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FUZZY ADAPTIVE PI CONTROLLER FOR SINGLE INPUT SINGLE OUTPUT NON-LINEAR SYSTEM

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ABSTRACT

The proposed fuzzy adaptive PI control algorithm is designed for non-linear level process to improve the control performance better than the conventional PI controller. The conventional PI controller works well only if the mathematical model of the system could be computed. Hence it is difficult to implement the conventional PI controller for variable as well as complicated systems. But fuzzy logic control does not require any precise mathematical model and works good for complex applications also. In this paper, a two input and two output fuzzy adapting PI controller is designed to control the chosen non-linear level process.

Keywords: PI controller, fuzzy adaptive.

1. INTRODUCTION

An adaptive controller is a controller with a mechanism to adjust the controller parameters according to the situation. An adaptive controller is therefore intuitively a controller that can modify its behavior subject to the changes in the plant to be controlled or in the environment. The most important situation that demands adaptive control is either the variation in the plant characteristics or in the disturbance characteristics. Fuzzy logic can be verbalized as 'computation using words rather than numbers', while fuzzy control is 'control using sentences rather than equations'. It is more natural to use sentences or rules for an operator controlled plants with the control strategy written in terms of if-then clauses. If the controller furthermore takes the corrective action without human intervention then it is adaptive. In daily conversation to adapt means to modify according to changing circumstances.

Industrial process control systems have many features such as non linear, inertial lag, time delay, time varying and so on. Because of the diversity of these facts, finding mathematical model of such systems is very difficult. Thus traditional PI algorithm doesn't hold good for such systems which has disturbances by nature. A new algorithm that can deal with these limitations has to be considered. The fuzzy controller is a non-linear controller and the fuzzy control algorithm is based on the intuition and experience about the plant to be controlled. Therefore it doesn't rely on the precise mathematical modeling. Compare to conventional PI control, fuzzy adaptive PI control has many advantages in the form of fast response, minimal overshoot and good anti-interference ability.

A two input and two output fuzzy adaptive PI controller is designed in this paper. This controller is simulated in MATLAB.

2. PARAMETER ADJUSTMENT MECHANISM

A typical structure of a PI control system, where it can be seen that in a PI controller, the error signal *e(t)* is used to generate the proportional, integral actions, with the resulting signals weighted and summed to form the PI controller is where *u(t)* is the input signal to the plant model, the error signal *e(t)* is defined as *e(t)* = *r(t)* - *y(t)*, and *r(t)* is the reference input signal. The fuzzy adaptive system in accordance with the desired response we shall here use the term training for the adaptation activity to align with the terminology used in neural network modeling. At the sampling instant *n*,

a) It reads the error and change in error, to find the PI controller parameters ΔK_P, ΔK_I.
b) To find the new PI controller tuning using the following equation:

$$u(t) = \Delta K_p e(t) + \Delta K_i \int_0^t e(t)\,dt$$

The self-tuning PI-type fuzzy controller is an auto adaptive controller that is designed by using an incremental fuzzy logic controller in place of the proportional term in the conventional PI controller to tune the parameters of PI controller on line by fuzzy control rules. The controller uses the error and change in error as its inputs and can meet desire of self tuning parameters based on time-varying e and ce.

2.1 Fuzzy adaptive PI control algorithm

The structure of fuzzy adaptive PI controller is shown in Figure-1. It consists of two parts, one is the conventional PI controller and the other is fuzzy logic controller. Controllers based on the fuzzy logic give the linguistic strategies control conversion from expert knowledge in automatic control strategies.

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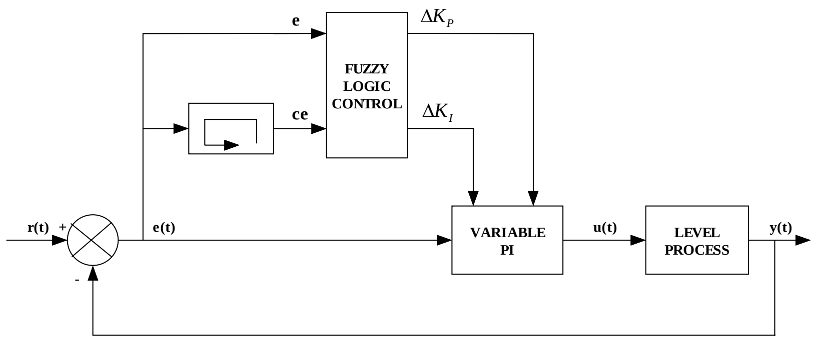

Figure-1. Structure of fuzzy adaptive PI controller.

