USING BIOGEOGRAPHY BASED OPTIMIZATION FOR TUNING FUZZY PID CONTROLLER

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USING BIOGEOGRAPHY BASED OPTIMIZATION FOR TUNING FUZZY PID CONTROLLER

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ABSTRACT

USING BIOGEOGRAPHY BASED OPTIMIZATION FOR TUNING FUZZY PID CONTROLLER

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In this work, the design and simulation of Proportional Derivative Integral (PID) controller based on Biogeography Based Optimization (BBO) algorithm and Fuzzy PID has been presented for controlling the double tank systems. The PID controller has been designed using three methods that are Root locus design, Symmetrical optimum design and Magnitude optimum design method. Then the output response characteristics for each method have been simulated and tested. The results of these methods are compared graphically and numerically. Furthermore, optimizing the parameters of PID controller by using a new evolutionary algorithm BBO. In addition to a comparison between the characteristics of output responses of PID controller design methods and the characteristics of output response of BBO.

In spite of the diversity in using PID controller, a lengthy time is needed for the trial and error tuning to find suitable PID parameters. Moreover, it is hard to achieve the desired control performance when applying PID controllers to some applications as in time varying systems because of the dynamic nature of these systems, so the most critical point in designing the PID controller is the selection of the parameters value of proportional, integral and derivative components. Because of the huge amount of values for these parameters, a lengthy time is needed to find the suitable values by trial and errors. So that, a systematic way must be used to get the optimum coefficients of PID terms. Therefore, control techniques are proposed to limit the drawback in the PID controller. One of these techniques is the Fuzzy logic controller which will be applied in this thesis.

In addition to that the response enhancement by using Fuzzy Logic Controller is simulated. Furthermore graphically and numerically comparison with PID controller, BBO and Fuzzy logic controller is also introduced.

In this study, we compared the results of using the BBO algorithm and the two Controllers PID and Fuzzified PID controller. First, we compared the results of the PID and the BBO algorithm in terms of overshoot, settling time, rise time, transient response and steady state error. Second, we compared the results of Fuzzified PID controller and BBO algorithm and PID controller. All simulations were presented using MATLAB Software and SIMULINK, which is used widely in control applications. Finally, the simulation results show that the output response of the system uses Fuzzified PID controller optimized by Biogeography based optimization is better than that of PID controller.

Keywords: PID Controller, BBO Algorithm, Fuzzy PID Controller, Settling Time, Rise Time, Steady State Error, Response Chracteristics.

ÖZ

BULANIK OİT DENETİMCİSİNİN AYARLANMASI İÇİN BİYOCOĞRAFYASI TABANLI OPTİMİZASYONU KULLANIMI

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Bu çalışmada BTO (Biyocoğrafyası Tabanlı Optimizasyon) algoritması ve bulanık OIT tabanlı OIT (Oransal-Integral-Türevsel) deneticilerinin tasarımı ve simülasyonu, çift tank sistemlerini kontrol etmek için sunulmuştur. OIT deneticileri üç metot kullanılarak tasarlanmıştır; kök yer eğrisi modeli, simetrik optimum modeli ve magnitüd optimum modeli. Daha sonra her metotta ortaya çıkan tepki özellikleri benzeştirilmiş ve test edilmiştir. Bu metotların sonuçları grafiksel ve sayısal olarak karşılaştırılmıştır. Ayrıca, OIT denetici tasarım modelinin ortaya çıkan etkilerinin özellikleri ve elde edilen BTO etkilerinin özellikleri arasında karşılaştırılma yapılmış

ve buna ek olarak, yeni bir BTO evrimsel algoritma yöntemiyle OIT deneticilerinin parametreleri en iyi şekilde kullanılmıştır.

OIT deneticilerinin kullanımındaki çeşitliliğe rağmen uygun OIT parametrelerinin bulunmasında deneme ve hata ayarı için uzun bir zaman gereklidir. Ayrıca zamanla değişen sistemlerde olduğu gibi bazı uygulamalarda OIT deneticileri kullanıldığında bu sistemlerin dinamik yapısından dolayı istenen kontrol performansını elde etmek zordur bu yüzden OIT deneticilerini tasarlamadaki en kritik nokta, oransal, integral ve türevsel bileşenlerin parametre değerlerinin seçimidir. Bu parametreler için büyük miktarda veri olduğundan deneme ve hatalarla uygun değerleri bulmak için uzun bir zaman gereklidir. Öyle ki, OIT devrelerinin optimum katsayılarını elde etmek için sistematik bir yol izlenmelidir. Bu yüzden OIT deneticisindeki engeli ortadan kaldırmak için kontrol teknikleri tasarlanmıştır. Bu tekniklerden bir tanesi, bu tezde uygulanacak olan bulanık mantık denetimcisidir.

