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Real-Time Performance Evaluation of a Fuzzy PI + Fuzzy PD Controller for Liquid-Level Process

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Abstract- **In this paper, a comparative study was carried out to evaluate the real-time performance of fuzzy proportional-integral plus fuzzy proportional-derivative (Fuzzy PI + Fuzzy PD) controller with the real-time performance of Conventional PI for a liquid-level process experiment. The process considered for this experiment shows highly nonlinear behavior due to equal percentage pneumatic control valve. NATIONAL INSTRUMENTS™ based hardware and software tools (LabVIEW™) were used for precise and accurate acquisition, measurement and control. The real time implementation of the Fuzzy PI + Fuzzy PD controller was carried out in two configurations: namely, feedback and cascade. In cascade control configuration Fuzzy PI + Fuzzy PD controller was implemented in the primary loop. The secondary loop was tuned using the conventional PI controller. It was evaluated that Fuzzy controller perform better in comparison with conventional controller in both the feedback and cascade control configurations.**

***Index Terms*— Fuzzy PI + Fuzzy PD, PID, Cascade Control. Process Control.**

1. INTRODUCTION

Intelligent Process Control methods such as fuzzy logic control have shown some success, there is a significant need to evaluate their real time performance relative to conventional control approaches, particularly in an experimental setting. Such evaluations help to determine the performance of the new intelligent process control methods, and provide the engineer with general guidelines on how to apply them to more complex real-world applications [12-15]. Despite a lot of research and the large number of different solutions proposed, most industrial control systems are still based on conventional PID regulators. Different sources estimate the share taken by PID controllers at between 90 and 99%. This is because of their low cost, inexpensive maintenance, simplicity of operation, ease of design, and effectiveness for most systems [6,17,21]. In practice, it is often being integrated into complex control structures in order to achieve a better control performance. Among those complex control structures, cascade control scheme is commonly used for the purpose of reducing both maximum deviation and integral error of disturbance responses. The advantages of easy implementation and potentially large control performance improvement have led to wide spread applications of cascade control for several decades. It has become a standard application provided by industrial process controllers [10, 22].

Cascade control systems are constructed by two control loops: an inner loop with fast dynamic to eliminate input disturbances, while the outer loop to regulate output performance [2,7].

However, conventional PID controllers cannot provide a general solution to all control problems. The processes involved are in general complex and time-variant, with delays and non-linearity, and often with poorly defined dynamics. When the process becomes too complex to be described by analytical models, it is unlikely to be efficiently controlled by conventional approaches. To overcome these difficulties, various types of modified conventional PID controllers such as autotuning and adaptive PID controllers were developed lately [6,17]. Also, a class of nonconventional type of PID controller employing fuzzy logic has been designed and simulated for this purpose [6,9,11].

Fuzzy Logic Controller (FLC) has emerged as one of the most active and useful research areas in the fuzzy control theory. That is why fuzzy logic controllers have been successfully applied for control of various physical processes. Basically there are two approaches to a fuzzy controller design: an expert approach and a control engineering approach. In the first, the fuzzy controller structure and parameters choice are assumed to be the responsibility of the experts. Consequently, design and performance of a fuzzy controller depend mainly on the knowledge and experience of the experts, or intuition and professional feeling of a designer. This dependence, which is considered far from systematic and reliable, is the flaw of this approach. However, this approach could assist in constructing a fuzzy model or an initial version of a fuzzy controller. The second approach supposes an application of the knowledge of control engineering and a design of a fuzzy controller in some aspects similar to the conventional design with the parameter's choice, depending on the information of their influence on the controller performance [3-4]. On the other hand best-known industrial process controller is Proportional-Integral-Derivative (PID) controller because of its simple structure and robust performance in a wide range of operating conditions. The similarity of FLC and PID controllers and there improvement is still being investigated [1].

Quang and Negenevitsky have proposed a scheme to tune the PI controller in Cascade loop with Fuzzy Logic. They have given the simulation result only [20]. Another simulation result was given by Santos and Cruz [18]. However, not many observations have been reported so far in the literature on the effect of use of fuzzy logic controller in the cascade control strategy *in real time.* The present research work is focused on the implementation of

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Fuzzy PI + Fuzzy PD Controller in simple feedback and cascade configuration in real time for liquid-level process experiment in our laboratory in order to evaluate the performance of intelligent controller over conventional PI controller. The level-process is controlled by manipulating an equal percentage pneumatic control valve. Due to its equal percentage characteristics it shows nonlinear behaviour.

