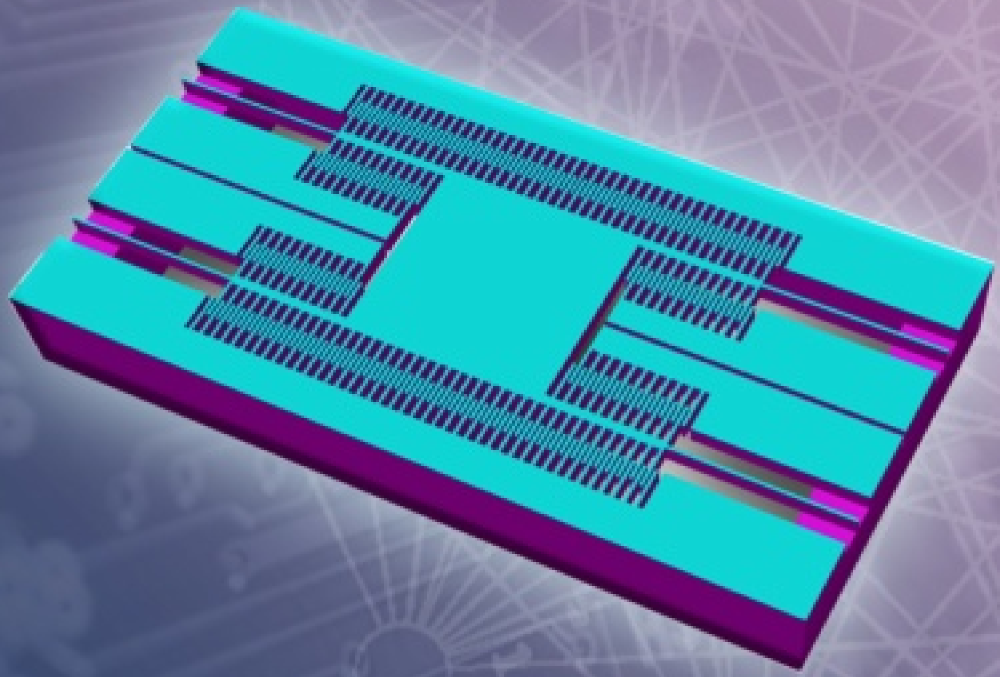
ISSN 1726-5479

SENSORS & TRANSDUCERS

12/12
vol. 17
Special



Sensors and Intelligent Systems

International Frequency Sensor Association Publishing

Sensors & Transducers

Volume 17, Special Issue
December 2012

www.sensorsportal.com

ISSN 1726-5479

Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA).
Available in electronic and on CD.

Sensors & Transducers Journal

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Volume 17
Special Issue
December 2012

www.sensorsportal.com

ISSN 1726-5479

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Sensors & Transducers Journal, Vol. 17, Special Issue, December 2012, pp. 110-124

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

Development and Implementation of Hybrid Controllers for Flow Control Application

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Received: 29 September 2012 /Accepted: 29 October 2012 /Published: 18 December 2012

Abstract: The main objective of this paper is to design and implement Hybrid Controllers, which consist of Adaptive Fuzzy PID Controller (AFPIDC) and Adaptive Neuro-Fuzzy Inference System (ANFIS) for flow control application. The implementation has been accomplished onto mobile pilot plant for flow control process unit. Currently, controlling and tuning is done via KONICS PID controller that is mounted on the local control panel. However, it is unable to provide adequate response and need to be manually tuned. Thus, the AFPIDC and ANFIS are developed and implemented as alternatives to the existing PID controller with the capability of Human Machine Interface (HMI) using MATLAB/Simulink. For AFPIDC, Fuzzy Logic reasoning is used to produce adaptive PID gain while for ANFIS; Fuzzy Logic will be tuned by using Artificial Neural Network (ANN) algorithm. Overall, the control performances for PID, AFPIDC and ANFIS will be compared and analyzed for flow control application. *Copyright © 2012 IFSA.*

Keywords: Adaptive fuzzy PID controller, ANFIS, Flow control, Fuzzy logic controller, Artificial neural network, PID controller.

1. Introduction

Control refers to those things that maintain a desired system output by altering the flow of energy from the source to the output device. Thus, control will provide influences to the final outcome of a process or operation. The fundamental of any control system is the ability to measure the output of the system and take any necessary action for the correction if the measured values deviate from the desired values. Basically, a feedback control system will have several elements such as controller, final element (control valve), plant and sensors [1].

PID controller is one of the conventional controllers that are widely used in process industries due to its simplicity and effectiveness for linear system, especially for first and second order system [18]. Unfortunately, it cannot function well for non-linear systems. In order to find a controller that can give good performances for both situations, two types of hybrid controllers which are AFPIDC and ANFIS will be designed and implemented.AFPIDC is one of the new hybrid controllers that the PID parameters are adjusted by fuzzy rules in real-time [4]. The Fuzzy Logic Controller (FLC) is used to produce three auxiliary outputs which are proportional, integral and derivative operating units [$\Delta e_p(t)$, $\Delta e_i(t)$ and $\Delta e_d(t)$]. The inputs of the controller are composes of error, *e* and rate change of error, *delE*. The main input signal is the weighted system error and the weights are the additional PID parameters with fixed gains tuned in a traditional way. Since the output of the fuzzy logic controller is changeable, the gain of the controller is adjusted implicitly and adaptively. ANFIS is a combination between Fuzzy Logic and ANNwhichis capable to generate expert system by itself. By using ANN learning ability, ANFIS provide a method for the fuzzy logic to learn information about the data set in order to compute the best membership parameters that can track the given input – output data [18]. Simply put, ANN is a tuning method for FLC.

2. Problem Statement

The pilot plant currently uses a PID controller which is mounted locally on the local control panel for controlling purposes. However, the existing PID controller exhibit slow settling time and rise time and it will worsen when the system become non-linear due to the presence of disturbances. In addition, the designer needs to do mathematical calculations in order to fine tune the PID controller and it will have poor performance if the parameters are improperly tuned. Besides that, the pilot plant does not have DCS – HMI interface system on the local control panel for monitoring and recording of the process control. This has made the monitoring, controlling and tuning of the flow control application of the pilot plant to be more difficult and impractical. Therefore, in order to overcome these problems, new hybrid controllers; AFPIDC and ANFIS are proposed so that the new controllers hopefully will provide better control performance and will be more robust. In addition the HMI will be developed via MATLAB/Simulink for monitoring, controlling and tuning purposes.

