Real Time Implementation of Fuzzy Based Adaptive PI Controller for a Spherical Tank System

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***Abstract* — This paper proposes a new fuzzy adaptive variable digital PI controller for a single input single output non-linear spherical tank level process system. The open loop transfer function models are carried out at three different operating regions and those models are formulated based on the real laboratory scale system. The proposed FAPI controller is a combination of two input two output Fuzzy logic controller and a Variable digital PI controller. The input to the fuzzy controller is error and change in error and its outputs are K_P and K_I. The PI controller's parameters are estimated on-line based on error and change in error. The real time implementation and control of the process plant is done in MATLAB using VMAT-01 Data Acquisition Module. The objective is to make the output to settle fast with minimum overshoot and the disturbances do not affect the performances of the system.**

Keywords - Fuzzy Adaptive PI (FAPI), Spherical tank, SISO, VMAT-01

I. INTRODUCTION

Most of the process control industrial systems present challenging control problems due to the dynamic behavior, uncertain and time varying parameters. Controlling the level of the spherical tank is a challenging problem due to its change of shape which gives rise to the non-linearity. The spherical tanks find wide application in gas plants and petrochemical industries. The proportional Integral and Derivative (PID) controllers are commonly used in industries because of its simplicity in tuning the parameters and achieve satisfactory performance. Thus traditional PID algorithm doesn't hold good for such systems which has disturbances by nature, so the conventional controller is not enough to control the highly non-linear process like spherical tank because the change in shape gives rise to the non-linearity. It requires some intelligent controller or adaptive controller to achieve the optimum performance when facing different operating condition and various type of disturbances.

In this work, the proposed control algorithm that can overcome these limitations. The on-line estimation of the PI controller output u(k) is based on K_P and K_I, these parameters are estimated with current error (e) and change in error (ce) using fuzzy logic algorithm. 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. The Fuzzy adaptive PI control technology has been widely used in many fields because of its simplicity, high precision and high robustness. It has many advantages in the form of fast response, minimal overshoot and good anti-interference ability.

The real time liquid level spherical tank process is interfaced with MATLAB using simple cost effective VMAT-01 module. It consist of one ADC, one DAC and two PWMs.

II. FUZZY ADAPTIVE PI CONTROL ALGORITHM

The self-tuning fuzzy adaptive PI controller is an auto adaptive controller that is designed by combining fuzzy and digital PI controller. The structure of fuzzy adaptive PI controller is shown in Fig. 1. The fuzzy controller uses the error and rate of change in error as its input and meet desire of self-tuning parameters K_P and K_I. 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 on-line so as to meet different requirements and achieve good stability. The digital PI controller tune on-line by using those fuzzy parameters and find the new controller output by the following equation.

$$u(k) = K_P\left\{e(k) + \frac{T}{T_i}\sum_{i=0}^{k} e_i\right\} \tag{1}$$

In the above equation, u (k) is the output of adjuster in the k_{th} sampling. K is the sampling number (k=0, 1, 2…; K_P), and K_P is the adjuster scale factor; e (k) is the error value in the k_{th} sampling; T_i is the integral time; T is the sampling period. $K_I=K_P\times T/T_i$, write the above equation into the incremental control

