

Design of Fuzzy Adaptive PID Controller for Nonlinear Multivariable Process

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Abstract: - Most of the industrial processes are multivariable in nature. The multivariable system consists of many manipulated and controlled variables and thereby it is very difficult in controller design because of changes in process dynamics and interactions between process variables. A quantitative approach such as relative gain array is used in the analysis of the interactions between manipulated and controlled variables, and thus provides a best pairing to generate a control scheme. In this paper, the coupled tank control system has two inputs, which are the inlet flow rate to the tanks and two outputs, which are the liquid level height inside the tanks. PID controller has been commonly used in industrial automation. PID controllers are designed and simulated for the best loop pairings of manipulated and controlled variables. In this work, a MIMO system is converted to multivariable SISO system in the separation process for the coupled tank. In the consideration of nonlinearity, the fuzzy adaptive PID controller is introduced to obtain an excellent control performance. The PID parameters are then fed in an on-line manner from the fuzzy logic algorithm. That depends on the fuzzy inference rules, which are established between the PID parameters and the error and change in error. Simulation studies are then conducted based on the developed model using MATLAB Simulink. Based on the integral time absolute error index the best performance of the system is decided. Finally, the fuzzy adaptive PID controller is more robust than classical PID controller.

This paper is an improved version of the same article of the authors presented in the International Conference on Technical Sciences (ICST2019), March 2019, but the proceedings have not been published yet.

Keywords: - Coupled tank system, modeling, multivariable systems, interaction, ITAE, fuzzy adaptive systems

1. Introduction

The process industries such as petro-chemical industries, paper making and water treatment industries require liquids to be pumped, stored in tanks, and then pumped to another tank. The control of liquid in tanks and flow between tanks is a basic problem in the process industries. These industries are the vital industries where liquid level and flow control are essential. Many times the liquids will be processed by chemical or mixing treatment in the tanks, but always the level fluid in the tanks must be controlled, and the flow between tanks must be regulated too[1,2]. Level and flow control in tanks are the heart of all process engineering systems. The coupled-tank system consists of two small tanks coupled by an orifice and valves that allow water to enter inside the first and second tank. In process control terms, the input flow rate is known as the manipulated variable.

Control of multivariable systems requires more complex analysis than that of single variable system. Fortunately, essentially all methods and results learned for single variable systems are applicable to multivariable systems. Thus, aspects of a single variable system that make it easy or difficult to control have generally the same effects for multivariable systems. However, in multivariable systems new characteristics due to interaction must be considered. Interaction comes from process relationship that causes a manipulated variable to affect more than one controlled variable. This is the major difference from single loop systems and has a profound effect on the steady state and dynamics behavior of a multivariable system. Thus, it is not possible to analyze each manipulated – controlled variable connection individually to determine its performance; the integrated control system must be considered simultaneously[3].

In MIMO system, process interaction is an important factor influencing the behavior of the

multivariable systems. A quantitative measure of interaction is needed to proceed with multi-loop analysis method, and the relative gain array, which has proved useful in control system analysis, is introduced to meet this need[3]. The relative gain array is a matrix composed of elements defined as ratios of open-loop to closed-loop gains. In liquid level process, the manipulated variables are inlet flow rates, and the controlled variables are the level height in the two tanks. Other important variable, such as outlet flow rates are controlled tightly. In this process, to find the best pair of manipulated and controlled variables. Relative gain array technique has to be employed, after some computation works RGA will give a result in which best pair of the manipulated and controlled variables are found.

In process control, it is common practice to use PID controller for steady state regulation. PID controller is widely used in industrial applications of liquid level control, and allows for the functionality of liquid level control systems with good performance specifications. In this paper, the PID controller design based on Zeigler – Nichols method will be used to test the multivariable system performance.

Process is exposed to unexpected conditions and the controller fail to maintain the process variable in satisfied conditions and retune the controller is necessary. Furthermore, when parameters of the plants or environments change, the classical control techniques cannot adaptively compensate these changes and always lead to instability. Fuzzy logic-based controller is an intelligent control method based on the fuzzy set theory which proposed by L. A. Zadeh in 1965. The fuzzy controller imitates the humans thinking and needn't to know the accurate mathematical model of the controlled object. It shows good results when applying to control the nonlinear systems[4-7]. But the design of fuzzy rules which is the center of fuzzy control depends largely on the experience and knowledge of experts. There is no systematic method to design the number of rules and membership functions by now, and only the fuzzy logic control method may not guarantee satisfactory request. PID controller is a most widely used control method in industrial control, but it cannot regulate PID parameters under different conditions. Combining the two control methods that using fuzzy logic algorithm to regulate the PID parameters has proved to be a good solution, and

many researchers have down contributory research[8].

