Fuzzy-PID based Liquid Level Control for Coupled Tank (MIMO) Interacting System

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Abstract *– Process Liquid level control in a tank has always been an important issue in process industries. For MIMO nonlinear system the multivariable control strategy must be properly designed. Various control techniques based on particular performance index are applied for improving the dynamics of level control. PID controller is often used for the control of liquid level. Control signals of PID can be tuned by changing the PID parameters (Kp, Ki and Kd) for obtaining better oscillation, steady state response and reduced error. PID parameters are tuned using fuzzy logic controller and this gives promising results. A self-tuning fuzzy PID controller is designed based on the error approximation and by deciding the crisp values in the range. Two input and three output fuzzy controller is used instead of two input and single output. The control signal from the Self-Tuning Fuzzy-PID controller is then given to the coupled interacting tanks within the extreme points. As compared with classical PID the self-tuning fuzzy-PID controller shows better performance and can be implemented with positive approach.*

Keywords *– MIMO Theory, Coupled Tank System; Proportional-Integral-Derivative (PID) Controller; Fuzzy system; Self-tuning Fuzzy-PID Controller*

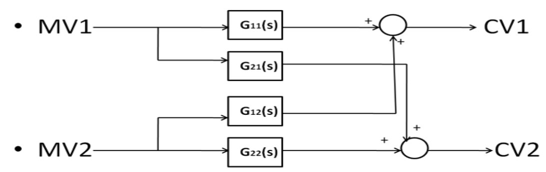
I. INTRODUCTION

Many industrial processes having problems related with turbulence and smooth inflow, level control is necessary. 25% of emergency shutdowns are caused due to improper control water level in steam generator. Such shutdowns greatly affect the plant availability and must be reduced. Water level control of coupled tank interacting system is a very difficult, because of the system nonlinearities and uncertainties. At present, constant gain PI controllers consisting problems related to peak overshoot are implemented in various small scale and large scale industries where process control is carried out. Therefor PI controller is avoided due to the overshoot and oscillatory problems. Performance improvement for process level control is therefore in great need.

Single-input single-output (SISO) systems are those in which one output is controlled by only one manipulated variable at a time. Multi-input multi-output (MIMO) systems are those in which two or more outputs are controlled by two or more manipulated variables. Because there is an interaction between other control loops of MIMO processes, therefore the method used for SISO system cannot be used for control of MIMO system. This paper focus on how the response of the PID controller can be improved by changing its coefficients using fuzzy logic controller. The very basic method behind this by giving error signal (difference between set point and actual level) and rate of change in error as the inputs to the fuzzy and the output from the fuzzy will be the PID parameters, this output signal then combines with the classical PID controller to give overall controlled signal. This controlled signal is then given to the coupled tank interacting system. The advantages of both PID and fuzzy logic controller can be achieved by this controller.

II. COUPLED TANK (MIMO) INTERACTION THEORY

While designing multi-variable control strategy the process must be parameterized using first order plus time delay transfer function.



- MV1 and MV2 are the two manipulated variables going into the tank.
- CV1 and CV2 are the two controlled variables going out of the tank.
- G11(s) represents the forward path dynamics between MV1 and CV1.
- G22(s) represents how CV2 responds to a change in MV2.
- Interaction effects are modeled using transfer function G21(s) and G12(s).
- G21(s) describes how CV2 changes with respect to a change in MV1.
- G21(s) describes how CV1 changes with respect to a change in MV2.

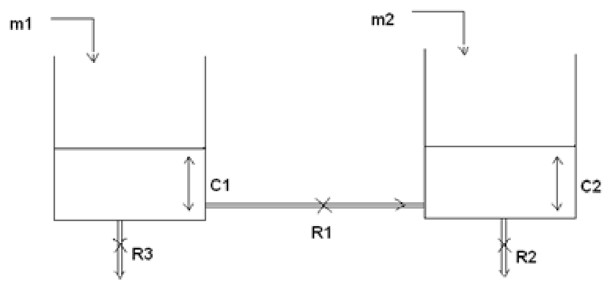


Fig 1. Coupled tank

Coupled tank system is shown in Fig.1 having constant cross –sectional area A1 and A2 for two tanks. The density of the liquid is assumed to be constant. m1 and m2 are the two inputs to the two different tanks. These two tanks are coupled to one another and act as interacting system because of the discharge valve R1 connected in between them.