Fuzzy control and Conventional control strategies have been applied to implement level control in the process control unit as shown in Fig.1. These strategies have been successfully implemented in both feedback and cascade control configurations. In the cascade control configuration, fuzzy control has been implemented in only the primary loop. In the secondary loop, only conventional control was used. It has been observed that the fuzzy controller out perform the conventional controller in both the feedback and cascade control configurations.

2. FAMILIARIZATION WITH THE PROCESS

2.1 Process Control Unit

Fig.1 & Fig.2 gives a description of the process control unit and Liquid Level Process. The block diagram of process is shown in Fig.3. In this unit the level in the overhead tank has to be controlled using feedback control and cascade control.

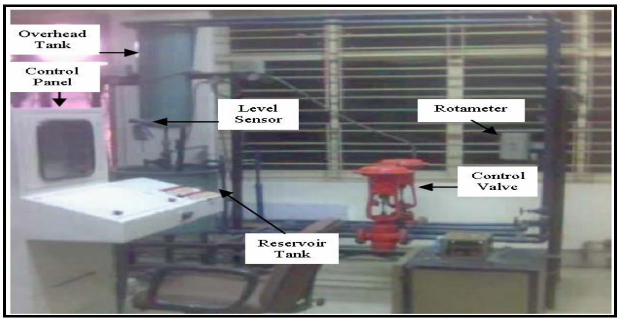

Fig.1. Process Control Unit

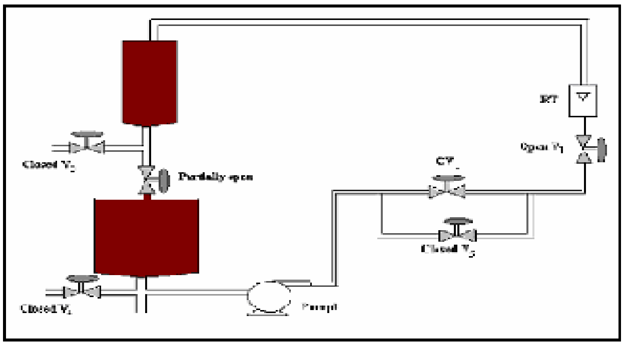

Fig.2. Liquid-Level Process Setup

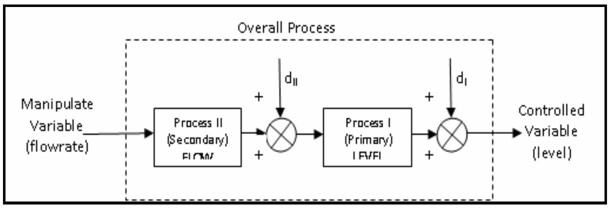

Fig.3. Block diagram of process

The system consists of a reservoir tank, which stores the incoming water. This reservoir opens up into an outlet pipe, which has a valve whose opening can be adjusted to vary the disturbance. The pump motor attached to the pipe sucks water from the reservoir when switched on. This water travels through the pipes and then reaches the control valve, which controls the flow of this water as per its lift, which is in turn controlled by the controller. The flow of this pipe was gauged by a rotameter which is installed in the pipe. This pipe, further empty into an overhead tank, in which the level control has been implemented. The level was sensed by a level sensor (pressure type) and the data for the same was acquired with the help of a data acquisition (DAQ) card.

As the incoming water fills in the reservoir, the desired level (set point) is given as the input to the computer and according to the error in the current level of the tank (as sensed by the level transmitter) and in the input, the computer generates a control action which was converted using a DAQ card into an analog signal. This is transmitted to the I-P converter, which converts the current to pneumatic signal (i.e. 4-20mA to 3-15psi). The pneumatic signal then increases or decreases the opening of the control valve so as to attain the desired flow in the pipes, which can eventually give the desired level in the overhead tank. This is how level is controlled in the above system using a feedback loop.

2.2 Control Valve

A pneumatic control valve of equal percentage characteristics was used to regulate the liquid flow-rate. The plug of the valve was Globe type and it was operating in air-to-open mode. The valve was in use for the last 5 years and experienced wear and tear, rusting, and accumulation of dust particles. As a result the valve was not able to get opened to full-scale. The flow characteristic of pneumatic control valve is shown in Fig.4. The input-output characteristic of control valve shows highly nonlinear behavior. Therefore, due to valve the overall system becomes highly complex and nonlinear.

