

Modeling and Designing a Control System Using PID Controller & Fuzzy Logic Controller with Matlab/Simulink

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Abstract:

This work studies the design and simulation of a water level and temperature controller using Proportional Integral Derivative (PID) Controller and Fuzzy logic (FL) Controller. The simulation of the design system was achieved by utilizing MATLAB and Simulink.

The experiment displayed some challenges of methods, non-linear PID Controller and fuzzy logic (FL) in the system designed. PID

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controllers were implemented separately to control the water level and temperature with deferent parameters.

howeves the (FL) process was implemented to control both, water level and temperature. The challenges with this method lead in the tuning and selection of the fuzzy sets. The experiment showed that both control systems are important in their own right.

The two controllers used to combine the system in order to improve the accuracy and precision of the result. Results demonstrated that more accurate response was obtained using a PID system, which did not show any study state error, whereas Fuzzy Logic Controller is relatively easy as compared to the Proportional Integral Derivative Controller with the despite of complex mathematical modeling.

Keywords: *Simulation, Water Level, Temperature ,PID Controller, fuzzy Logic (FL), MATLAB & SIMULINK, Proportional Integral Derivative Controller.*

1- Introduction.

Advanced Control module using PID controller which is generic control loop feedback mechanism widely used in industrial control system. This system controls more than 95% closed loop industrial processes.[1] in their introduction to the research paper of the PID acknowledged this fact.

The proportional-integral-derivative (PID) controller structure is pointed out that more than 95% of the controllers used in the process control applications are PID-type.

The popularity of such controllers is mostly due to the fact that their structure is simple, and their principle is easy to understand that

such controllers have sufficient ability of solving many practical problems.

The process includes the design and simulation of a control system using the Fuzzy Logic Controller, which was introduced by[2]. This system allows the use of information expressed verbally to perform computations.

This work aimed to design a control system to control both water level and temperature in tank using PID and Fuzzy Logic Controllers.

The investigation mainly focused on four tasks namely,

- Development of Mathematical Model.
- Design the PID Controller.
- Designing a Fuzzy Logic Control System.
- Working with the SIMULINK.

2 - Physical Tank Layout

The schematic layout of the tank was given as shown in figure (1) ;

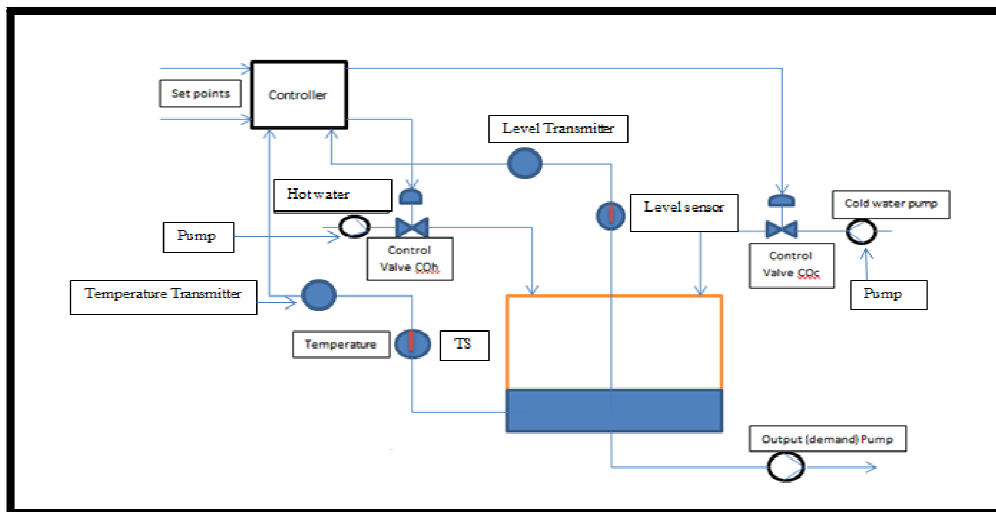


Figure (1) shows the schematic of tank layout.

2.1- Problem Specifications

- Inlet cold water temperature $T_{cold} = 4^{\circ}\text{C}$
- Initial hot water temperature $T_{hot} = 60^{\circ}\text{C}$
- Maximum water flow rate into the tank for both hot and cold = $0.3\text{m}^3/\text{s}$
- Water flow rate out of the tank = $0.35\text{m}^3/\text{s}$
- Volume (V) of the tank = 1.0m^3
- Cross-section area of the tank (A) = 0.5m^2
- Initial water level $L_0 = 0.1\text{m}$ and temperature $T_0 = 10^{\circ}\text{C}$
- Pump voltage varies between 0 to 10Volts

Not : if we used Pump voltage varies more than 10 Volts will not give an accurate result.

2.2- Design Specifications

- Water level and temperature are measured separately by the level sensor and temperature sensor
- Outlet temperature T_2 must equal the set point temperature of 37°C
- The water level must not exceed 2m
- The temperature has a first order delay with time constant = 2.5 s
 $\left(\frac{1}{2.5s+1}\right)$
- The water level measurement has a first order delay of a time constant = 1.5 s

3 - Development of Mathematical Models

The mathematical equations were formulated and subsequently the engineering models as detailed below.

i. Volume of the Tank, \implies For a cylinder, $V = A * h$

Where V= volume, A= Cross section area (CSA) and h=height of the cylinder

In this case the volume of the tank is equivalent to the amount of water going into the tank or less than the water flowing.

$$V = Fc + Fh - Fo$$

Whereas, Fc=cold water inflow, Fh=hot water inflow and Fo=water outflow.