3. Objectives

Some objectives have been outlined to support the aim of this research. Amongst others is to investigate, design and develop AFPIDC and ANFIS for flow control pilot plant. Besides that, the idea is to make some analysis and comparison between PID, AFPIDC and ANFIS in terms of their control performance.

It is good to highlight that all investigation will be based on the Mobile Pilot Plant and MATLAB/Simulink as the main software. A USB Data Acquisition card will be utilized in receiving controlled variables from the plant and transmitting manipulated variables to the pilot plant.

4. Literature Review

2.1. Adaptive Fuzzy PID Controller (AFPIDC)

Adaptive Fuzzy PID Controller (AFPIDC) is one of the hybrid controller that combine both PID controller and Fuzzy Logic controller (FLC). FLC is used to produce three operating units (proportional, integral and derivative operating units) that make the PID gains proposed to be adapted implicitly [4]. It can be best illustrated as in Fig. 1.

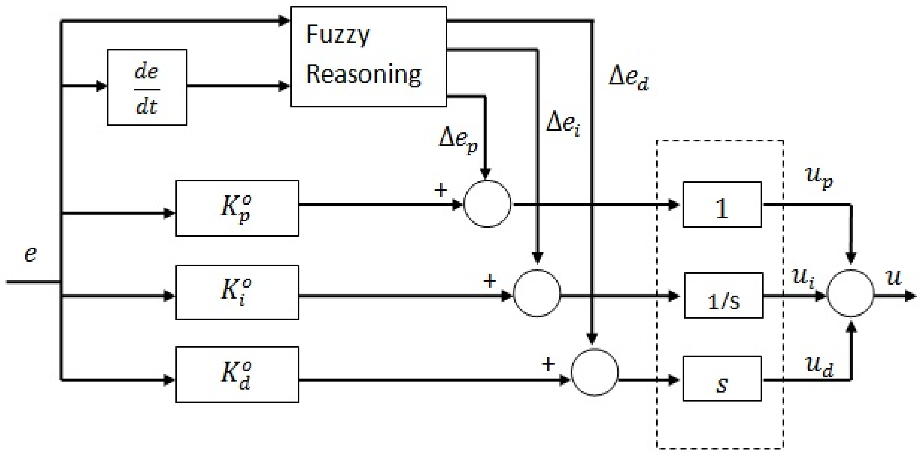

Fig. 1. Proposed AFPIDC.

The initial PID controller can be equivalently represented as:

$$u^0(t) = K_p^0 e(t) + K_i^0 \int_0^t e(\tau)d\tau + K_d^0 de(t)/dt \quad (1)$$

The parameters in Equation 1 which are K_p^0, K_i^0 and K_d^0 are time invariant constants where it is the initial PID gain obtained earlier. The output of initial PID gain is $u^o(t)$.

Then using Fuzzy Logic controller, the output of the FLC is the adaption of PID gain as:

$$\Delta u(t) = \Delta e_p(t) + \int_0^t \Delta e_i(\tau)d\tau + \frac{d[\Delta e_d(t)]}{dt} \quad (2)$$

Finally, adaptive Fuzzy PID controller (AFPIDC) uses the combination of initial PID gain from Equation 1 with the adaptive PID gain from Equation 2.

$$u(t) = [K_p^0 + \Delta e_p]e(t) + \int_0^t [K_i^0 + \Delta e_i(\tau)]e(\tau)d\tau + \frac{d[K_d^0 + \Delta e_d(t)]e(t)}{dt}$$

$$u(t) = \Delta u(t) + u^0(t) \quad (3)$$

From Equation 3, the output of initial PID controller gain ($u^o(t)$) and output of FLC which is adaptive PID gain (Δu(t)) will be summed together to produce main output of the AFPIDC which is u(t). Thus, the implicit adaption approach is not to make the parameters of PID controller adaptive but produce adaptively a series of signals in such a way that the PID parameters K_p^0, K_i^0 and K_d^0 is implicitly adaptive [3].

2.2. Adaptive Neuro-Fuzzy Inference System (ANFIS)

Adaptive Neural-Fuzzy Inference System (ANFIS) was developed by Roger Jang in 1993. It is a combination between Fuzzy Logic and Artificial Neural Network (ANN). Below is the architecture for ANFIS controller.

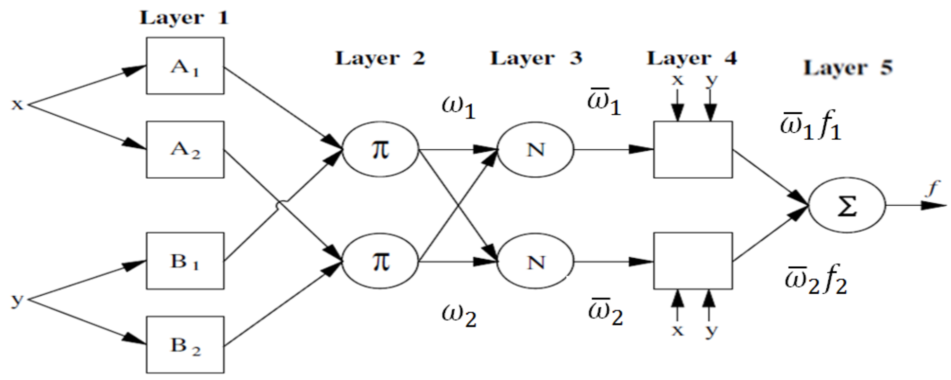

Fig. 2. ANFIS Architecture.

The circular nodes represent nodes that are fixed whereas the square nodes have parameters to be learnt / adjusted. This model will provide:

- RHS (*consequent parameters*) tuning by implementing the first order Takagi-Sugeno fuzzy logic as a network;
- LHS (*premise parameters*) tuning by using back-propagation algorithm.

The above system has x and y as inputs while *f* is the output function. The system contains two rules of Takagi-Sugeno type.

