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LIQUID LEVEL CASCADE CONTROL USING VARIOUS COMBINATIONS OF CONTROLLERS

MOURAD ALLAD, DALILA ACHELI

Key words: Cascade control, Level and flow, Proportional-integral and derivative control (PID), Fuzzy logic control (FLC), Predictive functional control (PFC).

This paper presents all possible combinations between three controllers (PI, PFC and FLC) in order to realise the cascade control strategy. The control strategy is applied on the level and flow apparatus. The control serves to maintain the liquid level in tank at desired value by manipulating the fluid into the reservoir. We have used the level and flow apparatus PUL-2/EV of Elettronica Veneta of Italian company, the LabJack U3 card acquisition and the laptop where we have developed a professional platform MATLAB Guide. In this work, we have shown the various experimental results: PI, PFC and fuzzy logic simple loop and the cascade control strategy for different combinations of controllers. We have also discussed the obtained results of the performance and rejection of disturbances for each combination under similar conditions, and, in conclusion, we have highlighted the importance of the combinations.

1. INTRODUCTION

The industrial application of liquid level control is tremendous, especially in petroleum refineries and chemical process industries. Level control, therefore, is one of the key control system variables in the process industries. The liquid level and flow control in tanks are at the heart of all chemical engineering systems. The objective of the controller in the liquid level control is to maintain a level set point at a given value and be able to accept new set point values dynamically. It is not always possible to control them with classical controllers, the ordinary PID traditional control methods cannot provide satisfactory results. In order to develop the modern control theory, many advanced control strategies are used in the study of system control. The cascade control, which uses different types of controllers, is one of them. An intensive research activity has been devoted to use the cascade control. The following indicated.

The cascade control of dc motor is given by Bhavina *et al*. (2014) using two PID controllers [1]. One master PI controller serves as an outer loop for speed control, and the second slave P controller is used as an inner loop for current control in cascade structure. The control law is implemented on PIC 18F. The authors have concluded that the cascade PID control gives a better response than single PID control. For the current control loop, the P controller eliminates the higher current peak oscillation, enabling to have robustness and a negligible delay, and speed is controlled by PI.

A comparative study between two cascade techniques ((fuzzy (master) – fuzzy (slave)) and (fuzzy- fuzzy neural network (FNN))) applied on the ball and beam system was conducted by Lin *et al*. (2014) [2]. The FNN control parameters are obtained using gradient descent method. The simulation and experimental results illustrate that the proposed FLC-FNN can provide better performance than FLC-FLC. Zhou *et al*. (2013) applied combining predictive PFC and PID control on heat treatment electric furnace [3]. The results obtained from the different simulations show that the cascade PFC-PID control provides satisfactory results when compared with conventional PID control. Pratama *et al*. (2011) used RIG 38-714 plant in order to control the pressure [4]. They opted for cascade control.

The outer loop is the pressure with adaptive network based fuzzy inference system (ANFIS) controller using self tuning regulator (STR). In the inner loop, there is the flow with PI controller. The simulation shows that ANFIS using STR can considerably improve the performance of the system, as a faster rise and settling time is obtained.

The combination design of predictive functional control and PID method (PFC-PID) for liquid level in industrial coking equipment is presented by Zhang *et al.* (2009) in order to maintain the liquid level of a coking fractionating within a set range by manipulating the fluid flow into the coking furnaces, while rejecting the effect of disturbances [5]. The performance of the proposed controller is verified by the real-time application. The PFC-PID provides a better response when compared with traditional PID.

The simulation results of cascade fuzzy logic control are applied by Vasičkaninova *et al.* 2005, 2007 on the distillation column and the chemical reactor [6, 7]. They demonstrate that the fuzzy controllers can be successfully applied as primary and secondary controllers in cascade control and give a better performance.