$$u(k) = u(k-1) + K_P\left[e(k) - e(k-1)\right] + K_I e(k) \tag{2}$$

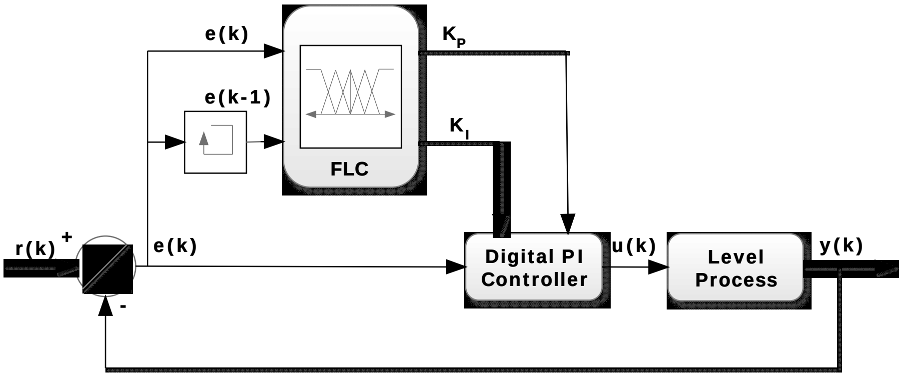

Figure 1. Structure of Fuzzy Adaptive PI controller

The proportional gain K_P improves the study state error, but higher value of K_P may produce the large overshoot and the system may be oscillating, therefore the integral gain K_I is used to eliminate the study state error.

A. Fuzzy Logic Controller

A fuzzy logic system (FLS) can be defined as the nonlinear mapping of an input data set to a scalar output data. A FLS consists of four main parts: fuzzifier, rules, inference engine, and defuzzifier.

The fuzzy logic system is characterized by a set of simplified IF-THEN rules expressed in the following form R^k : If x_1 is $F_i^{k_1}$ …… and x_n is $F_i^{k_n}$ Then y is y^k (k = 1,…..,p) Where $p=\prod_{i-1}^{n} p_i$ is the total number of rules, and y^k is the crisp output for the k_{th} rule.

The final output of the fuzzy system is calculated as follows

$$y(x)=\frac{\sum_{k-1}^{p}\mu_k(x)y^k}{\sum_{k-1}^{p}\mu_k(x)} \tag{3}$$

Where

$$\mu_k(x)=\prod_{i-1}^{n}\mu_{F_i}k_i(x_i), k_i \in \{1,2,......., p_i\} \tag{4}$$

The inference mechanism then decides what rules to apply for these inputs by matching the fuzzified inputs to the premises of the rules in the rule base. The inference mechanism provides a fuzzy set that indicates the certainty that the plant input should take on various values. Then de-fuzzification is used to convert the fuzzy set produced by the inference mechanism into a crisp output to be used by the plant.

B. Membership Function

In fuzzy logic controller, all membership functions are triangular membership function with seven segments. The fuzzy subset are Negative Big (NB), Negative Medium (NM), Negative small (NS), Zero (ZE), Positive small (PS), Positive Medium (PM) and Positive Big (PB). Zero (ZE) is the center of the membership function and all other partitions are symmetric about the Zero membership function. The membership function of the fuzzy controller outputs K_P and K_I as shown in Figs. 2 and 3.

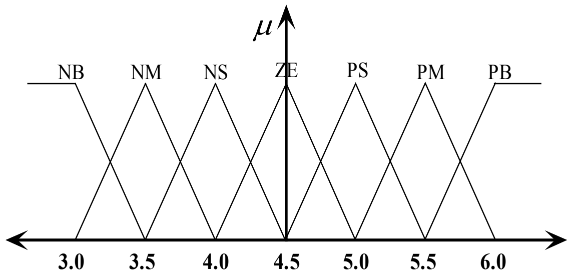

Figure 2. Membership function for controller output K_P

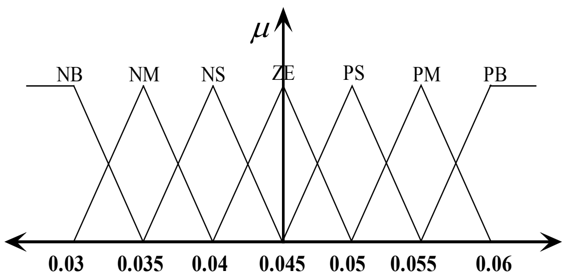

Figure 3.Membership function for controller output K_I

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 I and II.