Since the water level is changing with time as showed below

$$\frac{dV}{dt} = Fc + Fh - Fo, \quad \text{But } \frac{dV}{dt} = \frac{d(Ah)}{dt}$$

$$\text{Therefore: } \frac{dh}{dt} = \frac{1}{A}(Fc + Fh - Fo) \dots \dots \dots \text{Equation (1)}$$

ii. Temperature of the water

$$\text{Temperature at any point of time } VT = FcTc + FhTh - FoT$$

Since the temperature of the water in the tank depends of the flow

$$\frac{dVT}{dt} = FcTc + FhTh - FoT = V \frac{dT}{dt} + T \frac{dV}{dt}$$

$$V \frac{dT}{dt} = FcTc + FhTh - FoT - T \frac{dV}{dt} \text{ But } \frac{dV}{dt} = Fc + Fh - Fo$$

$$\text{Therefore: } V \frac{dT}{dt} = FcTc + FhTh - FoT - T(Fc + Fh - Fo)$$

$$\begin{aligned} \frac{dT}{dt} &= \frac{1}{Ah}(FcTc + FhTh - FoT - TFc - TFh + T Fo) \\ &= \frac{1}{Ah}(FcTc + FhTh - TFc - TFh) \end{aligned}$$

$$\frac{dT}{dt} = \frac{1}{Ah}(Fc(Tc - T) + Fh(Th - T)) \dots \dots \dots \text{Equation (2)}$$

The mathematical model was then development using MATLAB/SIMULINK as shown in figure 2 below.

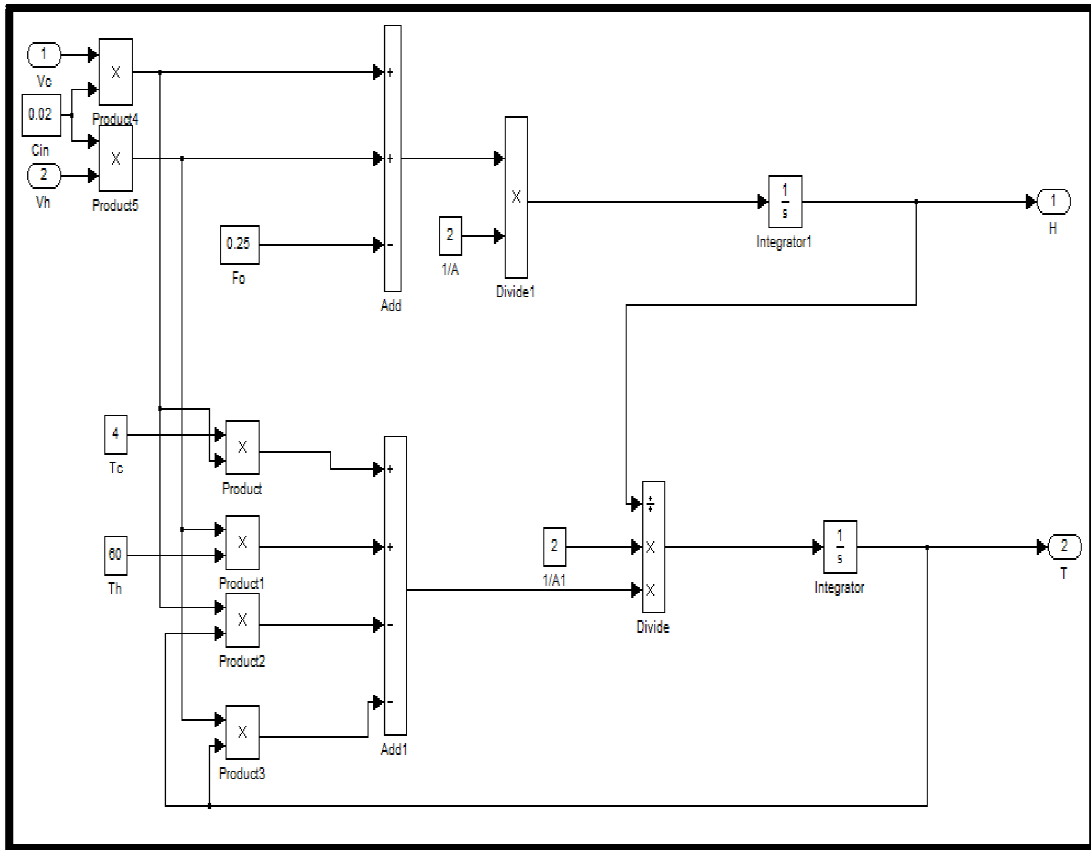


Figure 2 showing the modelling of water level and temperature

4 - Designing the Pid Controller

The engineering model was then saved as a subsystem and two PID controllers with two feedbacks of first order delays of time constants equal to 2.5 and 1.5secs for the temperature and water level respectively were introduced as shown in figure 3.

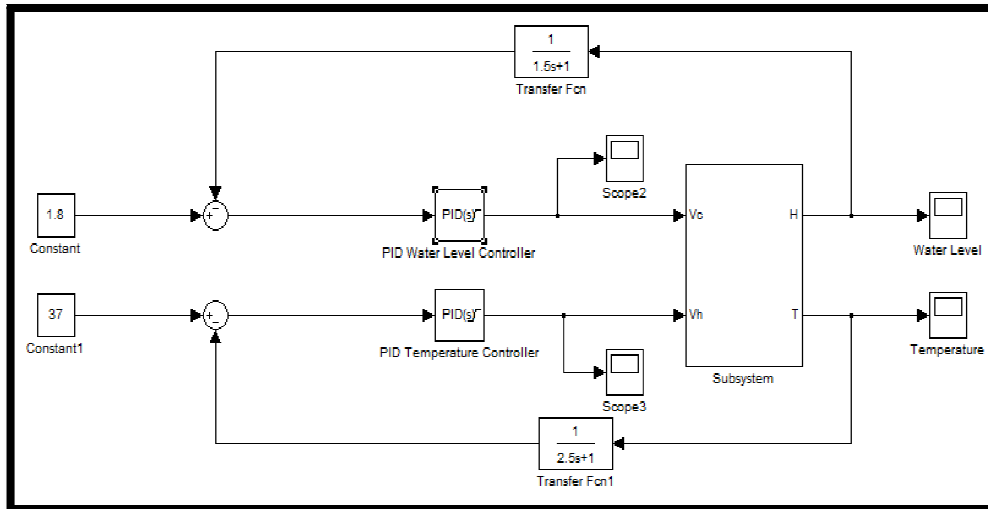


Figure (3) showing the simplified layout of Simulink Model with PID Controllers

4.1 - Tuning the Pid Controllers

In order to tune the two controllers, Ultimate Cycle Method of Ziegler-Nichols of tuning

