Modeling, Simulation and Intelligent Control of Coupled Tank System

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Abstract. **In the present paper, a hybrid, Adaptive neuro fuzzy inference system (ANFIS) that combine the advantage of Adaptive control, Neural Network and Sugeno-type Fuzzy logic control has been proposed. The proposed method has been applied to a level control of nonlinear interacting and non-interacting coupled tank system as a case study. For this purpose, nonlinear dynamical models for two different configured coupled tank system namely, integrating and non-integrating have been developed. Further, transfer function of these developed models have been derived using various sample acquired from experiment performed at Indian Institute of Technology Roorkee. To investigate the capability of proposed ANFIS, a conventional controller PID and intelligent controller, Fuzzy logic control (FLC) are designed. Finally, the performance of the proposed techniques based on the control parameters such as: Overshoot, rise time, settling time and tracking capability have been investigated and found that ANFISis able to eliminate the overshoot and it has faster response with better tracking capabilities.**

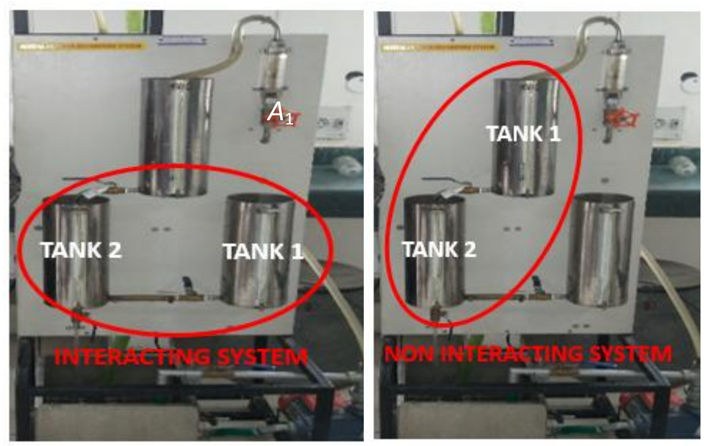
Keywords**: Fuzzy Logic Control, Nonlinear Dynamics, PID control, Adaptive-Neuro-Fuzzy-Inference System, Coupled tank system.**

I. INTRODUCTION

Level control is one of the most important applications in any of the process industries especially, in chemical process industries, such as food beverages processing, dairy industries, textile industries, water purification and effluents treatment, chemical and pharmaceutical industries and boilers of pulp and paper mills, sugar mills, nuclear power plants, etc [1,2,3,4]. Conventionally, family of PID controller contributes about more than 80% as an industrial level controller due to its simple design and implementation with comparable installation cost and having reasonably better control parameter performances. In spite of this fact, PID controller may not always a better option and not serve the purpose where the control requirement is more stringent [5]. However, a minor improvement in the control performance results a better product quality with effective deduction in product cost. The purpose of any control is to maintain a constant level of fluid with better tracking, rejection of the disturbances and optimal control performance parameters. To achieve the following target, a hybrid,Adaptive neuro fuzzy inference system (ANFIS) that combine the advantage of Adaptive control, Neural Network and Sugeno-type Fuzzy logic control has been proposed.The proposed method has been applied to a level control of nonlinearinteracting and non-interacting coupled tank system. Therefore, the present investigation begins with development of nonlinear dynamical models of mentioned system and further, transfer function single-input single-output are derived. Finally, the models are applied for the simulation using conventional PID and intelligent controller, fuzzy logic and ANFIS.

II. EXPERIMENTAL SETUP

The experimental setup has been illustrated in Fig. 1. It consists of two coupled tank system configured with interacting and non-interacting type system. All the control valves shown in Fig. 1 are manually controlled. Output of the level sensors are acquired and used to evaluate the time constant of each tank that finally yield the transfer function of mentioned process. All the controllers are designed in MTALAB Simulink environment. All the sensors are assumed with the calibration to provide unity feedback gains.