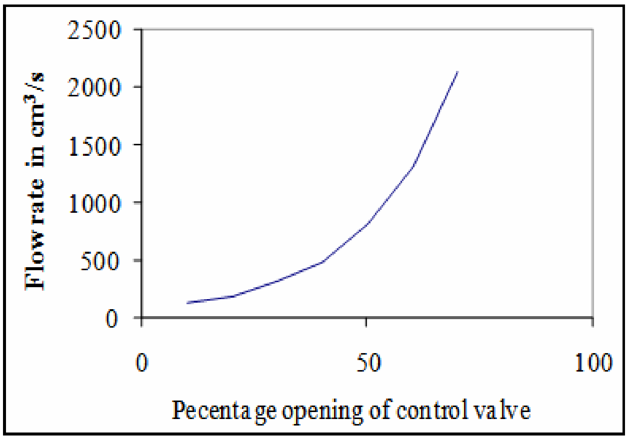

Fig.4 Flow characteristic of pneumatic control valve

2.3 Data Acquisition

A PCI compatible DAQ card (NI-6035E, 200KS/s, 12Bit) was used to acquire the data and also to generate the control signal. Input and output were synchronized appropriately. A virtual instrument was developed for this task.

2.4 Transducer

Pressure-type level sensor was used to sense the level in a tank/reservoir and then convert the sensed signal into equivalent electrical signal (in the range of 4-20mA).

Rotameter was used to measure the flow through a pipeline and then convert this flow signal into an electrical analog signal (in the range of 4-20mA).

3. CASCADE CONTROL LOOP

For controlling level in the overhead tank, using cascade control, the disturbance caused by the inflow rate was minimized. The block diagram of cascade control system is shown in Fig.5.The level transmitter senses the level in the overhead tank and transmits the signal to the level controller built in the computer. This level controller computes a set point for the flow loop, which is then fed to the flow controller. The flow controller provides an actuating signal to the control valve in a manner so as to nullify the disturbance due to flow before it is able to affect the primary control variable, level. This actuating signal is proportional to the error calculated by the flow controller, which is the difference between the computed value of the flow by the level controller and the actual value of the flow in the pipe leading to the overhead tank, measured by the rotameter. The changed flow rate in the pipe connecting the overhead tank will cause the inner loop to respond before the error in the level becomes evident in the overhead tank. So the purpose of the inner loop is to detect a disturbance before it becomes evident as error in the outer loop.

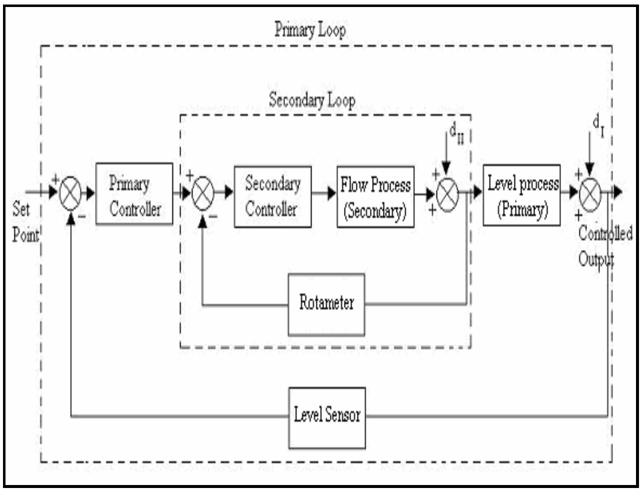

Fig.5. Cascade control in real time (for level control)

4. FUZZY PI + FUZZY PD CONTROLLER

A conventional PID controller follows the control law:

$$u_{PID}(t) = K_C\{e(t) + \frac{1}{\tau_I}\int e(t)dt + \tau_D \frac{de(t)}{dt}\} \quad \text{.........} \ (1)$$

where K_C is the proportional constant of PID controller, τ_I is an integral constant, τ_D is a derivative time constant, $e(t)$ is an error signal, $e(t) = r(t) - y(t)$, $r(t)$ is the desired value, $y(t)$ is the output from process and $u_{PID}(t)$ is the output from controller - the action value. Its discrete approximation is:

$$u_{PID}(k) = K_C\{e(k) + \frac{1}{\tau_I}\sum_{i=1}^{k} e(i)T_S + \tau_D \frac{e(k) - e(k-1)}{T_S}\}, \ (2)$$

where T_S the sampling period, k is the step. To implement the Fuzzy PID controller three inputs $e(k)$, $\sum e(k)$ and $\Delta e(k)$ are required. Increasing the number of input variables causes a rise in the dimension of the rule table and, therefore, in the complexity of the system; this makes its implementation more complicated. For this reason, a combination of Fuzzy PI + Fuzzy PD controller was employed instead of three input Fuzzy PID controller. The Fuzzy PI + Fuzzy PD controller is a digital controller, which contains a Fuzzy PI & Fuzzy PD control unit's arrangement [11, 16].