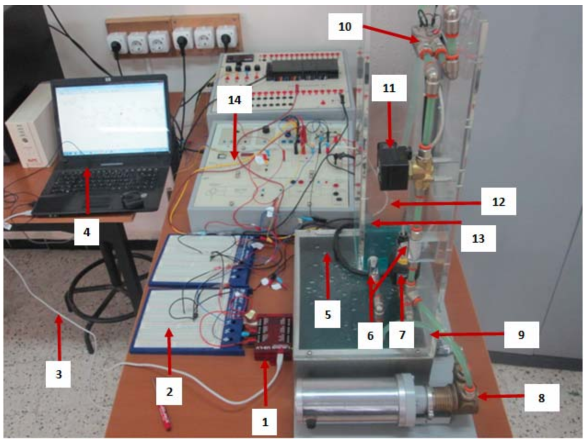

Fig. 1 –Experimental test bench components:
1: LabJack U3-LV, 2: adaptation of the signals, 3: USB cable, 4: laptop, 5: reservoir, 6: hand valve, 7: on/off valve, 8: pump, 9: pipe, 10: flow sensor, 11: proportional valve, 12: tank, 13: level sensor, 14: panel of the level & flow transmitters, supply and control signal.

Boumerdes University, Hydrocarbons and Chemistry Faculty, Industrial Processes Automation and Electrification Department, Boumerdes 35000, Algeria, E-mail:mouradallad@yahoo.fr

This paper is structured in five sections. It begins with a description of the liquid level and flow apparatus presenting its various components (Fig. 1). Second, it presents the identification of the system and explains the PID, PFC and FLC controllers. Third, it discusses the cascade control. Fourth, it shows a real time implementation results. All tests were carried out at control laboratory of Automatic department. Finally, some concluding remarks are given.

2. OPERATING PRINCIPALE

The controller acts on the level control valve (proportional valve). If the signal control is zero, the valve is closed; and if it is maximal, i.e. equal to 5 Volts, the signal of output power amplifier is equal to 24 V. In this case, the proportional valve is totally opened. The opening degree is proportional to the applied voltage.

The measurement signals of the level and flow provide 0 to 2.44 V. The level and flow vary between 0 to 500 mm and 0 to 5 l/min respectively. All the signals are adapted to evolve between 0 to 10 V. The On/Off valve serves to generate a disturbance.

The identified model is never perfect. This imperfection is due to factors like components reliability, errors of measurement and used method, etc. The choice of the identification method and the type of controller is of a crucial importance.

Obviously, the first task was to determine static and dynamic behaviour of the system so to obtain a suitable mathematical model.

The static characteristic is shown in Fig. 2.

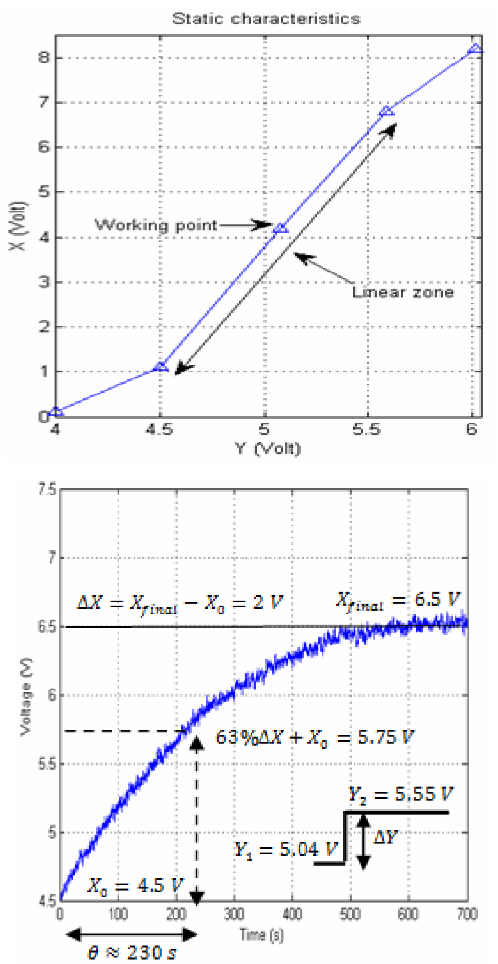

Fig. 2 – Static characteristics and measured step response

The depicted points have been obtained by measuring the steady outputs X (level) for 5 values of input Y (hand control). As can be seen, the system is nonlinear because the static characteristic is not a straight line. The linear zone has been chosen between $Y \in 4.5$ V to 5.6 V for all following control experiments. Finally, the working point value is chosen equal to $Y_1 = 5.04$ V which corresponds to the level voltage $X_0 = 4.5$ V. Subsequently, the step response X for the change of Y from 5.04 V to 5.55 V has been measured and recorded in Fig. 2.