(a) (b)

Fig. 1 Coupled tank system configured with (a) Interacting system (b) Non-interacting system

2.1Mathematical Modeling of non-interacting process

The series of developed nonlinear dynamic model equations that govern the couple tank system are transformed to a linear time invariant system. Usually, such models have been derived from thermodynamic first principles of mass and energy conservation. Fig. 2 illustrates the non-interacting system with inlet flow, q(t) and product outlet flow q_2(t) with target to maintained the levels of tank 1 and 2 at h_1 and h_2 height respectively.

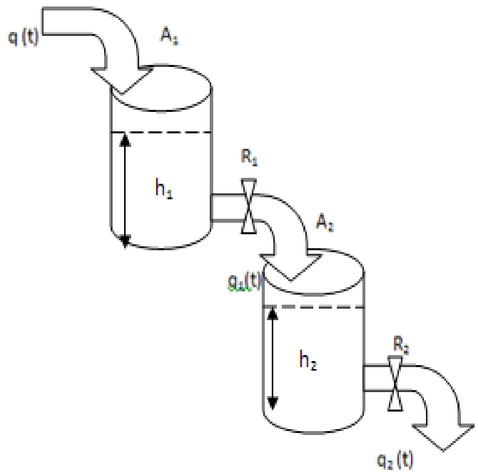


Fig.2 Non-Interacting coupled tank System

Applying mass transfer around each tank,

Around first tank,

$$q - q_1 = A_1 \frac{dh_1}{dt} \tag{1}$$

The valve resistance, R_1 and outlet flow, q_1 is related by

$$\frac{h_1}{R_1} = q_1 \tag{2}$$

Using Eqs. (1) and (2)

$$q - \frac{h_1}{R_1} = A_1 \frac{dh_1}{dt} \tag{3}$$

However, at steady state,

$$q_s - \frac{h_{1_s}}{R_1} = 0 \tag{4}$$

Hence, the deviation from the steady state is given by

$$(q - q_s) - (\frac{h_1 - h_{1s}}{R_1}) = A_1 \frac{dH_1}{dt} \tag{5}$$

Representing Eq. (5) as

$$Q - \frac{H_1}{R_1} = A_1 \frac{dH_1}{dt} \tag{6}$$

Where-

$$q - q_s = Q$$

$$h_1 - h_{1_s} = H_1$$

Using the Laplace transform

$$Q(s) = A_1 s H_1(s) + \frac{H_1(s)}{R_1} \tag{7}$$

On solving Eq. (7)

$$Q(s) = (\frac{R_1 A_1 s + 1}{R_1}) H_1(s) \tag{8}$$

Hence the transfer function becomes,

$$\frac{H_1(s)}{Q(s)} = \frac{R_1}{1 + s\tau_1} \tag{9}$$

Finally, the outlet flow of the tank 2 is given by

$$Q(s) = (\frac{R_1 A_1 s + 1}{R_1}) H_1(s) \tag{10}$$

where-

$$\tau_1 = R_1 A_1$$

Similarly,

$$\frac{H_2(s)}{Q_1(s)} = \frac{R_2}{1 + s\tau_2} \tag{11}$$

From equation (2)-

$$\frac{h_1}{R_1} = q_1(s) \tag{12}$$

Laplace of equation (2)-

$$R_1 Q_1(s) = H_1(s) \tag{13}$$

Put the value of $H_1(s)$ in equation (13) from equation (9) –

$$\frac{Q_1(s)}{Q(s)} = \frac{1}{1 + s\tau_1} \tag{14}$$

Now combine the equation (11) & (14)-

$$\frac{H_2(s)}{Q(s)} = \frac{R_2}{(1 + s\tau_1)(1 + s\tau_2)} \tag{15}$$

2.1.1 LABORATORY OBSERVATION:

Case I: Data set for the step response of Non-Interacting models

Table1 Parameters of Non-Interacting Tanks

S.No.	Parameter (S)	Value (s)
1.	Diameter of tanks	9.2 cm
2.	Initial flow rate (LPM)	0
3.	Initial steady state level of tank-1(cm)	35.007
4.	Final flow rate (LPM)	2 or (33.34cm^3/second)
5.	Final steady state level of tank-2(cm)	50.76015

