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European Journal of Advances in Engineering and Technology, 2017, 4 (7): 532-540

Research Article ISSN: 2394 - 658X

Design of Adaptive Neuro-Fuzzy Controller for Flow Systems

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ABSTRACT

This paper presents three methods for controlling the flow of liquids. This is highly important in industrial applications such as boilers in nuclear power plants. The paper investigates the effectiveness of water flow rate using Proportional-Integral-Derivative (PID), Fuzzy Logic (FL) and Adaptive Neuro-Fuzzy (ANFS) controllers. These three controllers are implemented in MATLAB/SIMULINK to test the behaviour of the system. The responses of the three controllers are compared with each other. The results show that the ANFIS is the best controller than the other two controllers, with small overshoot, minimal rise time and zero steady state error.

Keywords: Flow Control, Fuzzy Logic Controller, PID Controller, Adaptive Neuro-Fuzzy Controller

INTRODUCTION

Proportional-Integral-Derivative (PID) is the most widely used controller in the industries for the past two decades due to its simplicity and efficiency [1]. The importance of PID controllers in process industry cannot be over emphasized because more than half of the industrial controllers in use today utilize PID or modified PID control schemes. PID controller has a simple control structure that is easily understood by the operators and easy to be tuned satisfactorily. Tuning of PID is therefore an important aspect of its implementation [2].

The conventional methods for tuning a PID controller have certain limitations. These limitations can be taken care by tuning the PID controller using intelligent techniques such as fuzzy logic, neural network and neuro- fuzzy [3]. Unlike the conventional PID controller the fuzzy logic controller has benefits on the system response, a unique fuzzy logic controller using a small number of rules and straightforward implementation has been used to solve a class of level control problems with unknown dynamics or variable time delays commonly found in industry which cannot we reduced easily with the help of PID controller. Fuzzy logic controller is easy to implement than PID controller. Additionally, the fuzzy logic controller can be easily programmed into many currently available industrial process controllers. The fuzzy logic controller on a level control problem with promising results can be applied to an entirely different industrial level controlling apparatus [4]. Fuzzy systems are indicating good promise in consumer products, industrial and commercial systems, and decision support systems. The term fuzzy refers to the ability of dealing with imprecise of vague inputs. Instead of using complex mathematical equations, fuzzy logic uses linguistic descriptions to define the relationship between the input information and the output action. In engineering systems, fuzzy logic provides a convenient and user friendly front end to develop control programs, helping designers to concentrate on the functional objectives, not on the mathematics [5]. The characteristics of the fuzzy controller that were observed during its performance validation stage were quite satisfactory. In fact, based on the results of the performance validation, it was concluded that the fuzzy controller developed was suitable for application to the control of the liquid level [6]. Fuzzy logic control has been successfully utilized in various industrial applications; it is generally used in complex control systems, such as chemical process control. Today, most of the fuzzy logic controls are still implemented on expensive high- performance processors [7].

A neuro-adaptive learning technique facilitated the learning of information about the data set by the fuzzy modelling procedure, in order to compute the membership function parameters that best allowed the associated FIS to track the given input/output data, rather than choosing the parameters associated with a given membership function arbitrarily [8]. ANFIS technique involves more computation, but provides 100% accuracy of detection and classification [9].

The Neuro- Fuzzy determines the number of rules automatically, reduces computational time, learns faster and produces lower errors than other methods [10]. The advantage of using ANFIS is that it trains the data and computes the membership functions parameters that best allows the associated fuzzy inference system to track the given input/output data [11].

MATHEMATICAL MODEL OF COUPLED TANK SYSTEM

The coupled tank system consists of two vertical tanks interconnected by a flow channel as shown in Fig. 1 [12], which causes the levels of the two tanks to interact. Each tank has an independent pump for inflow of liquid. The sectional area of the outlets present and the base of each tank and the channel connecting the two tanks can be varied with rotary valves. The amount of water which returns to the reservoir is approximately proportional to the head of water in the tank since the return tube is made of flexible tubing which aids in varying the hydraulic resistance.

However, if any disturbance occurs which results in the change in either the inflow rate or the outflow rate or changes that maybe necessary for process then the liquid level in the tank would change and settle at different steady –state level. If the outflow rate is greater than the inflow rate, the liquid level will settle at the lower level than before. Assuming that a steady state condition had already been achieved before the tank is empty. Similarly, if the inflow rate is higher than the liquid level will settle at a higher level, assuming that the steady state condition achieved before the tank is overflow. The control objective is that the input flow rate has to be adjusted in order to maintain the level at the previous condition. In the case where the out flow rate is greater than the inflow rate, the inflow rate has to be adjusted so that the liquid level in the tank increased and settled [12].