Rule 1: *If* x *is* A_1 *and* y *is* B_1, *then* $f_1 = p_1x + q_1y + r_1$
Rule 2: *If* x *is* A_2 *and* y *is* B_2, *then* $f_2 = p_2x + q_2y + r_2$

Each node of each layer in the ANFIS structure has same function family as described below:

Layer 1

The output of each node is:

$$\begin{aligned} O_{1,i} &= \mu_{A_i}(x) \qquad for\ i = 1,2 \\ O_{1,i} &= \mu_{B_{i-2}}(y) \qquad for\ i = 3,4 \end{aligned} \tag{4}$$

$O_{1,i}(x)$ is the membership degree for x and y inputs. The membership functions can be any shape but for illustration purposes, bell shaped function will be used which is given by:

$$\mu_A(x) = \frac{1}{1 + \left| \frac{x - c_i}{a_i} \right|^{2b_i}}, \tag{5}$$

where a_i, b_i, c_i are parameters to be adjusted. These are the *premise parameters*.

Layer 2

Every node parameters in this layer is fixed. This is where the t-norm is used to 'AND' the membership degree.

$$O_{2,i} = w_i = \mu_{A_i}(x)\mu_{B_i}(y), \quad i = 1,2 \tag{6}$$

Layer 3

Layer 3 also contains fixed nodes which calculate the ratio of the firing strengths of the rules:

$$O_{3,i} = \overline{w}_i = \frac{w_i}{w_1 + w_2} \tag{7}$$

Layer 4

The nodes in this layer are adaptive and perform the consequent of the rules:

$$O_{4,i} = \overline{w_i} f_i = \overline{w_i}(p_i x + q_i y + r_i) \tag{8}$$

The parameters in this layer (p_i, q_i, r_i) are to be determined and are referred to as the *consequent parameters*.

Layer 5

There is a single node here that computes the overall output [17, 18]:

$$O_{5,i} = \sum_i \overline{w_i} f_i = \frac{\sum_i w_i f_i}{\sum_i w_i} \tag{9}$$

3. Hardware and Tools

- PcASimExpert Mobile Pilot Plant SE 231B-21 - Flow Control and Calibration Process Unit
- A desktop
- Data Acquisition Card (DAQ); USB-1208FS
- Matlab with Data Acquisition, Fuzzy Logic and ANFIS Toolboxes

Connection between pilot plant with the PC using DAQ card is shown in Fig. 3.

4. Controllers Development

4.1. Designing AFPIDC

Fuzzy Inference System (FIS) for the AFPIDC is designed using Fuzzy Logic Toolbox in MATLAB/Simulink. Using Mamdani approach, there are two inputs to the FIS which are error, *E* and rate of change of error, *delE*. The FIS will produce three outputs as shown in Fig. 1. The three outputs [$\Delta e_p(t)$, $\Delta e_i(t)$, $\Delta e_d(t)$]will be added with the conventional PID gains which are [K_p^0, K_i^0, K_d^0].

The output of the controller is the control signals to the control valve which is the manipulated variable, *mv*. The input – output relationships are used to develop the IF-THEN rules for the fuzzy inference system (FIS). There are 49 rules created using Fuzzy Logic reasoning for each of the FIS. However, the rules can be made larger as it will ensure better control performance with better accuracy even when there are smaller errors. The relationship between inputs and output are shown in Tables 1 and 2.

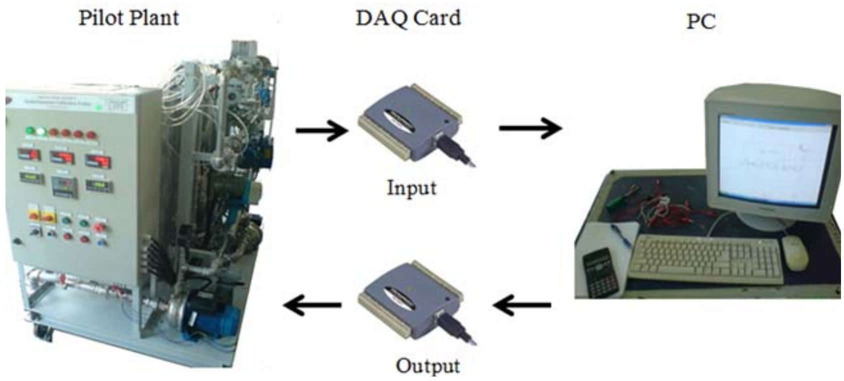

Fig. 3. Plant Setup.

Table 1. FIS for adaptive Proportional gain.

delE \ E	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PM	Z	PS	PS	Z
NM	PB	PB	PM	Z	PS	Z	Z
NS	PM	PM	NM	Z	Z	NS	NM
Z	PM	PS	PS	Z	NS	NM	NM
PS	PS	PS	Z	Z	NS	NM	NM
PM	Z	Z	NS	Z	NM	NM	NB
PB	Z	NS	NS	Z	NM	NB	NB

Table 2. FIS for adaptive Integral gain.

delE \ E	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NM	Z	Z
NM	NB	NB	NM	NM	NS	Z	Z
NS	NM	NM	NS	NS	Z	PS	PS
Z	NM	NS	NS	Z	PS	PS	PM
PS	NS	NS	Z	PS	PS	PM	PM
PM	Z	Z	PS	PM	PM	PB	PB
PB	Z	Z	PS	PM	PB	PB	PB

FIS for Δe_d will be considered as zero because for this project, the Derivative operating unit is not needed. The reason for this is because the flow control application is the fastest control application than pressure, level and temperature control application. The derivative action will provide the controller rapid and faster response to compensate the error. Therefore for flow control application, it does need to have derivative action as it does not have a capacity to be filled before it can respond to changes given. Thus, for this project, the PID controller is actually PI controller without Derivative action to avoid unstable controller response.

The inputs, *E* and *delE*, and output, *MV* has seven membership functions i.e. negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM) and positive big (PB). From the Fig. 5, the range for the first input, *E*, is [-50 50] following the range of operation for Orifice Flow meter in the plant which is set from 15 *l/min* to 45 *l/min*. The valve operation is non- linear in nature as can be seen from Fig. 4 will provide best linearity from 29 % to 70 % of opening.

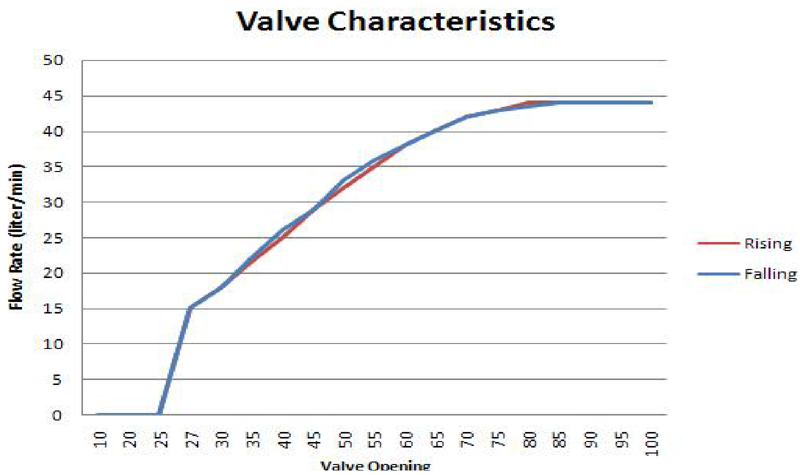

Fig. 4. Control Valve Characteristic for Orifice Flow Meter.