The curve shown in Fig. 2 was approximated by first order system response.

According to this step response, we can determine that:

- Static gain

$$K = \frac{\Delta X}{\Delta Y} = \frac{6.5-4.5}{5.55-5.04} = 3.92 \approx 4. \qquad (1)$$

- Constant time: $\theta \approx 230$ s.

The transfer function can be expressed by:

$$G(p) = \frac{K}{1+\theta p} = \frac{4}{1+230\,p}. \qquad (2)$$

3. CONTROLLERS

3.1. PID CONTROLLER

The anterior investigations, several works have described the PID structure such as series or interacting form, standard or non-interacting form and parallel form. Different methods were used in order to determine PID parameters (Ziegler and Nichols, Broïda, etc). In our case, reference model method is used.

Despite the abundance of sophisticated tools including advanced controllers, the PID controller is still the most widely used in modern industry, controlling more than 95 % of closed-loop industrial processes by referring to Aström and Hägglund (1995) [8].

For parallel PI, the control signal is given by:

$$Y(t) = G_r\, \varepsilon(t) + \frac{1}{T_i}\int_0^t \varepsilon(t)\, dt \qquad (3)$$

By imposing the closed loop transfer function (reference model): $F(P) = \dfrac{C(p)G(p)}{1+C(p)G(p)} = \dfrac{1}{1+\theta_d\, p}$.

The transfer function of controller is:

$$C(p) = \frac{1}{\theta_d\, p G(p)} \rightarrow C(p) = \frac{1+\theta p}{K\theta_d\, p} \qquad (4)$$

$$\text{Parallel PI: } C(p) = G_r + \frac{1}{T_i\, p}. \qquad (5)$$

By similitude of (4) and (5), the parameters of PI are:

$$G_r = \frac{1}{K}\frac{\theta}{\theta_d} \text{ and } T_i = K\theta_d \qquad (6)$$

We assume that: $\theta_d = 28$ s (desired time of closed loop response). The maximum filling time to attain 250 mm when the valve totally open is approximately 33 s.

The proposed method gives the controller parameters:

$$G_r = 2.05 \text{ and } T_i = 1.86 \text{ min } (111.6 \text{ s}).$$

All control signals have saturation because their output values are between 0 to 5 V.

3.2. PREDICTIVE FUNCTIONAL CONTROLLER (PFC)

This section is dedicated to briefly recall the main steps of the predictive functional control scheme used below for the implementation. The principles PFC were established in 1968 and the first applications took place in the early 70's. Richalet developed it in late 80’s for the application. The main concept of the algorithm is presented.

A general description of PFC and its design procedure can be referred to Khadir and Ringwood, 2008; Richalet and O’Donovan, 2009; Richalet *et al.*, 2014 [9, 10, 11].

Consider the first order system:

$$G(p) = \frac{K}{1+\theta p} \tag{7}$$

Step 1. Formulation of the internal model

$$G_M(p) = \frac{K_M}{1+\theta_M p} \tag{8}$$

The model plus zero-order hold (ZOH) gives the following equation:

$$X_M(k) = \alpha X_M(k-1) + K_M(1-\alpha) Y(k-1) \tag{9}$$

$$\alpha = \exp\left(\frac{-T_e}{\theta_M}\right) \tag{10}$$

where T_e is the sample time.

If the function used is step, then:

H : Prediction horizon

$$X_A(k+H) = \alpha^H X_M(k) \tag{11}$$

$$X_F(k+H) = K_M\left(1-\alpha^H\right) Y(k), \tag{12}$$

where X_A and X_F are free and forced responses.

Step 2. X_R is the expression of reference trajectory. H is the coincidence point where the process output X_P is equal to X_R .

$$W(k+H) - X_R(k+H) = \lambda^H \left(W(k) - X_P(k)\right), \tag{13}$$

where:

$$X_R(k+H) = W(k+H) - \lambda^H \left(W(k) - X_P(k)\right), \tag{14}$$

$$T_{ref} = \frac{\text{CLTR}}{3}, \tag{15}$$

with closed-loop time response (CLTR), where λ is given by:

$$\lambda = \exp\left(\frac{-T_e}{T_{ref}}\right), \tag{16}$$

λ – reference trajectory decrement.

