International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-9 Issue-1, May 2020

Direct Adaptive Controllers for a Multi Input Multi Output Process

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Abstract*: Control of nonlinear dynamic systems is of great practical importance, since virtually all real world systems belong to this class. The prevalent approach is to use a model of the process linearized about the steady state operating point to design linear controllers. The Multi Input Multi Output (MIMO) process considered in this paper has varying system dynamics. This paper focuses on the performance evaluation of multi-loop Adaptive MIT(AMIT) controller and Adaptive PI(API) controller with vanishing adaptation technique for a laboratory interacting coupled tank MIMO process.

***Keywords* : Coupled Tank, MIMO, MRAC, AMIT, API.**

I. INTRODUCTION

The MIMO system chosen in this work is interacting coupled tank system. Model Reference Adaptive Control (MRAC) comes under Direct Adaptive Controller (DAC) [1]. Asan Mohideen *et al*. designed a MRAC for a coupled tank system [2]. Priyank Jain and Nigam dealt with the design of a Model Reference Adaptive Scheme (MRAS) for a second order system [3]. In this paper, process models are identified using open loop responses for different operating regions in real time. Using these process models, the proposed AMIT controller and API controller are designed and their performances are compared.

In this paper, the description of coupled tank process is given in section 2. Modelling and identification of the chosen process are outlined in section 3. In Section 4, design of Adaptive MIT controller is discussed. Design of Adaptive PI controller is presented in section 5. The real time responses of the designed controllers are given in Section 6 and 7. Finally, conclusion is given in Section 8.

II. PROCESS DESCRIPTION

Fig. 1 shows the setup of the chosen process in this work. This process contains two cylindrical tanks namely Tank1 and Tank2. These two tanks are connected by an interconnecting valve. Water comes from reservoir tank to Tank1 and Tank2. To measure the inflow rates, rotameters (R1 and R2) are used. Motorized Control Valves (MCV1 and MCV2) are used to adjust the flow rates. To sense the level in the two tanks Level transmitters (LT1 and LT2) are used. Data Acquisition Card (DAQ) VDAS-01 receives input from these transmitters. The control signal from VDAS-01 actuates the motorized control valves to control the levels in the tank.

Fig. 1. Laboratory Coupled tank process

III. IDENTIFICATION OF PROCESS

Fig. 2 shows the interfacing diagram of the process. The inflow rate into the tank1 is q_{in1}. The inflow rate into the tank2 is q_{in2}. The outflow rate from tank1 is q_{01}. The outflow rate from tank2 is q_{02}. The height of the liquid in tank1 is h_1 and the height of the liquid in tank2 is h_2.

VDAS-01 card is used to acquire open loop input/output data from the process for specific operating ranges. These input/output data are used to estimate the parameters of the model. Step changes in flow rates in terms of Litres Per Hour (LPH) are entered in Personal Computer (PC). The digital control signal from PC is converted into voltage using DAQ card and the inbuilt signal converter is used to convert this voltage to current signal to actuate the MCVs. These Motorized Control valves manipulate the inflow rates to the tanks. The height of the tanks are obtained from LTs. The level transmitter outputs are send to the PC via DAQ card.

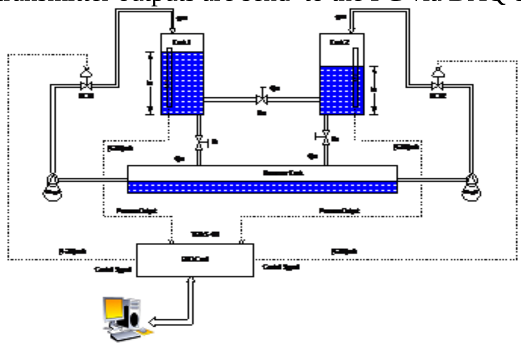

Fig. 2. Real time Interfacing diagram of Interacting coupled tank process

Manuscript received on April 02, 2020.
Revised Manuscript received on April 15, 2020.
Manuscript published on May 30, 2020.
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Here the manipulated input variables are inflow rates. The controlled output variables are levels. The open loop responses are shown in Fig. 3 and Fig. 4.