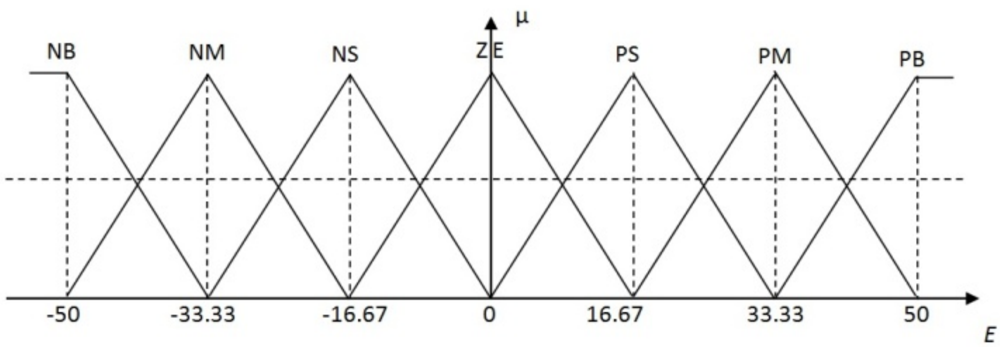

Fig. 5. Membership Function for error, *e.*

The error would not exceed ±20 *l/min*, because the largest set point change can only be ±20 *l/min.* For the second input in Fig. 6, *delE*, the range is chosen at [-20 20] because during in the empirical modeling stage, the change in error is found to be averaging around ±20 *l/min* when there is a step change in the set point.

Meanwhile for the output, the range is [-0.2 0.2] which can be seen in Fig. 7. The output of the controller will be accumulated and added together with the value of initial PID gain before it is fed to the control valve. The output range must not be too large as it will provide too aggressive response that caused the control to be unstable and not too small as it will not have enough "kick" and slower response.

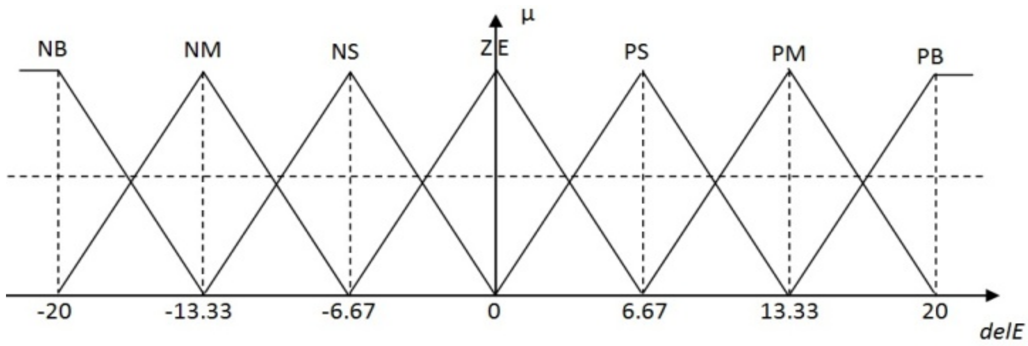

Fig. 6. Membership Function of *delE.*

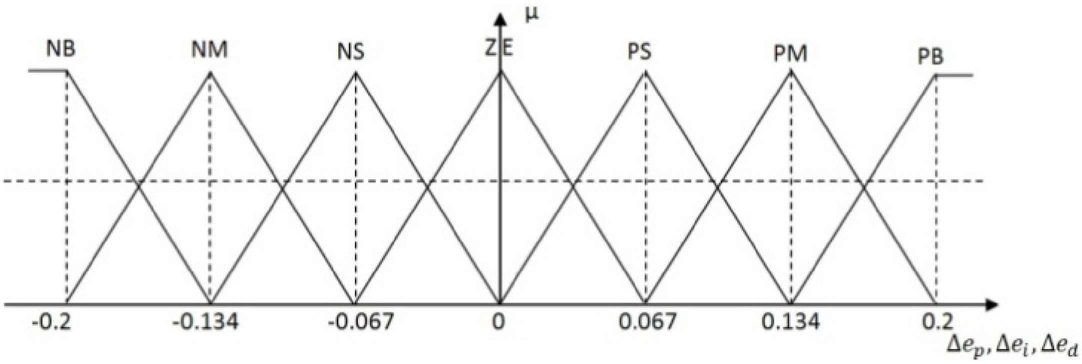

Fig. 7. Membership Function of Output.

Meanwhile, the FIS for each $\Delta e_p(t)$, $\Delta e_i(t)$, $\Delta e_d(t)$are set based on a few rules [4, 5]:

1) If |E| is larger, then Δe_p should be larger meanwhile Δe_i should be limited to 0 or smaller to avoid the system appearing large overshoot.
2) If |E| is moderate, then Δe_p and Δe_i should be moderate.
3) If |E| is smaller, then Δe_p should be smaller and Δe_i should be larger for better steady state performance.

Meanwhile for *delE,* usually Δe_d will be changed for faster or slower response of controller but flow response is a fastest response than other applications, so Δe_d is left to be zero to avoid unstable response of controller.

4.2. Designing ANFIS

For the ANFIS controller development, the author had used ANFIS Editor Graphical User Interface (GUI) which can be access by using *anfisedit* command (Fig. 8). The controller has two inputs and one output. The inputs are from Set Point and Error of the process while the output is the controller response. Data training was obtained based on the PI controller performance. In order to make sure the ANFIS controller can operate accurately, the training data set which is obtained from the PID controller should possess sufficient operational range including the maximum and minimum values for input-output variables [17]. In addition, to make sure the ANFIS controller can be controlled with various inputs, the data training was obtained by setting the input of PID controller to be random input and the operating range between 15 *l*/min to 45 *l*/min.