Table2 Observation of level for Non-Interacting Tank

S. N O .	Time	H_1	H_2	H_1 (observed)	H_2 (observed)
1.	0	24	35.0071	0	0
2.	15	24.5	36.1	0.5	1.0929
3.	30	24.09	36.9	0.09	1.8929
4.	45	25.02	37	1.02	1.9929
5.	60	28.09	37.5	4.09	2.4929
6.	75	29.5	40.13	5.5	5.1229
7.	90	31	42.3	7	7.2929
8.	105	31.009	44.2	7.009	9.1929
9.	120	34.003	45.07	10.003	10.0629
10.	135	34.009	49.009	10.009	14.0019
11.	150	35	50.1	11	15.0929
12.	165	35.007	50.76	11.007	15.7529
13.	180	35.007	50.76015	11.007	15.75305

H(t) observed = (Level at time-t – Level at time 0)

Magnitude of step change = Flow after step input – Initial flow rate

$$\tau_1 = A_1 * R_1$$

$$\tau_2 = A_2 * R_2$$

Where $(\tau_1 \& \tau_2)$ are the time constant of tank-1 & tank-2(respectively) and $(R_1 \& R_2)$ are the resistance of outlet valve of tank-1& tank-2 (respectively).

Area of tank-1 & tank-2 are same (because diameter are same) i.e. $A_1 \& A_2 = \frac{\pi}{4}(d)^2$

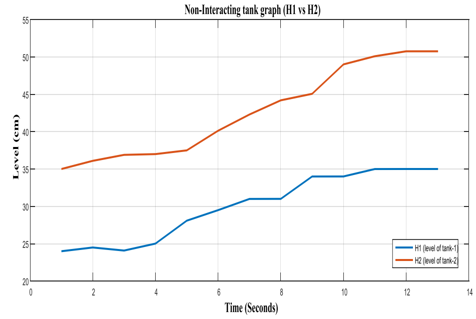


Fig. 3 Variations of heights in tanks 1 and 2 for Non-Interacting tank

Resistance at outlet valve of both tanks, can be calculated as-

$$R_1 = \frac{dH_1}{dQ}$$

$$R_2 = \frac{dH_2}{dQ}$$

Where dH_1 &dH_2 is the change in level of tank-1 & tank-2 respectively and dQ is the flow of from initial to final state.

Table 3 Calculated Parameters

S. No.	Parameter (S)	Value (s)
1.	A	66.4424 cm^2
2.	dH_1	35.007 cm
3.	dH_2	50.76015 cm
4.	dQ	33.34 cm^3/second
5.	R_1	1.05
6.	R_2	1.5225
7.	τ_1	69.76452 second
8.	τ_2	101.1586 second

Transfer function:

On the basis of the experimented data set the transfer function for the Non-Interacting System are

$$\frac{H_2(s)}{Q(s)} = \frac{R_2}{(1+s\tau_1)(1+s\tau_2)}$$

$$\frac{H_2(s)}{Q(s)} = \frac{1.5225}{7057.281173s^2 + 170.92312s + 1}$$

2.2 Modeling of Interacting tank-

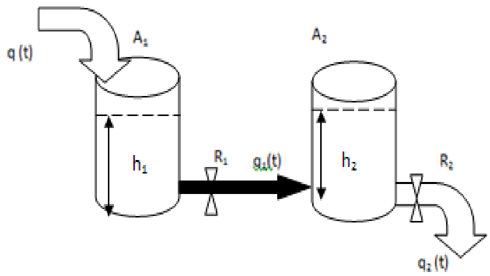


Fig.4 Interacting couple tank system

Similarly, applying the mass transfer for interacting couple tank system for tank 1,

$$q - q_1 = A_1 \frac{dh_1}{dt} \tag{16}$$

For interacting couple tank system for tank 2,

$$q_1 - q_2 = A_2 \frac{dh_2}{dt} \tag{17}$$

Using, Eqs. (12) and (16),

$$q - \frac{h_1}{R_1} = A_1 \frac{dh_1}{dt} \tag{18}$$

$$\frac{h_2}{R_2} = q_2 \tag{19}$$

For tank 2,

$$q - \frac{h_1 - h_2}{R_1} = A_1 \frac{dh_1}{dt} \tag{20}$$

Rewrite the equation (1) & (2)-

$$Q - Q_1 = A_1 \frac{dH_1}{dt} \tag{21}$$

Likewise,

$$Q - Q_1 = A_2 \frac{dH_2}{dt} \tag{22}$$

Rewrite the Eqs. (3) & (4)