PID was used.[3]

- The model (figure 3) was built using MATLAB/SIMULINK.
- The values of K_i and K_d were set to their minimum (zero) by setting the time constants τ_i and τ_d to infinity and zero respectively. This resulted in values of K_i and K_d to equal zero.
- The proportional constant K_p was initially set to low value of one 1 and then gradually increased.
- Scope windows 2 and 3 for water level and temperature were added to monitor the output signal for two PID Controllers respectively.
- The process was repeated for various values of K_p until the system was verge of instability resulting in continuous oscillation as shown in figure 4 and figure 5 respectively.

4.2- Pid Controller Results

The following graphs were obtained for the Water Level and Temperature PID Controller. The readings for the K_{pc} and corresponding T_c were obtained by taking measurement as shown in Appendix ii.

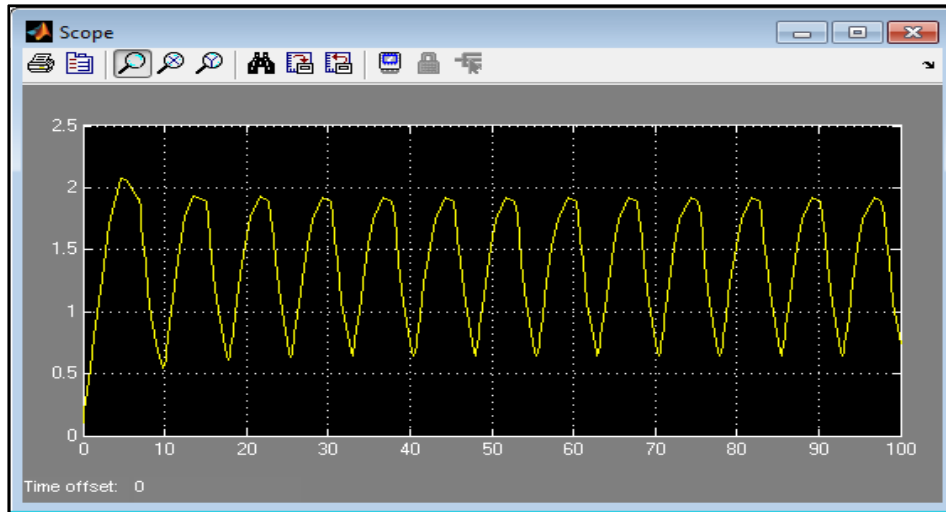


Figure (4) showing the continuous oscillations of the water level system

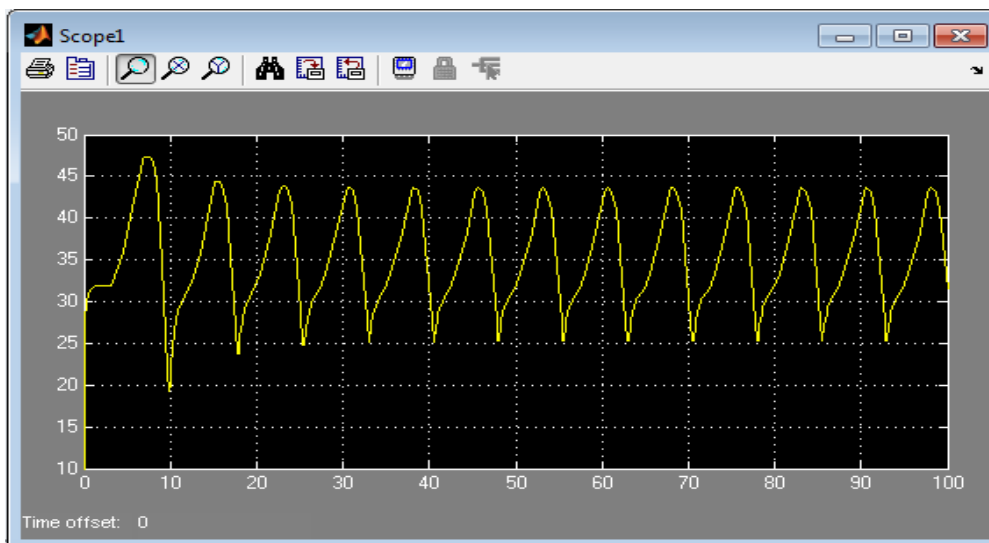


Figure (5) showing the continuous oscillations of the temperature model

The critical value for the proportional constant K_{pc} and the periodic time of the oscillations T_c were found to be.

PID	K_{pc}	T_c
Water Level	1.95	7.5
Temperature	43.65	7.7

Table (1) showing the values of K_{pc} and T_c obtained

The Ziegler-Nichols Tuning Rule Table shown below was then applied to get the values of K_p , K_i and K_d required for our system to meet the specifications.

Controller Model	K_p	K_i	K_d
P	$0.5K_{pc}$		
PI	$0.45K_{pc}$	$1.2/T_c$	
PID	$0.6K_{pc}$	$2.0/T_c$	$8/T_c$

Table (2) formulas for calculating values of K_p , K_i and K_d using Ziegler-Nichols method

This resulted in the following PID parameters.