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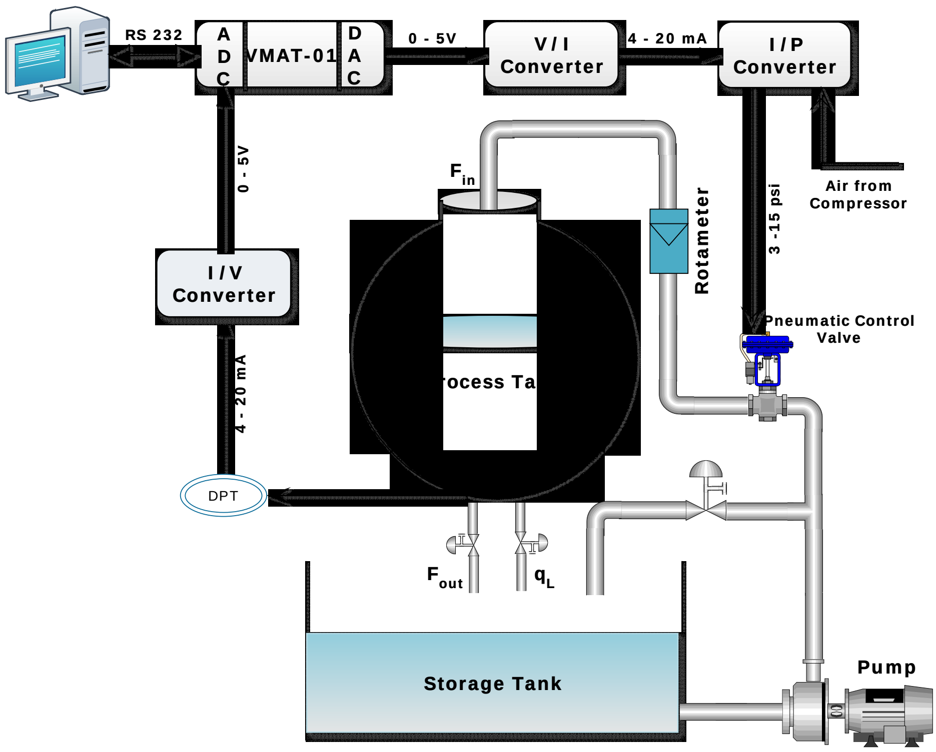

Figure 4. Experimental setup for Spherical Tank Liquid level Process

TABLE I: K_P FUZZY CONTROL RULE

e	ce						
	NB	***NM***	***NS***	***ZE***	***PS***	***PM***	***PB***
NB	PB	PM	PB	PM	PS	PS	ZE
NM	PM	PS	PM	PS	ZE	ZE	NS
NS	PM	PS	PS	ZE	NS	NS	NM
ZE	PS	PS	ZE	ZE	ZE	NS	NS
PS	PS	ZE	ZE	NS	NS	NM	NB
PM	PS	ZE	ZE	NS	NS	NM	NB
PB	ZE	NS	NS	NM	NM	NB	NB

TABLE II: K_I FUZZY CONTROL RULE

e	ce						
	NB	***NM***	***NS***	***ZE***	***PS***	***PM***	***PB***
NB	NB	NS	PS	ZE	PS	PM	PB
NM	NS	NM	NS	NS	NS	PS	PS
NS	NB	NS	NS	NS	PS	PM	PM
ZE	NB	NB	NS	NS	PS	PM	PB
PS	PS	ZE	ZE	NS	NS	PM	PM
PM	PM	PS	ZE	ZE	NS	PS	PM
PB	PB	PM	ZE	ZE	PS	PB	PM

III. REAL TIME EXPERIMENTAL SETUP

The real time experimental setup for highly non-linear spherical tank level process system is shown in Fig. 4. The process is interfaced with the personal computer through VMAT-01 interfacing module. The system consists of spherical tank, a water reservoir, a pneumatic control valve, a current to pressure (I/P) converter, pump, an interfacing VMAT-01 module and a personal computer (PC). The VMAT-01 module supports one Analog to Digital converter (ADC), one Digital to Analog converter (DAC) with voltage range from 0 to 5v and two Pulse Width Modulations (PWMs). The sampling rate of this module is 0.1 sec and baud rate is 38400 bits per sec with 8-bit resolution.