4.1 Fuzzy PI Controller

A classical PI controller is described by

$$u_{PI}(t) = K_C(e(t) + \frac{1}{\tau_I}\int e(t)d(t)). \quad \text{................................} \ (3)$$

Differentiating equation (3), the following equation is obtained:

$$\frac{du_{PI}(t)}{dt} = K_C\left(\frac{de(t)}{dt} + \frac{1}{\tau_I}e(t)\right),$$

In discrete form, the above equation can be written as:

$$\frac{[u_{PI}(k) - u_{PI}(k-1)]}{T_S} = K_C\left(\frac{[e(k) - e(k-1)]}{T_S} + \frac{1}{\tau_I}e(k)\right),$$

or, $\Delta u_{PI}(k) = K_C(\Delta e(k) + \frac{1}{\tau_I}e(k)),$

or $\Delta u_{PI}(k) = K_C\Delta e(k) + \frac{K_C}{\tau_I}e(k),$

where $\Delta e(k) = \frac{e(k) - e(k-1)}{T_S},$

and $\Delta u_{PI}(k) = \frac{u_{PI}(k) - u_{PI}(k-1)}{T_S},$

or $T_S\Delta u_{PI} = u_{PI}(k) - u_{PI}(k-1),$

or $T_S\Delta u_{PI} = u_{PI}(k) - z^{-1}u_{PI}(k),$

or $T_S\Delta u_{PI}(k) = (1 - z^{-1})u_{PI}(k),$

or $u_{PI}(k) = \frac{T_S}{(1 - z^{-1})}\Delta u_{PI}(k),$

or $u_{PI}(k) = \frac{K_{UPI}}{(1 - z^{-1})}\Delta u_{PI}(k).$ .... (4)

where, K_{UPI} (Gain PI) is the fuzzy control gain.

A physical meaning of the parameters for the fuzzy PI controller remains the same like for the PI controller (the controller gain K_C and the time integral constant τ_I) [6, 16, 19].

4.2 Fuzzy PD Controller

A classical PD controller is described by:

$u_{PD}(t) = K_C(e(t) + \tau_D\frac{de(t)}{dt})$ ....(5)

In discrete form, the above equation can be written as:

$$u_{PD}(k) = K_C\left(e(k) + \tau_D\frac{[e(k) - e(k-1)]}{T_S}\right),$$

or $u_{PD}(k) = K_C(e(k) + \tau_D\Delta e(k)),$

or $u_{PD}(k) = K_C e(k) + K_C\tau_D\Delta e(k),$ .... (6)

where $\Delta e(k) = \frac{e(k) - e(k-1)}{T_S}.$

A fuzzy PD controller can be realized as per the above equation [6, 16, 19].

4.3 Combination of Fuzzy PI +Fuzzy PD Controller

Finally, the overall Fuzzy PI + Fuzzy PD controller can be obtained by algebraically summing the equation (4) & equation (6).

$$u_{PID}(k) = u_{PI}(k) + u_{PD}(k),$$

or $u_{PID}(k) = \frac{K_{UPI}}{(1 - z^{-1})}\Delta u_{PI}(k) + u_{PD}(k).$ .... (7)

Fig.6 shows the configuration of Fuzzy PI + Fuzzy PD (in feedback mode) [19].

4.4 Fuzzy PI +Fuzzy PD Controller in cascade loop

In cascade control mode, normally a conventional P or PI controller is used for the secondary controller (inner controller); because the disturbances arising within the secondary loop are corrected by second controller before they can affect the value of the primary controller (outer controller) output. Any offset caused by P control in the secondary loop is not important since we are not interested in controlling the output of the secondary process. Therefore, in the present case conventional PI controller was implemented for secondary controller in order to get the faster response in secondary controller and Fuzzy PI + Fuzzy PD controller for primary controller. Fig.7 shows the implementation of Fuzzy PI + Fuzzy PD controller in cascade control loop [2,7,19].