B. COUPLED TANK EQUATION

Water inflows the coupled tank from the top and leaves through its outlet at the bottom. According to equation [1] shown which belongs to mass-balance equation, the first order equation for the tank can be written as

$$A\frac{dh}{dt} = q_i - q_o + q_{mn}$$

Where,

+ve sign indicates flow into the tank

q_i= rate of flow of water into the tank.

q_o= rate of flow of water out of the tank.

q_{mn} = flow rate from connected tank from tank m to n if any (not applicable for single tank)

h = liquid level in the tank.

A = Area of cross section of the tank.

In case of Multi Input Multi Output (MIMO) system the order of the tank equation changes. For two Coupled tank interacting system the tank equation based on the mass balance theory can be given as

$$A1\frac{dC1}{dt} = m1 - \frac{(C1 - C2)}{R1} - \frac{C1}{R3}$$

$$A2\frac{dC2}{dt} = \frac{(C1 - C2)}{R1} + m2 - \frac{C2}{R2}$$

Where, for PCT – 3T system

A1 = A2 = 0.0169 m2.

R1 = R2 = R3 = Discharge Coefficient (sec/m2) = 4.2 mm/LPH = 15552 sec/m2.

Substituting the parameters in above equations we get,

$$\frac{dC1}{dt} = 59.1715m1 - 0.0076095C1 + 0.0038047C2$$

$$\frac{dC2}{dt} = 59.1715m2 + 0.0038047C1 - 0.0076095C1$$

The above equations are now in state space form, and in matrix form they can be written as follow,

$$\frac{dC}{dt} = AC + BM$$

Where,

$$A = \begin{bmatrix} -0.0076095 & 0.0038047 \\ 0.0038047 & -0.0076095 \end{bmatrix}$$

$$B = \begin{bmatrix} 59.1715 & 0 \\ 0 & 59.1715 \end{bmatrix}$$

$$C = \begin{bmatrix} C1 \\ C2 \end{bmatrix}$$

$$M = \begin{bmatrix} m1 \\ m2 \end{bmatrix}$$

Now, transfer function can be found by taking the laplace transform of the above matrix equation which gives,

$$Gp = (SI - A)^{-1} * B$$

$$\begin{bmatrix} S + 0.0076095 & -0.0038047 \\ -0.0038047 & S + 0.0076095 \end{bmatrix} = (SI - A)$$

After calculating (SI-A)-1*B we can obtain the Gp11, Gp12, Gp21 and Gp22.

The transfer functions for Coupled tank interacting system are found out to be

- $G11 = \frac{S+0.0076095}{S^2+0.015219S+0.0000434287}$
- $G12 = \frac{0.0038047}{S^2+0.015219S+0.0000434287}$
- $G21 = \frac{0.0038047}{S^2+0.015219S+0.0000434287}$
- $G22 = \frac{S+0.0076095}{S^2+0.015219S+0.0000434287}$

The level is sensed by a suitable sensor generally bubbler method is used in which a bubble is inserted into the water tank and the pressure of liquid on the bubble is sensed by pressure sensor and converted to a signal (0-2.5v range) which is compatible to the controller. The controller calculates the difference between the set point and the manipulated variable and sends the required signal to the actuator. The objective of the fuzzy-PID controller is to control the level of water in both the tanks as close to the set point as possible.

IV. FUZZY-PID CONTROLLER

A. Block Diagram of PID Controller

PID controller circuit diagram can be seen in Fig. 2. There are two inputs and three outputs given to the Fuzzy controller. Inputs to the fuzzy logic controller are error between set level and actual level and the other is the rate of change in error. This controlled signal decides valve opening and valve closing (pneumatic control) or speed of the pump in case of electric control. The level in the tank is measured with the help of bubbler method as explained earlier.