Table -1 Parameters of the Coupled Tank System

Name	Expression	Value		
Cross sectional area of the coupled tank reservoir	A_1 and A_2	1 m^2		
Proportionality α constant that depend on discharge coefficient orifice cross sectional area and gravitational constant	αI subscript I denotes which tank it refers	α_1	α_2	α_3
		14.30 cm	14.30 cm	20.00 cm
Elevation of coupled tank	H_1	60 cm		
	H_2	50 cm		

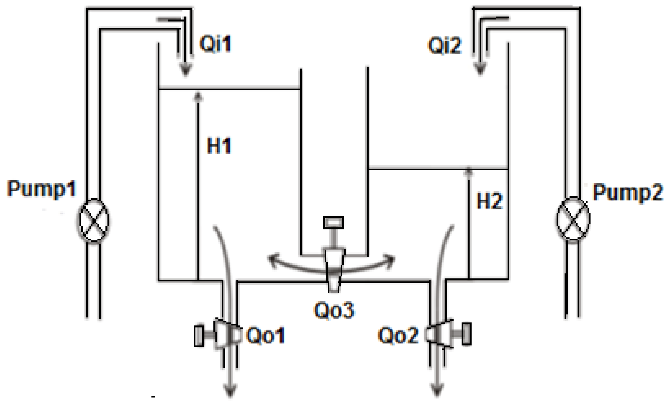

Fig. 1 Two interacting tanks

It is vital to understand the mathematical of how the coupled tank system behaves. System modelling involve devolving mathematical model by applying the fundamental physical laws of science and engineering in this system nonlinear dynamic model with time varying parameters are observed and steps are taken to drive each of the cross ponding linearized perturbation from the nonlinear model. A simple nonlinear mathematical model is derived with a help of Fig. 1. Let H_1 and H_2 be the liquid level in each tank measured with respect to the corresponding outlet considering a simple mass balance the rate of change of liquid into the tank. Thus for each of tank 1 and tank 2 the dynamic equation is developed as follows:

$$A_1\frac{dH_1}{dt} = Q_{i1} - Q_{01} - Q_{03} \tag{1}$$

$$A_2\frac{dH_2}{dt} = Q_{i2} - Q_{02} - Q_{03} \tag{2}$$

Here: H_1, H_2: are heights of liquid in tank 1 and tank 2, respectively, A_1, A_2: are cross-sectional areas of tank 1 and tank 2, Q_{03}: is the flow rate between tanks, Q_{i1}, Q_{i2}: are pump flow rate into tank 1 and tank 2, respectively and Q_{01}, Q_{02}: are the flow rate of liquid out of tank 1 and tank 2, respectively.

Each outlet drain can be modelled as a simple orifice Bernoulli's equation for steady a non-viscous incompressible fluid shows that the outlet flow in $tank_2$ is proportional to the square root of the head of the water in the tank similarly the flow between the two tanks is proportional to the square root of the head differentia:

$$Q_{01} = \alpha_1\sqrt{H_1} \tag{3}$$

$$Q_{02} = \alpha_2\sqrt{H_2} \tag{4}$$

$$Q_{03} = \alpha_3\sqrt{H_1 - H_2} \tag{5}$$

Here: α_1, α_2 and α_3 are proportionality constants which depend on the coefficients of discharge the cross sectional area of each area and gravitational constant. By using Equations from (3) to (5) in (1) and (2) the nonlinear equations that describe the dynamics of the multi-input and multi output system are derived as:

$$A_1\frac{dH1}{dt} = Q_{i1} - \alpha_1\sqrt{H_1} - \alpha_3\sqrt{H_1 - H_2} \tag{6}$$

$$A_2\frac{dH_2}{dt} = Q_{i2} - \alpha_2\sqrt{H_2} - \alpha_3\sqrt{H_1 - H_2} \tag{7}$$

Suppose that for set inflows $Q_{i1}$and Q_{i2} the liquid level in the tanks is at some steady state levels $H_1$and H_2 consider small variations in each inflow, q_1 in Q_{i1} and q_2 in Q_{i2}. Let the resulting perturbation in level be h_1 and h_2 respectively. From Equations (6) and (7) the following equations can be derived for tank1 and tank2 respectively.

$$A_1\frac{d(H_1+h)}{dt} = (Q_{i1+}q_1) - \alpha_1\sqrt{H_1 + h_1}\alpha_3\sqrt{H_1 - H_2 + h_1 - h_2} \tag{8}$$

$$A_2\frac{d(H_2+h)}{dt} = (Q_{i2+}q_2) - \alpha_2\sqrt{H_2 + h_2} - \alpha_3\sqrt{H_1 - H_2 + h_1 - h_2} \tag{9}$$