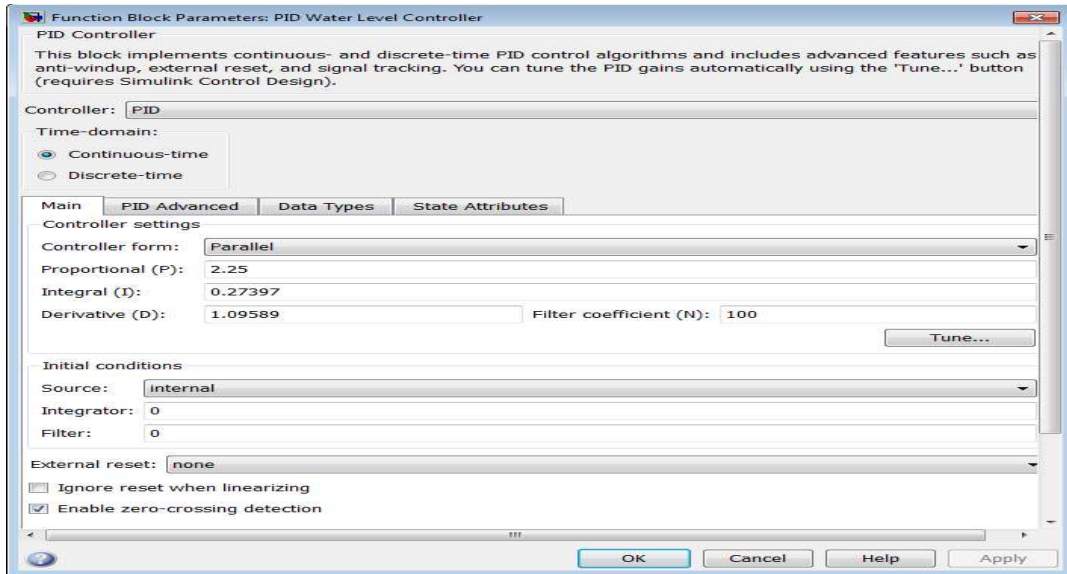
PID	K_p	K_i	K_d
Water Level	1.17	0.267	1.067
Temperature	26.19	0.260	1.039

Table (3) calculated values of the two PID controllers.

However, these values did not yield the expected result. The PIDs were then smoothly tuned by gradually changing the values of K_p , K_i and K_d . Table 4 and figures 6, 7, 8 and 9 shows the respective value that yield some expected results and the corresponding graphs.

PID	K_p	K_i	K_d
Water Level	2.140	0.274	1.096
Temperature	2.340	1.096	1.127

Table (4) final values of the two PID controllers



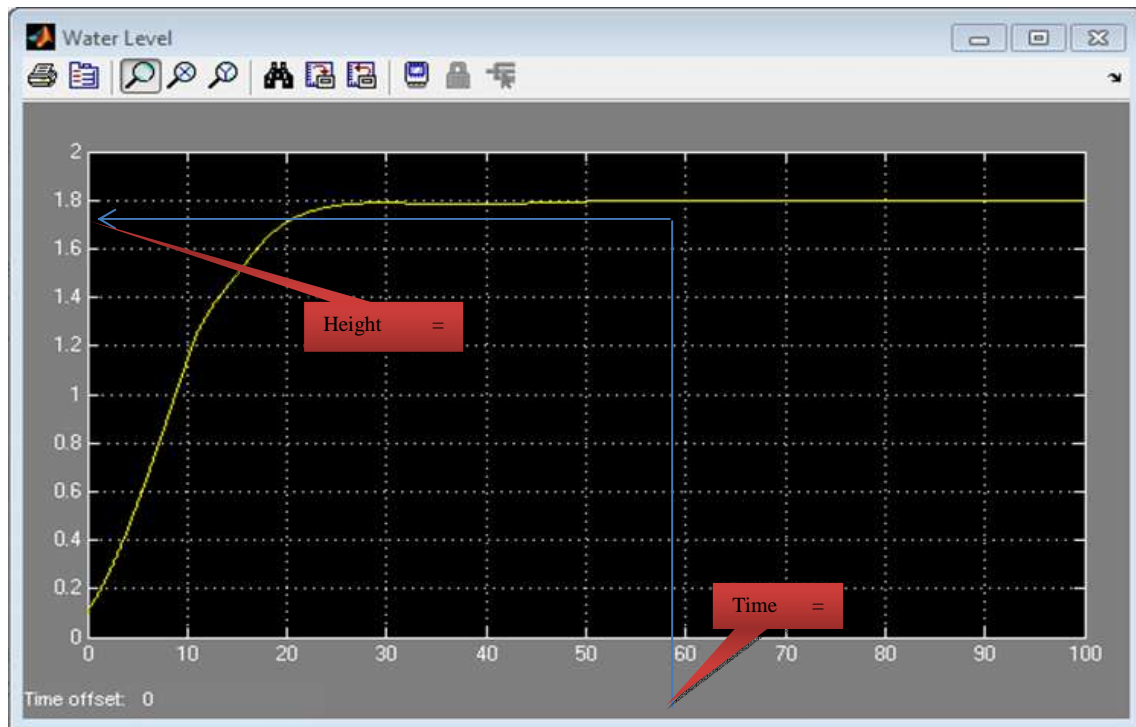


Figure (6) PID setting for the water level.