$$Q_1 = \frac{H_1 - H_2}{R_1} \tag{23}$$

$$Q_2 = \frac{H_2}{R_2} \tag{24}$$

Using laplace transform the final transfer function for the interacting system is given as

$$\frac{H_2(s)}{Q(s)} = \frac{R_2}{\tau_1 \tau_2 s^2 + (\tau_1 + \tau_2 + A_1 R_2)s + 1} \tag{25}$$

The obtained models are cross validated on different experimental inputs.

2.2.1 LABORATORY OBSERVATION:

Case-II: Data set for the step response of Interacting models

Table 5 Parameters of Interacting Tanks

S.No.	Parameter (S)	Value (s)
1.	Diameter of tanks	9.2 Cm
2.	Initial flow rate (LPM)	0
3.	Initial steady state level of tank-1(cm)	52.5105
4.	Final flow rate (LPM)	2 or (33.34 cm^3/second)
5.	Final steady state level of tank-2(cm)	33.0066

Table 6 Observation of level for Interacting Tank

S.NO.	Time	H_1	H_2	H_1(observed)	H_2(observed)
1.	0	28	15	0	0
2.	15	28.53	17.089	0.53	2.089
3.	30	29.623	18.5	1.623	3.5
4.	45	32.5	20.23	4.5	5.23
5.	60	33	20.41	5	5.41
6.	75	36.01	22.987	8.01	7.987
7.	90	41	24.56	13	9.56
8.	105	45.101	26.03	17.101	11.03
9.	120	48.23	27.131	20.23	12.131
10.	135	51.051	30.012	23.051	15.012
11.	150	52.1	32.1	24.1	17.1
12.	165	52.5105	33.0066	24.5105	18.0066
13.	180	52.5	33.0066	24.5	18.0066

H(t) observed = (Level at time-t – Level at time 0)
Magnitude of step change = Flow after step input – Initial flow rate

$$\tau_1 = A_1 * R_1$$
$$\tau_2 = A_2 * R_2$$

Where ($\tau_1 \& \tau_2$) are the time constant of tank-1 & tank-2(respectively) and ($R_1 \& R_2$) are the resistance of outlet valve of tank-1& tank-2 (respectively).

Area of tank-1 & tank-2 are same (because diameter are same) i.e. $A_1 \& A_2 = \frac{\pi}{4}(d)^2$

Resistance at outlet valve of both tanks, can be calculated as

$$R_1 = \frac{dH_1}{dQ}$$

$$R_2 = \frac{dH_2}{dQ}$$

Where dH_1 &dH_2 is the change in level of tank-1 & tank-2 respectively and dQ is the flow of from initial to final state.

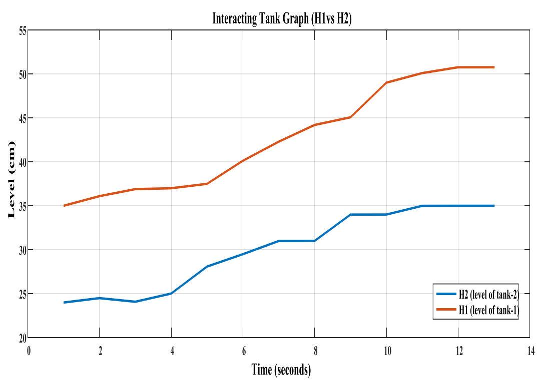


Fig. 5 Variations of heights in tanks 1 and 2 for Interacting tank

Table 7 Calculated parameters

S.No.	Parameter (S)	Value (s)
1.	A	66.4424 cm^2
2.	dH_1	52.5105 cm
3.	dH_2	33.0066 cm
4.	Dq	33.34 cm^3/second
5.	R_1	1.575
6.	R_2	0.99
7.	τ_1	104.6468 second
8.	τ_2	65.77798 second

Transfer function

On the basis of the above data set the transfer function for the Interacting System are

$$\frac{H_2(s)}{Q(s)} = \frac{R_2}{\tau_1\tau_2 s^2 + (\tau_1 + \tau_2 + A_1R_2)s + 1}$$

$$\frac{H_2(s)}{Q(s)} = \frac{0.99}{6883.455117s^2 + 236.202756s + 1}$$

III. DESIGN OF CONTROLLER

Here are the three types of controllers which have been used PID, Fuzzy & ANFIS these are explained in detail & comparisons among them have been done.