The tank is made up of stainless steel and is mounted over the stand. Water enters from top of the tank through pneumatic control valve and leaves out the bottom of the tank. The one more outlet is provided through solenoid valve q_L and also placed at the bottom of the tank, both the outflows are directly placed over the storage tank. The real time laboratory setup for spherical tank level process system is shown in Fig. 5. The controller is designed and developed by using MATLAB Simulink software in PC which is interfaced with VMAT-01 module through RS-232 cable as shown in Fig. 6.

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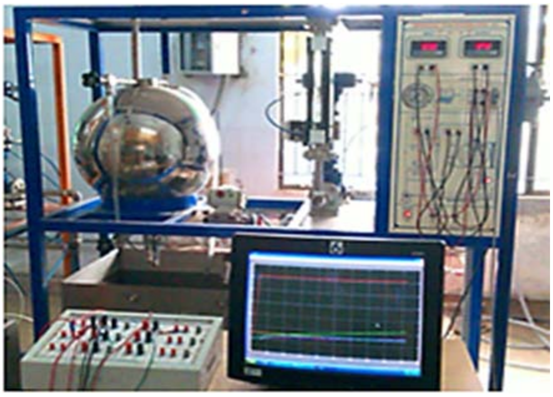

Figure 5. Real Time Laboratory setup for Spherical Tank Process

Figure 6. Real Time MATLAB Interface Card

The pneumatic control valve is air to close, adjusts the flow of the water pumped from the water reservoir to the spherical tank. The level of the water in the tank is measured by means of the differential pressure transmitter (DPT) and it is transmitted in the form of 4-20mA current signal and it is converted in to voltage with the help of I/V converter. The output of the I/V converter is given to VMAT-01 module, it consists of multifunction high speed 8-bit ADC and DAC. The VMAT-01 module is interfaced with Personal Computer (PC) through RS-232 cable. After computing the control algorithm the control signal is transmitted to the current to pressure (I/P) converter in the form of current signal 4-20mA to 3-15 psi, which passes the air signal to the pneumatic control valve. The pneumatic control valve actuated by this signal produces the required inflow of the water to the tank. To maintain the level of the tank, the outflow is constant and the inflow rate is controlled so as to reaches the desire set point. Table III shows the various technical specifications of experimental setup.

TABLE III: TECHNICAL SPECIFICATIONS OF EXPERIMENTAL SETUP

Part Name	Details
Spherical Tank	Material: Stainless Steel Diameter – 50 cm, Volume: 65 liters
Storage Tank	Material : Stainless Steel (l=78cm, b=48cm, h=43cm) Volume:160 liters
Differential Pressure Transmitter	Type Capacitance, Range (2.5- 250) mbar, span limit(0.65 – 65) Kilo Pascal, Output (4 -20) mA ABB Make
Pump	Centrifugal 0.5 HP
Control valve	Size ¼ "Pneumatic actuated" Type: Air to open Input (3 – 15) psi
Rota meter	Range (0 – 1000) LPH
Air regulator	Size ¼ " BSP Range (0 – 2.2) bar
I / P converter	Input (4 – 20) mA Output (0.2 – 1) bar
Pressure gauge	Range (0 – 30) psi Range (0- 100) psi

IV. Mathematical Model Of The Spherical Tank Process

Here the schematic diagram of spherical tank is shown in Fig. 7, F_{in} is the inflow, F_{out} is the outflow and q_L is the load disturbance applied to the tank.