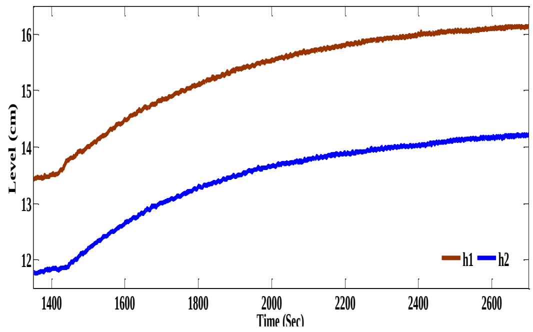

Fig. 3. Response of the process in open loop for change in q_{in1}.

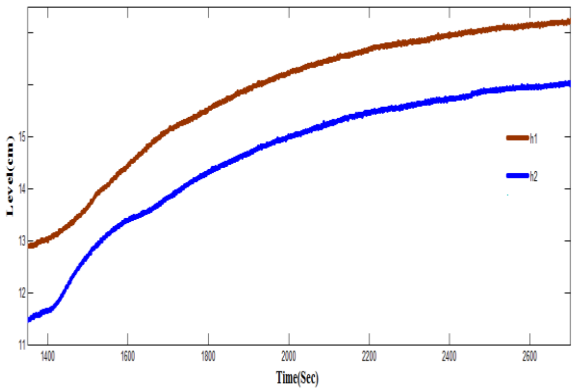

Fig. 4. Response of the process in open loop for change in q_{in2}.

The process transfer functions are calculated using Fig.3 and Fig. 4. They are given in Table-I[4].

IV. MULTI-LOOP ADAPTIVE MIT CONTROLLER

The set point of height of two tanks are h_{spi}. The controlled outputs are h_i (where i=1,2 represents the index for two tanks) Here the reference model is (h_m) [5]-[7]. In the reference models, the damping ratio is chosen as 0.7. The undamped natural frequency is chosen as 1.

The error equation is given in (1).

$$e_i = h_i - h_m \qquad (1)$$

The controller parameters (θ_{ni}) are given by (2).

$$J(\theta_{ni}) = \frac{1}{2} e_i^2 \qquad (2)$$

where n=1,2 represents controller parameter. The Adaptive MIT (AMIT) algorithm is given in (3)[8].

$$\frac{d\theta_{ni}}{dt} = -\gamma e_i \frac{\partial J}{\partial \theta_{ni}} = -\gamma e_i \frac{\partial e_i}{\partial \theta_{ni}} \qquad (3)$$

The parameter $\frac{\partial e_i}{\partial \theta_{ni}}$ is the derivative of the error with respect to controller parameters (θ_{ni}). The parameter, γ is the adaptation rate. The linearized model is given in (4).

$$G_{pi} = \frac{h_i}{u_i} = \frac{b_i}{s^2 + a_{1i}s + a_{2i}} \qquad (4)$$

where b_i, a_{1i}, a_{2i} are the parameters of the process. The control signal u_i, is given in (5).

$$u_i = \theta_{1i} h_{spi} - \theta_{2i} h_i \qquad (5)$$

By substituting (5) in (4), the closed loop transfer function of Adaptive MIT controller is given in (6).

$$\frac{h_i}{h_{spi}} = \frac{b_i \theta_{1i}}{s^2 + a_{1i}s + a_{2i} + b_i \theta_{2i}} \qquad (6)$$

The transfer function of the reference model is given by

$$G_m = \frac{h_m}{h_{spi}} = \frac{b_{m1i}s + b_{m2i}}{s^2 + 2sa_{m1i} + a_{m2i}} \qquad (7)$$

where b_{m1}, b_{m2}, a_{m1} and a_{m2} are the reference model parameters.

Table-I : Process Transfer Functions

Operating region(OR)	Tank1 (Keeping q_{in2} constant)			Tank2 (Keeping q_{in1} constant)			Process Transfer Function $G_p(s)$
	Δq_{in1} (LPH)	Δh_1 (cm)	Δh_2 (cm)	Δq_{in2} (LPH)	Δh_1 (cm)	Δh_2 (cm)	
OR1	50-65	13.5-16.1	11.6-14.2	50-65	13.5-17.2	11.6-16.0	$\begin{bmatrix} \frac{0.683}{399s^2+64s+1} & \frac{0.48}{207s^2+72s+1} \\ \frac{0.428}{983s^2+97s+1} & \frac{0.6}{300s^2+65s+1} \end{bmatrix}$
OR2	65-80	16.1-18.1	14.2-15.9	65-80	17.2-18.5	16.0-17.4	$\begin{bmatrix} \frac{0.8}{375s^2+80s+1} & \frac{0.6}{600s^2+70s+1} \\ \frac{0.44}{113s^2+100s+1} & \frac{0.68}{618s^2+90s+1} \end{bmatrix}$
OR3	80-95	18.1-18.8	15.9-16.6	80-95	18.5-19.0	17.4-17.9	$\begin{bmatrix} \frac{0.9}{171s^2+60s+1} & \frac{0.56}{900s^2+100s+1} \\ \frac{0.46}{120s^2+22s+1} & \frac{0.8}{112s^2+58s+1} \end{bmatrix}$