3.1 Proportional Integral Derivative (PID) Controller

The PID controller parameters are Proportional Gain (K_P), Integral Gain (K_I) & Derivative Gain (K_D). Many methods have been proposed for finding the parameter values, here we find the values by using Zeigler-Nichols tuning method.

The calculated values are: K_p=1.776, K_I= 0.01298 , K_D= 31.51 & N= 0.482.

3.2 Fuzzy Logic Controller (FLC)

The most important aspect of the design of the fuzzy logic controller is its application itself. e.g. the FLC designed for a discrete process control will be different from the one for a continuous process control application.

The system developed has five main parts:

1. Input variables
2. Method of fuzzification through membership functions for input variables
3. Rule-base (if-then rules)
4. Method of defuzzification through membership functions for output variables
5. Output variables

Here ,two input variables are being used, error (E) and change in error (DE). In case of Fuzzification, Membership function describes input variable fuzzification i.e. conversion of membership function into linguistics variables. the membership function of input variables are as follows-

S. No.	Linguistic Value	Variance	Centre
1	NL	0.1132	-1.333
2	NM	0.1132	-0.7
3	NS	0.1132	-0.366
4	Z	0.1132	0.0334
5	PS	0.1132	0.3666
6	PM	0.1132	0.7
7	PL	0.1132	1.333

TABLE.8. Parameters of Linguistic Values

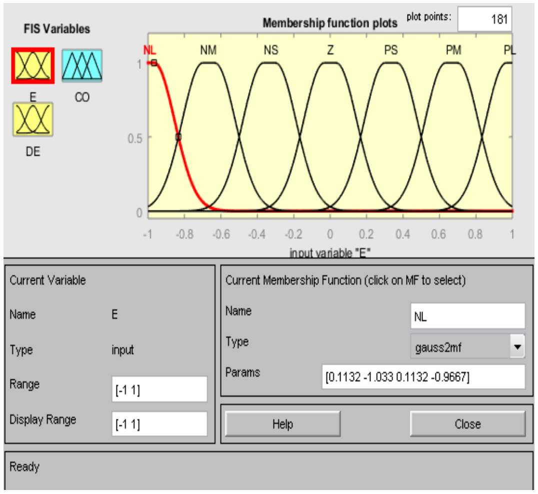


Fig.6.Membership function for error (E)

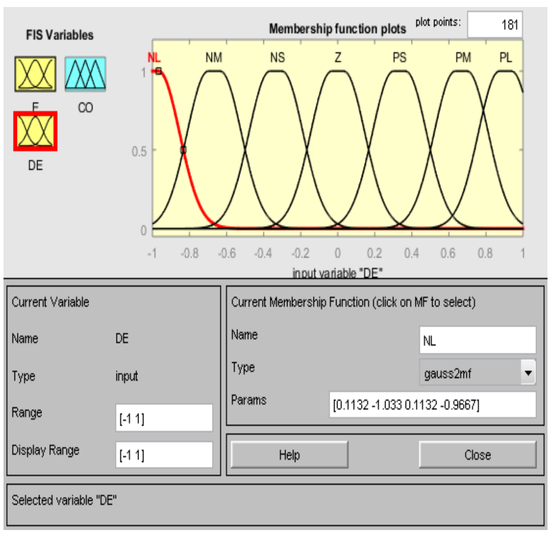


Fig.7.Membership function for change in error (DE)

E / DE O	NL	NM	NS	Z	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	Z
NM	NL	NL	NL	NM	NS	Z	PS
NS	NL	NL	NM	NS	Z	PS	PM
Z	NL	NM	NS	Z	PS	PM	PL
PS	NM	NS	Z	PS	PM	PL	PL
PM	NS	Z	PS	PM	PL	PL	PL
PL	Z	PS	PM	PL	PL	PL	PL

Table.9. Rule Base

Now, the defuzzification converts fuzzy value into crisp value. Centre of area (centroid) method is used for defuzzification & the membership function is shown in Fig.8. for controlled output with its surface viewer in Fig.9.