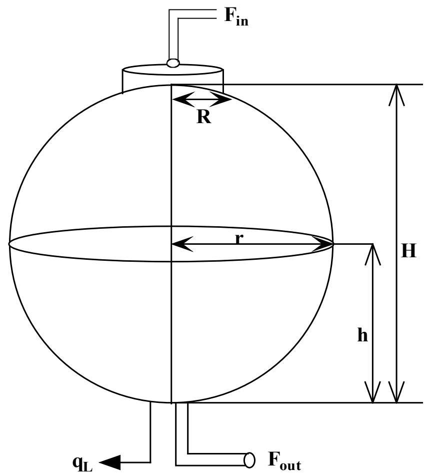

Figure 7. Schematic Diagram of Spherical Tank

F_{in} - Inlet flow rate to the tank (m^3 /min)
F_{out}- Outlet flow rate to the tank (m^3 /min)
q_L - Load applied to the tank (m^3 /min)
H - Height of the Spherical tank (m)
h - Height of the liquid level in the tank at any time 't'(m)

R - Top radius of the Spherical tank (m)
r - Radius of the spherical vessels at a particular level of height h (m)

The dynamic model of the spherical tank system when nominal operating level 'h' is given by

$$A\frac{dh}{dt} = F_{in} - F_{out} \tag{5}$$

The equation can be re-written as

$$\frac{dh}{dt} = \frac{F_{in}}{\pi(2rh - h^2)} - \frac{bx\sqrt{h}}{\pi(2rh - h^2)} \tag{6}$$

Linearization of the differential equation (5) using Taylor series around the nominal operating point $(\overline{F_{in}}, \overline{h})$

$$\frac{dh(t)}{dt} = Ah(t) + BF_{in}(t) \tag{7}$$

Where

$$A = \frac{-bx}{2\pi\sqrt{\overline{h}}(2r\overline{h} - (\overline{h})^2)^2} \tag{8}$$

$$B = \frac{1}{\pi(2r\overline{h} - (\overline{h})^2)^2} \tag{9}$$

Taking Laplace transform of equation (7)

$$\frac{h(s)}{F_{in}(s)} = \frac{-\left(\frac{B}{A}\right)}{-\left(\frac{1}{A}\right)s + 1} = \frac{K_p}{\tau_P s + 1} \tag{10}$$

Hence the process gain K_P and process time constant τ_P at given operating point $(\overline{F_{in}}, \overline{h})$ is given as

$$K_P = -\left(\frac{B}{A}\right) = \frac{2\sqrt{\overline{h}}}{bx} \tag{11}$$

$$\tau_P = -\left(\frac{1}{A}\right) = \frac{2\pi\sqrt{\overline{h}}(2r\overline{h} - (\overline{h})^2)^2}{bx} \tag{12}$$

V. TRANSFER FUNCTION MODEL OF THE SPHERICAL TANK SYSTEM

The system identification of this non-linear spherical tank system is done by using block box modelling. For fixed inflow rate and outflow rate of the Spherical tank, the tank is allowed to fill with water from 0 to 50cm. At each sample time the data from differential pressure transmitter i.e. between 4 to 20mA is being collected and fed to the system through the serial port RS - 232 using VMAT-01 interfacing module. Thereby the data is scaled up in terms of level (in percentage). The total height of the tank is 0-50cm. It is converted in terms of 0-100%. Using the open loop method, for a given input step change, the output response of the system is recorded with help of PC.

In order to find the open loop transfer function model of the spherical tank system at three different operating regions, the level ranges from 20% to 39%, 40% to 59% and 60 to 75% for lower, middle and upper level of the tank respectively. The transfer function parameters for above mentioned levels are listed in Table IV and also the controller parameters using ZN-PI open loop techniques are shown in Table V.

TABLE IV: TRANSFER FUNCTION PARAMETERS AT DIFFERENT OPERATING LEVELS

	Level (%)	K_P	τ_p	Td
Model 1	**20 – 39**	5.083	620.24	29
Model 2	**40 – 59**	5.469	1015.8	30
Model 3	**60 – 75**	4.202	1291.2	30

TABLE V: CONTROLLER PARAMETER FOR THREE MODELS

	K_P	K_I
Model 1	3.786903	3.91e-002
Model 2	5.572134	5.57e-002
Model 3	9.218467	9.21e-002

VI. RESULTS

The FAPI controller and digital PI controller are designed and implemented in MATLAB Simulink software to control the spherical tank liquid level process in real time laboratory system with various operating regions. The output of both the controllers are listed, it is clearly notices that the proposed controller gives minimal overshoot and fast settling time as compared to digital PI controller. Moreover, when the set point changes the digital PI controller is used to change the controller parameter but proposed controller is an auto adaptive self-tuning parameters. The performance of the proposed controller and digital PI Controller for various operating regions are displayed in Figs. 8-13 and also compared the time domain specifications of both the controllers are tabulated in Table VI.