The partial derivatives of error are given in (8) and (9)

$$\frac{\partial e_i}{\partial \theta_{1i}} = \frac{b_i}{s^2 + 2sa_{m1i} + a_{m2i}} h_{spi} \qquad (8)$$

$$\frac{\partial e_i}{\partial \theta_{2i}} = \frac{-b_i}{s^2 + 2sa_{m1i} + a_{m2i}} h_i \qquad (9)$$

Substituting (8) and (9) in the MIT algorithm in (3), the parameters of the controller are obtained and are given in (10) and (11).

$$\theta_{1i} = -\frac{\gamma'}{s} e_i \frac{1}{s^2 + 2sa_{m1i} + a_{m2i}} h_{spi} \qquad (10)$$

$$\theta_{2i} = \frac{\gamma'}{s} e_i \frac{1}{s^2 + 2sa_{m1i} + a_{m2i}} h_i \qquad (11)$$

where $\gamma' = \gamma b_i$.

V. MULTI-LOOP ADAPTIVE PI CONTROLLER

In Adaptive PI (API) control, which is a type of DAC, the performance index is given in terms of a reference model [9]. An error signal between the desired and actual output is employed to update controller parameters in online. The PI control law used in this controller is given in (12).

$$u_i = K_{ci}(h_{spi} - h_i) + \frac{K_{ii}}{s}(h_{spi} - h_i) \qquad (12)$$

The Adaptive PI (API) controller transfer function is given in (13).

$$\frac{h_i}{h_{sp_i}} = \frac{bK_{ci}s + bK_{ii}}{s^2 + s[bK_{ci} + a] + K_{ii}b} \qquad (13)$$

The second order reference model is presented in (14).

$$\frac{h_m}{h_{spi}} = \frac{b_{m1i}s + b_{m2i}}{s^2 + 2sa_{m1i} + a_{m2i}} \qquad (14)$$

The condition for model to be matched is given in (15)

$$s^2 + s[bK_{ci} + a] + K_{ii}b = s^2 + 2sa_{m1i} + a_{m2i} \qquad (15)$$

By substituting (13) and (14) in (16), the modeling error (e) is obtained as given in (17).

$$e_i = h_i - h_m \qquad (16)$$

$$e_i = \frac{bsK_{ci} + bK_{ii}}{s^2 + s[bK_{ci} + a] + bK_{ii}} h_{spi} - \frac{b_{m1i}s + b_{m2i}s}{s^2 + 2sa_{m1i} + a_{m2i}} h_{spi} \qquad (17)$$

Then,

$$\frac{\partial e_i}{\partial K_{ci}} = \frac{sb[h_{spi} - h_i]}{s^2 + 2sa_{m1i} + a_{m2i}} \qquad (18)$$

$$\frac{\partial e_i}{\partial K_{ii}} = \frac{b[h_{spi} - h_i]}{s^2 + 2sa_{m1i} + a_{m2i}} \qquad (19)$$

The parameters of the controller are given in (20) and (21).

$$K_{ci} = -\frac{\gamma'}{s} e_i \frac{s}{s^2 + 2sam_{1i} + am_{2i}} [h_{sp_i} - h_i] \qquad (20)$$

$$K_{ii} = -\frac{\gamma'}{s} e_i \frac{1}{s^2 + 2sam_{1i} + am_{2i}} [h_{sp_i} - h_i] \qquad (21)$$

VI. RESPONSES OF API CONTROLLERS

The control algorithms thus designed are implemented in real time process using USB based MATLAB interfacing card VDAS-01. Fig. 5. presents the servo output of h_1 and h_2 for Δh_{sp1} (set point change in h_1) and their corresponding level variations to tank1 and tank2 with API controllers. The Initial condition of h_1 is 13.5cm and h_2 is 11.6cm. In servo1, a set point is applied at 600th sec in h_1. As a result, h_1 increases and settles in its set point. Due to interaction there is a considerable fluctuation in h_2 and settles in its set point due to the controller action in loop2. At 1100th sec, h_{sp1} (servo2) is increased from 14 to 14.5cm. Due to interaction h_1 and h_2 both increases and tracks to their set points due to the action of controllers in loop1 and loop2.