Figure (7) showing the resulting graph for the water level

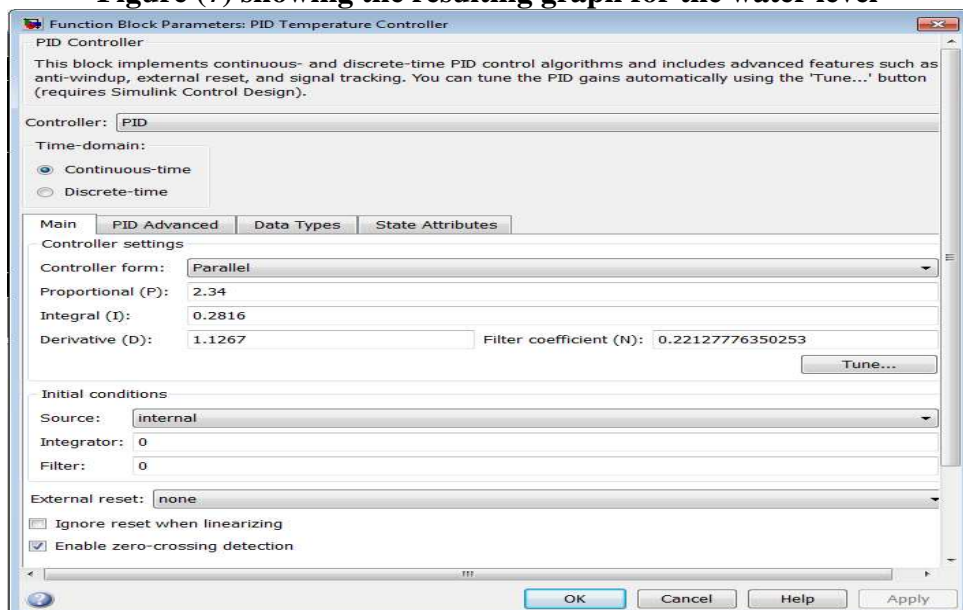


Figure (8) PID setting for the temperature.

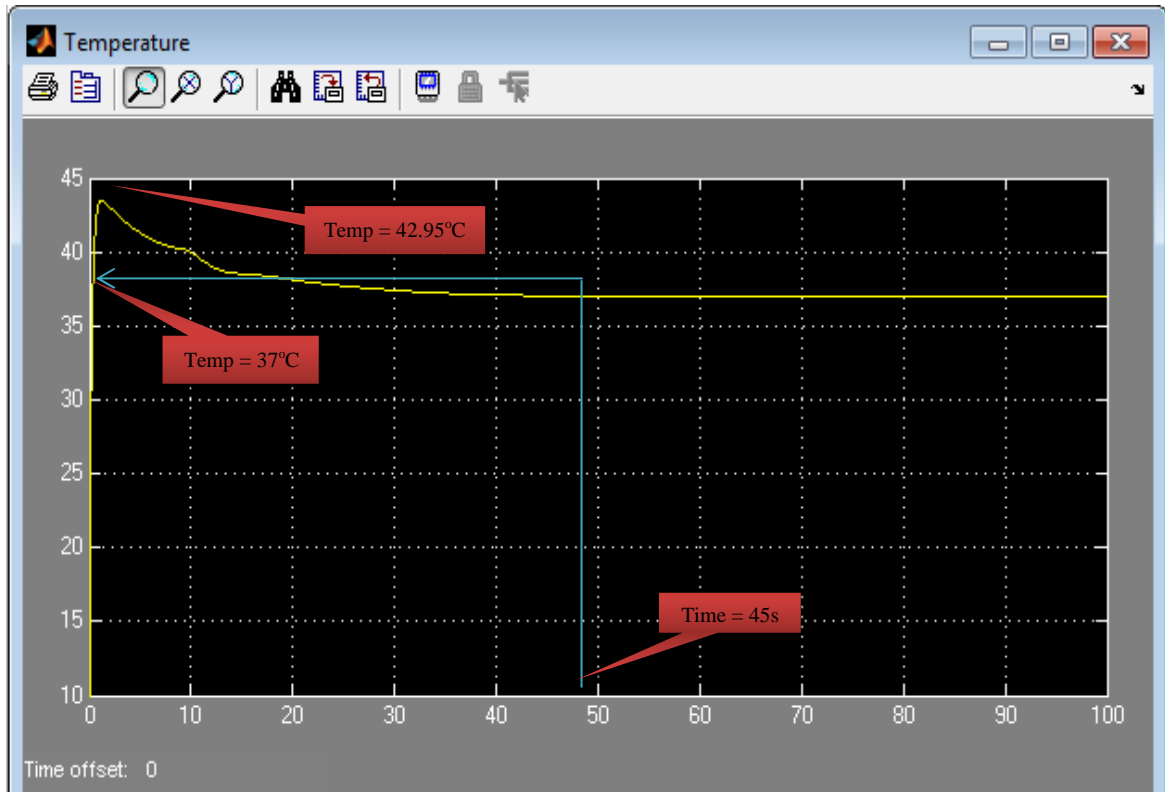


Figure (9) showing the resulting graph for the Temperature

5.-Designing A Fuzzy Logic Control System

There are two main methods for designing a Fuzzy Logic Controller (FLC) namely the Mamdani Method introduced by Professor Drankovat London University and Fuzzy Inference introduced by Nguyen.[4][5] The difference of two inference methods lies in the calculation of crisp outcome value of controller at defuzzification stage. The Mamdani method uses the centroid technique also known as the **center of gravity (COG)** while the Sugeno method uses the Weighted Average (WA).[6][7]

However, the two methods follow the same four basic steps namely;

i) Fuzzification of Input Variables

Taking crisp input in this case the water level and temperature into appropriate fuzzy sets.

ii) Inference

This is the application of the fuzzified inputs to the antecedents of the fuzzy rules.

iii) Aggregate Of Rule Outputs

This is the process of unification of the outputs of all rules

iv) Defuzzification

This is the process of evaluation of the rules in order to come up with a single crisp number, which is the output of the Fuzzy Logic Controller.

5.1 - Designing The Flc for The Water Tank Level and Temperature Control

The basic outlay of a FLC for a closed loop is as shown in the figure 10 below where;

$e(t)$ = the error signal into the control with respect to time (t)

$\Delta e(t)$ = differential error which is the difference in error from one sample time to the other also referred to as the rate of change of error.

$u(t)$ = the output signal of the controller (control signal).

$\Delta u(t)$ = The differential output signal of the controller. It is the difference in the out signal from one sample time to the other.