In (8) and (9) note that the coefficients of the perturbations in the level are function of steady state operating points H_1 and H_2. the two equations can also be written in the form (10) and (11) where q_{01} and q_{02} represent perturbation in the outflow at the drain pipes this would be appropriate in the case where outflow is controlled by attaching external clamp for instance based on the developed linearized model. Subtracting Equations (6) and (7) from Equations (8) and (9) the equations obtained are:

$$A_1\frac{dH_1}{dt} = q_1 - \alpha_1(\sqrt{H_1 + h_1} - \sqrt{h_1}) - \alpha_3(\sqrt{H_1 - H_2 + h_1 - h_2} - \sqrt{h_1 - h_2}) \tag{10}$$

$$A_2\frac{dH_2}{dt} = q_2 - \alpha_2(\sqrt{H_2 + h_2} - \sqrt{h_2}) - \alpha_3(\sqrt{H_1 - H_2 + h_1 - h_2} - \sqrt{h_1 - h_2}) \tag{11}$$

for small perturbations

$$\sqrt{H_1 + h_1} = \sqrt{H_1(1 + \frac{H_1}{2H_1})} \tag{12}$$

therefore, consequently

$$\sqrt{H_1 + h_1} - \sqrt{H_1} = \frac{h_1}{2\sqrt{H_1}} \tag{13}$$

similarly

$$\sqrt{H_2 + h_2} - \sqrt{H_2} = \frac{h_2}{2\sqrt{H_2}} \tag{14}$$

$$\sqrt{H_1 - H_2 + h_1 - h_2} - \sqrt{H_2 - H_1} = \frac{h_2 - h_1}{2\sqrt{H_2 - H_1}} \tag{15}$$

The configuration is achieved by having the baffle raised at as small height this a allows flow of water from $tank_1$ to $tank_2$ and with this second order configuration h_2 will be the process variable that is to be set whist q_1 is the manipulated variable that is to be controlled. The other variable like q_2 will be assumed zero as the model is derived under the circumstances of no disturbance abiding by this approximation (16) and (17) are established.

$$A_1\frac{dH_1}{dt} = q_1 - \alpha_1\frac{h_1}{2\sqrt{H_1}} - \alpha_3\frac{h_2 - h_1}{2\sqrt{H_2 - H_1}} \tag{16}$$

$$A_2\frac{dH_2}{dt} = q_2 - \alpha_1\frac{h_1}{2\sqrt{H_1}} - \alpha_3\frac{h_2 - h_1}{2\sqrt{H_2 - H_1}} \tag{17}$$

performing Laplace transforms on (16) and (17) and assuming that initially all variables are at their steady state values.

$$A_1Sh_1(s) = q_1(s) - (\frac{\alpha1}{2\sqrt{H_1}} + \frac{\alpha3}{2\sqrt{H_2 - H_1}})\, h_1(s) + \frac{\alpha3}{2\sqrt{H_2 - H_1}}h_2(s) \tag{18}$$

$$A_2Sh_2(s) = q_2(s) - \left(\frac{\alpha 2}{2\sqrt{H_2}} + \frac{\alpha 3}{2\sqrt{H_2 - H_1}}\right)h_2(s) + \frac{\alpha 3}{2\sqrt{H_2 - H_1}}h_1(s) \quad (19)$$

by rearranging and rewriting in abbreviated manners

$$(T_1S+1)\, h_1\ (s) = k_1q_1(s) + k_2q_2(s) \quad (20)$$

$$(T_2S+1)\, h_2\ (s) = k_2q_2(s) + k_{21}q_2(s) \quad (21)$$

Step1: Substitute all values in Table -1 into (20) and (21) can be obtained as:

$$\tau_1 = \frac{A_1}{\frac{\alpha_1}{2\sqrt{H_1}} + \frac{\alpha_3}{2\sqrt{H_1 - H_2}}} \quad (22)$$

$$\tau_2 = \frac{A_2}{\frac{\alpha_2}{2\sqrt{H_2}} + \frac{\alpha_3}{2\sqrt{H_1 - H_2}}} \quad (23)$$

$$K_1 = \frac{1}{\frac{\alpha_1}{2\sqrt{H_1}} + \frac{\alpha_3}{2\sqrt{H_1 - H2}}} \quad (24)$$

$$K_2 = \frac{1}{\frac{\alpha_2}{2\sqrt{H_2}} + \frac{\alpha_3}{2\sqrt{H_1 - H_2}}} \quad (25)$$

$$K_{12} = \frac{\frac{\alpha_3}{2\sqrt{H1 - H_2}}}{\frac{\alpha_1}{2\sqrt{H_1}} + \frac{\alpha_3}{2\sqrt{H_1 - H_2}}} \quad (26)$$

$$K_{21} = \frac{\frac{\alpha_3}{2\sqrt{H_1 - H2}}}{\frac{\alpha_2}{2\sqrt{H_2}} + \frac{\alpha_3}{2\sqrt{H_1 - H_2}}} \quad (27)$$