Buna ek olarak, Bulanık Mantık Denetimcisini kullanarak tepki geliştirme uyarlanmıştır. Ayrıca OIT denetimcisiyle grafiksel ve sayısal olarak mukayese edildiğinde BTO ve Bulanık Mantık Denetimcisi de uygulamaya koyulmuştur.

Bu çalışmada, BTO algoritması, iki adet OIT denetimcisini ve Bulanık OIT denetimcisini kullanarak sonuçları karşılaştırdık. İlk olarak OIT ve BTO algoritması sonuçlarını; aşırı salınım, yatışma süresi, yükselme süresi, geçici tepki ve kalıcı durum hatası açısından mukayese ettik. İkinci olarak, Bulanık OIT denetimcisinin ve BTO algoritması ve OIT denetimcisinin sonuçlarını kıyasladık. Tüm benzetimler, MATLAB Software ve SIMULINK kullanılarak sunulmuştur ki bunlar kontrol uygulamalarında yaygın bir şekilde kullanılmıştır. Son olarak, benzetim (simülasyon) sonuçları gösteriyor ki, sistemden elde edilen tepki, optimizasyona dayalı biyocoğrafya ile en iyi hale getirilmiş olan Bulanık OIT denetimcisini kullanmaktadır ki bu durum OIT denetimcisinden daha iyidir

Anahtar Kelimeler: OIT Kontrolör, BTO Algoritması, Bulanık OIT Kontrolör, Yatışma süresi, Yükselme Süresi, Kalıcı Durum Hatası, Tepki Özellikleri.

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MY FATHER who raised me up and made me who I am who died before this date. I wish his dream to become in reality. I hope for everyone who read this thesis pray for him.

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LIST OF ABBREVIATIONS

PID	Proportional Integral Derivative
PD	Proportional Derivative
PI	Proportional Integral
FLC	Fuzzy Logic Controller
FC	Fuzzy Controller
BBO	Biogeography Based Optimization
EBBO	Enhanced Biogeography Based Optimization
PDFLC	Proportional Derivative Fuzzy Logic Controller
DOF	Degree of Freedom
GAs	Genetic Algorithms
HIS	Habitat Index Suitable
FL	Fuzzy Logic
GMT	General Modus Tollens
GMP	General Modus Ponens
TS	Takagi Sugeno
SIMO	Single Input Multi Output
SISO	Single Input Single Output
MIMO	Multi Input Multi Output
MISO	Multi Input Single Output
COA	Centroid of Area
MOM	Mean of Maximum
MM	Maximum Method
BOA	Bisector of Area
SOM	Smallest of Maximum
LOM	Largest of Maximum
Re	Reynolds Number

ZN	Ziegler-Nicholas
Max	Maximum
EA	Evolutionary Algorithms
HIS	Habitat Suitability Index

LIST OF SYMBOLS

$r(t)$	Reference Input
K	Controller Gain
E	Maximum Emigration Rate
I	Maximum Immigration Rate
S	Species
μ	Emigration Rate
P_s	Probability of Species
$x_k(s)$	The s-th independent Variable
N	Population Size
μ_A	Membership Function
U	The universe of Discourse
T(X)	The set of The names of The linguistic Variable
Δe	Change of Error
C(t)	System Output
V	A flow Average Velocity
ρ	The fluid Mass
D	The characteristic Length
Q	Steady-State Liquid Flow Rate
H	Steady - State Head
K_t	Constant
R_t	Resistance Turbulent
C	Capacitance
q_{in}	Input Flow
q_{out}	Output Flow
K_P	Proportional Gain
H	Deviation of Head From Its Steady-State Value
K_I	Integral Gain