The development of the control system based on fuzzy logic involves the following steps:

a. Fuzzification strategy
b. Data base building
c. Rule base elaboration
d. Inference machine elaboration
e. Defuzification strategy

In addition, design of fuzzy logic controller can provide desirable both small signal and large signal dynamic performance at same time, which is not possible with linear control technique. The development of the fuzzy logic approach here is limited to the design and structure of the controller. The input constraints were terminal voltage error and its variations; the output constraint was the increment of the voltage exciter.

Fuzzy controller is the hardcore of the system. Fuzzy controller makes the input accurate quantity to fuzzy quantity. It maps the input to the corresponding discourse. The knowledge base contains the experienced knowledge of the process station. Data base contains the membership function of every linguistic variable. Control rules are described by the data base. Defuzzification again transforms the fuzzy quantity into accurate quantity.

As said earlier, a two input and two output fuzzy adaptive PI is designed in this paper. The inputs are the error and the change in error rate. The outputs are the K_P and K_I values.

The objective is to find the fuzzy relations among K_P, K_I, error, and rate of change in error. With continual testing, the two output parameters are adjusted online so as to meet different requirements and achieve good stability. The variable PI controller adds the output value of the fuzzy controller and default PI values.

2.2. Membership function

The membership function used by fuzzy controller is triangular membership function and Gaussian membership function. The fuzzy subset are Negative Big, Negative Small, Zero, Positive Small, and Positive Big respectively termed as NB, NS, ZO, PS, PB.

The quantization factor and the scaling factor play an important role in the performance of the fuzzy controller. The control rules are framed to achieve the best performance of the fuzzy controller. These rules are given in the Tables 1 and 2.

Table-1. K_P Fuzzy control rule.

E \ CE	NB	NS	ZO	PS	PB
NB	PB	PS	PS	PS	ZO
NS	PB	PB	PS	ZO	ZO
ZO	PS	PS	ZO	NS	NS
PS	ZO	ZO	NS	NS	NB
PB	ZO	NS	NB	NB	NB

Table-2. K_I Fuzzy control rule.

E \ CE	NB	NS	ZO	PS	PB
NB	PS	PS	ZO	PB	PB
NS	NS	NS	NS	NS	PS
ZO	NB	NS	NS	PS	PS
PS	NS	NS	NS	PS	PS
PB	PS	ZO	ZO	PB	PB

Using this control rules kp.fis and ki.fis are created. This control rules are framed using the fuzzy logic toolbox available in MATLAB. The above said membership function with the mentioned fuzzy subsets and the control rules form the fuzzy controller. These .fis files are called in the simulink environment and the connection is established between them. The inference engine used here is the mamdani inference engine.

2.3. Rule surface viewer of the fuzzy controller

Based on the established fuzzy rules, the surface view of K_P, K_I are shown in Figures 2, and 3, respectively.

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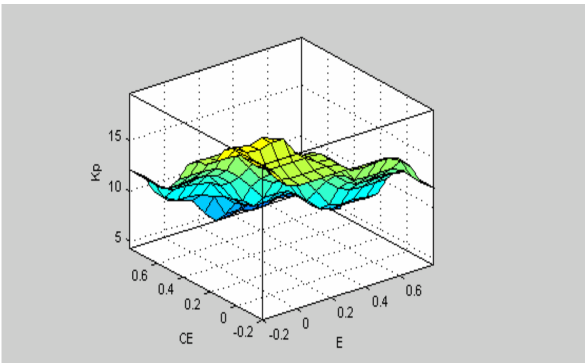

Figure-2. Surface view of K_P.

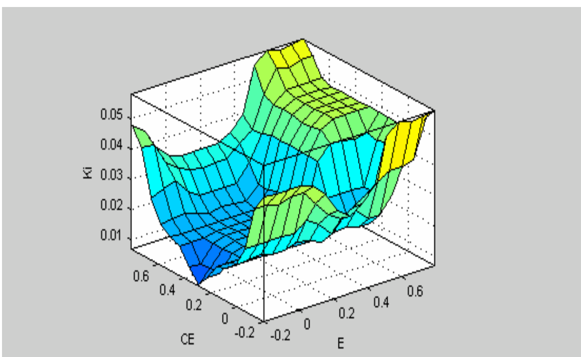

Figure-3. Surface view of K_I.