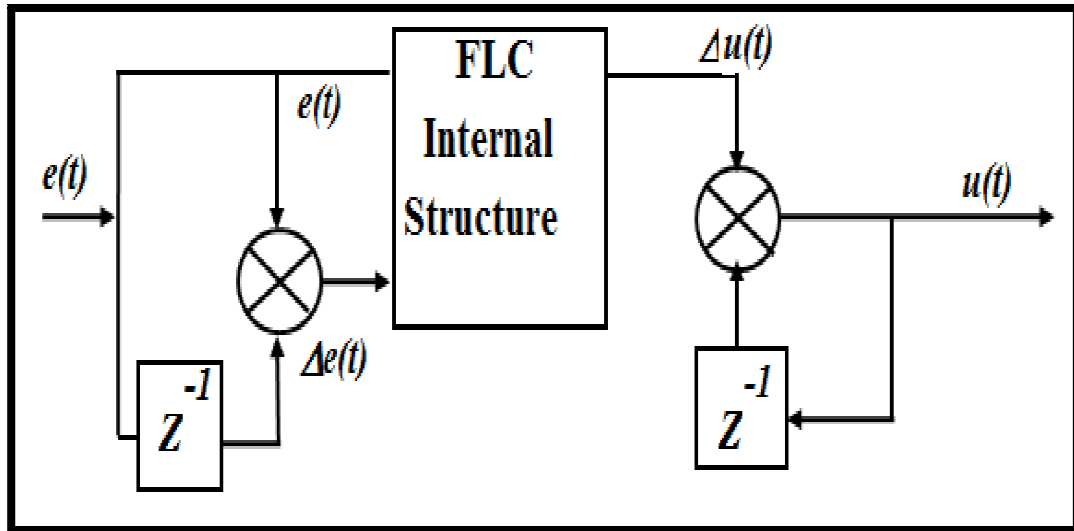


Figure (10) showing the basic layout of a fuzzy based control system

In order to design a FLC, one requires the understanding or experience of how the system (plant) to be controlled operates. This knowledge will therefore assist in determining the input and output parameters of the control system in fuzzy form.

5.2 - Determination of Inputs and Outputs Variables

The model has got two inputs and two outputs namely the water level & temperature and cold water supply & hot water supply respectively.

In this regards, the inputs to the controller were taken to be the errors $e(t)$ which were the differences between the set values of the water level and temperature and the corresponding feedback values and the rate of change of these errors $\Delta e(t)$. The table below shows the definition of membership functions.

	RANGE	DESCRIPTION	MEMBERSHIP FUNCTION	SHAPE
INPUT				
WL	0.5 – 1.25	Low	-2.12 -2.02 -0.13 - 0.0052(trap)	Trapezium
WL	1.0 – 1.75	Ok	-0.153 0 0.164 (tri)	Triangle
WL	1.5 – 2.0	High	0.005 0.513 2.08 2.09 (trap)	Trapezium
TE	10 – 30	Low	-46.8 146.6 -9.63 0.105 (trap)	Trapezium
TE	25 – 40	Ok	-3.49 0 4.13 (tri)	Triangle
TE	35 – 45	High	0.105 10.26 40.3 40.7 (trap)	Trapezium
OUTPUT				
Fc	0.00 – 0.15	Low	-1.23 -1.12 1.24 4.51	Trapezium
Fc	0.10 – 0.25	Normal	0.161 4.966 0.162 5.061	Gaussian
Fc	0.20 – 0.35	High	5.49 8.63 10 11.2	Trapezium
Fh	0.00 – 0.15	Low	-1.2 -1.04 1.23 4.35	Trapezium
Fh	0.10 – 0.25	Normal	0.2004 4.931 0.2236 5.056	Gaussian
Fh	0.20 – 0.35	High	5.54 8.23 10.5 10.6	Trapezium

Table (5) showing the fuzzy membership functions of the inputs and outputs

It should be noted that the modeling was based on the voltage input ratios and not the actual setting such as the water level and temperature. This is in conformity with the design in the PID controller. Table 5 shows the membership function that provided a solution to the problem after tuning the FLC.

The fuzzy rules were designed as follow;

1. IF WL is Low and TE is Low THEN Fc is low and Fh is Low
2. IF WL is Low and TE is Ok THEN Fc is Low and Fh is Normal
3. IF WL is Low and TE is High THEN Fc is Low and Fh is High
4. IF WL is Ok TE is Low THEN Fc is Normal and Fh is Low
5. IF WL is OK and TE is Ok THEN Fc is Normal and Fh is Normal
6. IF WL is Ok and TE is high THEN Fc is Normal and Fh is Normal
7. IF WL is High and TE is Low THEN Fc is High and Fh is Low
8. IF WL is High and TE is OK THEN Fc is High and FhNormal
9. IF WL is High and TE is High THEN Fc is High and Fh is High

6.-Working With Simulink

The system subsystem was the same as shown in figure 2. The Simulink Model for the Fuzzy Logic Controller was built in MATLAB/SIMULINK as shown in figure 11 below.