2. Mathematical Model of Coupled-Tank System

A coupled tank has been used in chemical engineering laboratories to illustrate the performance limitations for multivariable systems posed by ill-conditioning. The coupled tank system consists of two tanks. The schematic of the coupled tank system is presented in Fig. 1.

It is vital to understand the mathematics of how the coupled tank system behaves. System modelling involves developing a mathematical model by applying the fundamental physical laws of science and engineering to the system. Nonlinear dynamic model with time-varying parameters are observed and steps are taken to derive each of the corresponding linearized perturbation model from the nonlinear model[9].

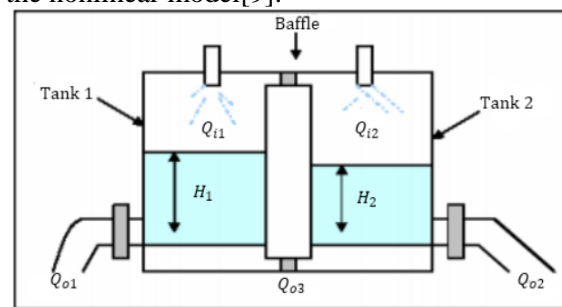


Figure 1: Schematic diagram of coupled tank system.

A simple nonlinear mathematical model is derived with a help of this diagram 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 and the rate of change of liquid into the tank. Thus for each of tank 1 and tank 2, the dynamic equations are developed as follow.

$$A_1 \frac{dH_1}{dt} = Q_{i1} - \alpha_1 \sqrt{H_1} - \alpha_3 \sqrt{H_1 - H_2} \quad (1)$$

$$A_2 \frac{dH_2}{dt} = Q_{i2} - \alpha_2 \sqrt{H_2} + \alpha_3 \sqrt{H_1 - H_2} \quad (2)$$

Where

H_1, H_2 = height of liquid in tank 1 and tank 2 respectively

A_1, A_2 = cross-sectional area of tank 1 and tank 2 respectively

Q_{o3} = flow rate of liquid between tanks.

Q_{i1}, Q_{i2} = pump flow rate into tank 1 and tank 2 respectively

Q_{o1}, Q_{o2} = flow rate of liquid out of tank 1 and tank 2 respectively.

α_1, α_2 , and α_3 are proportionality constant which depend on the coefficients of discharge, the cross-sectional area of each orifice and the gravitational constant.

For a linearized model, suppose that for set inflows Q_{i1} , and Q_{i2} , the liquid levels in the tanks are at some steady state levels H_1 and H_2 . Consider small variations in each inflow, q_1 in Q_{o1} and q_2 in Q_{o2} . Let the resulting perturbation in level be h_1 and h_2 respectively. From equations (3) and (4), the following equations can be derived:

For tank 1,

$$A_1 \frac{d(H_1 + h_1)}{dt} = (Q_{i1} + q_1) - \alpha_1 \sqrt{H_1 + h_1} - \alpha_3 \sqrt{(H_1 - H_2 - h_1 - h_2)} \quad (3)$$

For tank 2,

$$A_2 \frac{d(H_2 + h_2)}{dt} = (Q_{i2} + q_2) - \alpha_2 \sqrt{H_2 + h_2} + \alpha_3 \sqrt{(H_1 - H_2 - h_1 - h_2)} \quad (4)$$

Subtracting equations (1) and (2) from (3) and (4), the equation will become,

$$A_1 \frac{dh_1}{dt} = q_1 - \alpha_1 (\sqrt{H_1 + h_1} - \sqrt{H_1}) - \alpha_3 (\sqrt{(H_1 - H_2 - h_1 - h_2)} - \sqrt{H_1 - H_2}) \quad (5)$$

$$A_2 \frac{dh_2}{dt} = q_2 - \alpha_2 (\sqrt{H_2 + h_2} - \sqrt{H_2}) + \alpha_3 (\sqrt{(H_1 - H_2 - h_1 - h_2)} - \sqrt{H_1 - H_2}) \quad (6)$$