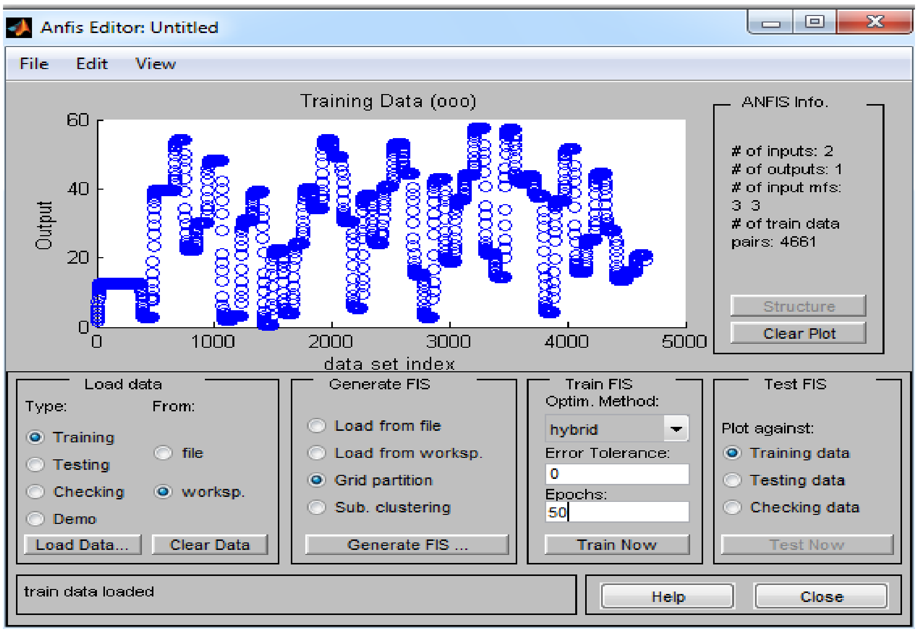

Fig. 8. ANFIS Editor GUI.

The steps for designing the ANFIS controller are as follow:
1. Generated training data set is loaded to ANFIS Editor from workspace.
2. The Fuzzy Inference System (FIS) was generated based on Grid partition. The parameters for both inputs are as below:
• Number of MF = 9 for each input
• Input MF type = Triangle
• Output MF type = Linear
3. For the training process:
• Optimization method = hybrid
• Error tolerance = 0
• Epochs = 50

Since there is no standard method to find the optimum value for epochs, a trial and error procedure was used.

The developed AFPIDC and ANFIS will be implemented to control the operation of the pilot plant and the performances for those controllers will be compared with PID controller. The implementation is done via two data acquisition card USB1208FS connected between desktop to Control Valve as output and from Orifice Flow Meter as input. The flow control operation will be done by using MATLAB/Simulink with Data Acquisition, Fuzzy Logic and PID Controller toolboxes [6].

Simulink model circuit for the implementation of each controller (PID, FLC and AFPIDC) is illustrated in Fig. 9. Some of the features of the Simulink model used for are:

a) DCS- like HMI feature with scopes to show real time data for PV, MV and SP
b) User friendly approach where the operator can input the set point and change from auto to manual easily
c) Engineering Units for SP and PV are used in liter per min and MV with percentage of opening
d) Data can be collected over a very long period of time and saved to the workspace or file.
e) Gaussian filter used to filter noise in the signal obtained from Flow Meter.

f) For FLC and AFPIDC, the controller includes a memory block to act as an accumulator that adds up the controller output over time.

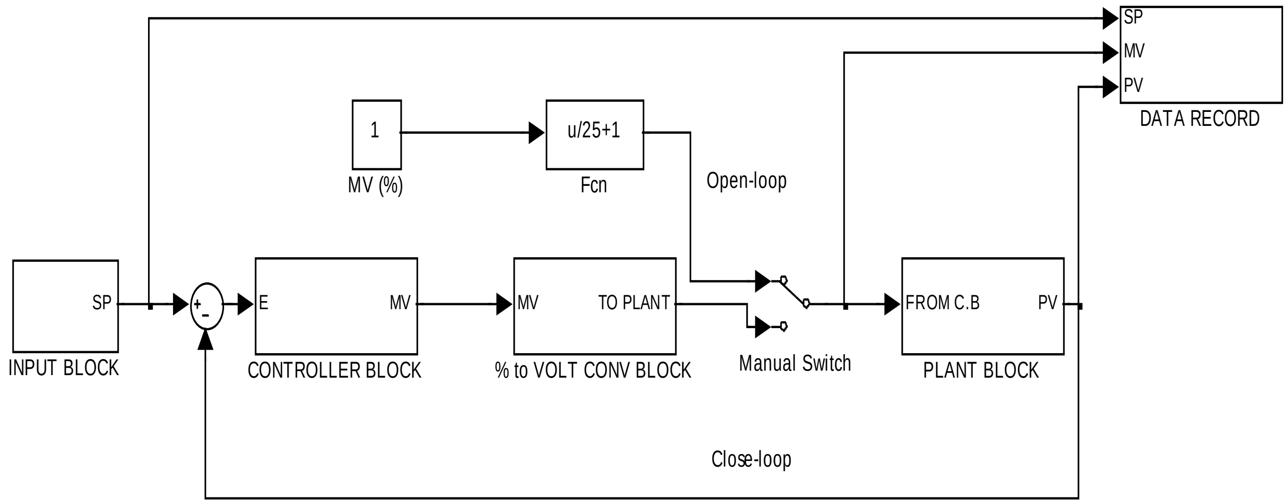

Fig. 9. Simulink Model for Controller Implementation.

5. Result and Analysis

5.1. Controllers' Response

To evaluate the robustness of the controller, all controllers have been subjected to random set point changes using the "uniform random number" block in Simulink. Since the operating range of the plant is set from 15 *l/min* to 45 *l/min.* with an interval of 20 seconds for PID and AFPIDC while 3 seconds for ANFIS. This shall provide the controller sample time to settle to steady state with each set point changes. Below are the results for three controllers for random set point changes.

From the result of each controller's response due to random set point change, it is obvious that the best controller is ANFIS followed by AFPIDC and PID controller. Generally, hybrid controller response will provide faster response in terms of rise time and settling time with zero steady state error is better than PID controller (Fig.10). So, by using hybrid controllers such as AFPIDC and ANFIS, it can be seen that it provides better control performance than PID controller as seen in Fig. 11 and Fig. 12.