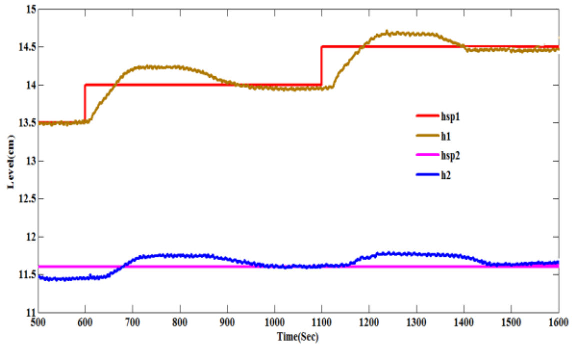

Fig. 5. Servo Responses of h_1 for Δh_{sp1}

The corresponding responses of API controllers for set point changes in h_1 are shown in Fig. 6. For servo1 and servo2, q_{in1} rises and q_{in2} decreases in order to track the set point change in h_1.

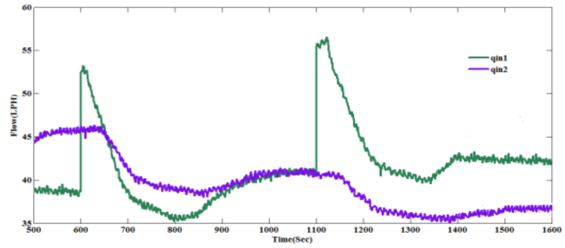

Fig. 6. Responses of API Controllers

The adaptation of controller parameter (K_c) in API controllers is given in Fig. 7.

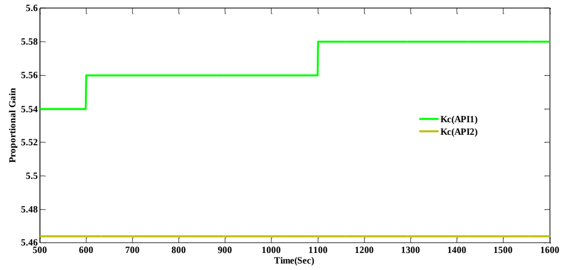

Fig. 7. Adaptation of controller parameters

The adaptation of controller parameter (K_i) in API controllers is given in Fig. 8.

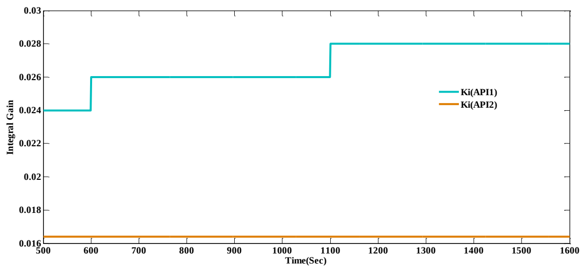

Fig. 8. Adaptation of controller parameters

Fig. 9. presents the servo responses of h_2 and h_1 for Δh_{sp2} (change in set point of h_2) and its corresponding level variations in tank1 and tank2 with API controllers. The initial conditions of h_1 is 13.5cm and h_2 is 11.6cm. In (servo3), a set point change is applied at 1000th sec in h_2. As a result, h_2 increases and settles in its set point. Due to interaction there is a fluctuation in h_1 and settles in its set point.

Retrieval Number: A1639059120/2020©BEIESP
DOI:10.35940/ijrte.A1639.059120
Journal Website: www.ijrte.org

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At 1550[th] sec, h_{sp2} (servo4) is increased from 12.1 to 12.6cm. Due to interaction, both $h_2$and h_1 increases and tracks to their set points due to the action of controllers in loop2 and loop1.