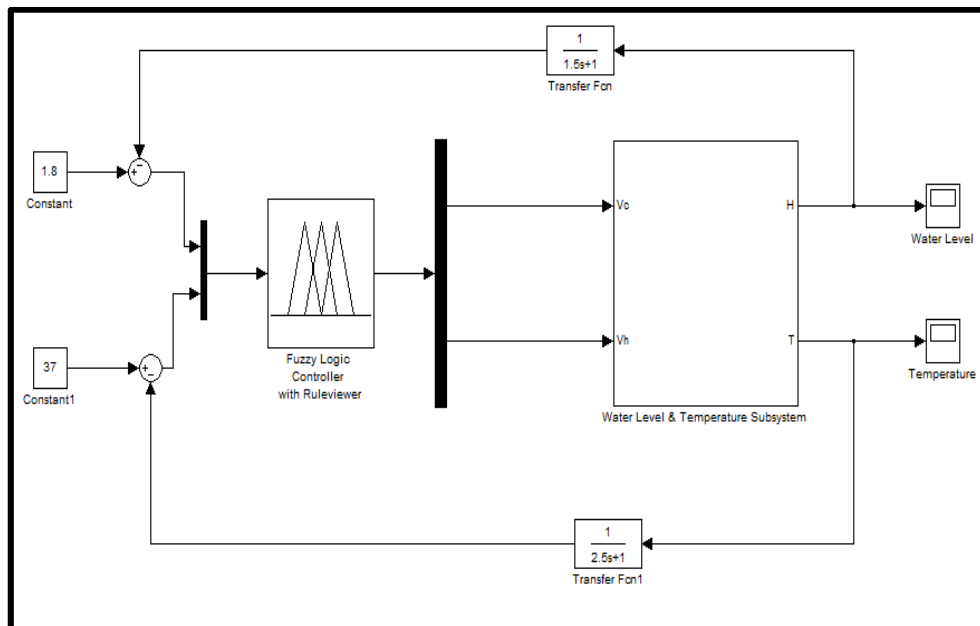


Figure (11) showing the FLC Simulink Model

After simulation, the Fuzzy Logic Controller produced the following Rule Viewer as shown in figure 12.

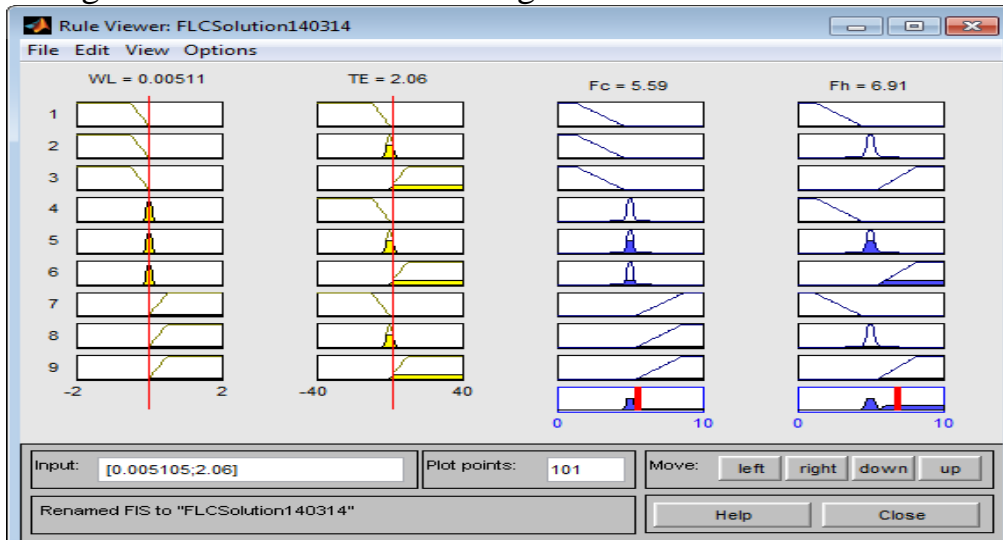


Figure (12) showing the Ruler Viewer for the Fuzzy Logic Controller
The resulting graphical response of the system are shown in figures 13 and 14

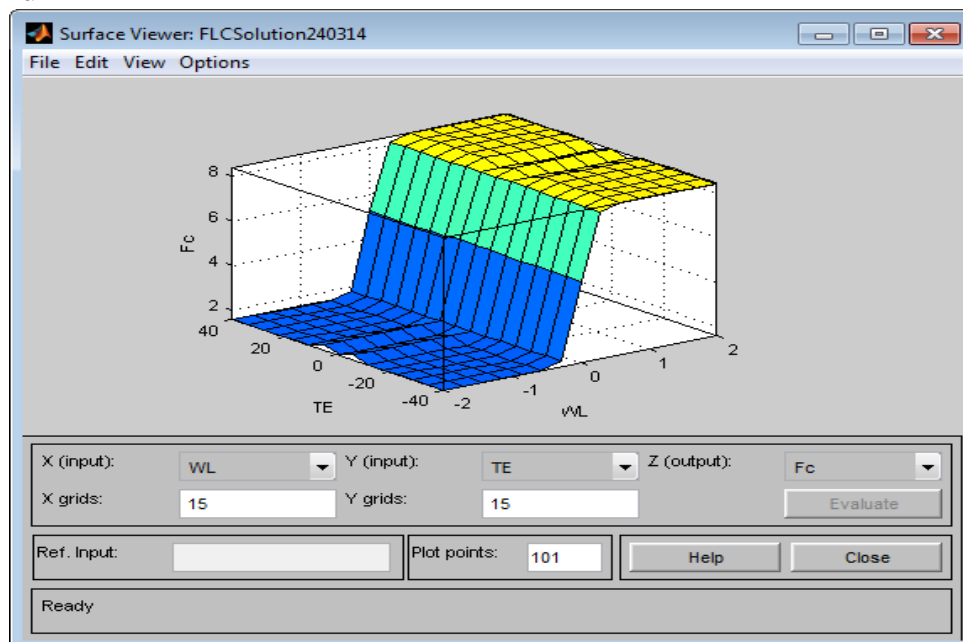


Figure (13) showing the responding graph of surface.



Figure (14) showing the resulting graph for the temperature control
The corresponding surface viewer is shown in figure 15.

