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Performance Comparison of Optimal PID Controller Design for TITO System

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Abstract: Precise process control is one of the most significant problem and now a day's decentralized Proportional Integral Derivative (PID) controller have commonly used in industries for MIMO system. Design methodologies of a PID controller for the TITO system with time delay based on the predefined reference model of the systems. To obtain PID controller parameters of TITO system are designed using Ziegler-Nichols, Skogestad-IMC, IMC, direct synthesis and Genetic algorithm. The design methodologies use simplified decoupling method to reduce the interaction of TITO system. The simulation result shows that SIMC/GA is superior as compared to all other methods due to the performance parameters of each transient response for the TITO system.

Key words: Internal Model Control (IMC), PID controller, TITO system, transient responses, methods, delay

INTRODUCTION

In any process industry to be found as multiple inputs and multiple outputs (MIMO) in practice (Seborg *et al*., 2004; Shinskey, 1996). Most of the MIMO systems can observe as Two Inputs and Two Output (TITO) systems (Hajare and Patre, 2015; Besta and Chidambaram, 2016; Paul *et al*., 2016; Zhuang and Atherton, 1993; Chang *et al*., 2014) where two loops remain interrelated with each other (Anil and Sree, 2015). These TITO systems have an existence of an interaction between the loops gives the complication in designing feedback controllers. On the other hand, existing of the dead time in the control loop affecting the tuning job is more difficult. Controlling of such MIMO system loops with dead time is an exposed topic to the control communal. Many control policies are projected by the academicians (Paul *et al*., 2016) for such dead time TITO systems then the maximum number of the works recommended for the right selection of decoupler (Branislav *et al*., 2010).

In industrial process controlling action, multiple loops of Single Input Single Output (SISO) controllers are frequently used to monitor the systems which are MIMO dynamic model. The greatest smart benefits of such techniques are fundamental structural easiness as well the lenience to handle loop failure. The various strategical approaches conveyed in modern literature for multiple loops SISO controller designs. In design methodology, the off-diagonal elements of system transfer function matrix to be neglected and the diagonal elements of the controller transfer function are tuned centered on single loop controller design methodology. The diagonal elements of the controller tuned through the interface measure by a Relative Gain Array (RGA) matrix. In this study, every controller does primarily design for a resultant diagonal element based on classical methods which are Ziegler-Nichols (ZN) tuning, Skogestad-IMC, IMC, direct synthesis (Besta and Chidambaran, 2016; Paul *et al*., 2016; Anil and Sree, 2015; Sharma *et al*., 2016; Begum *et al*., 2016) and Genetic algorithm rules. The main benefit of this technique is its easiness on the other hand, it can lead to a slow or oscillatory response.

The PID controllers are regular use in process industries because of its effortlessness and the extensive choice of applications. In the literature, different techniques have projected on the tuning of PID controller designs for integrating systems. There are many practically useful methods, direct synthesis method (Anil and Sree, 2015), Internal Model Control (IMC) method (Begum *et al*., 2016), frequency domain method, stability analysis method, Two Degree of Freedom (2DOF) control scheme (Viteckova and Vitecek, 2010), Ziegler-Nicholas method (Ziegler *et al*., 1942) and optimization techniques (Chang and Chen, 2014; Nawi *et al*., 2011). They have some benefits and drawbacks in the tuning of PID parameter settings through exhausting of these methodologies. Selected techniques couldn't give an excellent performance for setpoint changes or else load disturbance may not be even perfect in input concern and several additions can't work with parameter uncertainty or can't be practical for all practice of integrating systems.

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MATERIALS AND METHODS

Description of system

MIMO system description: A general description of multivariable or multiloop system plants having n inputs and m outputs structure is given in Fig. 1. Here, r = [r1, r2, ..., rn] is the vector of setpoint inputs, y = [y1, y2, ..., ym] is the vector of process actual outputs, e = [e1, e2, ..., en] = [r1-y1, r2-y2, ..., rn-ym] is the vector of incorrectness or error signals, u = [u1, u2, ..., un] is the vector of manipulated input signals through the PID control outputs. Alternatively, the MIMO process G_p (s) is a multivariable transfer function matrix is expressed as (Chang and Chih-Yung, 2014; Lengare *et al*., 2012):

$$G(s) = \begin{pmatrix} g_{11}(s) & \dots & g_{1n}(s) \\ . & . & . \\ . & . & . \\ . & . & . \\ g_{m1}(s) & \dots & g_{mn}(s) \end{pmatrix} \quad (1)$$

where, g_{ij} (s) is the transfer function of a sub controlled system involving to the ith process outputs and the jth control inputs and also for i = 1, 2, …., m and j =1, 2, ..., n.