Step 3. Predicted output process. The predicted output process with auto-compensation is given by:

$$\hat{X}_P(k+H) = X_M(k+H) + \left(X_P(k) - X_M(k)\right) \tag{17}$$

Step 4. Law control. At the coincidence point H , we want:

$$X_R(k+H) = \hat{X}_P(k+H) \tag{18}$$

$$W(k+H) - \lambda^H \left(W(k) - X_P(k)\right) = X_M(k+H) - X_M(k)$$

In the case: $W(k+H) = W(k)$ (19)

$$W(k)\left(1-\lambda^H\right) - X_P(k)\left(1-\lambda^H\right) + X_M(k)\left(1-\alpha^H\right) = K_M\left(1-\alpha^H\right) Y(k) \tag{20}$$

The final law control is:

$$Y(k) = \frac{\left(W(k) - X_P(k)\right)\left(1-\lambda^H\right)}{K_M\left(1-\alpha^H\right)} + \frac{1}{K_M} X_M(k). \tag{21}$$

3.3. FUZZY LOGIC CONTROLLER (FLC)

A fuzzy logic controller has three main elements, which are: fuzzification, rule base and Inference engine and defuzzification.

In fuzzy control, two inputs for the system are chosen. They are an error ε and an error derivative $\dot{\varepsilon}$. The output of the system is a voltage that is sent to a proportional valve. The block diagram of a fuzzy controller used is shown in Fig. 3 [12, 13, 14], with K_ε and $K_{\Delta\varepsilon}$ – input scaling gains. K_γ – output scaling gain.

The values of K_ε, $K_{\Delta\varepsilon}$ and K_γ are determined to satisfy the performance ($\theta_d = 28$s). The addition of precedent control signal $Y(t-1)$ is used only for the control of the liquid level (Fig. 3), or master controller, but not for the flow controller. A fuzzy logic attitude controller has been developed with five fuzzy labels: Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Big (PB). Also, 9 control rules were used (Table 1) in our application.

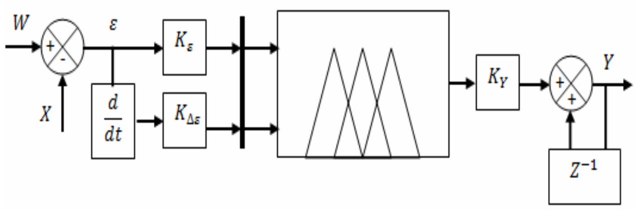

Fig. 3 – Block diagram of a PD-type FLC.

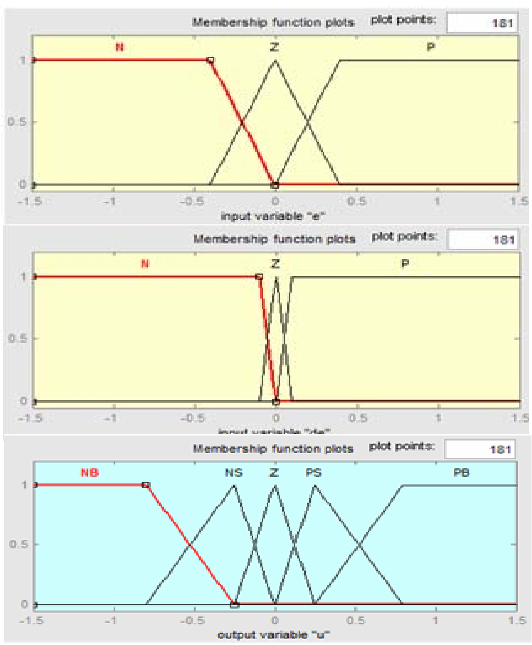

Fig. 4 – Membership functions.

Table 1

Fuzzy rules table

$d\varepsilon$ \ ε	N	Z	P
N	NB	NS	Z
Z	NS	Z	PS
P	Z	PS	PB

Figure 4 shows the graphics of fuzzy logic membership functions used for this application.

