness in performance.

Control of First Order Processes with large Time Delay (FOPTD): The transfer function of a first order plus time delay process is given in Eq. 19 where the value of θ>1 and even larger. The DTS based PID/Smith PID was applied to a process having k_P = 1 and θ = 2, 3, 4 and 5.

$$g(s) = \frac{k_p}{s+1} e^{\theta s} \tag{19}$$

Figure 5 and 6 compare the closed loop performance of the proposed PID controller scheme based on DTS algorithm and the tunings proposed by Kookos and Syrcos (2005).

The response of the proposed PID controller scheme is found to be comparatively equal in performance to the settings given by Kookos and Syrcos (2005) for various values of dead-time/Lag ratios. Table 5 compares the performance index versus the Tuning parameters against the method of mathematical programming based PID controller given by Kookos and Syrcos (2005) and the Direct Search based Tabu search

Table 5: Comparison of the tuning parameters for unit step set point response of FOPTD system-case study 4.4

	PID controller using Kookos				PID controller using DTS PID			
θ	K_P	K_I	K_D	ISE (φ)	K_P	K_I	K_D	ISE (φ)
2	0.8447	0.6303	0.8466	2.4097	0.8403	0.4469	0.4469	2.3841
3	0.7025	0.3785	0.8970	3.4820	0.7006	0.2998	0.2998	3.6944
4	0.6385	0.2642	0.9118	4.5451	0.6407	0.2226	0.2226	4.9494
5	0.6031	0.2013	0.9193	5.6122	0.6072	0.1757	0.1757	5.5394

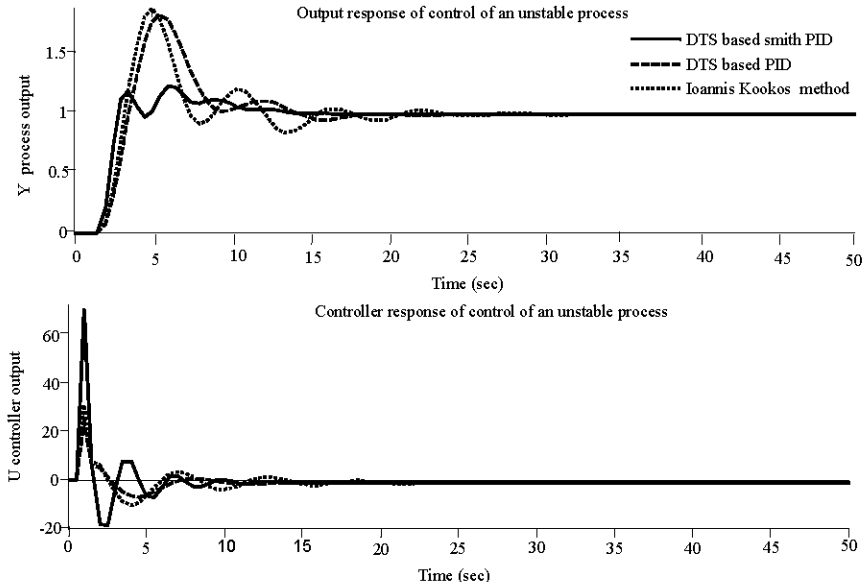

Fig. 3: Unit step set point response of an unstable system with delay-case study 4.2

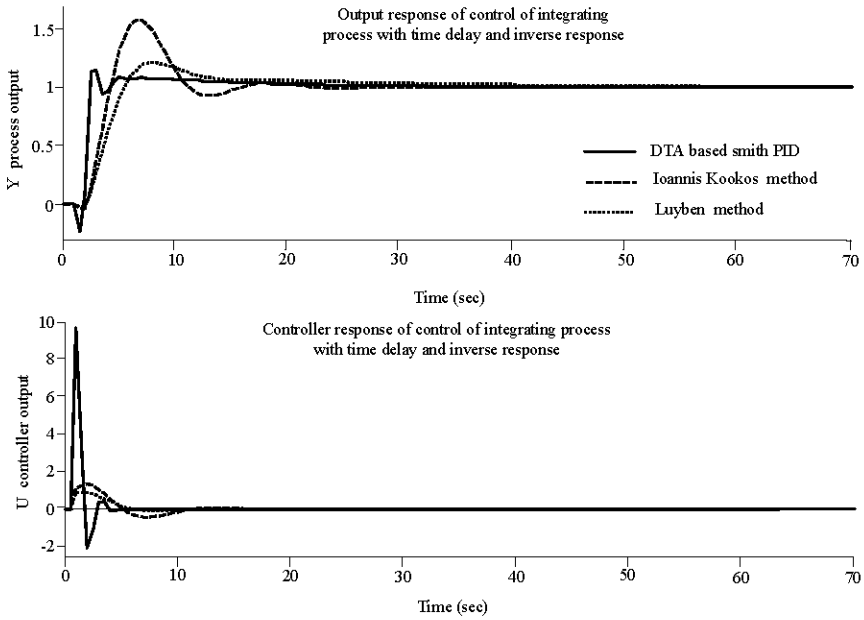

Fig. 4: Unit step set point response of the integrating process with inverse response and time delay-case study 4.4

method. It is observed that direct search Tabu based PID scheme exhibits more or less the same response characteristics and closed loop behaviour as the (Kookos and Syrcos, 2005) scheme. The ISE index is nearly close for all the cases of the delay values considered.