3. PROCESS

The Figure-4 shows the experimental setup which consists of a conical process tank, a pneumatic control valve, a storage tank, a pump, an I/P converter, a differential pressure level transmitter, VMAT interfacing card and I/V and V/I converter. Water from storage tank is pumped continuously to the conical tank through a pneumatic control valve. A differential pressure level transmitter (DPLT) measures the level by sensing the difference in pressure between the bottom of the conical tank and the vent. The DPLT then transmits a current signal (4-20mA) to the I/V converter. The output of the I/V converter (1-5V) is given to the VMAT interfacing hardware consisting of multifunction high speed ADC and DAC. The onboard data converters of the VMAT can be directly linked with the Simulink tool of MATLAB thus forming a complete close loop system. The signal from the PC is transmitted to I/P converter through V/I converter. The output from I/P converter is the pressured air in the range 3-15 psi for actuating the control valve, which regulates the flow of liquid into the conical tank.

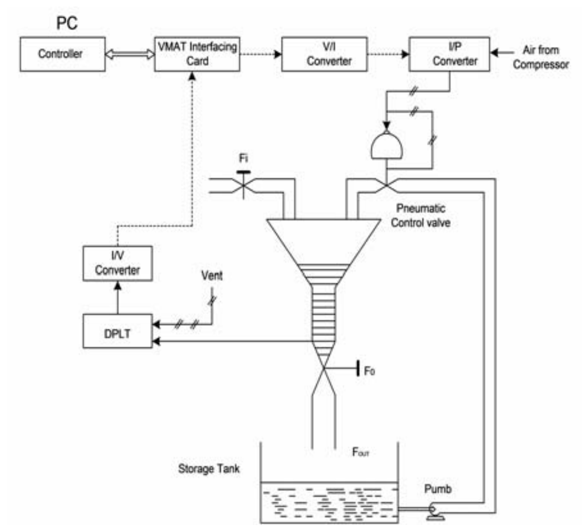

Figure-4. Functional block diagram of a conical tank level process.

3.1. Description of the conical tank level process

The tank is made up of stainless steel body and is mounted over a stand vertically. Water enters the tank from the top and leaves the bottom to the storage tank.

The System specifications of the tank are as follows:

Table-3. System specifications of conical tank.

PART NAME	DETAILS
Conical tank	Stainless steel body, height = 65cm, top diameter = 33.5cm, Bottom diameter = 3.5cm
Differential pressure level transmitter	Capacitance type, range 2.5-250m bar, output 4-20 mA
Pump	Centrifugal 0.5 HP
Control valve	Size ¼ Pneumatic actuated type: air to open, input 3-15PSI
Rota meter	Range 0-460 LPH
Pressure gauge	Range 0-30 PSI
Compressor	20 PSI

4. MATHEMATICAL MODEL OF THE CONICAL TANK LEVEL PROCESS

Here F_i is the inlet flow rate to the tank, F_0 be the outlet flow rate from the tank, F_L be the disturbance applied to the tank.

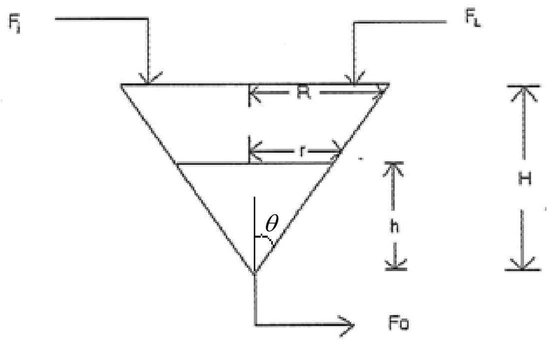

Figure-5. Diagram of conical tank.