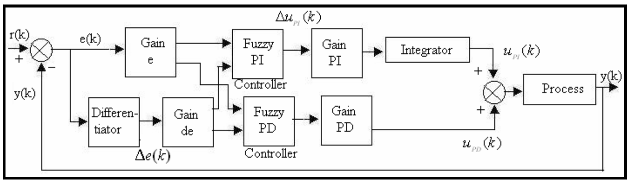

Fig.6. Fuzzy PI + Fuzzy PD (in feedback mode)

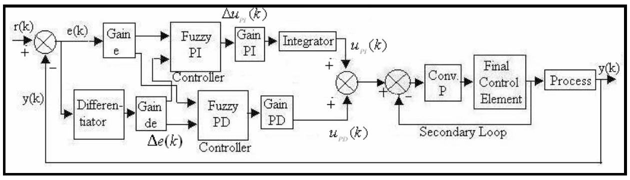

Fig.7 Fuzzy PI + Fuzzy PD (Cascade) Configuration

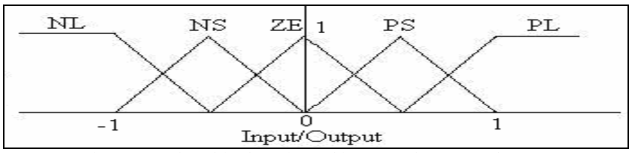

Fig.8. Membership function of input and output of FLC

5. PRE-REQUISITES FOR DESIGN OF FLC

5.1 Fuzzification

Input and output variables of the FLC are usually quantized into sets of classes defined by linguistic labels such as “positive large”, “positive medium”, “positive small”, “zero”, “negative small”, “negative medium”, “negative large”, and so forth. For the experimentation, the inputs and outputs were quantized into 5 fuzzy sets, namely:

PL – Positive Large
PS – Positive Small
ZE – Zero
NS – Negative Small
NL - Negative Large

This quantization was carried out in the range of [-1,1] for inputs as well as output. The membership functions for $e(k)$, $\Delta e(k)$ and $\Delta u_{PID}(k)$ were of triangular type and are shown in Fig.8 [16].

5.2 Rule Base

Theoretically, the rule based should be different for Fuzzy PI controller and Fuzzy PD controller but in order to reduce the complexity of design and to increase efficiency, a simple structure of Fuzzy PI + Fuzzy PD controller was used with a single rule base. A PI rule base was considered because PI controller is generally more important for steady state performance [8].

The rule base for this Fuzzy controller can be imagined to be a two dimensional matrix as summarized in Table 1.The rows represent the various linguistic values that change of error $\Delta e(k)$, can take and columns indicate the values of error $e(k)$. The entries in this matrix would be the control action that has to be taken described in the linguistic terms. The control action has been calculated based upon the process reaction curve [3-4].

Table1: Rulebase for Fuzzy Controller

	Change of error (de)					
Error (e)		NL	NS	ZE	PS	PL
	NL	NL	NL	NL	NS	ZE
	NS	NL	NL	NS	ZE	PS
	ZE	NL	NS	ZE	PS	PL
	PS	NS	ZE	PS	PL	PL
	PL	ZE	PS	PL	PL	PL

5.3 Fuzzy Inference Engine

The basic function of the fuzzy inference engine is to compute the overall value of the control output variable based on the individual contribution of each rule in the rulebase. For the present research work, Mamdani inference mechanism has been used. The differences in using the various implication techniques are described in [5]. It was observed that Mamdani's technique is the most suitable for hardware implementation due to simple min–max structure. The first phase of Mamdani's implication involves *min*-operation since the antecedent pairs in the rule structure are connected by a logical 'AND'. All the rules are then aggregated using a *max*-operation [16].

5.4 Defuzzification

In the present work center of gravity defuzzification method (COG) was used to defuzzify the fuzzy sets into a crisp control signal [17].

6. REAL TIME RESULTS

Fuzzy PI + Fuzzy PD controller described in last section was implemented in real time in feedback and cascade control configurations for controlling the liquid-level in the overhead tank shown in the process control unit Fig.1. The National Instrument™, USA hardware and software (LabVIEW™) were used for real time implementation of measurement and control. LabVIEW™ (Laboratory Virtual Instrument Engineering Workbench) is a powerful and flexible instrumentation and analysis software development application created by National Instrument™, USA.