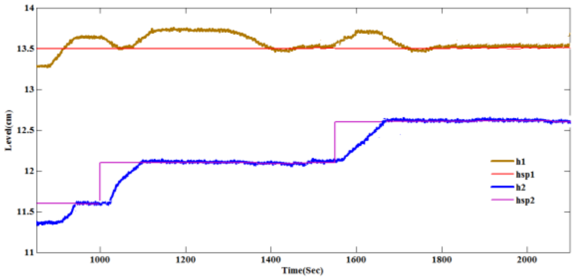

Fig. 9. Servo Responses of $h_2$for Δh_{sp2}

The corresponding responses of API controllers for set point changes in h_2 are shown in Fig. 10. The controllers take corrective actions depending upon the variations in h_1 and h_2.

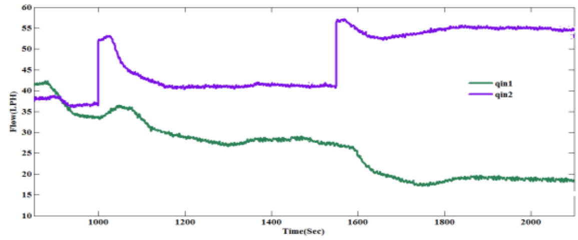

Fig. 10. Responses of API Controllers

The adaptation of controller parameter (K_c) in API controllers is given in Fig. 11.

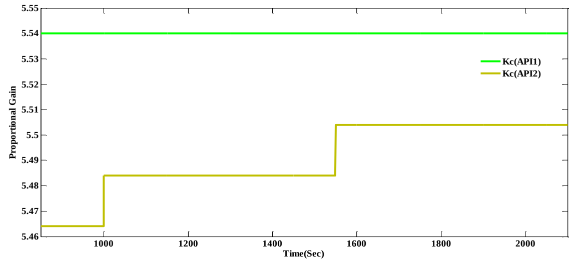

Fig. 11. Adaptation of controller parameters

The adaptation of controller parameter (K_i) in API controllers is given in Fig. 12.

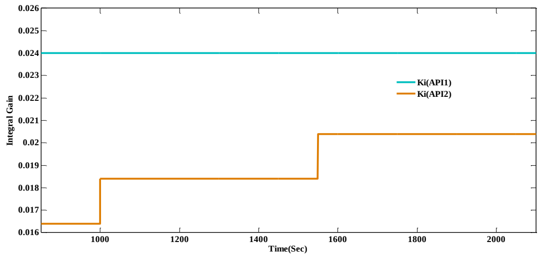

Fig. 12. Adaptation of Integral Gains

VII. RESPONSES OF AMIT CONTROLLERS

Fig. 13 presents the servo responses of $h_1$and h_2 for Δh_{sp1} and its corresponding level variations in tank1 and tank2 with AMIT controllers.

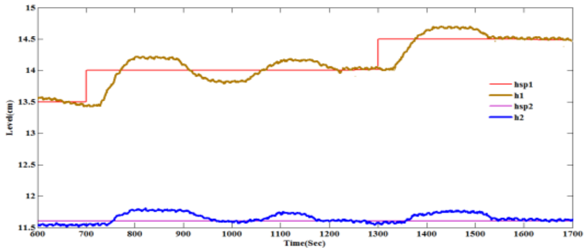

Fig. 13. Servo Responses of h_1 for Δh_{sp1}

The corresponding responses of AMIT controllers for set point changes in h_1 are shown in Fig. 14.

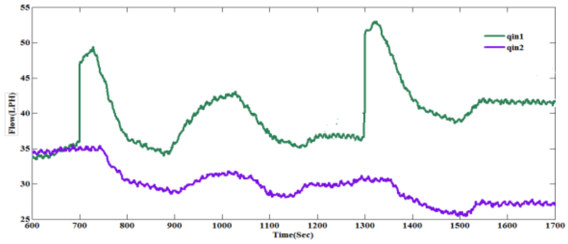

Fig. 14. Responses of AMIT Controllers

The adaptation of controller parameters (θ_1 and θ_2) of AMIT controllers is shown in Fig. 15.

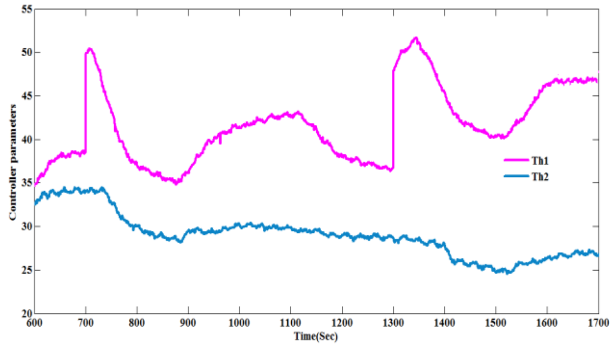

Fig. 15. Adaptation of Controller Parameters

Fig. 16 presents the servo responses of h_2 for Δh_{sp2}(change in set point of h_2) and its corresponding level variations in tank1 and tank2 with AMIT controllers.