For a small perturbation,

$$\sqrt{H_1 + h_1} = \sqrt{H_1} \left(1 + \frac{h_1}{H_1}\right)^{0.5} \approx \sqrt{H_1} \left(1 + \frac{h_1}{2H_1}\right)^{0.5}$$

Therefore consequently,

$$\sqrt{H_1 + h_1} - \sqrt{H_1} \approx \frac{h_1}{2\sqrt{H_1}}$$

Similarly,

$$\sqrt{H_2 + h_2} - \sqrt{H_2} \approx \frac{h_2}{2\sqrt{H_2}}$$

and

$$(\sqrt{H_1 + h_2 + h_2 - h_1} - \sqrt{H_1 - H_2}) \approx \frac{h_2 - h_1}{2\sqrt{H_2 - H_1}}$$

Abiding by this approximation, equations (7) and (8) are established,

$$A_1 \frac{dh_1}{dt} = q_1 - \frac{\alpha_1}{2\sqrt{H_1}} h_1 - \frac{\alpha_3}{2\sqrt{H_1 - H_2}} (h_1 - h_2) \quad (7)$$

$$A_2 \frac{dh_2}{dt} = q_2 - \frac{\alpha_2}{2\sqrt{H_2}} h_2 + \frac{\alpha_3}{2\sqrt{H_1 - H_2}} (h_1 - h_2) \quad (8)$$

The coupled-tank system may also be described by the linearized state-space model based on previous equations (7) and (8) as shown below,

$$\begin{bmatrix} \dot{h}_1 \\ \dot{h}_2 \end{bmatrix} = \begin{bmatrix} -K_1 - K_3 & K_3 \\ K_3 & -K_2 - K_3 \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} + \begin{bmatrix} 1/A_1 & 0 \\ 0 & 1/A_2 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \end{bmatrix}$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} \quad (9)$$

Where:

$$K_1 = \frac{\alpha_1}{2A_1\sqrt{H_1}}, K_2 = \frac{\alpha_2}{2A_2\sqrt{H_2}}, K_3 = \frac{\alpha_3}{2A_2\sqrt{H_1 - H_2}}$$

The parameter values and steady state operating points of the process are assumed as per the system and they are presented in Table 1.

Table 1: Coupled –tank system parameter.

Name	Expression	Value		
Cross section area of the couple tank reservoir	$A_1 \& A_2$	32cm ²		
Pump motor (valve) time constant	$\tau_{a1} \& \tau_{a2}$	1 sec (can be adjusted)		
Proportionality constant that depends on discharge coefficient, orifice cross sectional area and gravitational constant area and gravitational constant	α_i Subscript i denotes which tank it refers	α_1	α_2	α_3
		(3.9) 14.3 $cm^{3/2}/s$	14.3 $cm^{3/2}/s$	20 $cm^{3/2}/s$
Steady state value of the level height	H_i	H_1		H_2
		6 cm		2 cm

By substituting the parameter values of coupled-tank system parameter the final values for K_1 , K_2 , and K_3 can be computed.

$$K_1 = 0.0912 \quad K_2 = 0.158 \quad K_3 = 0.156$$

The cross sectional areas of the tanks A_1 and A_2 are assumed to be equal to each other and are represented by A. Substituting these values to the state space model in equation (9) which written as:

$$\begin{bmatrix} \dot{h}_1 \\ \dot{h}_2 \end{bmatrix} = \begin{bmatrix} -0.2472 & 0.156 \\ 0.156 & -0.314 \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} + \begin{bmatrix} 1/32 & 0 \\ 0 & 1/32 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \end{bmatrix}$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} \quad (10)$$

The valve/pump for two tanks actuator can be also modeled as it is, in fact, an important control element in the plant. The following differential equation describes the valve/pump actuator's dynamics:

$$\tau_a \frac{dq_i}{dt} + q_i(t) = Q_c(t) \quad (11)$$

Where:

τ_a : is the time constant of the valve/pump actuator.
 $q_i(t)$: is the time-varying input flow rate.
 $Q_c(t)$: is the computed or the commanded flow rate.

Thus, the state-space model of the plant with actuator can be written as,

$$\begin{bmatrix} \dot{h}_1 \\ \dot{h}_2 \\ \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} = \begin{bmatrix} -0.2472 & 0.156 & \frac{1}{32} & 0 \\ 0.156 & -0.314 & 0 & \frac{1}{32} \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \\ q_1 \\ q_2 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} Q_{c1} \\ Q_{c2} \end{bmatrix}$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \\ q_1 \\ q_2 \end{bmatrix} \quad (12)$$

Note that, after the actuator's model is merged with the plants, the commanded flow rate (Q_{c1} and Q_{c2}) from the actuator are actually the input flow rate (q_1 and q_2) into the first and second tanks respectively.