K_D	Derivative Gain
G(s)	Transfer Function
t_s	Settling Time
t_r	Rise Time
C(s)	Transfer Function of Controller

CHAPTER 1

INTRODUCTION

1.1. Background

The PID controller is one of most widely control technique used in control applications. [14].The varying parameters in PID control make it an easy method of controlling a process. The PID controllers consider a good method in industrial applications, it was invented in early of twentieth century, and Ziegler-Nichols' (ZN) tuning method in 1942 [7], [4] and [23], due to simplicity of implementation the PID controllers it becomes widely common in control theory. If the parameters of PID controllers are tuned properly it will provides robust and reliable performance for most systems [4]. Setting the PID parameters is called ***tuning***. From 1970s to now days, many methods have been discovered for calculating the PID controller gains. Some of those methods use the information concerning the open loop characteristics such as Cohen-Coon method. Other methods use the Nyquist curve plotting of the plant. All of these methods need to know a prior knowledge about the system. The PID controllers technique is used to enhance the characteristics of the system such as reducing the overshoot, speed up rising time, and eliminating the steady state error, each parameter in the PID controllers has specific criteria to enhance the characteristics of the controlled system. Fuzzy Logic Controller (FLC) is an emerging intelligent controller technique in control systems. Several studies states that the Fuzzy Controller (FC) performs superior to conventional controller algorithms. Zadeh [20] discovered the main idea of FLC and fuzzy set theory. Mamdani and his colleagues [14] have done a pioneering research work on FLC in the mid-'70 for engine steam boiler. The benefit of FLC is clear when the information about the controlled system does not exist or when the controlled process is too complicated to be analyzed using PID controller. FLC is classified into two methods: The first method used FL to provide online adjustment for the parameters of the conventional controller such as the PID control [15]. This method attempts to combine the merits of FL with those control techniques to expand the capability of linear control technique to handle the nonlinearity in the physical system. The second method, includes the fuzzy logic system based on a rule based on expert system, to determine the control action.

1.2. The Literature Survey

A lot of literature is available related to this topic .Here is the literature survey that is relevant with the work carried out four this thesis work.

In 1997, Jörgen Malmborg and Johan Eker designed a hybrid controller consisting of two simple controllers for double tanks system, one PID controller and one time-optimal controller. They showed that the use of this hybrid controller will lead to better performance. They got a control system giving good responses to new set points and also good disturbance rejection.

In 2005, Position control performed using independent joint control [1]. This method was using PID controller, and it worked by controlling each joint independently. The coupling effect between the joints and links could be ignored if the gear ratio was large.

In 2006, [19], the PDFLC fuzzy controller was combined with PID controller to enhance the performance and robustness of the controller. Simulation results showed that the combined structure did a very good controller.

In 2013, Vishal Vasistha. In his paper presents PID controller design for MIMO coupled water tank level control system that is second order system. PID Controller output is fuzzified to control water level in coupled tank system. Simulation has been done in Matlab (Simulink library) with verification of mathematical model of controller. PID controller design and program has been prepared in Lab VIEW. At the place of proportional valve, combinations of solenoid valves are used. The NI DAQ card is used for interfacing between hardware and Lab VIEW software. Experiment is fully triggered by Lab VIEW. Simulated results are compared with experimental results.

1.3. The Main Goals of This Thesis

The goals of this thesis are:

1- Mathematical modeling of the double tank system.
2-Designing a controller for double tank system to make control on the flow rate of the liquid through pipes of double tank system.
3- Using three methods for tuning PID controller, Magnitude optimum design, Root locus design, and Symmetrical optimum design.
4- Using BBO algorithm to optimize the parameters of PID controller.
5- Applying the Fuzzy Logic Controller (FLC).
6- Make a comparison between the performances of the design methods for PID controller, also the comparison between the performances of PID controller, BBO and fuzzy logic controller.

1.4. Thesis Organization

Chapter 2 presents PID control. Review of the structure the PID control and several tuning technique for PID parameters is presented, also gives an overview of the BBO algorithm and explains BBO terminology and mathematical modeling of the BBO. Finally presents the idea of the fuzzy logic control. Preliminaries of some basic concepts for fuzzy theory are discussed. First definition of the fuzzy set, the fuzzy subset and some operation of fuzzy logic are explained. Followed by the main block diagram of fuzzy controllers. Detailed description is discussed for each block of the FLC such as fuzzifier, inference mechanism and defuzzifier. Finally, designing the fuzzy PID and its several types is presented.
Chapter 3 presents a description for the fluid system, the mathematical modeling of single tank and double tank system.
Chapter 4 contains the results. It compares the results of PID controller, BBO and Fuzzy PID controller. Finally, Chapter 5 concludes the thesis and also proposes future work.