6.1 Performance criterion

For controlling level in the overhead tank of the process control unit the main performance evaluation criteria was taken as *peak of overshoot.* This is because in the level control system the main thing which has to be taken care of is the overflowing of the tank. If the overshoot is more the tank might overflow. Thus, the main factor which has been considered for evaluating the performance is the overshoot. The next priority in the performance criteria was given to the settling time i.e. how quickly the level settled down.

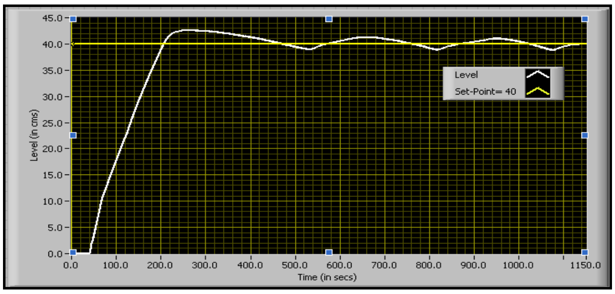

Fig.9. Fuzzy PI + Fuzzy PD real time response (feedback)

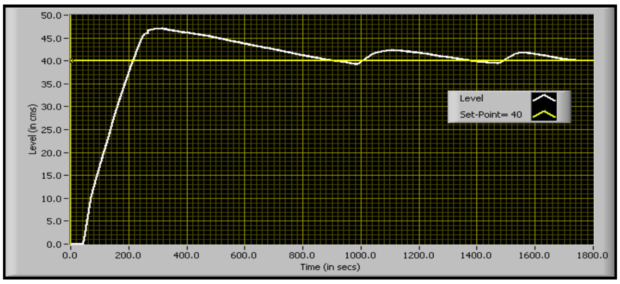

Fig.10. Conventional PI real time response (feedback)

6.2 Settings Used

The main settings which had to be done in the system were of the *set-point* and the *disturbance* (this was changed by adjusting the partially open valve shown in Fig.2.). The settings of these two were kept same for the whole experiment for carrying out the comparison of the readings. The height of the overhead tank is 80 cms so the set-point was kept at the middle point i.e. at 40 cms as the flow verses height characteristics were non-linear and were linearised at mid-point. The disturbance was set at 4-full hand turns.

6.3 Results of Feedback Configuration

The results obtained on implementing the fuzzy and conventional controllers, in the feedback loop, for controlling the level in the overhead tank of the process control unit are given below.

6.3.1. Fuzzy PI +Fuzzy PD Controller Response

Fig. 9 shows the real time response from Fuzzy PI + Fuzzy PD controller. The settings of the parameters for this controller as per Fig. 6 are given below:
Gain e = 1, Gain de = 5, Gain PI = 10,
Gain PD = 20, Setpoint = 40 cms.

6.3.2. Conventional PI Controller Response

The conventional PID controller was tuned using Ziegler Nichol's method. The performance of conventional PI controller was best among other conventional controller. Fig. 10 shows the real time response from a conventional PI controller. The settings of parameters for this controller were calculated using the relay method.

$K_c = 9.6505$; τ_i = 0.1528 min; Setpoint = 40cm;

6.3.3. *Comparison of Fuzzy and Conventional controller real time results for Level system (Feedback)*

The Table 2 compares the results of all the controllers, Fuzzy and Conventional in the feedback loop. It was observed that the fuzzy controllers performed better than the conventional PI controller.

Table 2: Comparison of Fuzzy and conventional controllers real time results (feedback)

Type of Controller	Rise Time (sec)	Peak (cms)	Overshoot (%)	Settling Time (sec)
Fuzzy PI + Fuzzy PD	169	42.6	6.5	313
Conventional PI	177	47.24	18.1	714

Table 2 shows that Fuzzy PI + Fuzzy PD controller stands out in performance with the least peak of 42.6 cms. The settling time has been calculated using the 5% tolerance band criteria. The Fuzzy PI + Fuzzy PD controller has the least settling time of 313 sec.

6.4 Results of Cascade Control Configuration

The various results obtained on implementing the fuzzy and conventional controllers, in the cascade loop, for controlling the level in the overhead tank of the process control unit are shown in Fig.11 & Fig. 12. The Fuzzy controllers were implemented only in the primary loop of the cascade controllers, while the secondary loop had conventional PI controller.