Step2: Substitute all values from step 1 into Equations (20) and (21), relates between the manipulated variable q_1 and presses variable h_2 the final transfer function equation can be obtained as:

$$\frac{h2(s)}{q1(s)} = \frac{k1k2}{\tau 1\tau 2s^2 + (\tau 1 + \tau 2)s + (1 - k12k21)} \quad (28)$$

By substituting the parameters in the plant model the transfer function of the plant Shown in Equation (29):
$\tau 1=3.47$, $\tau 2=3.38$, $k1=0.11$, $k_2=0.11$, $k_12=0.77$ and $k_{21}=0.77$

$$G(s) = \frac{0.0008}{s^2 + 0.85s + 0.003} \quad (29)$$

Step3: for the servo system considering the time constant T=0.2 and substituting in equation (2.2) the transfer function for the servo system shown in equation (30) [13].

$$C(s) = \frac{50}{s+50} \quad (30)$$

PID CONTROLLER DESIGN

The system shown in Fig. 2 is tuned using trial and error method for the PID controller to get value: K_p = 1.52, K_i = 0.337, K_d = 0.588.

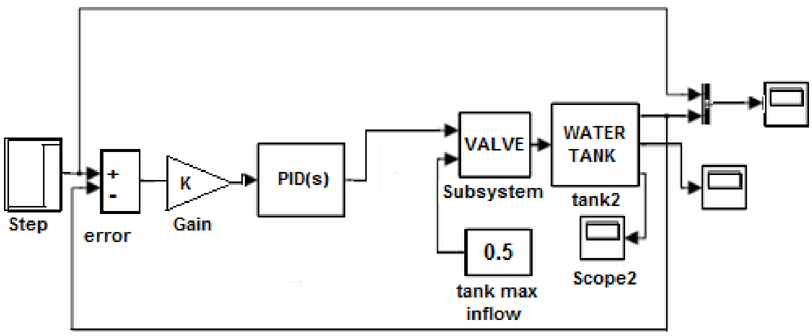

Fig. 2 Model of PID controller

FUZZY CONTROLLER DESIGN

The fuzzy controller in present work is a mamdani uses a rule base in linguistic terms There are two inputs the level and the change of liquid level and one output parameter the inlet valve control angle. The Gaussian membership functions are selected to fuzzify the inputs and the triangular is selected for output variables. There are set fuzzy sets taken (low, Ok and high) for level input and (negative, none and positive) for the rate input and five fuzzy sets for the output variable [14].

The FIS Editor

The fuzzy logic controller makes use of two inputs and one output. The first input is the level of the tank denoted as level while the second is change of the level denoted as rate. According to the rules written in the rule editor the controller takes the action and governs the opening of the valve which is the output of the controller and is denoted by valve. In order to start the FIS editor, 'fuzzy' is typed in the MATLAB command window and the enter button is pressed. The FIS editor pops up with the mamdani style of fuzzyfication set as. The FIS editor opens with only one input and one output. Therefore, in order to add a second input variable the 'add variable' option is selected from the edit option in the toolbar. The input and output blocks are selected and their names are written starting from the inputs as shown in Fig. 3.

The Membership Function Editor

The membership function editor is the tool that display and edit all of the membership function associated with all of the input and output variables for the entire fuzzy inference system. The second stage involves setting the membership functions of the two inputs and the output. Double clicking on level block found on the FIS editor opens the Membership function window. The name of the input is assigned by typing the name in the name box as seen in Fig. 4. The membership function window for the rate input parameter is gotten by double clicking on the rate block found in the FIS editor shown in Fig. 5. Function types for the output the range is set to (-1, 1) to cover the output range. The close fast membership function will have the parameters (-1, -0.9, -0.8). The close low membership function will be (-0.6, -0.5, 0.4) the no change membership function will be (-0.1, 0, 0.1), the open slow membership function will be (0.2, 0.3, 0.4) and the open fast membership function will be (0.8, 0.9, 1) which are shown in Fig. 6.

The Rule Editor

Constructing rules using the graphical rule editor interface is fairly self-evident based on the descriptions of the input and output variables defined with the FIS. Editor the rule editor allows constructing the rule statements automatically by clicking and selecting one item in each input variable box one item in each output box and one connection item. Such as if (level is ok) then (valve is no change) the rest shown in Fig. 7. The block diagram for fuzzy controller in MATLAB/SIMULINK and the rule viewer diagram are shown in Fig. 8 and Fig.9 respectively.