CHAPTER 2

PID CONTROLLER, BBO ALGORITHM AND FUZZY LOGIC CONTROLLER

2.1. PID Controller

In process control the PID controller is widely used in many industrial applications. The PID controllers included three main parameters are Proportional (P), Derivative (D) and Integral (I). Since the introduction of many modern control theories to complement the PID controller, things have not been the same, although the fundamental theory for designing one remains the same. Hence, we are greatly indebted to those who laid the foundation for developing PID control theory. The PID controllers have been in process form 1910. They remain a key ingredient in industrial application control as almost of today's industrial key ingredient in industrial application are controlled by PID controllers [16]. Due to its versatility, simplicity, speed, flexibility, robustness and reliability, many industries depend mostly on this stalwart controller for all types of control.

2.1.1. PID structure

PID algorithm, assumes the controlled plant is known, Figure 1 explains the construction of PID controller, $e(t)$ is the error signal [2]. If the error between the output and the input values is large, then large input signal is applied to the physical system. If the error is small, a small input signal is used. As its name suggested, any change in the control signal, $u(t)$ is directly proportional to change in the error signal for a given proportional gain K_P. Mathematically the output of the proportional controller is given as follows:

$$u(t) = K_P \, e(t) \tag{2.1}$$

Where $K_P = u(t)/e(t)$ indicates the change of the output signal to the change of the error signal.

Proportional term is not sufficient to be a controller in practical cases to meet a specified requirement (e.g. small overshoot, good transient response) because the large proportional gain gives fast rising time with large overshoot and oscillatory response. Therefore, a derivative term is added to form PD controller, which tends to adjust the response as the process approaches the set point. The output of PD controller is calculated depended on the sum of both current error and change of error with respect to time. The effects of PD give a slower response with less overshoot than a proportional controller only. Mathematically, PD controller is represented as:

$$u(t) = K_P\ e(t) + K_D\ \frac{de(t)}{dt} \tag{2.2}$$

The main function of the third term; integral control tends to reduce the effect of steady state error that may be caused by the proportional gain, where a smaller integration time result is the faster change in the controlled signal output. The general form of the PID controller in continuous time formula given as [16]:

$$u(t) = K_P\ e(t) + K_I \int_0^t e(t)dt + K_D\ \frac{de(t)}{dt} \tag{2.3}$$

The PID controller structure is:

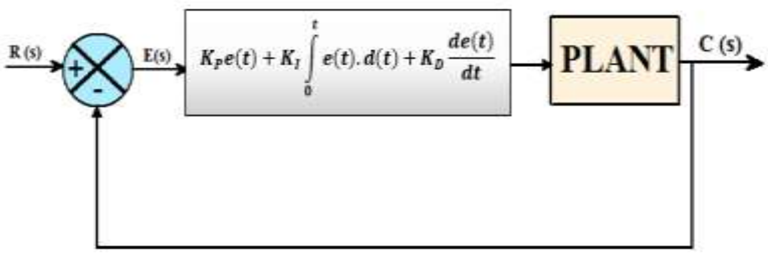


Figure 1 Structure of PID controller

Each term of the three components of PID controller in Figure 1, is amplified by an individual gain, the sum of the three terms is applied as an input to the plant to adjust the process. It will be noted that the purely derivative or derivative plus integral variations never used. The PID compensator gives at least one pole and one zero in all cases except proportional control.

2.1.2. Controller design methods

PID controller is commonly used in controlling applications. According to textbooks and dissertations that concerned in PID controller problem [6] and [5] there are two classes for designing PID parameters: time domain methods and frequency domain methods. Despite the time domain methods are widely used, many of these methods are based on trial and error design strategy. In these methods, the PID parameters are determined using a simulation program or some experiment. Time domain methods are more popular than frequency domain method for tuning PID parameters. However, the frequency domain methods are more convenient and suitable if the exact mathematical model of the physical system is known [8]. One of the advantages of the frequency domain methods is to guarantee the system stability, especially if the system characteristic is unpredictable. There are many method for tuning PID controller, we are used three method in this Thesis as discussed below.