TITO system description: Consider a TITO system with time delay is as given in Fig. 1 G (s) is the process transfer function model and D (s) is the simplified decoupler transfer function matrix (Nordfeldt and Hagglund, 2006). In order to reduce such interaction properties in the situation of TITO system, the addition of decoupling in control action is regular use. Alternatively as the above said TITO system has time delay is placed simplified decoupling in the feed forward path of the control loop such as presented in Fig. 1. In this Fig. 1, r1, r2 are setpoint (reference inputs), u1, u2 are controller outputs and v1, v2 are manipulated inputs to the process, y1, y2 are actual process outputs of the TITO process. The generalized TITO system model is given by Eq. 2:

$$G_p(s) = \begin{pmatrix} g_{11}(s) & g_{12}(s) \\ g_{21}(s) & g_{22}(s) \end{pmatrix} \quad (2)$$

Where:

$$g_{11}(s) = \frac{y_1(s)}{r_1(s)},\ g_{12}(s) = \frac{y_1(s)}{r_2(s)}$$

$$g_{21}(s) = \frac{y_2(s)}{r_1(s)},\ g_{22}(s) = \frac{y_2(s)}{r_2(s)}$$

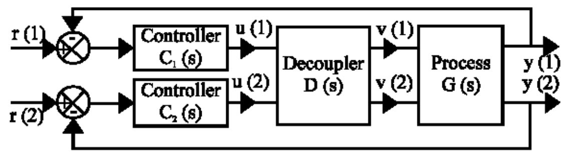

Fig. 1: TITO system with decoupler control design

The decoupler transfer function matrix (Jevtovic and Matausek, 2016) is given by Eq. 3, suggested by simplified method:

$$D(s) = \begin{pmatrix} 1 & d_{12}(s) \\ d_{21}(s) & 1 \end{pmatrix} \quad (3)$$

Where:

$$d_{12}(s) = \frac{-g_{12}(s)}{g_{11}(s)}$$

$$d_{21}(s) = \frac{-g_{21}(s)}{g_{22}(s)}$$

As soon as the simplified decoupler design is realized to the diagonal method then loop complexity of the TITO system gets reduced. The controllers $C_1(s)$ and $C_2(s)$ can remain viewed as independent SISO controllers. In view of various design methods of PID controller parameters to identified.

PID controller designs and settings

Development of P-I-D controllers: PID controllers exist everywhere, Due to its effortlessness and outstanding performance and PID controllers are running more than 95% of closed loop control industrial processes. Consider the description of the feedback control system with PID controller as exposed in Fig. 2. The main aim is to formulate PID controller design $G_c(s)$ of Fig. 2 which will give the preferred closed loop response.

The distinctive structure of a PID control system is given in Fig. 2, everywhere the error function e (t) is used to form the proportional, integral and derivative activities. The resultant signals weighted and summed to produce the control signal u(t) is applied/given to the plant/process/system model. An analytical explanation of the PID controller identified as:

$$u(t) = K_P[e(t) + \frac{1}{T_I}\int_0^t e(t)dt + T_D\frac{d}{dt}e(t)] \quad (4)$$

Where:

u (t) = Given as input (manipulated) signal into the each SISO plant prototype (Ramasamya and Sundaramoorthy, 2008)

e (t) = Significant error notice which is denoted as e(t) = r(t)-y(t)

r (t) = The setpoint (reference) input

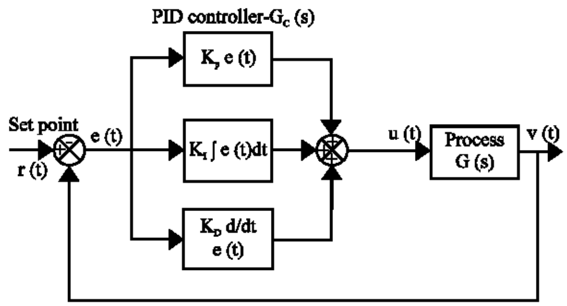

Fig. 2: Blocks of PID controller for SISO system

The P-I-D control actions could be as follows. P activity regularly maintained sufficient output and natural, I action is to minimize the offset and tight and D action is the future trend and peak overshoot-free but noise sensible. After grasping the characteristic of every control action, one should identify the exact combination of PID parameters for the controller to attain excellent control performance.