The transfer function matrices can be evaluated from the state space equation (12).

$$G(s) = \frac{1}{\Delta(s)} \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix}$$

Where:

$$G_{11}(s) = \frac{1}{\Delta(s)} (0.0313s^2 + 0.0411s + 0.0098)$$

$$G_{12}(s) = \frac{1}{\Delta(s)} 0.0049(s + 1)$$

$$G_{21}(s) = \frac{1}{\Delta(s)} 0.0049(s + 1)$$

$$G_{22}(s) = \frac{1}{\Delta(s)} (0.0313s^2 + 0.039s + 0.0077)$$

$$\Delta(s) = s^4 + 2.56s^3 + 2.17s^2 + 0.66s + 0.05.$$

3. Relative Gain Array

The RGA provides a quantitative approach to the analysis of the interactions between the control signals and the outputs, and thus provides a method of pairing manipulated and controlled variables to generate a control scheme. Relative Gain Array is an analytical tool used to determine the optimal input-output variable pairings for a multi-input-multi-output (MIMO) system. In other words, the RGA is a normalized form of the gain matrix that describes the impact of each control variable on the output, relative to each control variable's impact on other variables. The process interactions of open-loop and closed-loop control systems are measured for all possible input-output variable pairings[3]. The relative gain array (RGA) of a non-singular square matrix G is a square matrix defined as[10]:

$$RGA(G) = \Lambda(G) \triangleq G \times (G^{-1})^T$$

where \times denotes element-by-element multiplication (the Hadamard or Schur product). For a 2×2 matrix with elements K_{ij} the RGA is:

$$\Lambda(G) = \begin{bmatrix} \lambda_{11} & \lambda_{12} \\ \lambda_{21} & \lambda_{22} \end{bmatrix} = \begin{bmatrix} \lambda_{11} & 1 - \lambda_{11} \\ 1 - \lambda_{11} & \lambda_{11} \end{bmatrix}$$

$$\lambda_{11} = \frac{K_{11}K_{22}}{K_{11}K_{22} - K_{12}K_{21}}$$

The steady state gain matrix can be determined as:

$$K = \lim_{s \rightarrow \infty} G(s) = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} = \begin{bmatrix} 0.1838 & 0.091 \\ 0.091 & 0.144 \end{bmatrix}$$

The relative gain array can be evaluated from steady state gain matrix:

$$\Lambda(G) = \begin{bmatrix} 1.47 & -0.47 \\ -0.47 & 1.47 \end{bmatrix}$$

From the result of relative gain array best pairs of manipulated and controlled variables are found. Thus, the best pairing was found to be u_1 - y_1 and u_2 - y_2 .

4. Fuzzy Adaptive PID Controller Design

4.1 Proportional Integral Derivative (PID) Controller.

The PID controller has several important functions: it provides feedback; it has the ability to eliminate steady state offsets through integral action; it can anticipate the future through derivative action. PID controllers are sufficient for many control problems, particularly when process dynamics are benign and performance requirements are modest. PID controllers are found in large numbers in all industries. The controllers come in many different forms. There are stand-alone systems in boxes for one or few loops, which are manufactured by the hundred thousands yearly. PID control is an important ingredient of a distributed control system. The controllers are also embedded in many special purpose control systems. In process control, more than 95% of the control loops are of PID type[11]. The performance specifications of the systems such as rise time, overshoot, settling time and error steady state can be improved by tuning value of parameters K_p , K_i and K_d of the PID controller, because each component has its own special purposes. Mathematically it is represented as

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de}{dt}$$

Structure of Fuzzy Controller

Fuzzy logic controller as shown in Fig. 2 consists of main four parts fuzzification, rule base, inference engine and defuzzification.

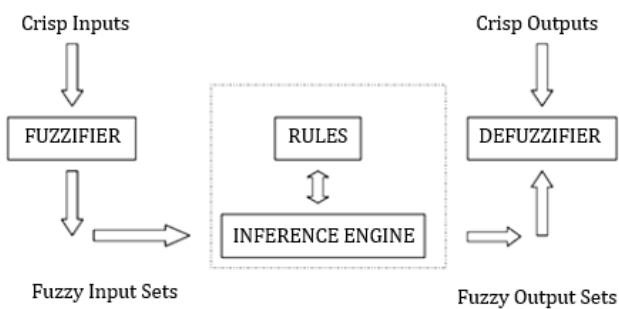


Figure 2: Fuzzy logic controller block.