6.4.1. Fuzzy PI +Fuzzy PD Controller Response

Fig.11 shows the real time response from Fuzzy PI +Fuzzy PD controller in primary loop. The settings of the parameters for this controller as per Fig. 7 are given below:

Primary loop (Fuzzy Controller):
Gain e = 1, Gain de = 1, Gain PI = 20, Gain D = 30
Secondary loop (Conventional PI controller):
$K_c = 5, \tau_i = 0.01$

6.4.2. Conventional PI Controller Response

Fig.12 shows the real time response from Conventional PI controller. The settings of the parameters for this controller had been calculated using the Zeigler Nichols tuning method. The settings obtained were:

Primary loop (conventional PI controller):
$K_c = 597.5, \tau_i = 0.022$
Secondary loop (conventional PI controller):
$K_c = 5, \tau_i = 0.01$

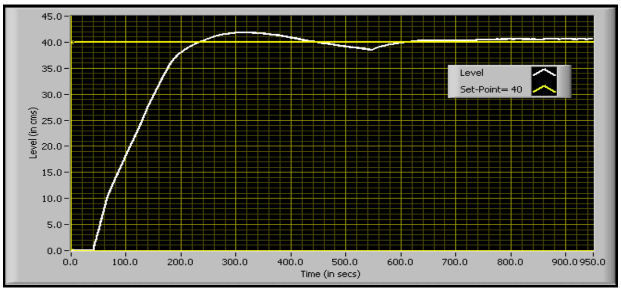

Fig.11. Fuzzy PI + Fuzzy PD response (cascade)

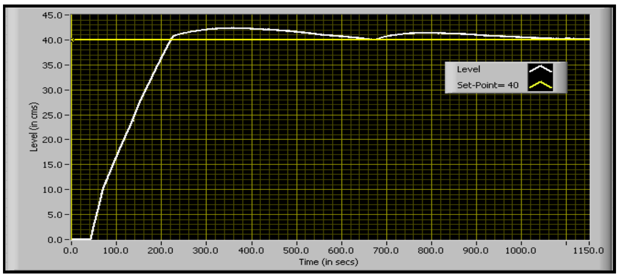

Fig.12. Conventional PI response (cascade)

6.4.3. Comparison of Fuzzy and Conventional controller real time results for Level system (Cascade)

Table 3 compares the results of Fuzzy and Conventional controllers in cascade loop. It was observed that the fuzzy controllers performed better than the conventional PI controller in cascade loop. The table shows that Fuzzy PI + Fuzzy PD controller stands out in performance according to our chosen criteria, with the least peak of 41.8 cms i.e. 4.5% overshoot. It's settling time has been calculated using the 5% tolerance band criteria. It was observed that the settling time has been reduced to 194 sec, which is less than the conventional PI in cascade configuration.

Table 3: Comparison of Fuzzy and conventional controllers real time result (cascade)

Type of Controller	Rise Time (sec)	Peak (cms)	Overshoot (%)	Settling Time (sec)
Fuzzy P I + Fuzzy PD (Primary) & Conventional PI (Secondary)	194	41.8	4.5	194
Conventional PI (Primary) & Conventional PI (Secondary)	183	42.5	6.25	364

7. CONCLUSIONS

Fuzzy PI + Fuzzy PD and conventional controllers were successfully implemented in real time, using both feedback and cascade control loops. The overall system performance was realized using the quality hardware for the measurement and state of the art software tools like LabVIEW™ with associated add-on modules. The performance of controller in cascade configuration was better than feedback configuration with respect to the performance criteria. From the Table 4, it was observed that the Fuzzy PI + Fuzzy PD controller in cascade configuration (in primary controller) perform superior than the conventional PI controller in both the feedback and cascade control configuration and fuzzy controller in feedback loop configuration.

Table 4: Comparison of real time results of feedback and cascade controller configuration

	Feedback				Cascade			
Type Of Controller	Tr (sec)	Peak (cms)	Mp (%)	Ts (sec)	Tr (sec)	Peak (cms)	Mp (%)	Ts (sec)
Fuzzy PI + Fuzzy PD	169	42.6	6.5	313	194	41.8	4.5	194
Conventional PI	177	47.24	18.1	714	183	42.5	6.25	364

Tr: rise time, Mp: Maximum overshoot in percentage,
Ts: settling time.

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REFERENCES

[1] B.G. Hu, G. K. I. Mann, and R. G. Gosine "A systematic study of fuzzy PID controllers-function-based evaluation approach", IEEE Transactions on Fuzzy Systems, Vol.9, Issue 5, Oct. 2001, pp.699 - 712.

[2] B. A. Ogunnaike and W. H. Ray, "Process Dynamics, Modeling, and Control", Oxford University Press, New York, 1994.