A more detailed study of the control performance is explained using the step change set point as input. All three of the controllers are subjected to the same conditions and a set point change from 25 *l/min* to 40 *l/min* is introduced to the system.

From the results shown in Fig. 13, 14 and 15, the control performances show that the hybrid controllers show better performance than PID controller. This is due to the AFPIDC and ANFIS provide better settling time, smaller integral of absolute error (IAE), smaller MV overshoot. The summary of the result analysis for three controllers (PID, AFPIDC and ANFIS) is shown in Table 3.

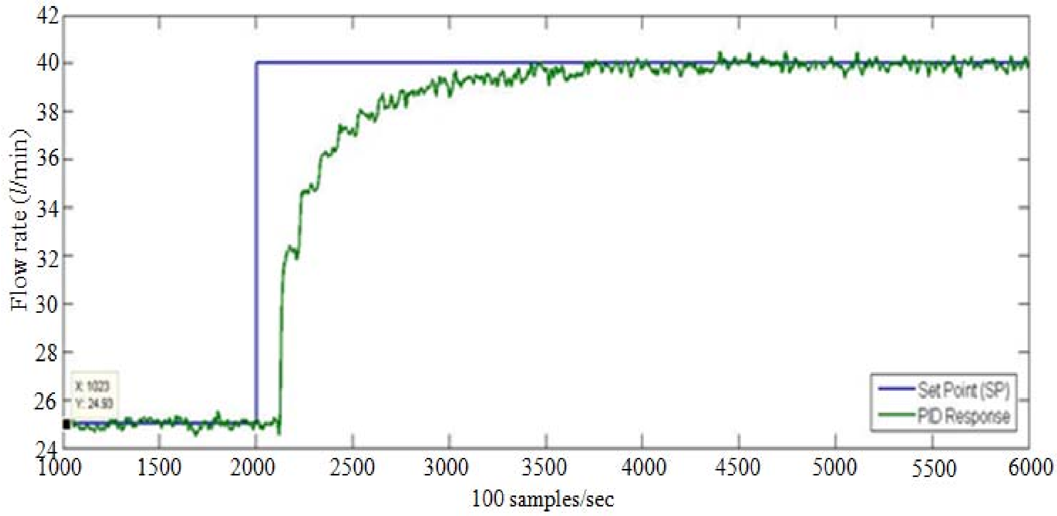

Fig. 10. PID Response to Random Set Point Input.

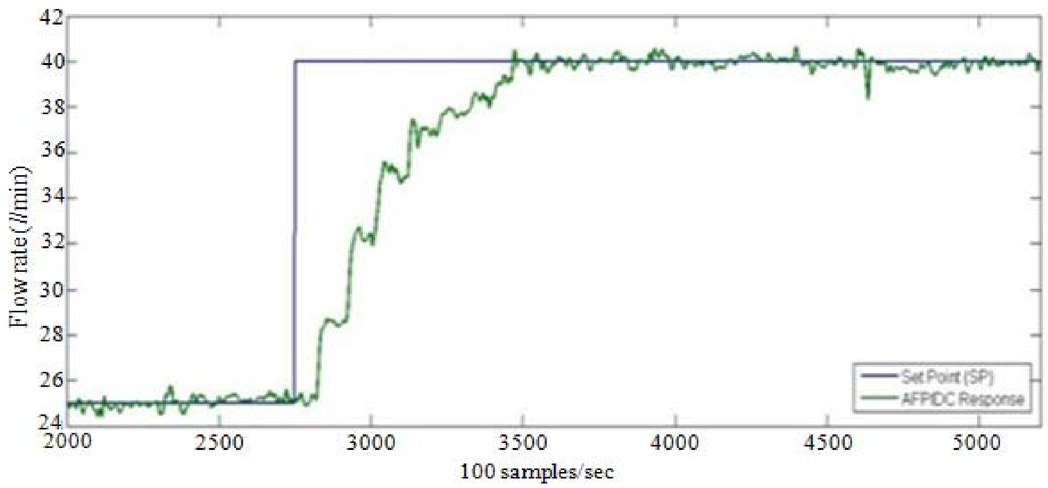

Fig. 11. AFPIDC Response to Random Set Point Input.

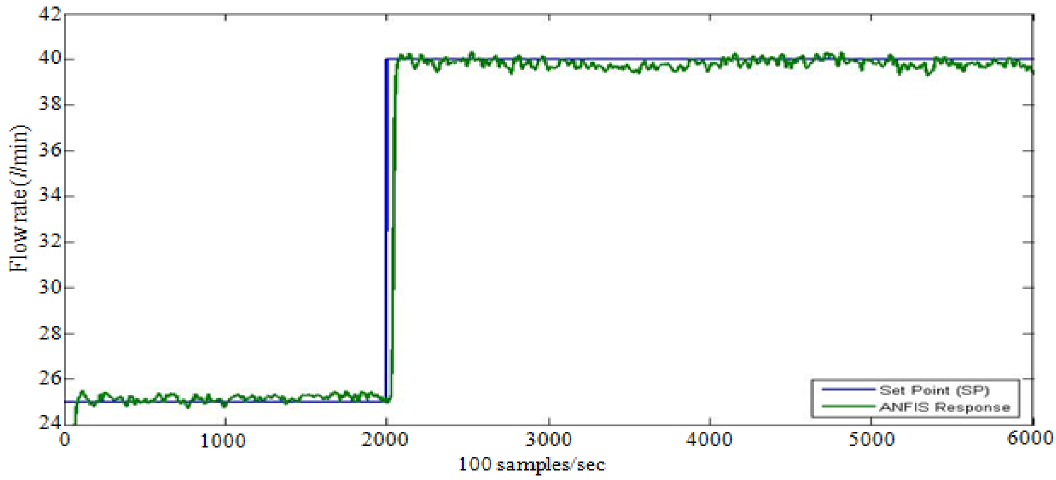

Fig. 12. ANFIS Response to Random Set Point Input.