Ziegler-Nichols method: The Ziegler-Nichols tuning scheme is an experimental technique for tuning a PID controller. The traditional Ziegler-Nichols tuning guidelines (Ziegler *et al*., 1942; Meshram and Kanojiya, 2012) as introduced in the 1940s, a huge effect in making feedback PID controllers satisfactory for the control engineers. With the Ziegler-Nichols rule, engineers finally had a real time and systematic approach of calibration PID control loops for better performance.

The proportionate gain (K_p) once raised until it reaches the ultimate gain (K_u) on what amount of the control loop has steady state and continuous oscillations. P, I and D gains are depends on ultimate gain (K_u) and the oscillation period (P_u) to established the which type of controller is preferred. The tuning guidelines absolutely recommend the PID gains to use as follows (Table 1 and 2).

Direct synthesis method: In Direct Synthesis (DS) method (Anil and Sree, 2015), the controller configuration depended on process/plant model and preferred closed loop response. The DS approach gives significant information inside the relation among the process model and the resultant controller. Despite some fact that these feedback controllers does not have all the time a PID arrangement, the DS technique is to have PI or PID controllers in place of each regular process model.

DS procedure for the setpoint (reference) tracking, a simple controller design method through the individual controller in a single feedback loop for all sessions of integrating processes. The preferred output performance of the closed loop can be known as a trail model, mainly on the process to design the essential practice of the controller. With this formal controller there could be difficulties as similar to the overshoot and settling time.

Table 1: Z-N based PID parameter tuning (Meshram and Kanojjiya, 2012)

Controller	K_P	T_I	T_D
P-control	$0.50K_u$	-	-
PI-control	$0.45K_u$	$P_u/1.2$	-
PID-control	$0.60K_u$	$P_u/2$	$P_u/8$

Table 2: Modified Z-N based PID parameter tuning Meshram and Kanojjiya (2012)

Controller	K_P	T_I	T_D
PID control (Some % M_P)	$0.5K_u$	$P_u/1.2$	$P_u/1.2$
PID control (No. % M_P)	$0.5K_u$	$P_u/1.2$	$P_u/1.2$

As specified by the DS scheme (Besta and Chidambaram, 2016) the closed loop trail model must specify the designing of the controller and then the controller can be design as:

$$G_c(s) = \frac{1}{G_p(s)} \frac{\left(\frac{y}{y_r}\right)_d}{1-\left(\frac{y}{y_r}\right)_d} \quad (5)$$

Where:

$G_p(s)$ = Process/plant model
$(y/y_r)_d = 1/\tau_c s+1$ = Desired closed loop response
τ_c = the preferred closed loop time constant from the specifications

Internal model control: An additional widespread model based design scheme is Internal Model Control (IMC), Morari and Coworkers introduced it by 1982 (Paul *et al*., 2016). The IMC arrangement builds upon an assumed process model and leads to exact analytical explanations for every controller settings. This design scheme is exactly correlating to produce the same controllers, if the controller design parameters identified in a consistent way. Anyway, the IMC approach has some improvement that it disables model uncertainty and the trade-off between the performance and robustness to viewed in a more systematic fashion. Controller design using IMC method (Seborg *et al*., 2004; Begum and Radhakrishnan, 2016) as follows:

$$G_c(s) = \frac{G_c^*}{1-G_c^* G_p} \quad (6)$$

Where:

G_c^* = $1/G_p f$ and $f = 1/(\tau_c s+1)^r$
G_p = $G_p^- G_p^+$ Factored Process Model
τ_C = The chosen closed loop time constant and r is a positive number of filter coefficient with the choice of 1

Table 3: Skogestad's formulas for PI(D) tuning ($\tau_c = 1.5$) (Skogestad, 2003)

		PID controller tuning parameters		
Process type	G_p(S)-Process T/F	K_P	T_I	T_D
Integrator+delay	$k/s\ e^{-\tau s}$	$1/K\ (\tau_c+\tau)$	$[c\ (\tau]_c+\tau)$	0
Time constant+delay	$K/Ts+1\ e^{-\tau s}$	$1/K\ (\tau_c+\tau)$	Min $(T, C\ (\tau_c+\tau))$	0
Integrator+time constant+delay	$K/(Ts+1)\ e^{-\tau s}$	$1/K\ (\tau_c+\tau)$	$[c\ (\tau]_c+\tau)$	T
Two time constants+delay	$K\ e^{-\tau s}/(T1s+1)\ (T2+1)$	$1/K\ (\tau_c+\tau)$	Min $(T1, C\ (\tau_c+\tau))$	T2
Double integrator+delay	$K/s^2\ e_{-\tau s}$	$1/K\ (\tau_c+\tau)$	$[4c\ (\tau]_c+\tau)$	$4\ (\tau_c+\tau)$

Therefore, all IMC controller design G_C* denotes equal to a vilified feedback controller G_C and vice versa.