A. Root locus method

There are several teqinuqe to design the PID controller one of them is Root locus method which is a good technique to design by giving various parameters change in description of the control system such as overshoot and rising time. This method is used to analyze the relationship between the poles, gains, and stability of the system [1]. Root locus means in control theory, the location of the poles and zeros of transfer function. The system stability is determined by pole location. The system would be unstable if the roots of transfer function in the right half plan of the continuous system or inside the circle of discrete systems. The system would be stable if these roots in the left half plan. In addition, when root location on jw axis, the system is considered marginal stable. The basic steps for applying the root locus design method are [29]:

Determine the open loop transfer function with a free gain parameter K:

Step 1:

$$G_0(s) = K\,C(s)\,G(s) \tag{2.4}$$

Step 2: Sketch the root locus plot of $G_0(s)$ (this can be done manually or using Matlab).

Step 3: Move the closed-loop poles to desired locations according to the closed-loop specification.

Step 4: Determine the controller gain K.

Step 5: Simulate the feedback loop with the designed controller and verify if the closed loop behavior is as desired.

B. Symmetrical optimum method

The symmetrical optimum method is one of the ways design PID controller designs that lead to reasonable responses both for reference steps and disturbance steps. Usually, responses are fast with zero steady-state error but with overshoot. The symmetrical optimum method requires plant models that can be represented

$$G(s) = \frac{K}{(1+sT_1)\ldots\ldots\ (1+sT_n)\,(1+s\,\tau)} \tag{2.5}$$

In this model, $T_1 \ldots T_n$ are time constants that are large compared to the single time constant τ . If the plant model is accordingly, a controller of the following form is used [29].

- $n+1$ is the order of the plant
- K_p is the controller gain
- T_P is the numerator time constant is the denominator time constant that is
- τ_p is usually chosen as $\tau_p < 0.1\, T_P$

Using the plant parameters n, $T_1, \ldots, T_n$, τ and K, the design equation for the symmetric optimum controller is given by

$$K_P = \frac{1}{2\,K\,\tau}\,\frac{T_1 \ldots\ldots T_n}{(4\,n\,\tau)^n} \tag{2.6}$$

$$T_P = 4\,n\,\tau \tag{2.7}$$

In summary, the symmetrical optimum enables the design of PID-type controllers for systems with several large time constants and one small time constant. It has a straightforward design equation, and leads to closed loops with fast responses to reference and disturbance steps [29].

C. Magnitude optimum design method

The magnitude optimum method is usually used to achieve good reference tracking. It is based on the assumption that we want to obtain $T(s) \approx 1$ [29] for the complementary sensitivity of the basic feedback loop [29] .The magnitude optimum can be applied to stable time-lag plants that can be represented in the form

$$G(s) = \frac{1}{A(s)} = \frac{1}{a_0 + \ldots a_n s^n} \tag{2.8}$$

The controller transfer function is chosen as an integral controller with.

$$C(s) = \frac{P(s)}{2s} = \frac{p_0 + \ldots + p_m s^m}{2s} \tag{2.9}$$

Then it desired to find the numerator coefficients of the controller transfer function. We basically study the cases of PI controller $(P(s) = p_0 + p_1 s)$ and PID controller $(P(s) = p_0 + p_1 s + p_2 s^2)$. For these cases, closed – form formulas for the controller parameters are as follow [29].

PI- controller:

$$P(s) = p_0 + p_1 s \tag{2.10}$$

$$P_0 = a_0 \frac{a_1^2 - a_0 a_1}{a_1 a_2 - a_0 a_3} \tag{2.11}$$

$$P_1 = a_1 \frac{a_1^2 - a_0 a_2}{a_1 a_2 - a_0 a_3} - a_0 \tag{2.12}$$

PID – Controller

$$P(s) = p_0 + p_1 s + p_2 s^2 \tag{2.13}$$

$$D = \begin{vmatrix} a_1 & -a_0 & 0 \\ a_3 & -a_2 & a_1 \\ a_5 & -a_4 & a_3 \end{vmatrix} \tag{2.14}$$