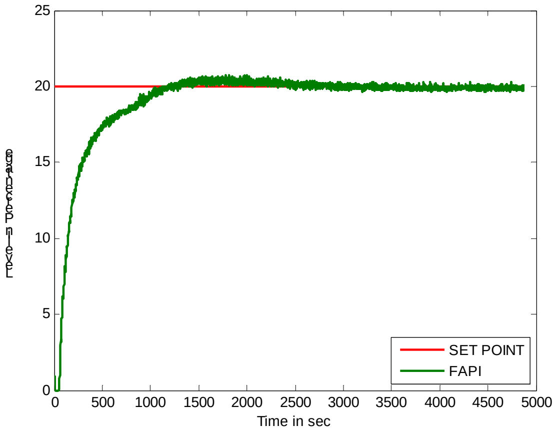

Figure 8. FAPI controller for the set point of 20(%)

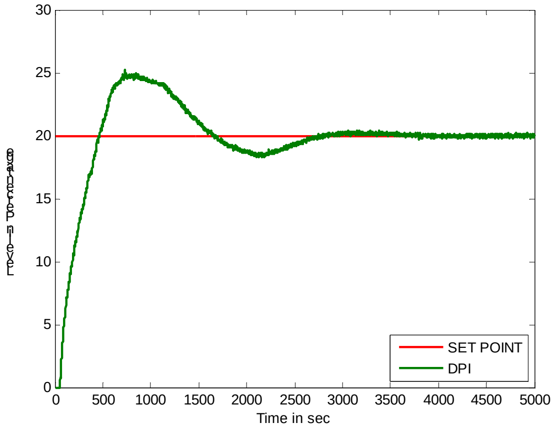

Figure 11. DPI controller for the set point of 20(%)

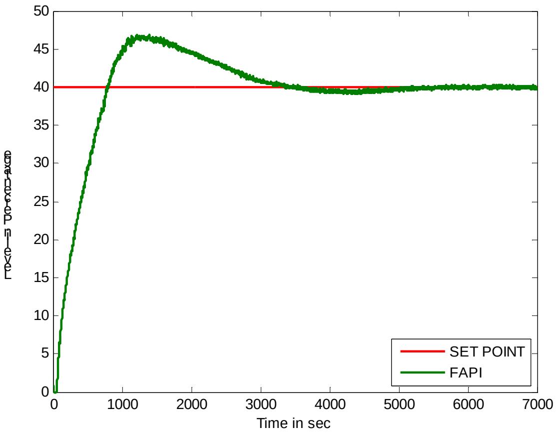

Figure 9. FAPI controller for the set point of 40(%)

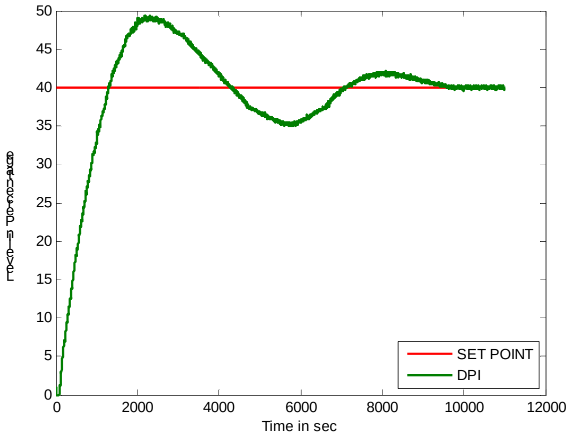

Figure-12: DPI controller for the set point of 40(%)