F_i = Inlet flow rate to the tank (m^3 / min)
F_0= Outlet flow rate from the tank (m^3 / min)
F_L= Load applied to the tank (1pm)
H = Height of the conical tank (m)
h = Height of the liquid level in the tank at any time't'(m)
R= Top radius of the conical tank (m)
r = Radius of the conical vessel at a particular level of height h (m)
A= Area of the conical tank (m^2)

The nominal operating level h is given by:

$$F_{in} - F_{out} = \frac{A(h)dh}{dt} \quad (1)$$

$$tan\theta = \frac{R}{H} \quad (2)$$

At any level (h)

$$tan\theta = \frac{r}{\boldsymbol{h}} \quad (3)$$

Equating (2) and (3) $\frac{R}{H} = \frac{r}{\boldsymbol{h}}$

$$r = \frac{R\boldsymbol{h}}{H} \quad (4)$$

Cross sectional area of the tank at any level (h) is:

$$A(h) = \pi r^2 \quad (5)$$

Substitute (4) in (5)

$$A(h) = \frac{\pi R^2 \boldsymbol{h}^2}{H^2} \quad (6)$$

Also $F_{out} = b\sqrt{\boldsymbol{h}}$ (7)

Substituting (7) in (1)

$$F_{in} - b\sqrt{\boldsymbol{h}} = \frac{A(h)d\boldsymbol{h}}{dt} \quad (8)$$

$$\frac{d\boldsymbol{h}}{dt} = \frac{Fin - b\sqrt{\boldsymbol{h}}}{\frac{\pi R^2 h^2}{H^2}} \quad (9)$$

From equation (8)

$$F_{in} - \frac{U\boldsymbol{h}}{\boldsymbol{2h}} = \frac{A(h)dh}{dt} \quad (10)$$

Where

$U = b\sqrt{\boldsymbol{h}}$ =Nominal value of outflow rate

Hence the transfer function of the above system is:

$$\frac{\boldsymbol{h}(s)}{Fin(s)} = \frac{k}{\tau s + 1} \quad (11)$$

Where
h and U are nominal values of PV and MV from equation (11)

Time constant of the level process $\tau = \frac{2\boldsymbol{h}A(\boldsymbol{h})}{U}$

The gain constant of the level process $k = \frac{\boldsymbol{2h}}{U}$

In order to find the open loop response, the step input of 2.0v is applied to the ADC input in simulink tool of MATLAB platform directly with the fixed inflow rate and outflow rate. For the given step input the system attains the steady state at 15cm. After that a step increment from 2.0v to 2.25v is given and various readings are noted till the process becomes stable. The same process is repeated to take different operating regions in the conical tank system. The experimental data are approximated to be a FOPDT model, the model parameters of the transfer functions for the above mentioned are tabulated in Table-4.

Table-4. Transfer function model of the conical tank level process for various operating region.

Input ADC voltage	Level in cm	Transfer function model
2.0v to 2.25v	15 - 30	$\frac{5.415\, e^{-100s}}{3000s + 1}$
2.25v to 2.50v	30 - 38	$\frac{2.999\, e^{-350s}}{3500s + 1}$
2.5v to 2.75v	38 - 42	$\frac{1.705\, e^{-405s}}{4000s + 1}$

Table-5. Control parameters for PI controller for the three models using ZN-PI technique.

Parameters	Model 1	Model 2	Model 3
K_P	4.9861	3	21.011
K_i	0.0149	0.00257	0.0628

5. RESULTS AND COMPARISONS

For comparison purpose, both the conventional PI as well as the proposed fuzzy adaptive PI control scheme has been simulated for various set points using MATLAB and the results are displayed in the Figures 10, 13 and 16. The simulation results clearly show that the fuzzy adaptive PI controller possesses minimal overshoot and fast response as compare to the conventional PI controller.

The simulation results also display the superiority of the proposed controllers adaptive ability and robustness over the conventional PI controller.

The performance index comparison for various set points to the plant models with the designed controllers is presented.

5.1. Performance index

The Fuzzy Adaptive PI controller has not only been compared with its time domain responses but also with its performance indices through the four major error criterion techniques such as Integral of Absolute Error (IAE), Integral Square of Error (ISE), Integral Time of Absolute Error (ITAE) and Integral Time of Square Error (ITSE).

The performance indices of both the proposed scheme as well as the conventional scheme for various set points applied to the chosen level process are presented in the Tables 6, 7 and 8. From the Tables it is clearly seen that the proposed control strategy performs fairly satisfactorily then the conventional scheme.

Table-6. Comparison of the performance index for set point of 20cm.