4.2 Structure of Fuzzy Adaptive PID Controller

Due to its simple algorithm, good control effect and high reliability, fuzzy PID controller is widely used in the system of process control, especially in the nonlinear system. In production field, the conventional method of fuzzy PID parameter can function well on the operating condition attributing to its complex method, bad parameters and

performance on automatic tuning. As one of the most advanced control system nowadays, the method of fuzzy inference applied in this paper not only keeps the simple principle and good control effect, but also possesses a better flexibility and ability for controlling the accuracy [1]. The system structure of parameter fuzzy adaptive PID controller mainly consists of two parts as the adjustable parameter PID and fuzzy control system, and its structure as Fig.3.

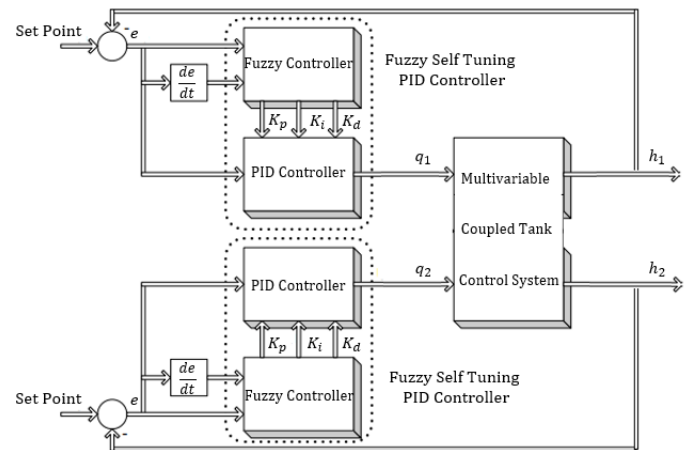


Figure 3: The block diagram of the fuzzy adaptive PID controller.

4.3 Design of Self-Tuning Fuzzy PID Controller

Regarding to the fuzzy structure, there are two inputs to fuzzy inference: error $e(t)$ and derivative of error $de(t)$, and three outputs for each PID controller parameters respectively K'_p , K'_i and K'_d . Mamdani model is applied as structure of fuzzy inference with some modification to obtain the best value for K_p , K_i and K_d . Fuzzy inference block of the controller design is shown in Fig.4. The aggregation and defuzzification method are used respectively max-min and centroid method.

Two fuzzy controllers are used to control the level height in the first and second tank. The design procedure of both fuzzy controllers are the same.

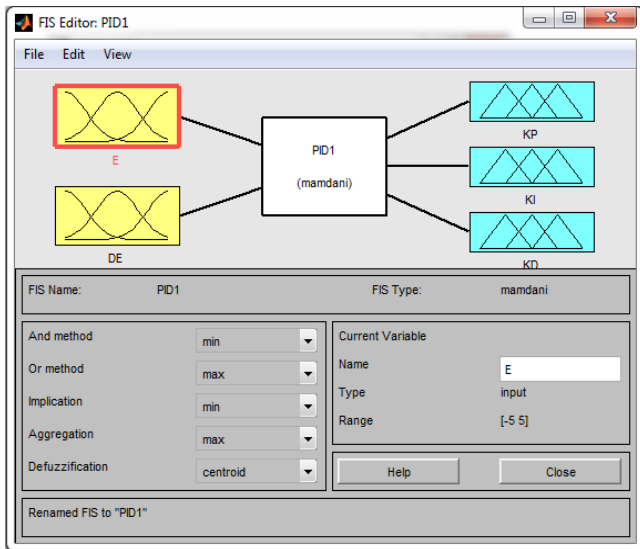


Figure 4: Fuzzy inference block for two controller.

The membership functions of these inputs fuzzy sets are shown in Fig. 5 and Fig. 6. The linguistic variable levels are assigned as NB: negative big; NS: negative small; ZE: zero; PS: positive small; PB: positive big. The ranges of these inputs are from -5 to 5, which are obtained from the absolute value of the system error and its derivative through the gains.