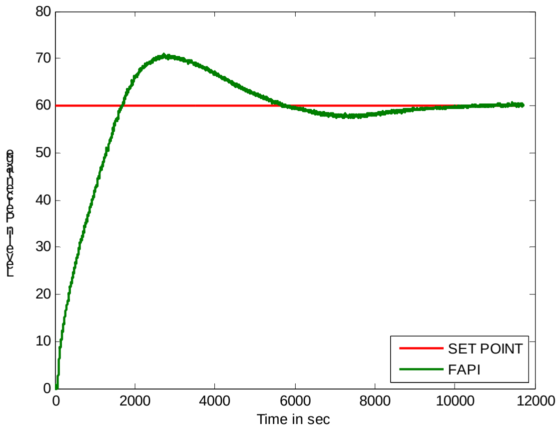

Figure 10. FAPI controller for the set point of 60(%)

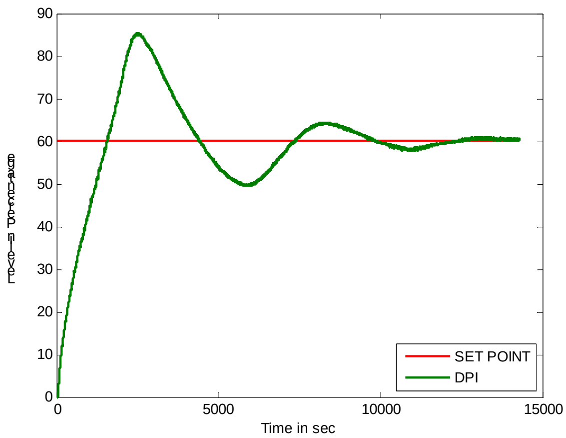

Figure 13. DPI controller for the set point of 60(%)

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A. *Set point variation of FAPI controller*

The positive step changes from different operating levels are shown in Figs. 14-16. It is observed that the controller has taken fast action to track the change in set point variations.