Method	PI	FAPI
IAE	144.4	109.2
ISE	14.6	6.905
ITAE	1.083e+05	1.007e+05
ITSE	5492	2720

Table-7. Comparison of the performance index for set point of 35cm.

Method	PI	FAPI
IAE	384.2	149.6
ISE	41.72	17.75
ITAE	1.10e+06	1.216e+05
ITSE	3.169e+04	4888

Table-8. Comparison of the performance index for set point of 40cm.

Method	PI	FAPI
IAE	191.4	186.8
ISE	16.96	24.84
ITAE	3.086e+05	2.186e+05
ITSE	9144	6919

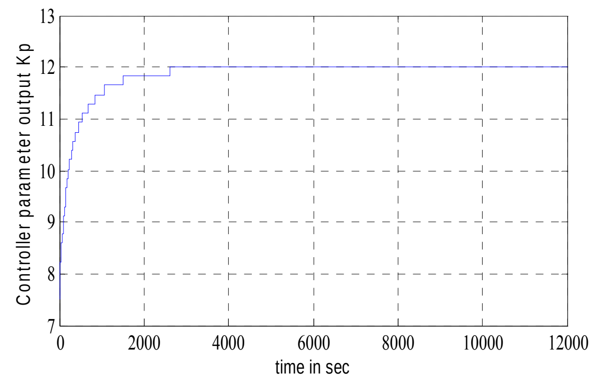

Figure-6. Controller parameter output K_P for the set point of 20cm.

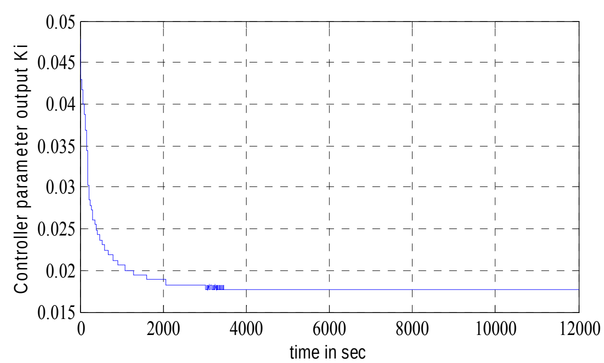

Figure-7. Controller parameter output K_i for the set point of 20cm.

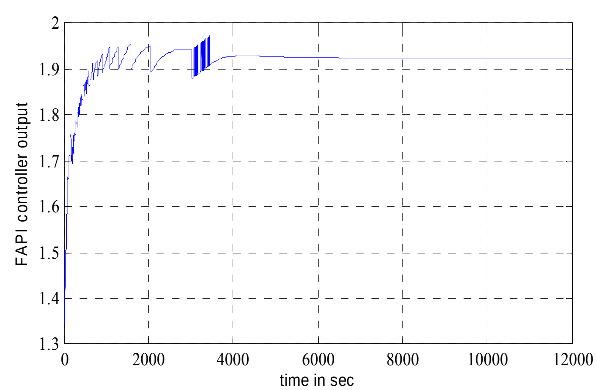

Figure-8. FAPI controller output for the set point of 20cm.

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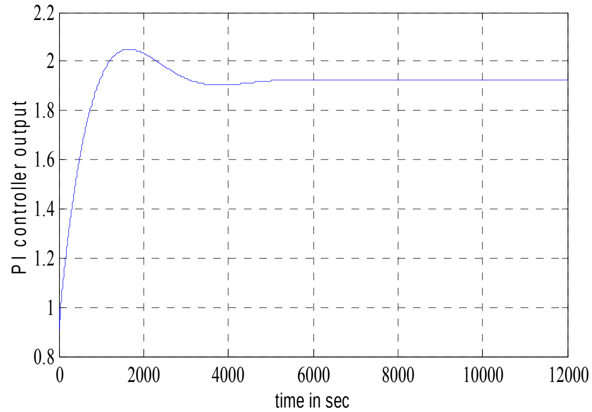

Figure-9. PI controller output for the set point of 20cm.