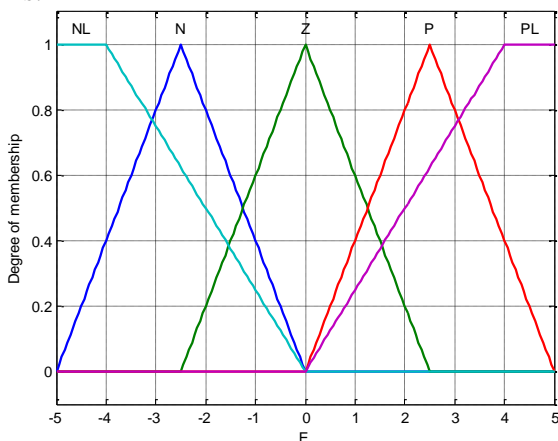


Figure 5: Membership function of e(t).

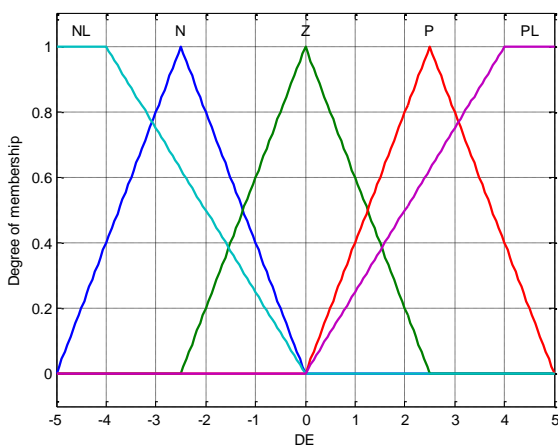


Figure 6: Membership function of de(t).

Whereas the membership functions of outputs K'_p , K'_i and K'_d , are shown in Figure 7.

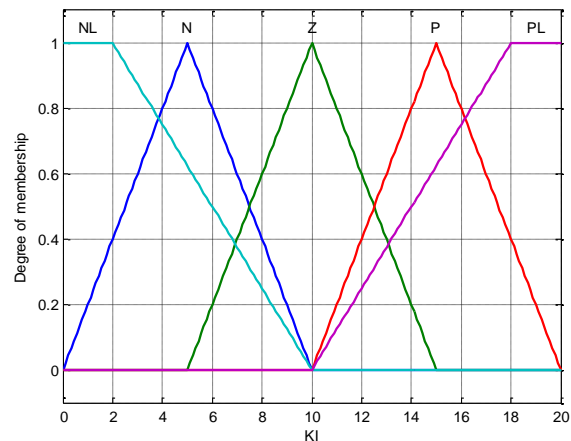


Figure 7: Membership functions of K'_p , K'_i and K'_d

The most important step is establishment of fuzzy inference rule between the input variables e, ec and the output variables K'_p , K'_i and K'_d based on the experience of experts or input-output data. In this paper, the laws of the PID parameters act on the erecting system are studied through simulations and experiments. Table 2 shows the Fuzzy rules of K_p, K_i , and K_d for controlling the level height at the two tanks. The total rules that should be given are 75 rules.

Table 2: The rule base of K_p, K_i , and K_d for two fuzzy controllers.

K_p/K_i $/K_d$	NL	N	Z	P	PL
NL	NL	NL	NL	N	Z
N	NL	NL	N	Z	P
Z	NL	N	Z	P	PL
P	N	Z	P	PL	PL
PL	Z	P	PL	PL	PL

5. Results and Discussion

This section presents the comparison of simulation results between classical PID and fuzzy adaptive PID controllers for the MIMO coupled-tank system. The performance of these controllers are evaluated. Then, compared in terms of smallest overshoot, fastest rise time and the fastest settling time. The best response will then be selected. The performance index, Integral Time Absolute Error (ITAE), is computed to demonstrate a performance comparison between the two controllers with a justification that having a lesser value of ITAE means better performance. The required

performance specifications of the MIMO system are to be:

1. Set-point or desired level height in the first tank is 10 cm.
2. Set-point or desired level height in the second tank is 8 cm.
3. No offset or steady state error should be observed for both tanks.
4. Overshoot less than 15% for both tanks.
5. Good transient response should be obtained.

To show the difference between the output response of the first tank and the second tank using the PID and fuzzy adaptive PID controller, the two responses are plotted on the same window as shown in Fig. 8 and Fig.9 respectively.