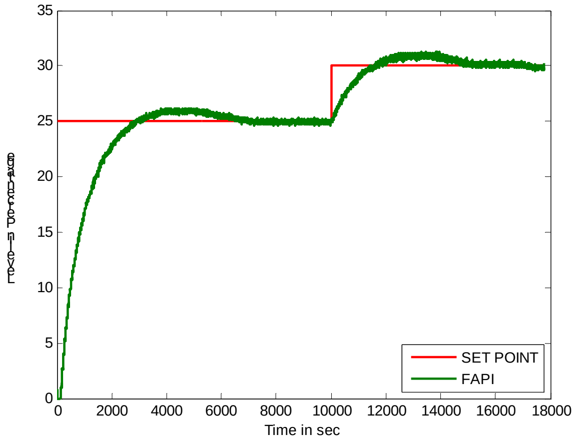

Figure 14. 20% positive step changes from 25% of level

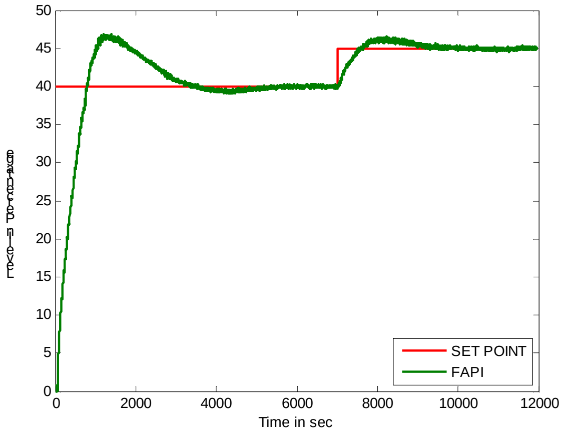

Figure 15. 11% positive step changes from 40% of level

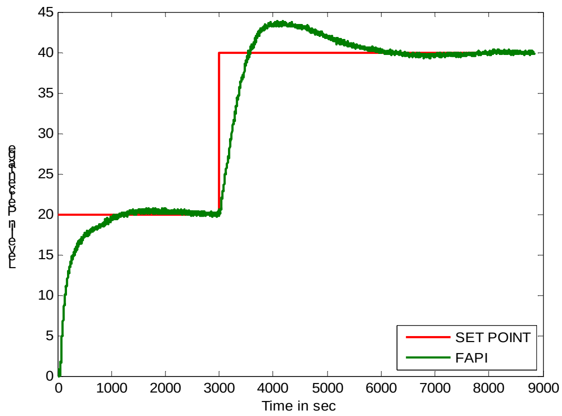

Figure 16. 100% positive step changes from 25% of level

B. *Servo and regulatory response of FAPI controller*

The controller take quick action when positive 20% step changes from 10000th sec and 100 lph constant load is applied at 18000th sec to the process as shown in Fig. 17.

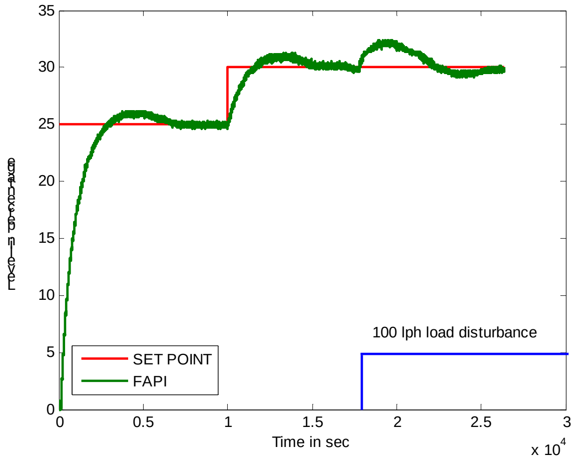

Figure 17. 20% positive step changes from 25% of level and 100 LPH Constant Load Applied

Table VI compares the time domain performance indices for various operating regions of FAPI and Digital PI controllers. From the table it is clearly seen that the proposed control strategy performs satisfactorily well over Digital PI.

TABLE VI. COMPARISON OF TIME DOMAIN SPECIFICATION AT DIFFERENT OPERATING LEVELS

LEVEL IN PERCENTAGE	SPECIFICATION	FAPI	PI
20	Rise Time (t_r)	522.07	333.82
	% Overshoot	3.70	25.99
	Settling Time (t_s)	2436.1	3057.1
40	Rise Time (t_r)	583.31	958.38
	% Overshoot	17.51	23.55
	Settling Time (t_s)	3229.6	9168.6
60	Rise Time (t_r)	1335.5	1271.2
	% Overshoot	17.98	41.50
	Settling Time (t_s)	9236.3	11707

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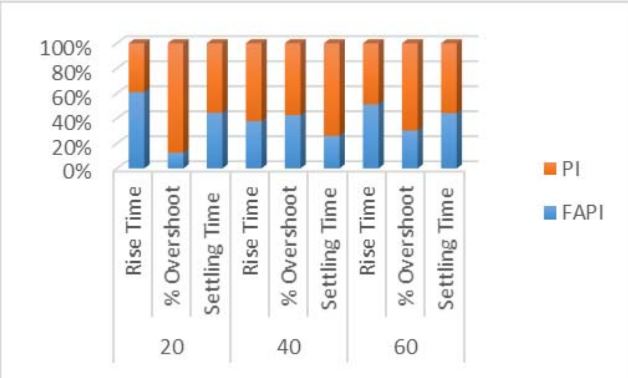

Figure 18. Percentage Comparison of time domain specification

VII. Conclusion

In this work, the Fuzzy Adaptive Digital PI controller is designed and implemented through MATLAB Simulink software using VMAT_01 module for highly non-linear liquid level spherical tank process. Regarding the performance of the proposed controller the overshoot is minimum and has fast settling time then Digital PI controller. The proposed controller work with the gain scheduling techniques, this techniques are mostly used in auto piloting in the navigation of Aircrafts. The FAPI controller is a giving excellent performance in DC motor speed control, power system damping, temperature control systems etc. In future the proposed controller may be implement in MIMO non-linear processes, pressure and flow control processes.

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