The different parameters of scaling factor of fuzzy logic used for level and flow loops are given in Table 2.

4. CASCADE CONTROL

Cascade control is the combination of two controllers, where output signal from first controller forms the setpoint of the second (Fig. 5).

Both inner and outer control loop are formed with an individual feedback controller. The outer loop controller is also known as the master or primary controller (C_1), and the inner loop controller is known as the slave or secondary controller (C_2). The major benefit using cascade control is the rejection of any disturbance by the secondary controller before the occurrence of this disturbance on the primary controlled output.

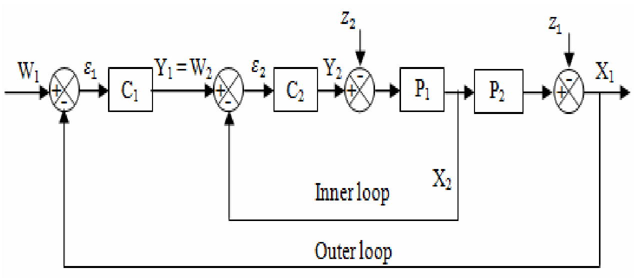

Fig. 5 – Cascade block diagram.

4.1. PARAMETERS OF THE MASTER AND SLAVE CONTROLLERS

The parameters of slave controller (flow) were obtained according to the various experimental test and their results. However, the master controller (level) parameters were obtained after process identification. For example, when PID controller is used, Zeigler & Nichols, Broïda or reference model methods are used in order to obtain the desired performance.

5. EXPERIMENTAL RESULTS AND DISCUSSIONS

5.1. DIFFERENT RESPONSES UNDER PI, PFC AND FUZZY CONTROLLERS (SIMPLE LOOP)

The step responses (level) of the three controllers are shown below. Figure 6 represents the response characteristics for each controller. It can be seen that fuzzy logic gives a better response than the others do, *i.e.* PI, PFC. It can be verified that it is faster to reach a steady state. Furthermore, for the value of settling time, fuzzy logic controller gives 69 s less than the PI settling time (85 s) and PFC (120 s). At a time of 150 s, we opened the On/Off valve for 4 s in order to create a disturbance. We noticed that the fuzzy logic controller acts quickly and rejects this disturbance after 50 s. However, the PI and the PFC responses take 100 s. After this elapsed time, the overshoot apparition is approximately 6 %, which will disappear after 100 s.

The different parameters of controllers are shown in Table 2.

Table 2

Different parameters of master and slave controllers

PI1 (level)	$G_{r1} = 2.05$	$T_{i1} = 111.6$ s	$T_{S1} = 0.2$ s		
PFC1 (level)	$T_{ref1} = 28$ s	$H_1 = 90$ s	$K_{M1} = 3.1$	$\theta_1 = 230$ s	$T_{e1} = 0.2$ s
Fuzzy1 (level)	$K_{\varepsilon 1} = 0.002$	$K_{\Delta\varepsilon 1} = 0.012$	$K_{Y1} = 4.7$		
PI2 (flow)	$G_{r2} = 1$	$T_{i2} = 2.4$ s	$T_{S2} = 0.1$ s		
PFC2 (Flow)	$T_{ref2} = 1$ s	$H_2 = 3$ s	$K_{M2} = 2$	$\theta_2 = 2$ s	$T_{e2} = 0.1$ s
Fuzzy2 (Flow)	$K_{\varepsilon 2} = 0.018$	$K_{\Delta\varepsilon 2} = 0.01$	$K_{Y2} = 1$		

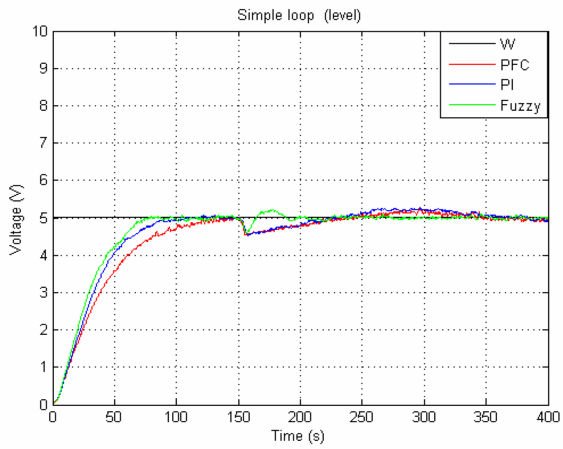

Fig. 6 – Step response of the closed loop level control system.