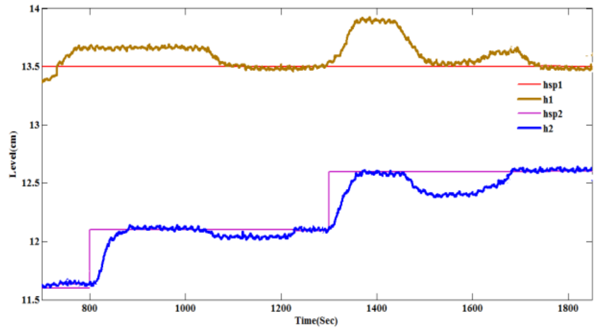

Fig. 16. Servo Responses of h_2 for Δh_{sp2}

The corresponding responses of AMIT controllers for set point changes in h_2 are shown in Fig. 17. The multi-loop AMIT controllers take corrective actions depending on the variations in h_1 and h_2.

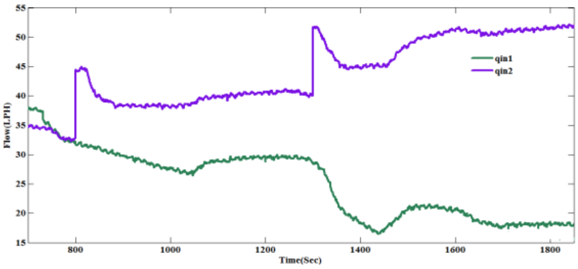

Fig. 17. Responses of AMIT Controllers

The adaptation of controller parameters (θ_1 and θ_2) of AMIT controllers is shown in Fig. 18.

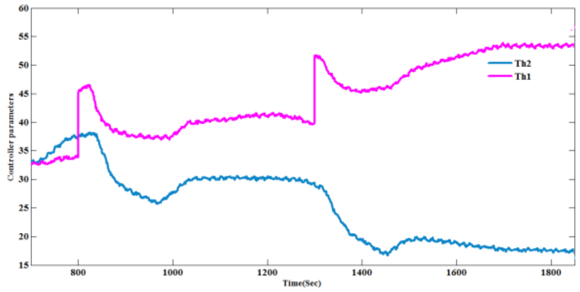

Fig. 18. Adaptation of Controller Parameters

VIII. RESULTS OF AMIT AND API CONTROLLERS

From the servo responses of AMIT and API Controllers when implemented in coupled tank process, the time integral criteria such as ISE (Integral Square Error), IAE(Integral Absolute Error) and ITAE(Integral Time Absolute Error) are compared and the results are tabulated.

Table-II presents the comparison of performance criteria of laboratory interacting coupled tank system with AMIT and API controllers for Δh_{sp1}.

Table-II Comparison of Performance Criteria with AMIT and API Controllers for Δh_{sp1}

Parameters	AMIT (Δh_{sp1})		API (Δh_{sp1})	
	Servo1	Servo2	Servo1	Servo2
Settling time (sec)	528	544	314	300
(for 1000 sec duration)				
ISE	1.965e+4		0.854e+4	
IAE	2317		878	
ITAE	6.879e+6		1.123e+6	

Table-III presents the comparison of performance criteria of AMIT and API controllers for Δh_{sp2}

Table-III Comparison of Performance Criteria with AMIT and API Controllers for Δh_{sp2}

Parameters	AMIT (Δh_{sp2})		API (Δh_{sp2})	
	Servo3	Servo4	Servo3	Servo4
Settling time (sec)	424	361	144	80
(for 1050 sec duration)				
ISE	2.582e+4		2.146e+4	
IAE	2487		2358	
ITAE	1.624e+7		1.287e+7	

IX. CONCLUSION

The design and experimental results of multi-loop direct adaptive controllers such as AMIT and API are analysed. The experimental results show that the proposed API controller has ability to obtain the desired dynamics. The controller parameter variations of API controller varies to a minimum extent when compared to that of AMIT controller.

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