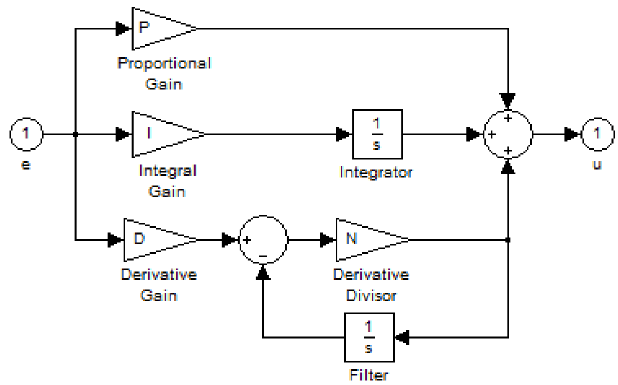


Fig 2. Block diagram of PID controller

B. Self-Tuning Fuzzy PID Controller

Three parameters of PID that is Kp, Ki and Kd when tuned using fuzzy logic controller it is termed as self-tuning fuzzy-PID controller. Tuning of PID controller parameters cannot be properly tuned manually. Therefore the PID parameters should change by its own at a particular time within particular limit. The figure below shows self-tuning fuzzy-PID controller.

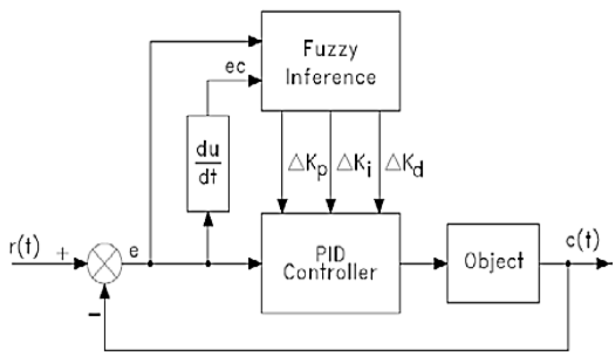


Fig 3. Self-tuning fuzzy PID controller

The main key stone in fuzzy-PID controller is PID, which implements the concept of fuzzy if-then rules and defuzzifies the output variable to automatically change the PID parameters. Error (set point – Manipulated value) and rate of change in error is calculated and fed to the controller as shown in fig. 3. These are used as the input variables to the fuzzy controller, and the output (defuzzified) variables are the parameters of PID control, those are ΔKp, ΔKi and ΔKd. Here, e denotes the error in liquid level; ec denotes rate of change in error in process.

V. FORMULATION OF SELF-TUNING FUZZY PID CONTROLLER

The fuzzy controller works basically by range of membership functions decided for the inputs and outputs. Generally the range of input to the fuzzy controller goes from extreme negative to extreme positive, while that of output is always positive. The fuzzy rules are then formed which keep updating according to the error signals. The aggregation method used here is max-min. Defuzzification method used is centroid.

In FIS block the two inputs are: error *e* and rate of change in error *ec*, and three outputs for each PID controller parameters *K'p*, *K'I* and *K'd* respectively. Two Mamdani type of fuzzy controllers should be used separately to control the manipulated are the actual level coming out from the each tank so that the controlled signal is passed to each process tanks separately.

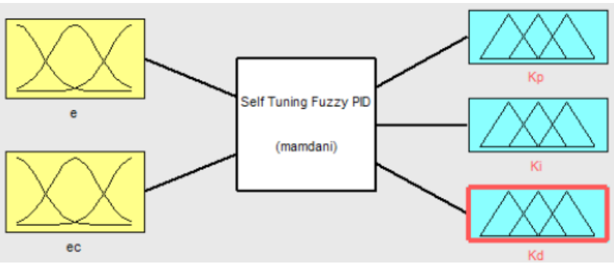


Fig 4. Fuzzy inference block

The parameters of PID controller Kp, Ki and Kd are given in the range of *Kpmin* to *Kpmax*, *Kimin* to *Kimax*, *Kdmin* to *Kdmax*. Based on the rule base, probability of error in the system and simulation results of PID the ranges of PID parameters are decided. The range of actual parameters without fuzzy involvement are, *Kp*□(3, 10), *Ki* □(1.5, 2.5) and *Kd*□(3, 4.5). Hence the output range of fuzzy control signal can be manipulated between (0-1).