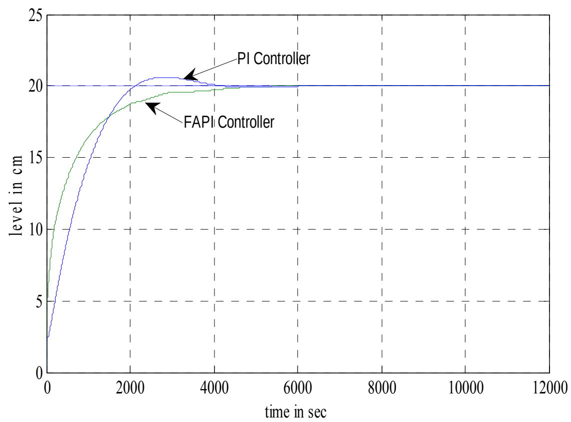

Figure-10. Comparison of FAPI and PI controller for the set point of 20cm.

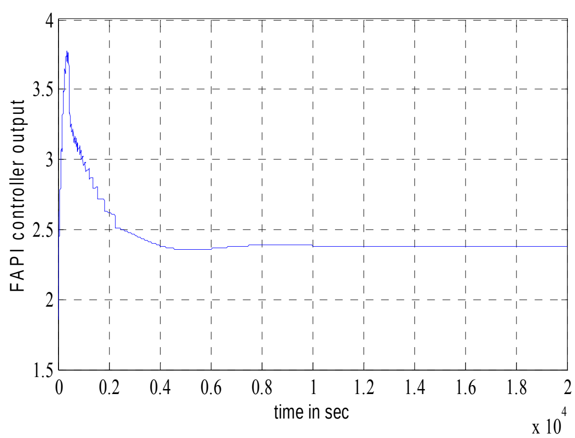

Figure-11. FAPI controller output for the set point of 35cm.

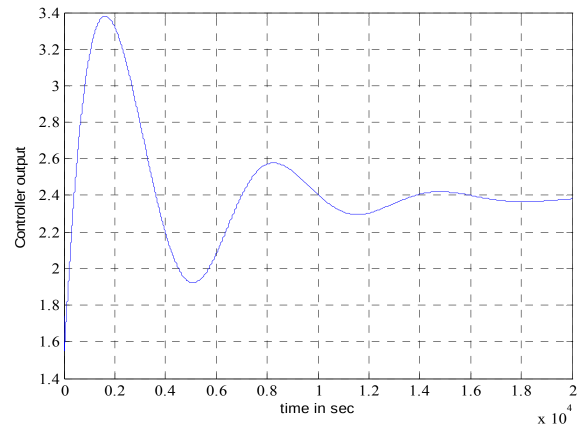

Figure-12. PI controller output for the set point of 35cm.

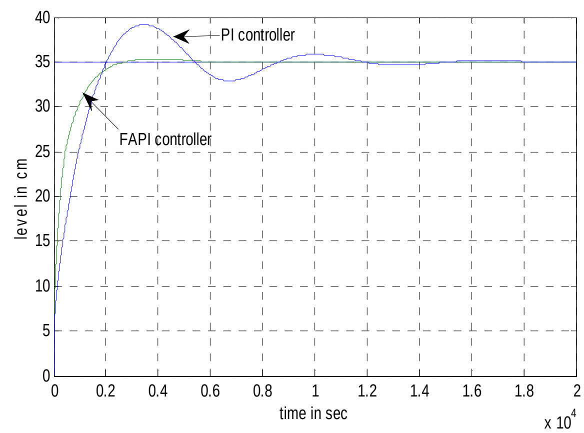

Figure-13. Comparison of FAPI and PI controller for the set point of 35cm.

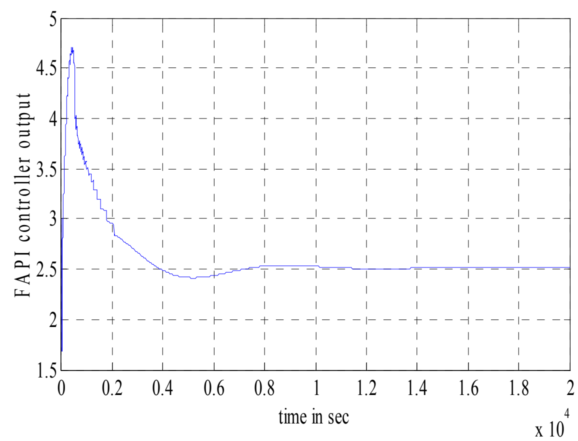

Figure-14. FAPI controller output for the set point of 40cm.