Skogestad internal model control: The Skogestad-IMC (SIMC) method exists based on traditional ideas existing earlier by Ziegler *et al.* (1940), the IMC PID tuning by Rivera *et al.* also, those strictly correlated to direct synthesis tuning guidelines. The design procedure of SIMC method (Skogestad, 2003, 2006) is as followed.

The controller scheme determining transfer function G (s) which gives the closed loop transfer function of the setpoint to the (filtered) process measurement, stated as a first order transfer function with dead time is:

$$G(s) = \frac{y(s)}{r(s)} = \frac{1}{t_c s+1} e^{-ts} \quad (7)$$

From the Fig. 2, the closed loop transfer function is:

$$G(s) = \frac{G_c(s)\ G_p(s)}{1+G_c(s)\ G_p(s)} \quad (8)$$

The setting, Eq. 8 is equal to Eq. 7 gives:

$$\frac{G_c(s)\ G_p(s)}{1+G_c(s)\ G_p(s)} = \frac{1}{t_c s+1} e^{-ts} \quad (9)$$

Here, the only unidentified is the controller assignment function, $G_c(s)$. By possessing certain suitable simplified calculations on the dead time, this controller turns into a PID controller or a PI controller for the process transfer function. Skogestad's tuning formulations for some methods given in Table 3.

Genetic algorithm: Genetic Algorithm (GA) research based on Darvin's theory of evolution and the survival of the fittest (Nawi *et al.*, 2011). GA leads the hunt for the solution by using accepted selection and genetic operatives such as selection, crossover and mutation (Fig. 3).

A genetic algorithm denotes some technique for solving both constrained and unconstrained optimization problems based on an average selection procedure that mimics genetic evolution. The algorithm frequently alters a population for best solutions. At every stage, the GA arbitrarily chooses individuals as of the current population and practices them as parents to create the children for the coming generation. Above continuous generations, the population "evolves" toward the best solution (Pereira and Pinto, 2005).

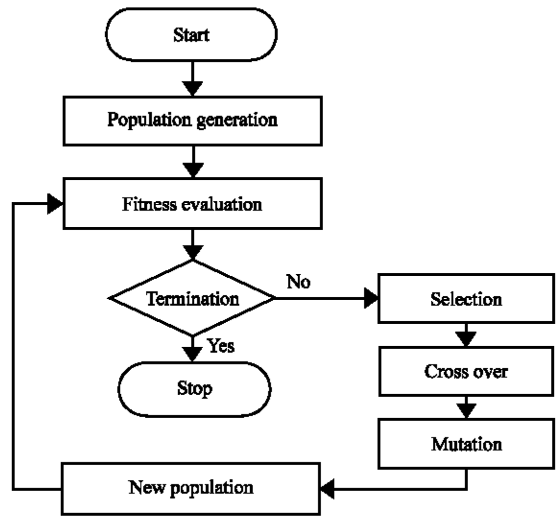

Fig. 3: GA flow chart (Pereira and Pinto, 2005)

RESULTS AND DISCUSSION

To discover the real time application of nonlinear coupled tank level system has recommended by Hajare and Patre (2015). The verification and simulation have been carried out by designing a decoupler controller to the TITO system. The complete transfer function of TITO process is given by Hajare and Patre (2015):

$$G(s) = \begin{pmatrix} \frac{0.43e^{-5s}}{29s+1} & \frac{0.145e^{-10s}}{40s+1} \\ \frac{0.172e^{-10s}}{35s+1} & \frac{0.37e^{-5s}}{27s+1} \end{pmatrix}$$

The decoupler matrix is computed using Eq. 3 as follows:

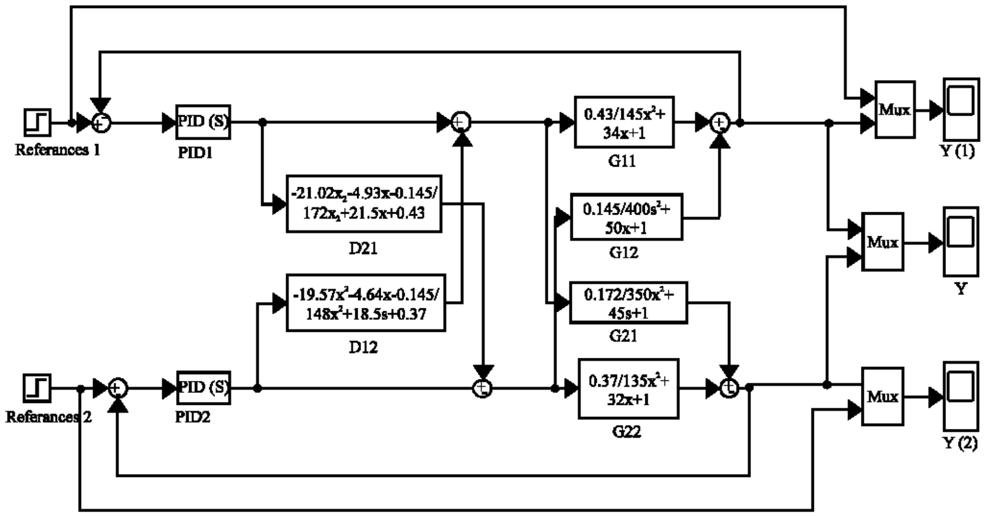

Fig. 4: MATLAB Simulink Model for TITO system with decoupled controllers

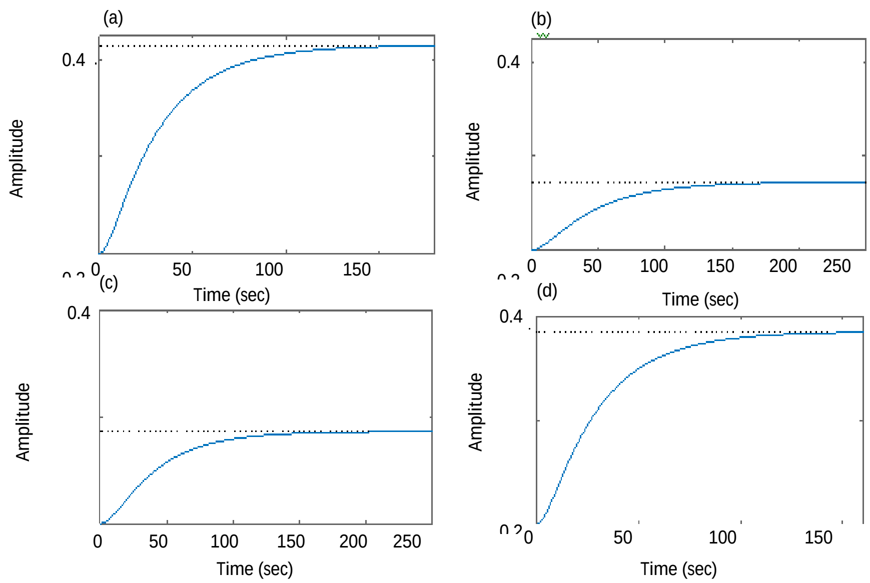

Fig. 5: Step response of open loop TITO [G(s)] system: a) G11; b) G12; c) G21 and d) G22

$$D(s) = \begin{pmatrix} 1 & \frac{(9.7s+0.337)e^{-5s}}{40s+1} \\ \frac{(12.5s+0.464)e^{-5s}}{35s+1} & 1 \end{pmatrix}$$

The whole Simulink model of the TITO system is established as shown in Fig. 4 as follows. Without tuning of PID controller without decoupler, the open loop step response of TITO is as follows in Fig. 5. The PID controller with designing of decoupler, the step response of open loop TITO is as follows in the Fig. 6 that is results to no interaction effect in between the TITO system input to output.

To inspect the quality if the process parametric ambiguity, the different closed loop control system responses as given in Fig. 7 and numerical transient response performance indices arranged in Table 3. Here, TITO system controlled with the decoupling PID controller. This controller has been designing with different conventional as well as optimization method (Table 4). It can determine that performance of the optimization based controller design is stable with less interaction among the variables of traditional controller design methods. The first output response and b the second output response comparison of transient response performance is given with bar chart in Fig. 8 as follows.