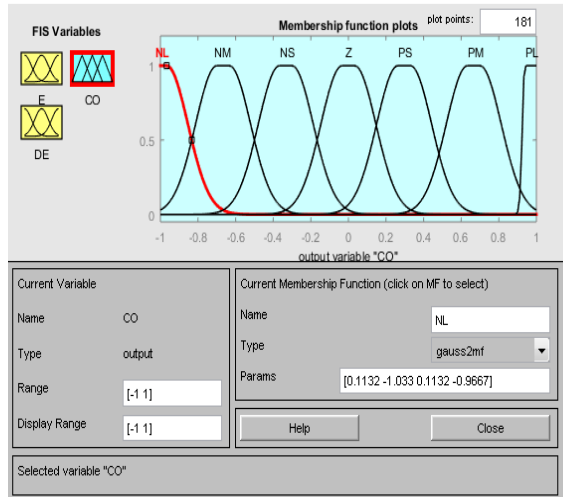


Fig.8.Membership function for Controlled output (CO)

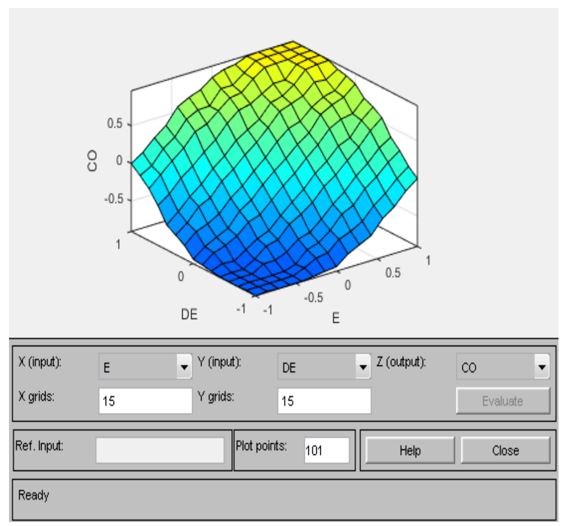


Fig.9.Surface viewer of modelled FLC

3.3 Adaptive Neuro Fuzzy Inference System (ANFIS) Controller

ANFIS employs gradient descent algorithm to fine-tune them. For consequent parameters that define the coefficients of each equation, ANFIS uses the least squares method to identify them. This approach is thus called hybrid learning method

3.3.1MODEL- SURFACE VIEWER

The surface viewer of designed ANFIS model is illustrated in Fig.10. which shows the variation of controlled output CO with the variation in input variables.

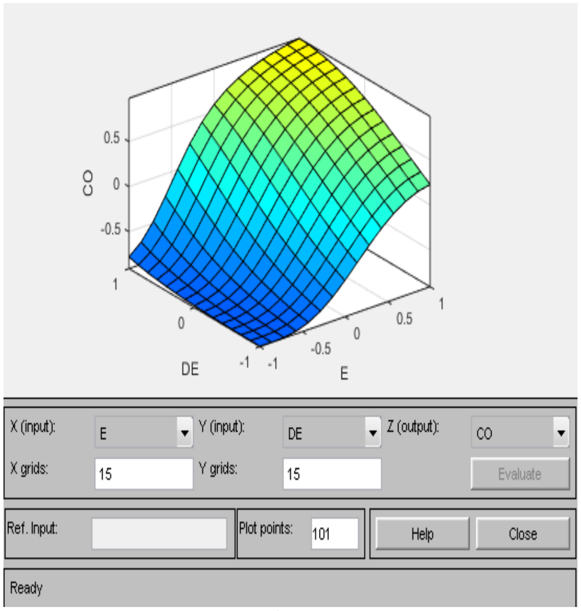


Fig.10. Surface Viewer

There are two inputs E and DE represented on axis X and Y respectively and moreover, the single output (CO) has been represented on Z-axis.