$$p_0 = \frac{1}{D} \begin{vmatrix} a_0^2 & -a_0 & 0 \\ -a_1^2 + 2a_0 a_2 & -a_2 & a_1 \\ a_2^2 + 2a_0 a_4 - 2a_1 a_3 & -a_4 & a_3 \end{vmatrix} \tag{2.15}$$

$$p_1 = \frac{1}{D}\begin{vmatrix} a_1 & a_0^2 & 0 \\ a_3 & -a_1^2 + 2a_0a_2 & a_1 \\ a_5 & a_2^2 + 2a_0a_4 - 2a_1a_3 & a_3 \end{vmatrix} \quad (2.16)$$

$$p_2 = \frac{1}{D}\begin{vmatrix} a_1 & -a_0 & a_0^2 \\ a_3 & -a_2 & -a_1^2 + 2a_0a_2 \\ a_5 & -a_4 & a_2^2 + 2a_0a_4 - 2a_1a_3 \end{vmatrix} \quad (2.17)$$

2.2. Biogeography Based Optimization

2.2.1. Introduction

Biogeography is new method of distributing species and optimizing environments for life, and is analogous to mathematical optimization. Assume that we have an optimization problem and some candidate solutions, which we call individual good individuals perform well on the problem, and poor individuals perform poorly a good individual is like to an island with a high Habitat Suitability Index (HIS), and a poor individual is like to an island with a low HSI [13].Good individuals resist change more than poor individuals, just like highly habitable islands have lower immigration rates than less habitable islands. By the same token, good individuals tend to share their features (that is, their independent variables) with poor individuals, just like highly habitable islands have high emigration rates. Poor individuals are likely to accept new features from good individuals, just like less habitable islands are likely to receive many immigrants from highly habitable islands. The addition of new features to poor individuals may raise the quality of those individuals. The EA that is based on this approach is called biogeography-based optimization (BBO). Each BBO individual is represented by an identical species count curve with Maximum Emigration rate (*E*) = Maximum Immigration rate (*I*), for simplicity. Figure 2 illustrates the migration rates for a BBO algorithm with these assumptions. S_1in Figure 2 represents a poor individual, while S_2 represents a good individual.The immigration rate for S_1 will be relatively high, which means that it will be likely to receive new features from other candidate solutions. The emigration rate for S_2 will be relatively high, which means that it will be likely to share its features with other individuals. Figure 2 is called a linear migration model since the μ and λ values are linear functions of fitness.

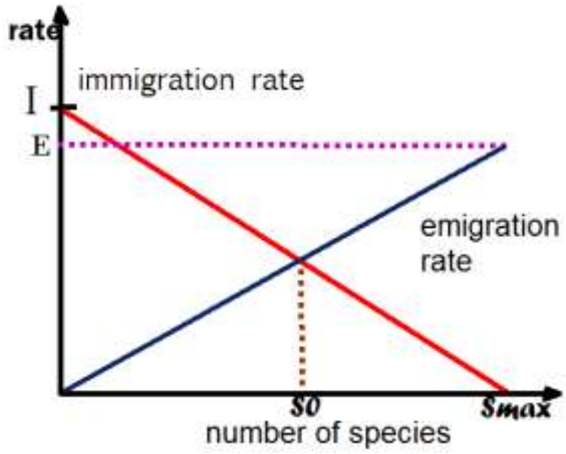


Figure 2 Migration rates of BBO algorithm

2.2.2. Mathematical model of BBO

The island contains S species. The probability P_s changes from time t to $(t+\Delta t)$ as follows:

$$p_s(t+\Delta t) = p_s(t)(1-\lambda_s \Delta t) + p_{s-1}(t)\lambda_{s-1}\Delta t + p_{s+1}(t)\mu_{s+1}\Delta t \qquad (2.18)$$

Where λ_s and μ_s are the immigration and emigration rates when there are S species on the island. This equation holds if we assume that Δt is small enough so that the probability of more than one migration between time t and $(t+\Delta t)$ can be ignored. Therefore, to have S species at time $(t+\Delta t)$, one of the following conditions must hold:

1. There were S species at time t, and no immigration or emigration occurred between t and $(t+\Delta t)$; or,

2. There were $(S-1)$ species at time t, and one species immigrated; or,

3. There were $(S+1)$ species at time t, and one species emigrated.

Define $n = S_{max}$, and $P = [\,Po \cdots Pn\,]^T$. Can arrange the $(n+1)$ equations of Eq. (2.19) into the single matrix equation.

$$P = \begin{cases} -(\lambda_s + \mu_s)P_s + \mu_{s+1}P_{s+1} & S = 0 \\ -(\lambda_s + \mu_s)P_s + \mu_{s+1}P_{s+1} + \lambda_{s-1}P_{s-1} & 1 \le S \le S_{max} - 1 \\ -(\lambda_s + \mu_s)P_s + \lambda_{s-1}P_{s-1} & S = S_{max} \end{cases} \quad (2.19)$$

$$\dot{P} = AP \quad (2.20)$$

Where the matrix A is given as:

$$A = \begin{bmatrix} -(\lambda_0 + \mu_0) & \mu_1 & 0 & \cdots & 0 \\ \lambda_0 & -(\lambda_1 + \mu_1) & \mu_2 & \ddots & \vdots \\ \vdots & \ddots & \vdots & (\lambda_{n-1} + \mu_{n-1}) & \vdots \\ \vdots & \ddots & \lambda_{n-1} & & \mu_n \\ 0 & \cdots & 0 & \lambda_{n-1} & (\lambda_n + \mu_n) \end{bmatrix} \quad (2.21)$$

For the straight line migration rates of Figure 2, we have

$$\mu_k = Ek / n \quad (2.22)$$

$$\lambda_k = I\left(1 - \frac{k}{P}\right) \quad (2.23)$$

For the special case E = I, we have for all $k \in [0, n]$ $\lambda_k + \mu_k = E + I$

$$A = E\begin{bmatrix} -1 & 1/n & 0 & \cdots & 0 \\ n/n & -1 & 2/n & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & 2/n & -1 & n/n \\ 0 & \cdots & 0 & 1/n & -1 \end{bmatrix} \quad (2.24)$$

$= EA'$

Where A' is defined by the above equation.

* The $(n+1)$ eigenvalues of A' , for any natural n, are

$$x\left(\grave{A}\right)=\left\{0,-\frac{2}{n},-\frac{4}{n},\cdots,-n\right\} \tag{2.25}$$

$= -2k / n \; ,k \in [o,n]$

Furthermore, the eigenvector corresponding to x eigenvalue is

$$v(x)=[v_0(x)\ldots\ldots v_n(x)]^T \tag{2.26}$$

Where;

$$v_k(x)=\binom{n}{k}=\frac{n!}{k!(n-k)!} \qquad k \,\grave{o}\, [0,n] \tag{2.27}$$

The probability of the number of each species is given by

$$P(t)=\frac{v(x)}{\sum_{k=0}^{n} v_k(x)} \tag{2.28}$$

2.2.3. Migration and mutation

The main goal of using the migration rates of each individual to probabilistically share information between individuals. There are many different methods to implement the details of BBO, but in this study we focus on the original BBO formulation [17].Using our standard notation, we suppose that we have a population size of *N*, that x_k is the *k*-th individual in the population, that the dimension of our optimization problem is n and that, $x_k(s)$ is the s-th independent variable in x_k where $k \in [1, N]$ and $s \in [1, n]$.

At each generation and for each solution feature in the k-thin dividual, there is probability of λ_k (immigration probability) that it will be replaced:

$$\lambda_k = \text{Probability that s-th independent variable in } x_k \text{ will be replaced} \quad (2.29)$$

For $k \in [1, N]$ *and* $s \in [1, n]$. If a solution feature is selected to be replaced, then, we select the emigrating solution with a probability that is proportional to the emigration probabilities $\{\mu_i\}$. We can use any fitness-based selection method for this step if we use roulette-wheel selection, then

$$\Pr(x_j) \text{ is selected for emigration} = \frac{\mu_j}{\sum_{i=1}^{N} \mu_j} \quad (2.30)$$

Figure 4 illustrates migration in BBO. The figure shows that individual Z_k immigrates features. Using Eq. (2.29) to decide whether or not to replace each feature in z_k. In the example Figure 4, we see the following migration decisions:

1. Immigration is not selected for the first feature; that is why the first feature in Z_k remains unchanged.
2. Immigration is selected for the second feature, and Eq. (2.30) chooses X_1 as the emigrating individual; that is why the second feature in Z_k is replaced by the second feature from X_1.
3. Immigration is selected for the third feature, and Eq. (2.30) chooses X_3 as the emigrating individual; that is why the third feature in Z_k is replacedby the third feature from X_3.
4. Immigration is selected for the fourth feature, and Eq. (2.30) chooses X_2 as the emigrating individual; that is why the fourth feature in z_k is replaced by the fourth feature from X_2.