[3] C. C. Lee, "Fuzzy Logic in control systems: Fuzzy Logic Controller – Part I," IEEE Trans. Syst. Man Cybern., vol. 20, no. 2, Mar./Apr. 1990, pp. 404-418.

[4] C. C. Lee, "Fuzzy Logic in control systems: Fuzzy Logic Controller – Part II," IEEE Trans. Syst. Man Cybern., vol. 20, no. 2, Mar./Apr. 1990, pp. 419-435.

[5] F.S.Smith and Q.Shen, "Selecting Inference and Defuzzification Techniques for Fuzzy Logic Control", *Proc. of UKACC Intern. Conference on Control*, 1–4 Sept. 1998, pp. 54–59.

[6] G. Chen, "Conventional and fuzzy PID controllers: an overview", International Journal of Intelligent and Control Systems, 1, 1996, pp. 235±246.

[7] G. Stephanopoulos, "Chemical Process Control: An Introduction to Theory and Practice", Prentice-Hall of India, New Delhi, 1984.

[8] H. X. Li and H. B. Gatland, "Conventional Fuzzy Control and Its Enhancement", *IEEE Trans. Syst., Man, Cybern. B*, vol. 26, Oct. 1996, pp. 791–797.

[9] H. X. Li, "A comparative design and tuning for conventional fuzzy control," *IEEE Trans. Syst., Man, Cybern. B*, vol. 27, Oct. 1997, pp. 884–889.

[10] I. Kaya, N. Tan and D. P. Atherton, "Improved Cascade Control Structure and Controller Design", Proceedings of the 44th IEEE Conference on Decision and Control, and the European Control Conference 2005 Seville, Spain, December 12-15, 2005, pp 3055-3060.

[11] J. Carvajal, G. Chen and H. Ogmen, "Fuzzy PID Controller: Design, Analysis, performance evaluation, and stability analysis", Information Sciences, 123, 2000, pp. 249-270.

[12] J. Zumberge and K.M. Passino, "A case study in intelligent vs. conventional control for a process control experiment", Intelligent Control, 1996., Proceedings of the 1996 IEEE International Symposium on , 15-18 Sept. 1996, pp 37 – 42.

[13] J. Zumberge and K.M. Passino, "A Case Study in Intelligent vs. Conventional Control for a Process Control Experiment", Journal of Control Engineering Practice, Vol. 6, 1998, No. 9, pp. 1055–1075.

[14] K. Passino, "Towards bridging the perceived gap between conventional and intelligent control", in Intelligent Control: Theory and Applications, IEEE Press, 1996, ch. 1, pp. 1–27. Gupta, M.M. and Sinha, N.K. editors.

[15] K. Passino, "Bridging the gap between conventional and intelligent control", Special Issue on Intelligent Control, IEEE Control Systems Magazine, vol. 13, June 1993, pp. 12–18.

[16] K. M. Passino and S. Yurkovich, "Fuzzy Control", Menlo Park, CA: Addison Wesley Longman, 1998.

[17] K. S. Tang, K. F. Man, G. Chen and S. Kwong, "An Optimal Fuzzy PID Controller", IEEE Transactions on Industrial Electronics, vol. 48, no. 4, August 2001, pp. 757-765.

[18] M. Santos, J. M. de la Cruz, S. Dormido. "Self-Tuning of Fuzzy Logic Controllers in Cascade Loops", in *Intelligent Systems and Soft Computing for Nuclear Science and Industry*, World Scientific, 1996, pp. 258-264

[19] P. Pivonka; "Comparative Analysis of Fuzzy PI/PD/PID Controller Based on Classical PID Approach", Fuzzy Systems, 2002. FUZZ-IEEE'02. Proceedings of the 2002 IEEE International Conference, Vol. 1, 12-17 May 2002, pp.541 – 546.

[20] Q. P. Ha & M. Negenevitsky, "Cascade PI-Controller with Fuzzy Tuning" , Proceedings of the Sixth IEEE International Conference on Fuzzy Systems, vol.1, 1-5 Jul 1997, pp 361-366.

[21] S. Bennett, "Development of the PID controller," IEEE Contr. Syst. Mag., vol. 13, Dec. 1993, pp. 58–65.

[22] S.Song, L.Xie and Wen-Jim Cai, "Auto-tuning of Cascade Control Systems" IEEE Procedings of the 4th world Congress on Intelligent Control and Automation, June 10-14, 2002, Shanghai, P.R.China, pp 3339-3343.

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