Table 4: Transient response performance parameters for TITO system

Methods	ZN		DS		IMC		SIMC		GA	
Parameters	y(1)[a]	y(2)[b]	y(1)[a]	y(2)[b]	y(1)[a]	y(2)[b]	y(1)[a]	y(2)[b]	y(1)[a]	y(2)[b]
Rise time (t_r)	5.7	6.02	6.23	6.73	15.5	17.1	7.83	8.41	5.08	5.40
Peak overshoot (%M_P)	44.5	42.7	34.3	31.7	6.63	5.03	12.9	11.1	6.53	5.01
Settling time (t_s)	63.2	54.4	42.2	43.2	56.8	57.2	27.9	28.7	28.6	29.4

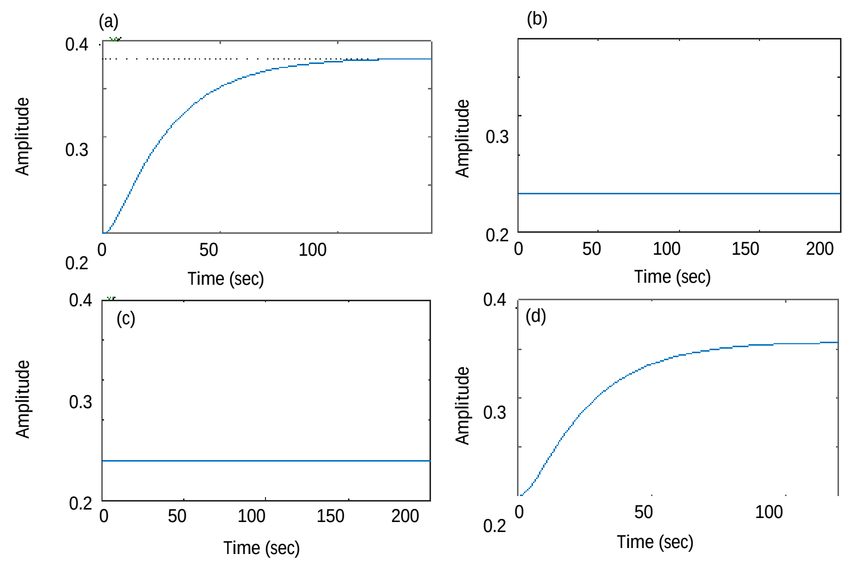

Fig. 6: Step response of open loop TITO system with the addition of decoupler

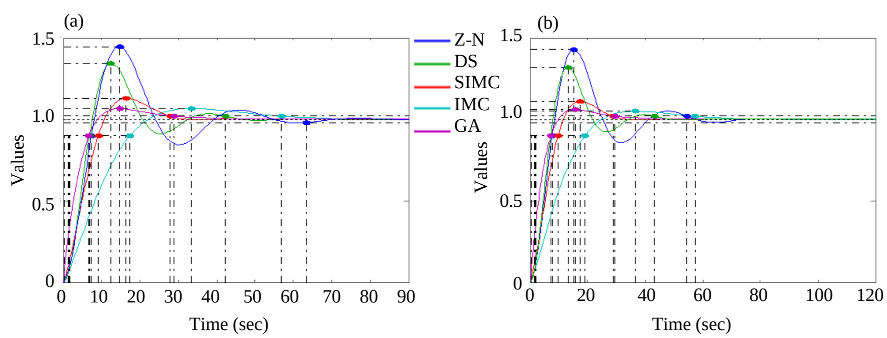

Fig. 7: TITO system response with PID tuning using different techniques

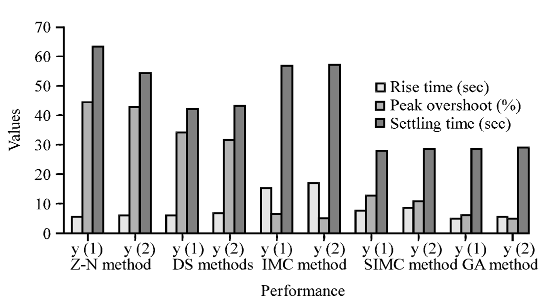

Fig. 8: Bar chat comparison of transient performence

CONCLUSION

The decentralized PID controller parameters are tuned using different conventional and optimization schemes for TITO system. Here, the decentralized PID controller is designed using simplified decoupling method and got minimum interaction between the variables. TITO process PID controller parameter tuning schemes have been observing that the conventional methods SIMC is giving the best control response and from all of the methods, genetic algorithm is much better control response.

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