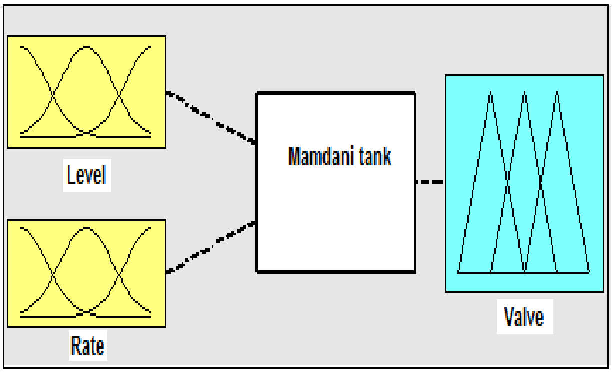

Fig. 3 Fuzzy FIS editor

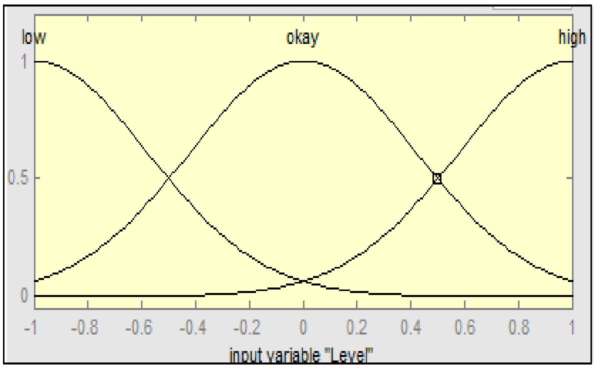

Fig. 4 Membership function editor for level

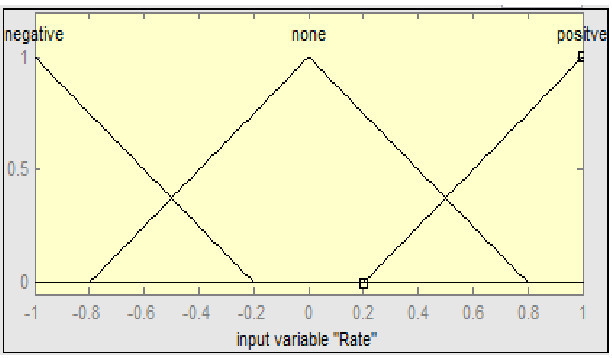

Fig. 5 Membership function editor for the rate

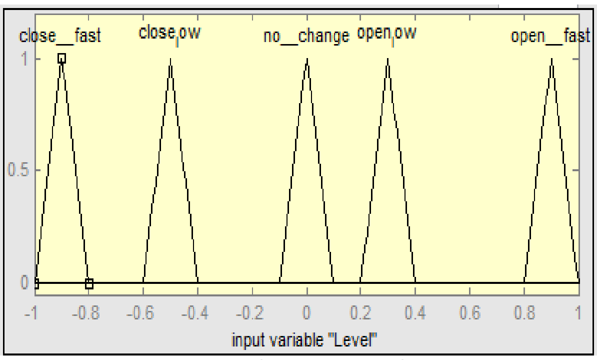

Fig. 6 Membership function editor for the valve

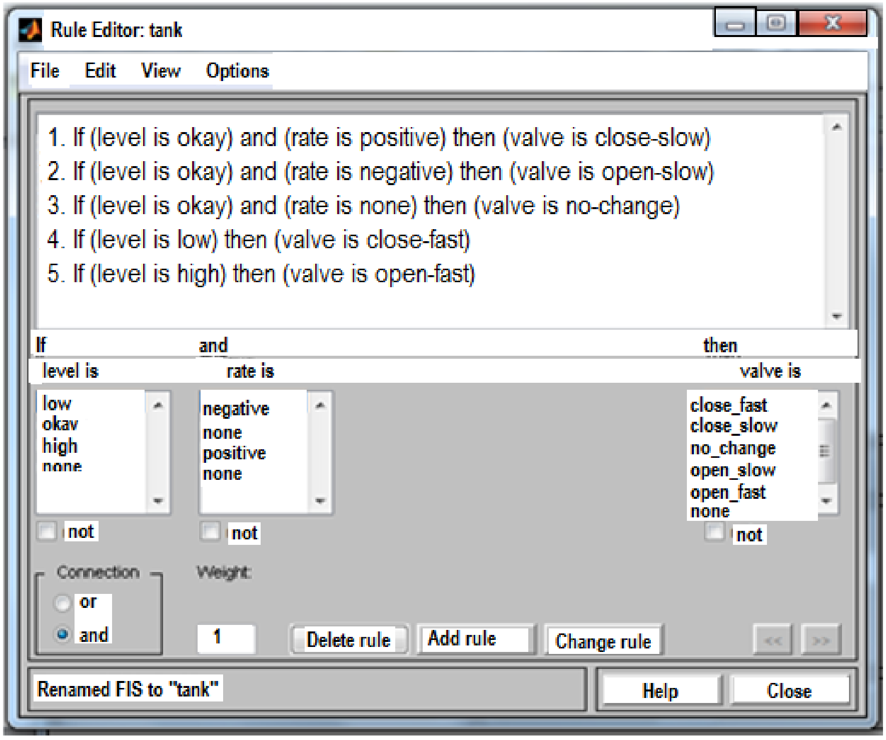

Fig. 7 The fuzzy rule for fuzzy controller

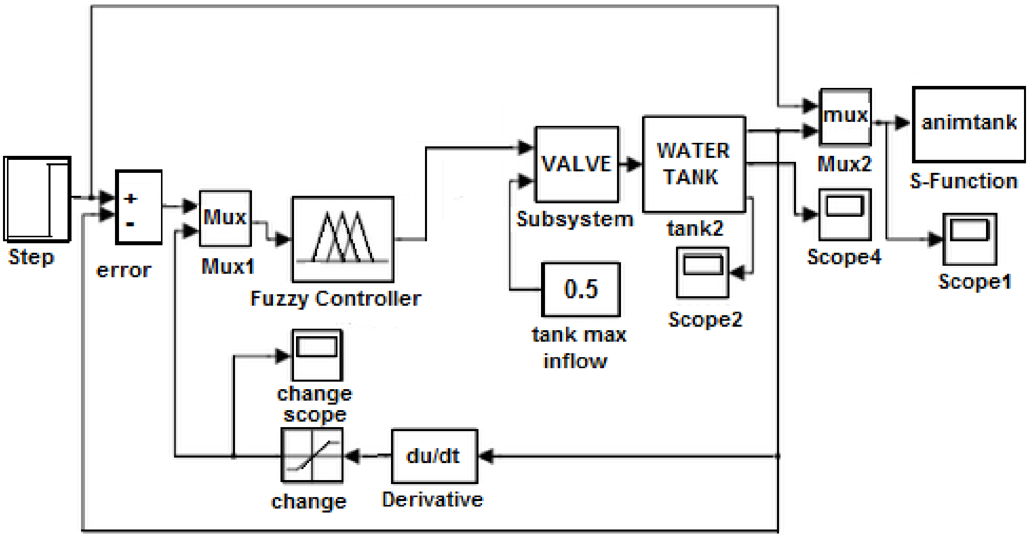

Fig. 8 Model of fuzzy controller

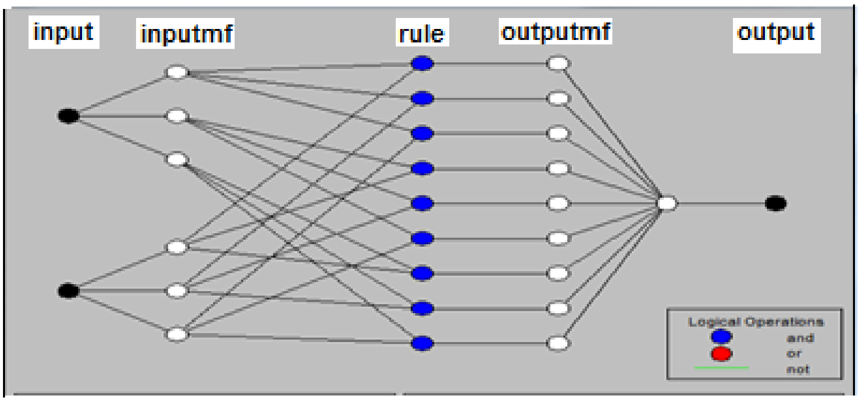

Fig. 9 ANFIS model structure

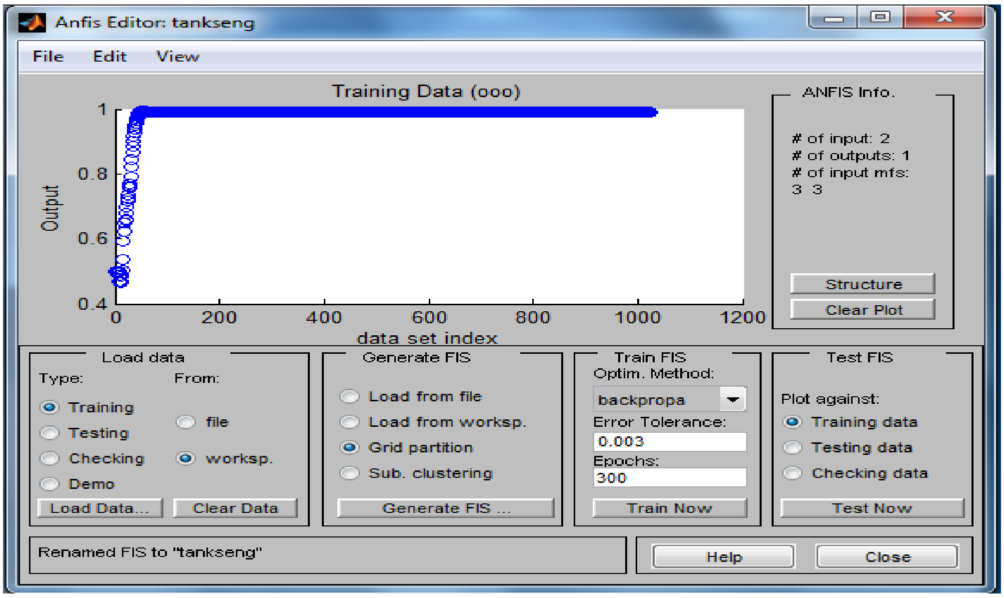

Fig. 10 ANFIS editor training the rules using back-propagation algorithm

ADAPTIVE NEURAL FUZZY INFERENCE SYSTEMS DESIGN

The Adaptive Neuro Fuzzy Inference System (ANFIS) controller is designed using MATLAB software. The error and change of error is used for rule formation in ANFIS controller. The tank system input/output data was used to train the Fuzzy Inference System (FIS). The membership function of each input (error and change of error) were tuned using back propagation and the least square estimation. For this system ANFIS structures uses the two inputs (level and the rate) and one output (the