The mathematical equation for PID parameters as shown below:

Kp= 7*K p*' +3, *Ki* = *Ki* ' + 1.5, and *Kd*= *Kd*' + 0.1.

The triangular membership functions of these input fuzzy sets are shown in Fig.5 and Fig.6.

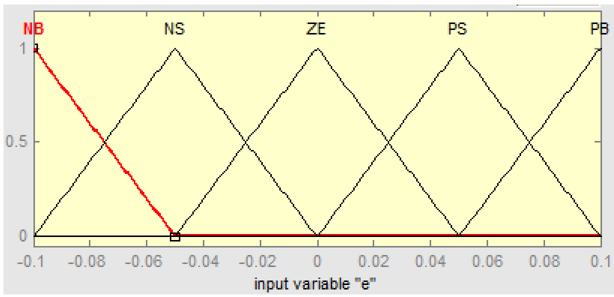


Fig 5. Membership functions of e(t)

The linguistic membership functions can be named as

NB	Negative big
NS	Negative small
ZE	Zero
PS	Positive small
PB	Positive Big

These membership functions are decided based on the extreme range of the errors.

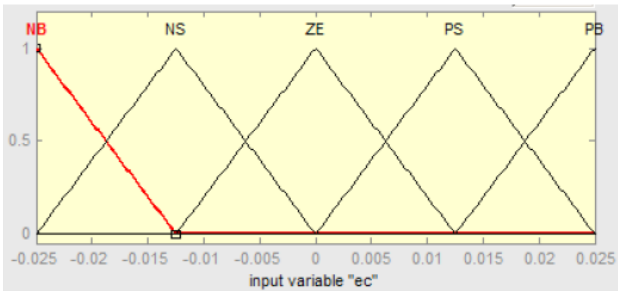


Fig 6. Membership functions for de(t)

The ranges of these fuzzy inputs are between -0.1 to 0.1 for error and -0.025 to 0.025 for rate of change in error, which are found from the absolute value of the system error and its derivative through the gains. Whereas the membership functions of outputs (*K'p*, *K'i* and *K'd)*, are shown in Fig. 7.

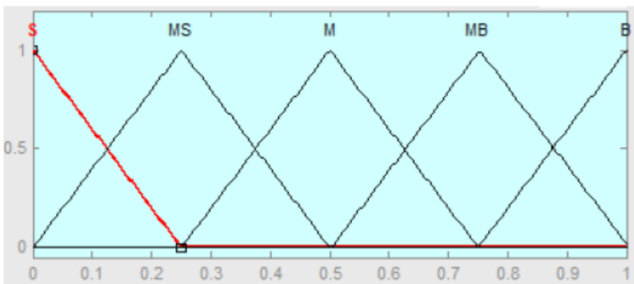


Fig 7. Triangular Membership functions of K'p, K'i and K'd

The membership functions of these output signals are named as

S	Small
MS	Medium small
M	Medium
MB	Medium Big
B	Big

The ranges of outputs go from 0 to 1 that is positive signal is given to PID. Generally, the fuzzy rules are depended on the process to be controlled and the type of the controller and from practical experiments conducted on the hardware. Regarding to the above fuzzy sets of the inputs and outputs variables, the fuzzy rules are performed according to the rule table and formulated as follows:

Rule *i*: If *e(t)* is A1*i* and *de(t)* A2*i* then *K'p*= B*i* and *K'i*= C*i* and *K'd*= D*i*.

Where *i*= 1, 2, 3... n, and n is number of rules, A1 and A2 are the membership functions for *e* and *ec* respectively. B, C and D are the membership functions for *K'p, K'I* and *K'd*. According to table 1, as we have 5 variables as input and 5 variables as output, hence we have 25 fuzzy rules.