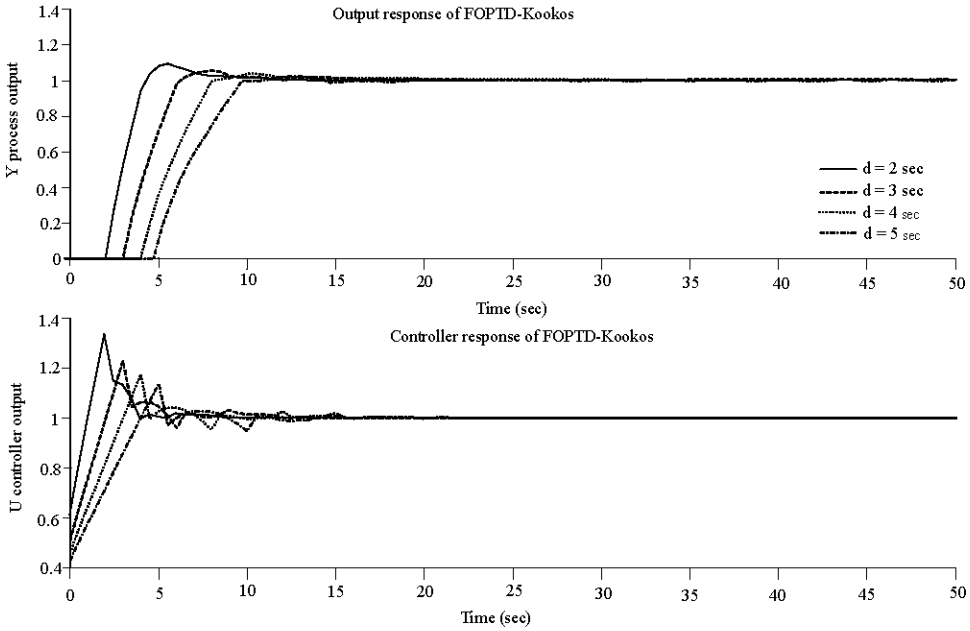

Fig. 5: Unit step set point response of the FOPTD system based on tunings proposed by Kookos and Syrcos (2005) case study 4.5

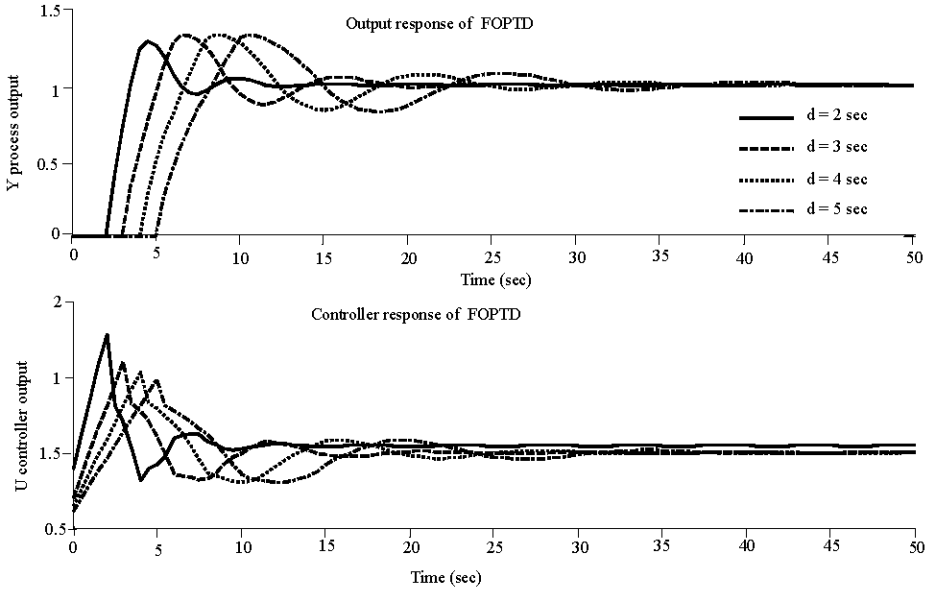

Fig. 6: Unit step set point response of the FOPTD system based on directed tabu search algorithm-casestudy 4.5

CONCLUSION

In this study, a novel meta heuristic based PID controller is designed for a class of time delay systems using hybridized Tabu search. The usefulness of the designed controller scheme is compared with different case studies involving delays.

The results show that the DTS based PID/Smith PID scheme offers good sensitivity for the closed loop performance with reduced performance index and the results are comparatively similar and even easier than the techniques proposed by Kookos and Syrcos (2005), Hedar and Fukushima (2004), Tyreus and Luyben (1992), Luyben (1996, 2001, 2003), Visioli (2001);

Chidambaram and Sree, 2003; Chidambaram, 1998; Marlin, 1995; Rotstein and Lewin, 1991). Encouragingly, the settling time and integral square error for the PID controller coefficients selected by DTS are seemingly the best compared to the choice made by other schemes for the case studies considered. Such evaluation helps to determine the value of the new intelligent control methods and provide the process engineer with general guidelines on how to apply them to more complex real world applications. The designed control scheme shall further be applied to MIMO systems and improved for even better performance.

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