3.3.2 Model Validation

Model validation is the process by which the input vectors from input/output data sets on which the FIS was not trained, are presented to the trained the FIS model, to check how well the FIS model predicts the corresponding data set output values. The various data of the developed ANFIS model are shown in table 10.

S. No.	Name	Value
1	Membership Function	Gaussian
2	No. of MF's	2
3	No. of epochs	500
4	Training error	0.016391
5	Testing error	0.016391

TABLE 10. ANFIS Data

IV. RESULTS & SIMULATION

Simulation studies are carried out on the coupled tank which presents the simulation of control of the derived plant tanks for interacting and non-interacting in Matlab using PID, FLC & ANFIS controller.

4.1 Non-Interacting Tank System

Simulation of Non-Interacting coupled tanks system which shows the step response.

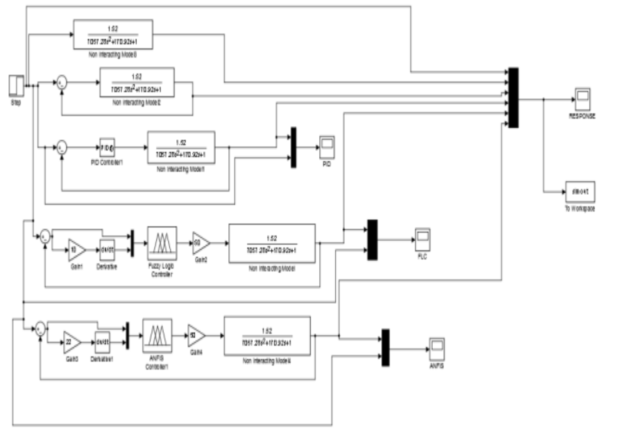


Fig.11. Simulink model of non-interacting coupled tank system with and without different control action.

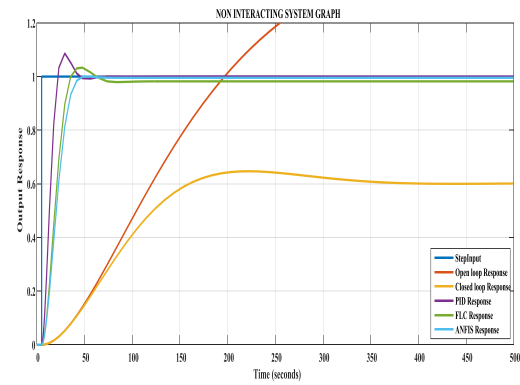


Fig.12. Step response of non-interacting coupled tank system with and without different control action

4.2 Interacting Tank system

Simulation of Interacting coupled tanks system which shows the step response.

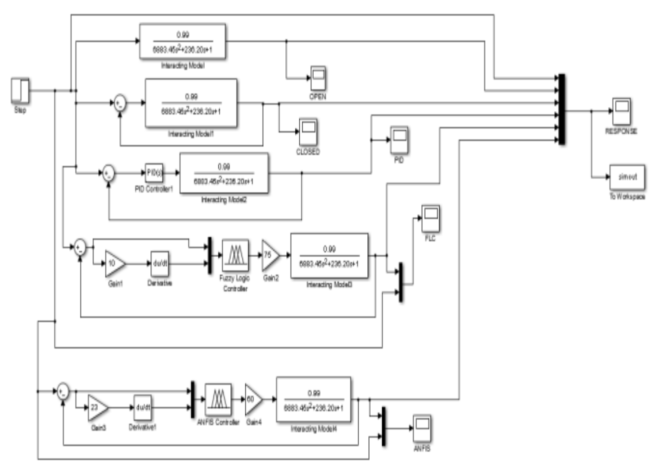


Fig.13. Simulink model of interacting coupled tank system with and without different control action