Table 1. Rules of the fuzzy inference

De\e	NB	NS	ZE	PS	PB
NB	S	S	MS	MS	M
NS	S	MS	MS	M	MB
ZE	MS	MS	M	MB	MB
PS	MS	M	MB	MB	B
PB	M	MB	MB	B	B

VI. RESULTS AND DISCUSSION

Self-tuning fuzzy PID controller simulation is as shown in Fig. 8. It consists of Fuzzy and PID block with some modification referred to the formula which is applied to calibrate the value of K'p, K'i and K'd from fuzzy block to obtain the value of Kp, Ki and Kd. Each parameter has its own calibration because of the control signal passed by the fuzzy. While, the complete Simulink block for whole system (closed loop system) including the control design and the plant is shown in Fig. 9.

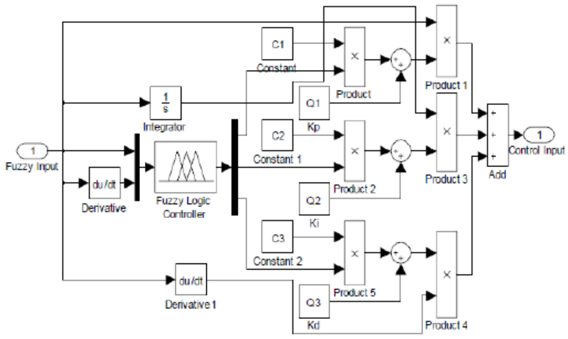


Fig 8. *Simulation of Fuzzy-PID controller for coupled tank interacting level control.*

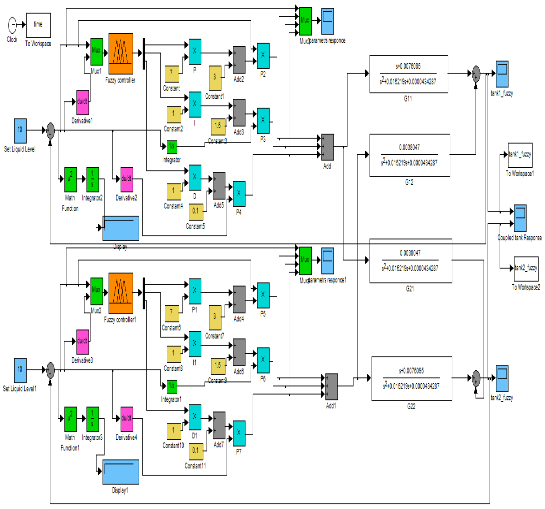


Fig 9. Matlab simulation of the Coupled tank interacting system using Fuzzy PID controller

Fuzzy logic controller sends control signals to the PID changing the *Kp*, *Ki* and *Kd* parameters. For the set point of 10cm the simulated output response for the two tanks using fuzzy-PID controller is shown in the fig. 10. It can be seen here that the response of tank based on fuzzy-PID has less settling time but that of PID has more settling time.

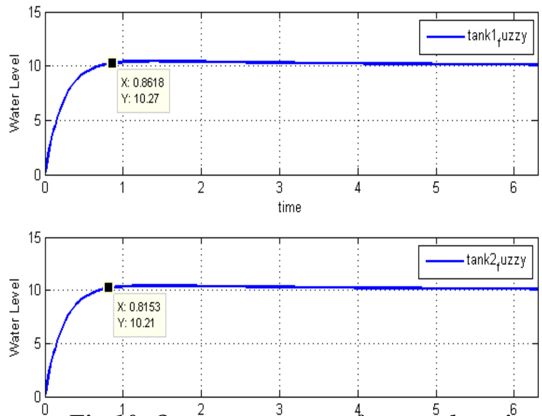


Fig 10. Output response of two tanks using Fuzzy-PID controller for set level of 10cm

The output response for the coupled tank interacting system using Fuzzy-PID controller is shown in the figure 10. It can be observed that for the two tanks the set value of 10cm liquid level is achieved with almost equal rate for the same set point.