5.2. DIFFERENT RESPONSES UNDER CASCADE CONTROL

Various parameters of slave controllers using three control laws are shown in Table 3.

Figure 7, having different steps, shows a good tracking; and the flow attains the desired value quickly. It can be said that the choice of different parameters is adequate.

The real time of cascade control results are presented below for each combination (Figs. 7, 8).

In order to examine the performance (desired time, settling time and rise time), all values have been deduced and shown them in Table 3. It can be seen that a combination of (PI-fuzzy) gives the smallest desired time: 27.89 s. The combining of (fuzzy-fuzzy) conducts to the fastest response characteristics: a settling time equal to 65.7 s and a rise time equal to 44.18 s.

So as to characterise the setpoint responses, four basic criteria are used: integral of absolute error (IAE), integral of squared error (ISE), integral of time multiply absolute error (ITAE) and integral of time multiply squared error (ITSE). For any possible criteria, the best response corresponds to the minimum value of the chosen criterion.

On the basis of Table 3, it can be seen which combination gives the minimal value: IAE (fuzzy-PFC) = 37.27, ISE (PI-fuzzy) = 23.22, ITAE (fuzzy-PFC) = 1.72e+003, ITSE (fuzzy-PFC) = 362.47.

The robustness test (reject of disturbance) is an important step. For that, we have generated a disturbance by opening the On/Off valve during 4 s at 250 s in all cases.

According to Fig. 8, in the moment when we apply a disturbance, the master and slave signals control increase dramatically in order to open more proportional valve. In other words, the controllers are very sensitive to the variations of the signal measurement. This is especially noticed when the master controller is fuzzy logic. Contrary to simple loop, an absence of overshoot after the application of disturbance is noticed for all combinations, but except the case when the master controller is fuzzy logic. This can be explained by that when we apply the disturbance, a slight overshoot appears for a period of time and subsequently disappear.

Table 3

Transient parameters responses and comparison of the practical results by IAE, ISE, ITAE and ITSE

Master	Slave	θ_d	ts (98%)	tr (10~90%)	IAE	ISE	ITAE (× 10^3)	ITSE
PI	PI	32.1 s	100 s	55 s	42.84	28.14	2.47	442.90
PI	Fuzzy	27.89 s	75.7 s	49 s	40.28	23.22	3	372.37
PI	PFC	33.31s	113 s	62.13 s	45.27	29.12	2.46	489.55
Fuzzy	PI	33.27 s	75.8 s	51.9 s	40.99	29.51	1.86	457.61
Fuzzy	PFC	30 s	66.2 s	44.87 s	37.27	26.49	1.72	362.47
Fuzzy	Fuzzy	31.52 s	65.7 s	44.18 s	40.57	28.05	2.48	416.09
PFC	PI	34.23 s	115 s	65.07 s	46.34	29.12	2.55	515.96
PFC	PFC	35.38 s	121 s	71 s	48.89	30.37	2.80	550.12
PFC	Fuzzy	28.88 s	75.7 s	48.42 s	40.57	25.39	2.71	395.70

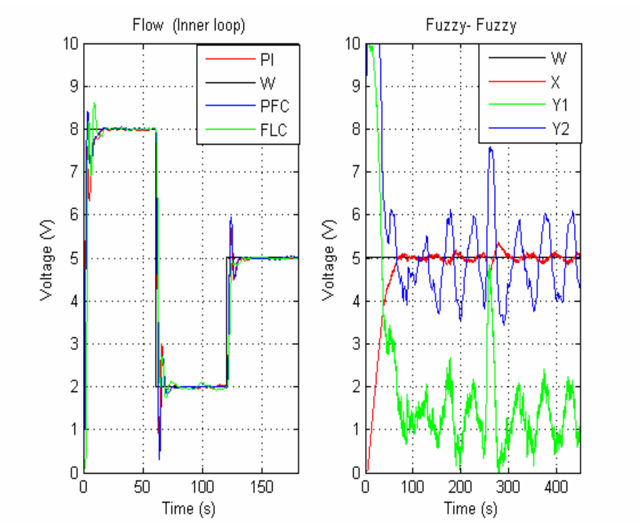

Fig. 7 – Flow control under PI, PFC and fuzzy logic controllers and liquid level control under (fuzzy-fuzzy) controllers.