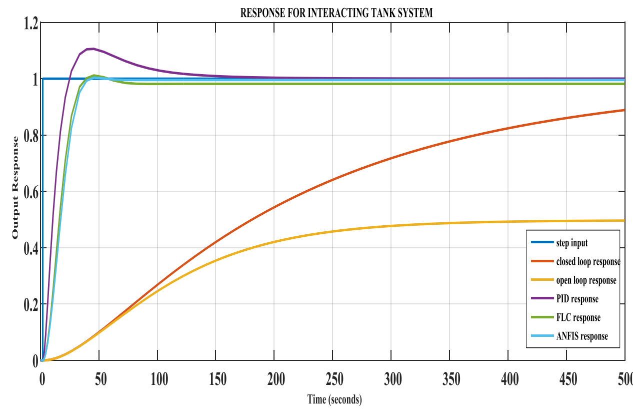


Fig.14. Step response of interacting coupled tank system with and without different control action

4.3 Non-Interacting & Interacting Coupled Tank System

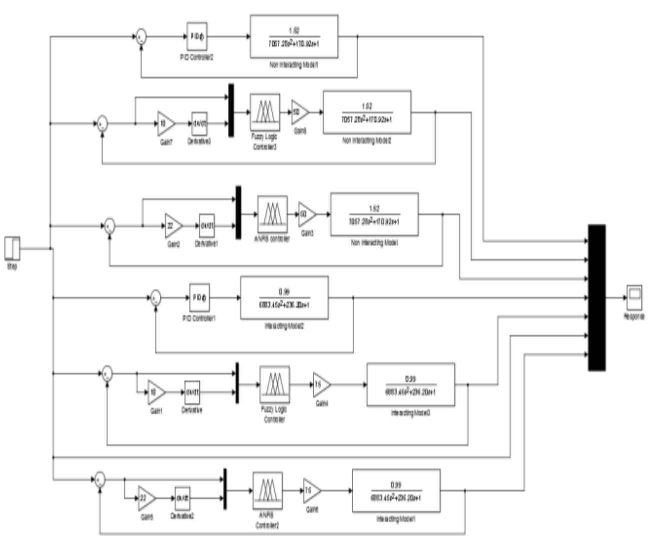


Fig.15. Simulink model of non-interacting and interacting coupled tanksystem with and without different control action

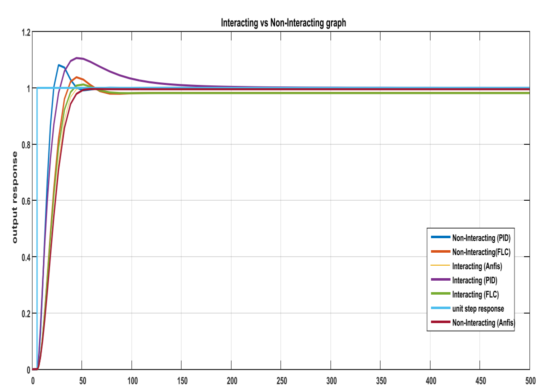


Fig.16. Step response of non-interacting and interacting coupled tank system with and without different control action

4.4 Comparison

Operation	Controller Action	Control Parameters					
		Rise time t_r(in sec)	Peak time t_p (in sec)	Delay time t_d (in sec)	Settling time t_s in 2% TB (in sec)	Peak overshoot M_p (in %)	Tracking capability
Non-Interacting	PID	22	44	13.5	53	0.087	Poor
	FLC	35	46	18.8	76	0.041	Fair
	ANFIS	33.6	56	20.4	46.8	0.002	Better
Interacting	PID	24.4	29.04	12.4	115	0.2	Poor
	FLC	38	46.8	17	80	0.02	Fair
	ANFIS	35.3	52.8	19.5	75	0	Better

Table 11. Obtained control parameters for different controlling actions

V. CONCLUSIONS

In this paper, three types of control action have been proposed PID, FLC and ANFIS type of control.

ANFIS are able to eliminate the overshoot parameters and settled the response quickly. PID controller is better option if the system requires faster response but at the same time overshoot parameter is not important. Tracking capabilities are evaluated on the basis of error i.e. integral square error (ISE) and it is concluded that ANFIS control action have better tracking capabilities for both the cases considered either in non-interacting and interacting coupled tank system.

Lastly, it is found that non-interacting coupled tank system response behavior is faster than the interacting type coupled tank system.

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