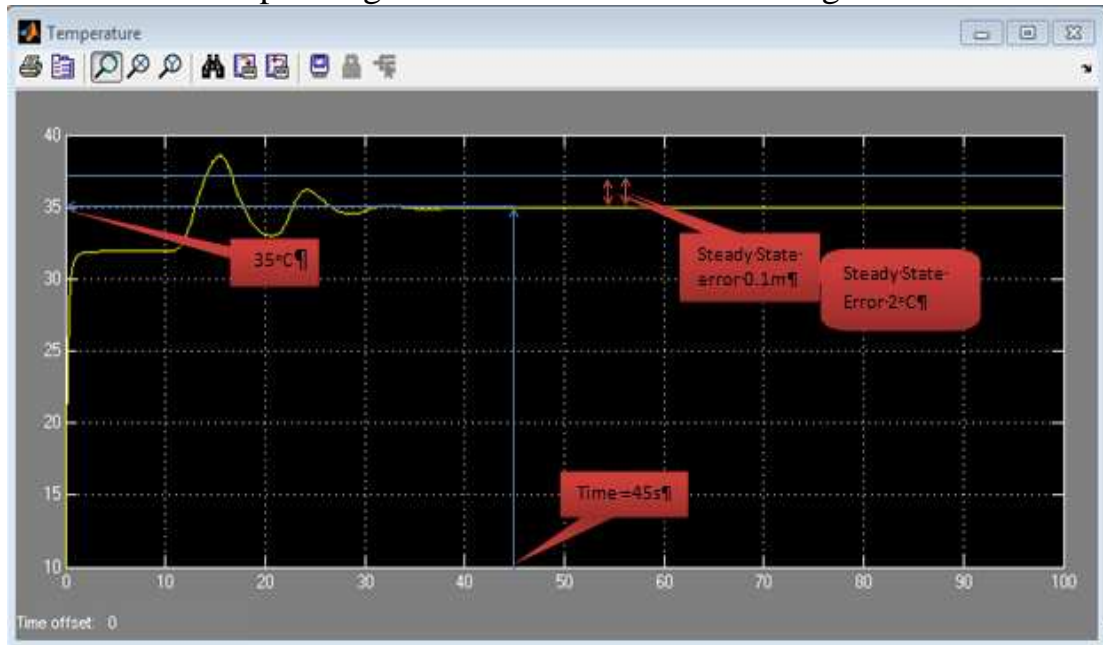


Figure (15) showing the FLC surface viewer.

7.-Observations

The following observations were made during the design and simulation of PID and FL controllers.

- i. The PID involved a lot of mathematical modeling and calculations, which could be complex hence posing serious challenges in the success of design process.
- ii. The system required two separate PID Controllers in order to control the two outputs; water level and temperature.
- iii. Since the two models, water level, and temperature were interconnected, the tuning of the two PID controllers was not easy. Also changing the controller parameters in one PID, affected outcome of the other. The two PIDs were not working independently.
- iv. To achieve the system stability was a challenge as guessing parameters K_p , K_i and K_d of the two controllers. Several attempts were made in order to achieve the above recorded results. This confirms the heuristic nature method of tuning PID Controllers.[8][9]
- v. The graphical response especially of, temperature almost instantaneously overshoot to the highest value of approximately 44°C and gradually settling to the steady state value of 37°C in 45sec. The temperature of 44°C was for a short period as tolerated. The settling time of 45sec is also within the expectation.
- vi. The graphical response of water level did not have a significant overshoot and the steady state value was achieved in approximately 55sec.

- vii. For system using FL Controller, the graphic response of temperature rose to highest value of approximately 37°C at 10sec, in operation state value of 34.9°C in 45sec.
- viii. The water level overshoot to approximately 1.9m being settled to a steady state value of 1.7m in 45sec.
- ix. The steady state values for both water level and temperature using PID and FL Controllers was as tabulated in table 6.

	PID	FUZZY LOGIC
WATER LEVEL	1.8m	1.7
TIME	55sec	45sec
TEMPERATURE	37°C	34.9°C
TIME	45sec	45sec

Table 6 showing steady state results for both the PID and FL Controllers

- x. Designing the Fuzzy Logic Controller was less challenging as compared to the PID Controller. Knowledge of complex mathematics computation is neither a prerequisite nor essential in designing Fuzzy Logic Controllers.[10][11]
- xi. Fuzzy logic control does not require mathematical models of plants information and expert knowledge into control signals
- xii. The design of the control was based on daily experience of typical usage of regulated water in the water bath/sink situation, which is supplied, by cold and hot water taps and a single drainage outlet. The knowledge to understand the problem and hence come up with

the possible design solutions. This fact is one of the key advantages of designing a Fuzzy Logic Controller.[12][6]

- xiii. Fuzzy logic control is one of the most useful approaches for utilizing the qualitative knowledge of system.
- xiv. The critical knowledge required was only on modeling and usage of MATLAB and SIMULINK packages. Otherwise, the designing process is understandable.
- xv. The system response was not as accurate as that of the PID Controller. There was a steady state error in both responses. These errors could probably have arisen due to the number of membership functions and fuzzy rules chosen.
- xvi. There is no unique proven formula for the design of the Fuzzy Logic Controller especially in the choice of the membership functions and consequently the fuzzy rules to be applied. This process challenges the designing of Fuzzy Controller as it relies on one's experience and understanding of the problem.[13]

8- Conclusions

From the results obtained in this work, the conclusion can be summarized as following.

- 1- The performance of the fuzzy logic control can be inconsistent because the fuzzy logic control depends mainly on the individual operators' experience. Therefore, despite the fact that much progress has been made in successfully applying fuzzy logic control to industrial control systems, it has become evident that many basic issues remain to be further addressed.

- 2- The design experiment of a PID and FL Controller to control both the water level and the temperature of a tank system confirmed that designing a Fuzzy Logic Controller is relatively easy as compared to the Proportional Integral and Derivative Controller. This is due to the fact that in FLC design, there is no need for the understanding of the complex model of the system to be controlled rather the normal operation of the system.
- 3- More accurate response was obtained using a PID system, which did not show any steady state error. The tuning of the PID using the Ziegler-Nichol method was easier but did not offer accurate parameters hence the need for considering other tuning alternatives such as the Steady Space and Frequency Response.
- 4- Despite the complex mathematical modeling involved in designing a PID Controller, it is a more accurate type of controller compared to the FL.

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