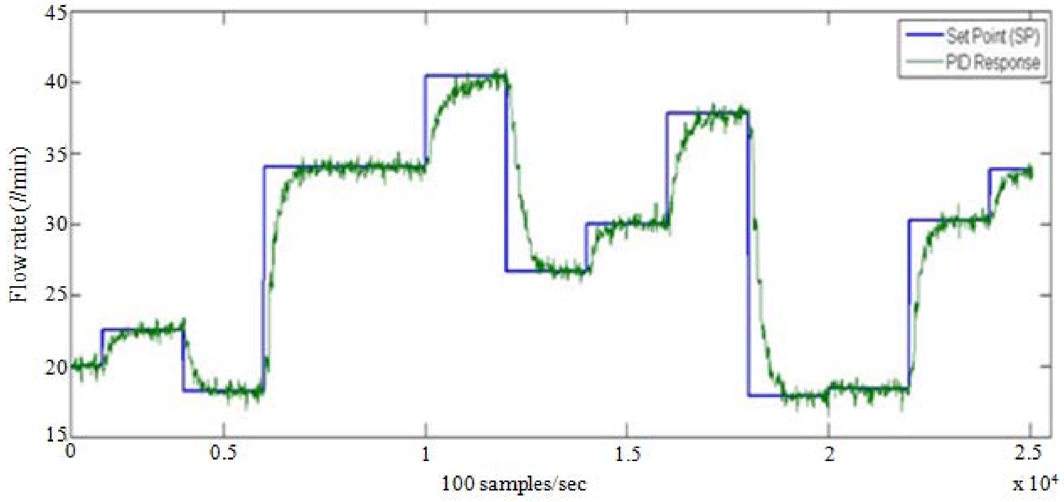

Fig. 13. PID Response to Step Input.

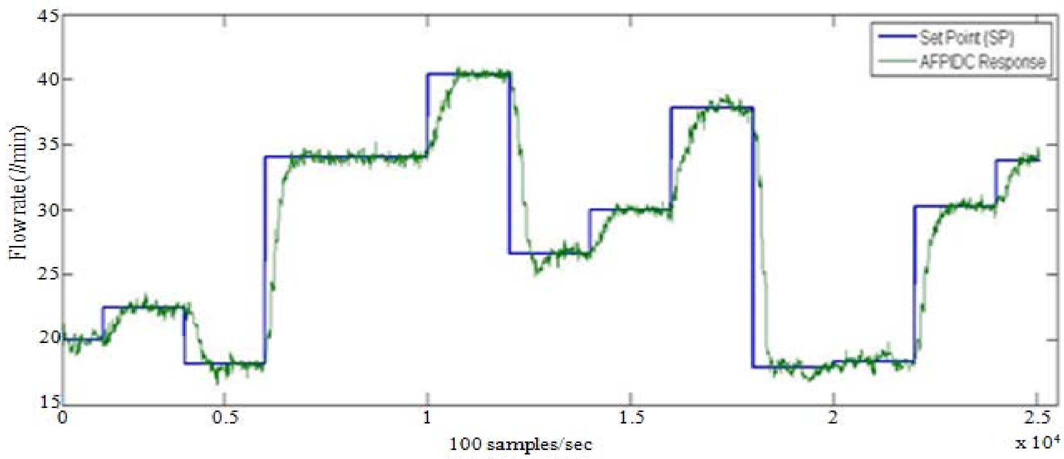

Fig. 14. AFPIDC Response to Step Input.

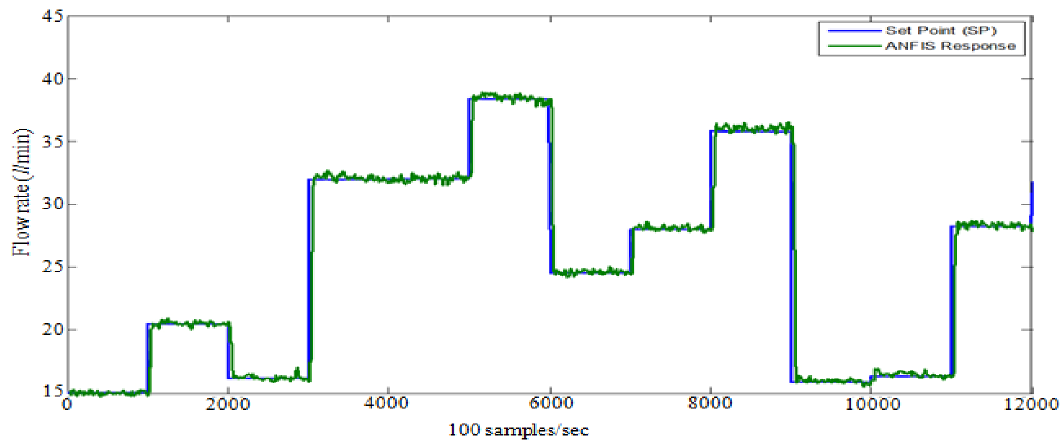

Fig. 15. ANFIS Response to Step Input.

Table 3. Controller Performance Comparison.

Control Performance	PID	AFPIDC	ANFIS
IAE	Intermediate	Small	Very Small
Rise Time	14.21 s	7.17 s	0.68 s
Settling Time	14.21 s	7.17 s	0.68 s
Decay Ratio	0.00	0.00	0.00
Steady State Error	Acceptable	Acceptable	Acceptable
% Overshoot	0.00 %	0.00 %	0.00 %

5.2. Bubble Noise Effect

Based on previous investigation [10], one of the common disturbances that affect the flow meter is the bubbling effect. Bubble noise is caused by the superposition of single pulses generated by individual bubbles which are randomly distributed in the liquid [11]. Bubble is produced by inserting air in the water inside the tank using a tube. Some bubbles will escape through the pipe lines and cause disturbances to the flow meter measurement. The output of the flow meter will fluctuate rapidly that affect the controller performances.

Fig. 16, 17 and 18 show the controller performances under bubbling noise disturbances. AFPIDC and ANFIS response exhibits no overshoot and provides faster response than PID controller under bubbling noise disturbances based on results in Table 4. The rise time and settling time for PID controller has increased for 2.7 seconds meanwhile for AFPIDC; they have only increased 0.64 seconds and for ANFIS it increase 0.12 seconds. Thus, AFPIDC and ANFIS provide stable controller response than PID controller with disturbances in the process plant.