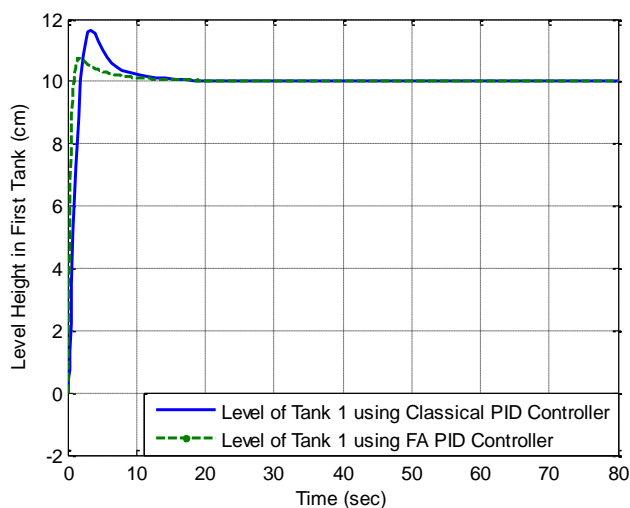


Figure 8: Output response of level height for first tank.

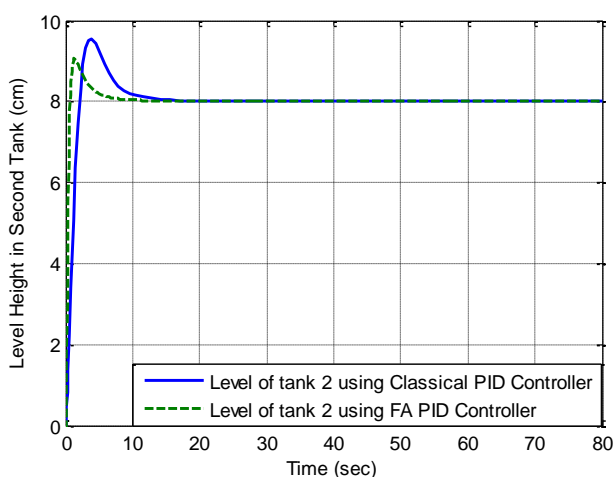


Figure 9: Output response of level height for second tank.

For the first tank, the two controller give a fast response. Even though, the response using FAPID has rise time with 2 sec. the level height response

using PID controller has high overshoot with 18% which is above the required specification while, the output response using FA PID controller has 5 % overshoot. The settling time of the output response is the same for both controllers with 9 second. But, FA PID controller more stable than classical PID controller. Also, to compare the performance of the system, the FA PID has smaller ITAE criterion than classical PID.

For the second tank, the output response using FA PID controller has a fast response than the classical PID controller where the PID controller has twice rise time to reach the desired level height. The level height response using PID controller shoots the desired level with a big value 20%. On the other hand, the response using STFC has 10% overshoot which is in the desired range. The time that required to reach the steady state value using classical PID controller is slower than FA PID controller with 10 seconds. In addition, FA PID controller has 7.612 ITAE criterion which is smaller than the classical PID controller. Finally, from the output responses it can be seen that the FA PID controller makes the system more stable.

6. Conclusion

In this paper, the mathematical model of coupled tank control system has been presented and two controller schemes were adopted to control the system as a multivariable system. A model for couple tank system is successfully designed and developed such that the level height of the two tanks can be controlled at any desired level. The interaction of MIMO coupled tank control system has been analyzed by using relative gain array and the best loop pairing was selected. The main contributions of this paper are deriving the mathematical model of the system, simulate the system with MATLAB SIMULINK and applied different control strategies to the system such as classical PID controller and FA PID controller to control the liquid level in the two tanks.

The classical PID controller design method is good for giving us as the starting point of what are the PID values. Meanwhile, this approach has successfully achieved the desired steady state error and has a fast response, but the overshoot is over the desired range due to the higher order process. Even though, the response of PID controller under the effect of disturbance has diverted the steady state value over a few time and then returned to its desired value.

The self-tuning fuzzy adaptive PID controller combines the advantage of fuzzy and PID controller

to make the PID controller parameters function of error and change of error. Any change in the error difference between the set-point and controlled level height will occur a change in the controller parameters. Thus, this approach has a fast response with low overshoot compared with PID controller. In addition, the response using this controller reached the desired level height in shortest time for both tanks. Both design techniques have a response with approximately zero steady state error. In conclusion, it can be conclude that the FA PID controller proves to be more robust and achieves an excellent control performance as compared to the classical PID.

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