valve). The ANFIS structure for liquid flow is shown in Fig. 9. The number of epochs was 300 for training. The number of MFs for the input variables level and rate is 3 and 3 respectively. The number of rules is 9. The Gaussian MF is used for two input variables. The data is loaded from fuzzy controller result as shown in Fig. 10.

SIMULATION RESULTS AND DISCUSSIONS

Simulation Result of PID Controller

Fig. 11 shows the response of the tuned PID controller when simulated with the given parameters. The graph shows that the controller has an overshoot and takes time to settle to the desired value of 1m.

Simulation Result of Fuzzy Logic Controller

Two inputs and one output system is simulated with fuzzy logic toolbox in MATLAB. As explained in chapter three fuzzy levels are considered for each of the two inputs and five levels for the output parameter. Rule base consisting of five rules is activated to follow-up the desired liquid level. Fig. 12 shows the response of fuzzy controller. The controller settles at the desired water level very quickly (50 Second).

Simulation Result of ANFIS Controller

Two inputs and one output system are simulated with fuzzy logic toolbox in MATLAB. Fig. 13 shows the result of ANFIS controller when using step input and it is settled at desired value (1m) at time (20 Second). Fig. 14 shows the comparison of fuzzy and PID controller transient response for 1m desired level. It is clear from the graph that the PID controller has a large overshoot compared to the fuzzy controller and also takes a lot of time to settle at the desired level. Fuzzy logic on the other hand has little overshoot and steady state error and settles quickly providing accurate level control. The advantages and disadvantages of PID control and fuzzy control just offset each other. The fuzzy controller can be used for rapid control and PID controller for accurate control The comparative shown that ANFIS controller is much better than fuzzy controller as it gives less rise time and settle faster than fuzzy controller. A comparison has been made between maximums overshoot, rise time, settling time and steady state values of flow system with three different controllers as illustrated in Table -2.

Table -2 Performance of the Three Controllers

Type of Controller	Overshoot	Rise Time (Sec.)	Settling Time (Sec.)	Steady State Value
Un controlled	0%	489	800	0.211
PID	10 %	40	120	1
Fuzzy	0%	30	50	1
ANFIS	0%	18	20	1