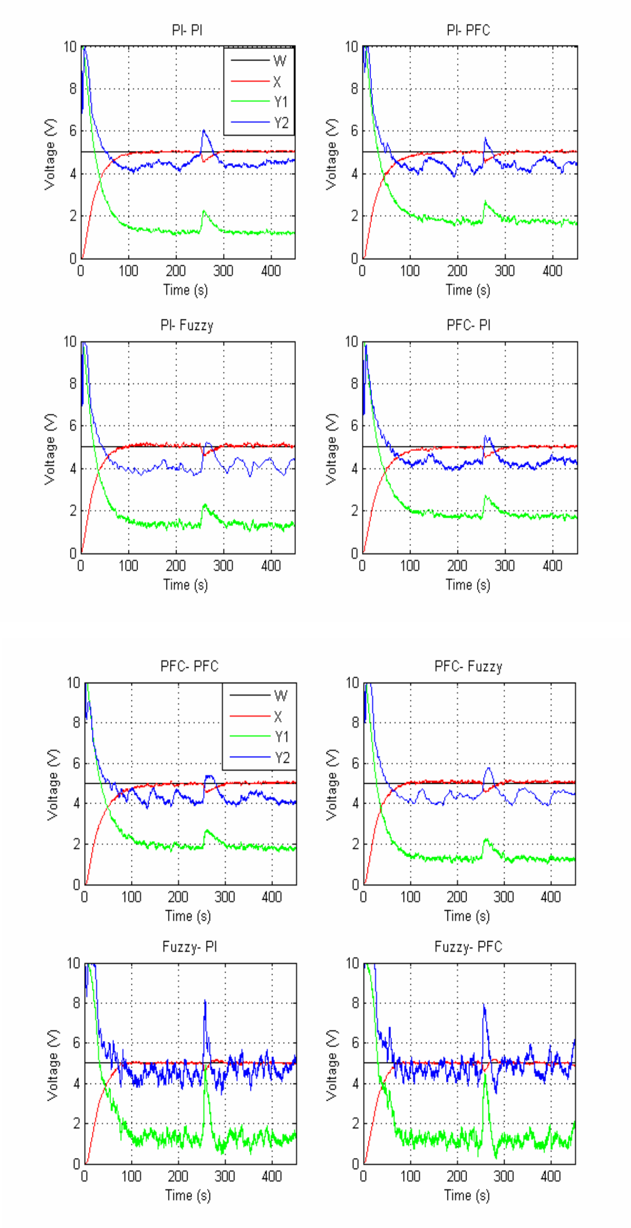

Fig. 8 – Liquid level control under different controllers.

6. CONCLUSION

In this study, a cascade control strategy is presented. We have chosen to manipulate the liquid level and flow system because of their availability at our laboratory. The controlled variable in the outer loop is the liquid level, and in the inner loop is the flow. The real time application of the different cases with three controllers led to verify and deduce the performance of each combining block diagram.

In most research studies, the authors present a comparative study between conventional control PID and one cascaded control scheme simulation, and sometimes a real time application is shown. Our present work, for its part, aims to contribute to a clarification of the obtained results of the various systems such as motor, digester, bioreactor, gas turbine, compressor, etc.

The characteristic of each cascade control combination is presented. We noted the best disturbance rejection if the master controller is fuzzy logic. The experiment shows that, the (fuzzy-fuzzy) combination improves the rise time and the settling time. Furthermore, the smallest desired time is guaranteed by (PI-Fuzzy) combination. In order to determine the performance criterion values, we refer to Table 3.

To sum up, despite the model uncertainty, the cascade control strategy has been demonstrated to provide the satisfactory performance and robustness results in the control of the liquid level. Consequently, it constitutes a very interesting strategy for control systems.

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