The simulation modeling of coupled tank Interacting system for conventional PID controller is shown in Fig.11

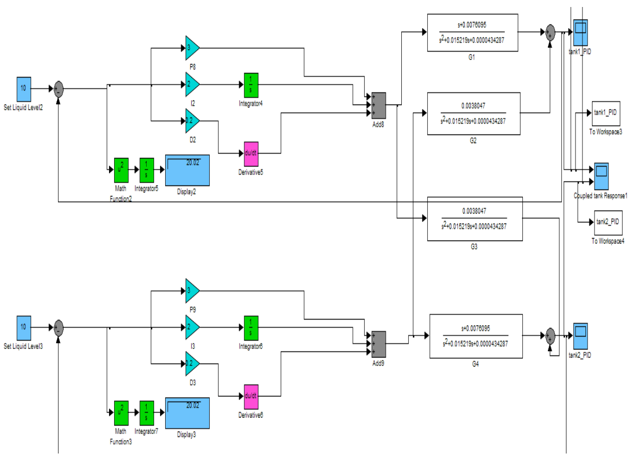


Fig 11.Simulink Model of PID controller for set Liquid level at 10 cm

The output response of the conventional PID controller for coupled tank interacting system is shown in figure 12. From the figure it can be observed that the response has some overshoot in the plot.

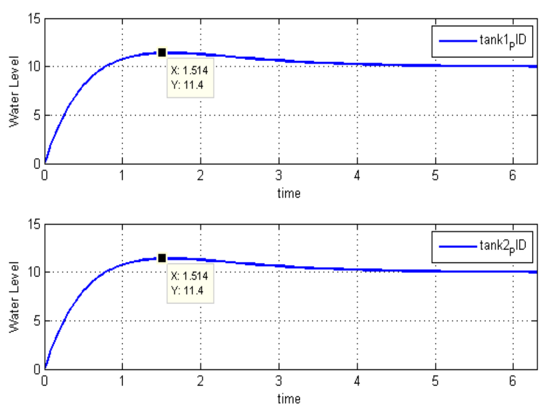


Fig 12. Simulation response of the Liquid level control using Conventional PID for set value of 10 cm

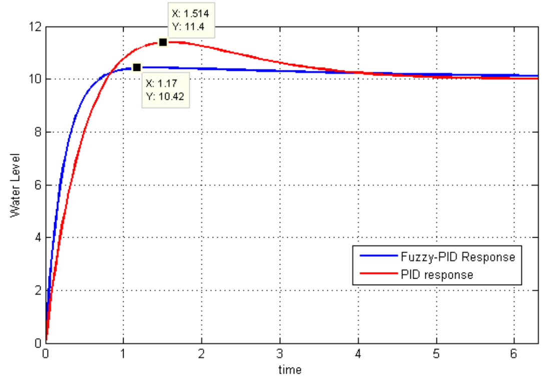


Fig 13. Simulation response of the Liquid level for set value of 10 cm

Table 2. Controllers performance comparison

Controller Type	Integral Square Error for set point of 10 cm
PID	**10.87**
Fuzzy-PID	**10.02**

Integral square error method shows the comparison between the fuzzy-PID and PID controller. Self-tuning fuzzy-PID controller is better then classical PID controller. The responses of the proposed control design look satisfied. However, the proposed control needs to be developed on actual hardware by including disturbance and any others nonlinearity and uncertainties in the design with various frequencies in reference input signals.

VII. CONCLUSION

In this paper It is designed and implemented PID control and Self-tuning fuzzy-PID controller to control (MIMO) coupled tank interacting system. Self-tuning fuzzy controller signals were applied to tune the value of *Kp*, *Ki* and *Kd* of the PID controller. The effects show that fuzzy-PID is a synthesized control method with the advantages of PID to achieve more correct resolution and fuzzy control to reduce the overshoot in the response. It has excellent dynamic and steady performance rather than PID and fuzzy controllers. The error between set point and manipulated variable is sensed by the fuzzy controller which eventually applies the required fuzzy rule and sends a positive defuzzified signal in the range mentioned to the classical PID. The

MIMO interacting system responses indicate that the water level in both the tanks can be controlled perfectly by the courtesy of the new self-tuning fuzzy-PID controller. This control strategy can be considered as the keystone for implementing it to the actual hardware.

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