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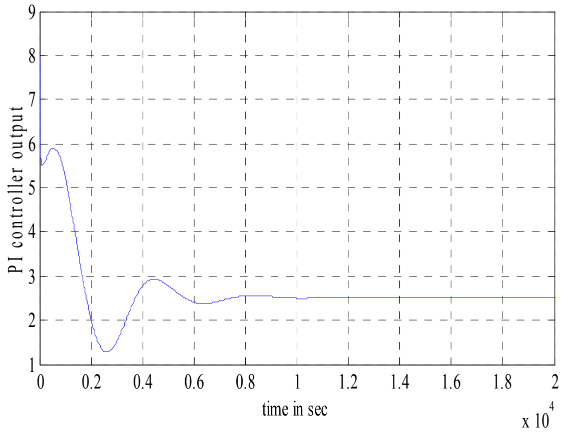

Figure-15. PI controller output for the set point of 40cm.

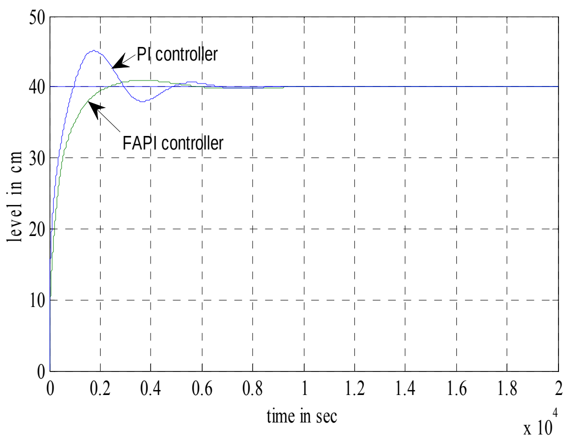

Figure-16. Comparison of FAPI and PI controller for the set point of 40cm.

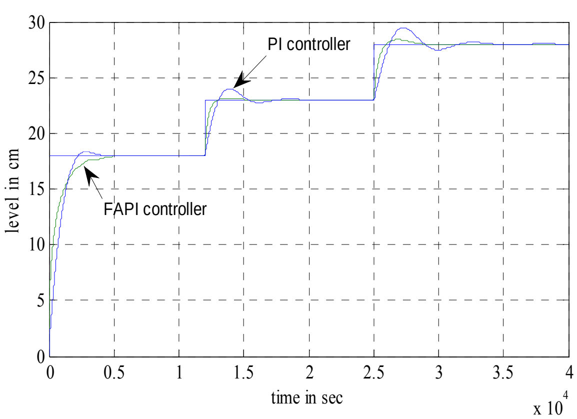

Figure-17. Servo response of FAPI and PI controller for different set point.

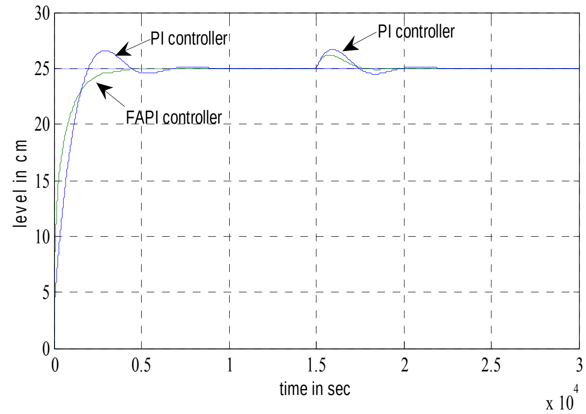

Figure-18. Regulatory response of FAPI and PI controller.

6. CONCLUSION

In this paper, a two input and two output fuzzy adaptive PI controllers for non-linear level process has been presented. The fuzzy control combined with conventional PI controller constitutes an intelligent control, which adjusts the control parameters depending upon the error.

The various results have been presented to prove the improved performance of the FAPI over the conventional PI. The simulation responses for the models validated reflect the effectiveness of the FAPI based controller in terms of performance indices. The performance indices of the proposed controller under the various error criteria exhibit its superiority over the conventional PI controller. The servo response of the system shows its stability over continuous change in set points at regular intervals. Simulation results show the effectiveness of the proposed scheme and guarantee the good robust performance of the FAPI controller against disturbances and plant variations.

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