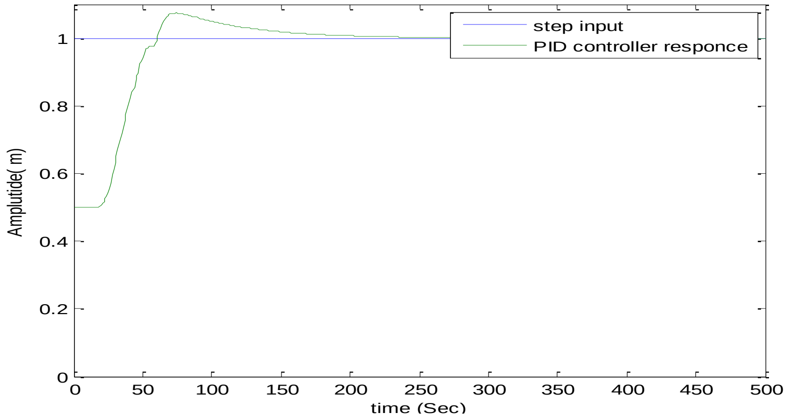

Fig. 11 PID unit step response

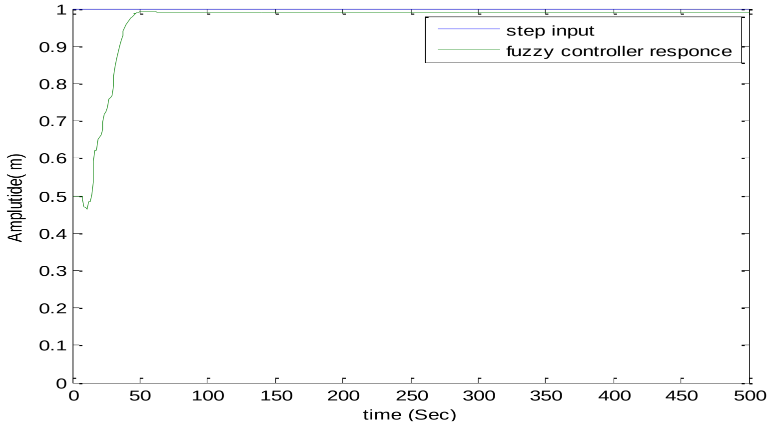

Fig. 12 Fuzzy controller unit step response

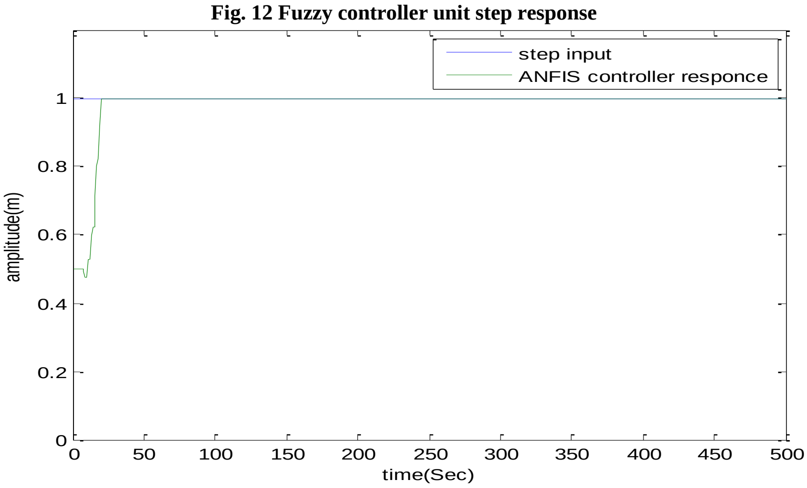

Fig. 13 ANFIS controller unit step response

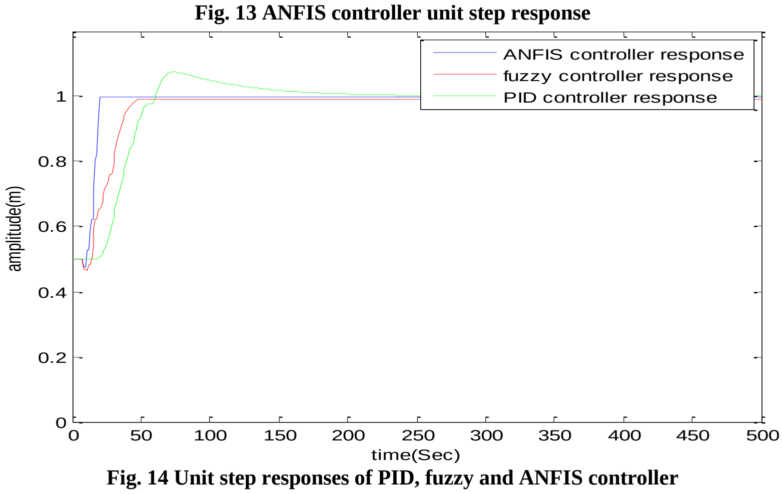

Fig. 14 Unit step responses of PID, fuzzy and ANFIS controller

CONCLUSION

In this paper, a control problem of controlling the flow of liquids has been studied. The study combines three methods the conventional PID controller, fuzzy controller and neuro-fuzzy controller. Controlled system with PID controller shows good results in terms of response time when PID parameters are well adjusted. For fuzzy controller the most important is to make a good choice of rule base and parameters of membership functions. When fuzzy controller parameters are well chosen, the system has very good time response specifications. In case of adaptive neuro–fuzzy controller, the method is simple since the system itself trains the data and adopts the membership values and determines the number of rules automatically. This reduces the computational time, learns faster and produces lower errors. Thus, by comparing the response and performance of the three controllers of the liquid flow system, it can say that the neuro fuzzy controller is better than the other two controllers. The analysis of different controller's shows ANFIS controller as better. The peak overshoot is minimized and a smooth response is obtained.

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