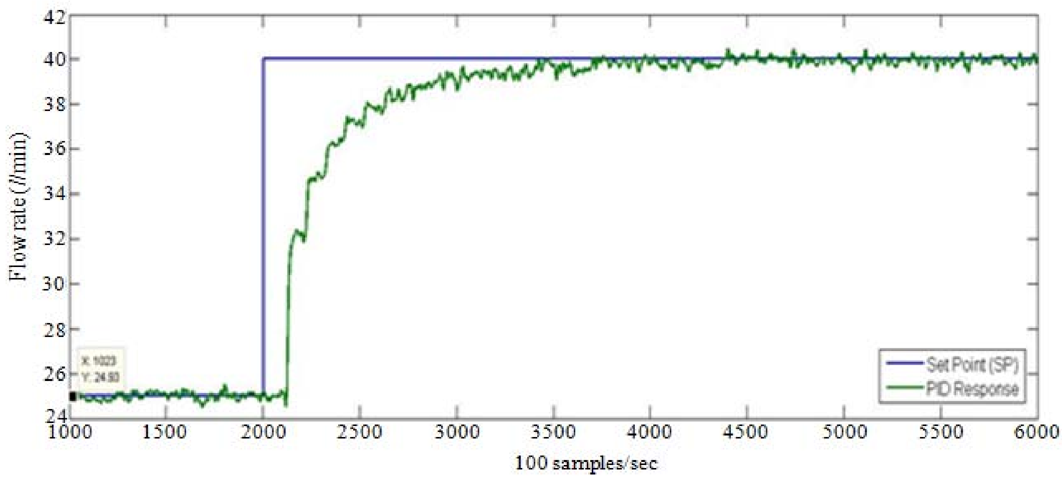

Fig. 16. Bubble created at the bottom of the tank.

6. Conclusion and Recommendation

Hybrid controllers such as AFPIDC and ANFIS are combination between two types of different controllers. By using this approach, hybrid controller is capable to overcome drawbacks that exist within a controller. Adaptive Fuzzy PID Controller (AFPIDC) uses the Fuzzy Logic reasoning to automatically tune the PID gain so that the controller will have better control performances than the conventional PID controller. While for ANFIS, ANN is used as a tuning method for the Fuzzy Logic construction. With the learning ability, ANN will tune the Fuzzy Logic membership function based on the applied input-output training data set. With the combination between Fuzzy Logic and ANN, ANFIS show better control performances in term of faster response and stability.

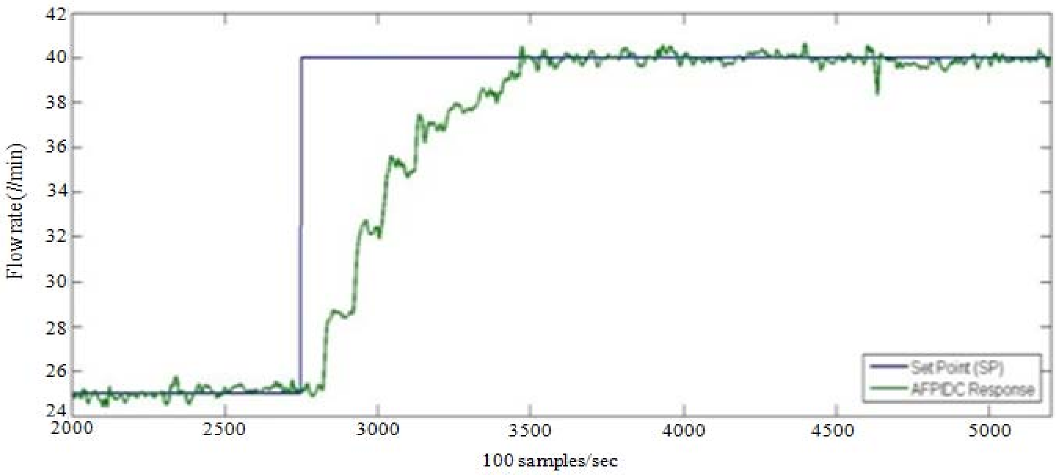

Fig. 17. PID and AFPIDC Response with Bubbling effect.

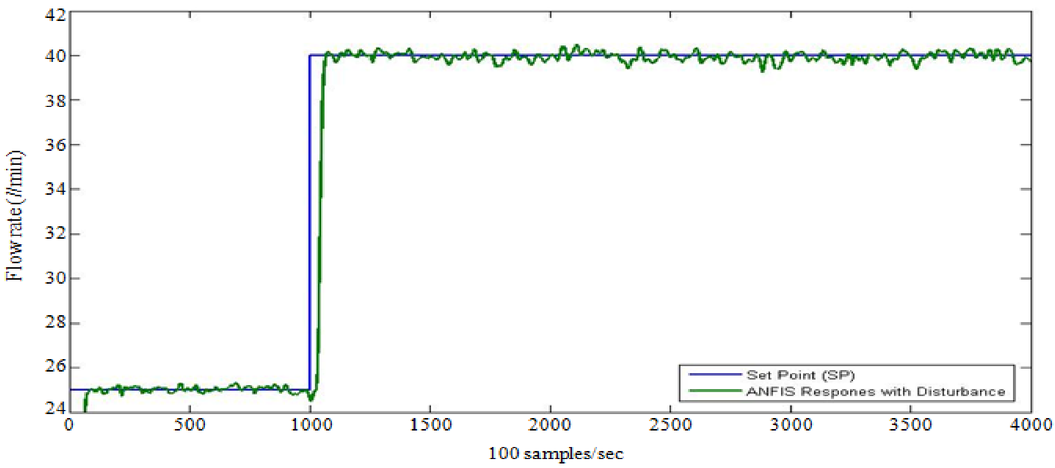

Fig. 18. ANFIS Response with Bubbling Effect.

Table 4. Controller Performance with Disturbance.

Control Performance	PID	AFPIDC	ANFIS
IAE	Intermediate	Small	Very Small
Rise Time	16.90 s	7.81 s	0.8 s
Settling Time	16.90 s	7.81 s	0.8 s
Decay Ratio	0.00	0.00	0.00
Steady State Error	Acceptable	Acceptable	Acceptable
% Overshoot	0.00 %	0.00 %	0.00 %

The objectives of this project which are to develop hybrid controllers such as AFPIDC and ANFIS, then implement onto the Mobile Pilot Plant for flow control application, and develop a DCS-HMI system have been achieved successfully. The most important part is that it has also managed to compare the controller performances between PID, AFPIC and ANFIS controllers.

As for further recommendation, other types of intelligent controllers such as PID- Fuzzy with Generic Algorithm (GA) and Model Predictive Control (MPC) can be implemented onto the pilot plant in order to compare the control performances.

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because of it is a peer reviewed international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per year by International Frequency Sensor Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc. Since 2011 the journal is covered and indexed (including a Scopus, Embase, Engineering Village and Reaxys) in Elsevier products.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

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