5. Finally, immigration is selected for the fifth feature, and Eq. (2.30) chooses X_N as the emigrating individual; that is why the fifth feature in z_k is replaced by the fifth feature from X_N

Figure 4 illustration of BBO migration for a five-dimensional problem. Feature 1 is not selected for immigration, but features 2-5 are selected for immigration. Eq. (2.30) is used to select the emigrating individuals.

Figure 3 explains the BBO algorithm with a population size of N. This algorithm is also known as partial immigration-based BBO.

Initialize a population of candidate solutions. {x_k} for $k \in [1, N]$

While not (termination criterion)

For each x_k set emigration probability $\mu_k \alpha$ fitness of x_k ,with $\mu_k \in [0,1]$

For each individual x_k , set immigration probability $\lambda_k = 1 - \mu_k$

$\{z_k\} \leftarrow \{x_k\}$

For each individual z_k

For each solution feature *s*

Use λ_k to probabilistically decide whether to immigrate to Z_k

(See Eq. (2.29))

If immigrating then

Use $\{\mu_i\}_i^n = 1$ to probabilistically select emigrating individual x_j

(See Eq. (2.30))

$z_k(s) \leftarrow x_j(s)$

End if

Next solution feature

Probabilistically mutate $\{z_k\}$

Next individual

$\{x_k\} \leftarrow \{z_k\}$

Next generation

Figure 3 BBO algorithm

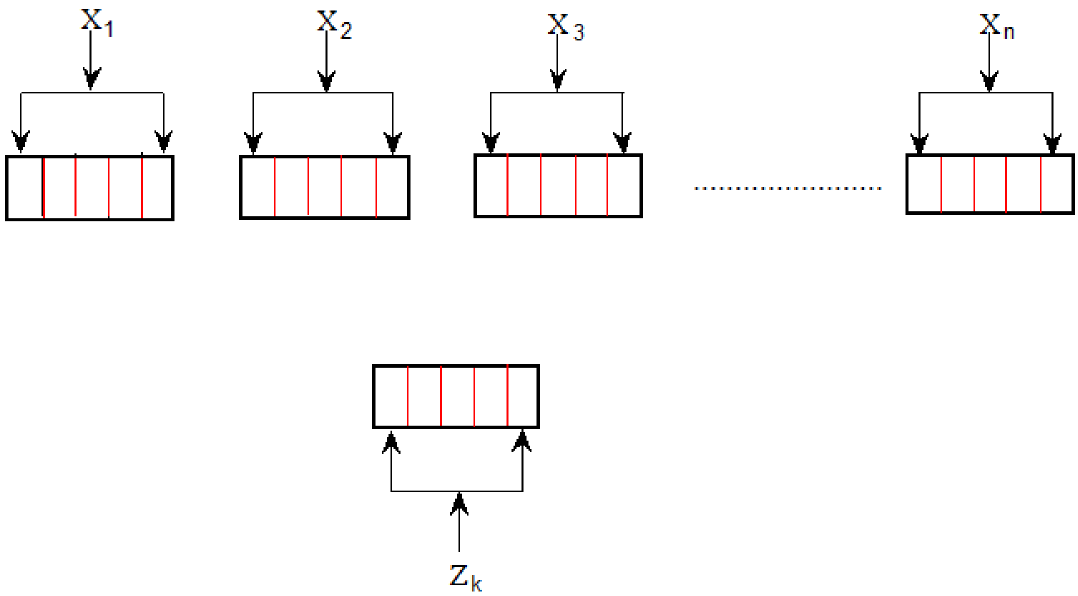


Figure 4 Example of BBO migrations for five - dimensional problem

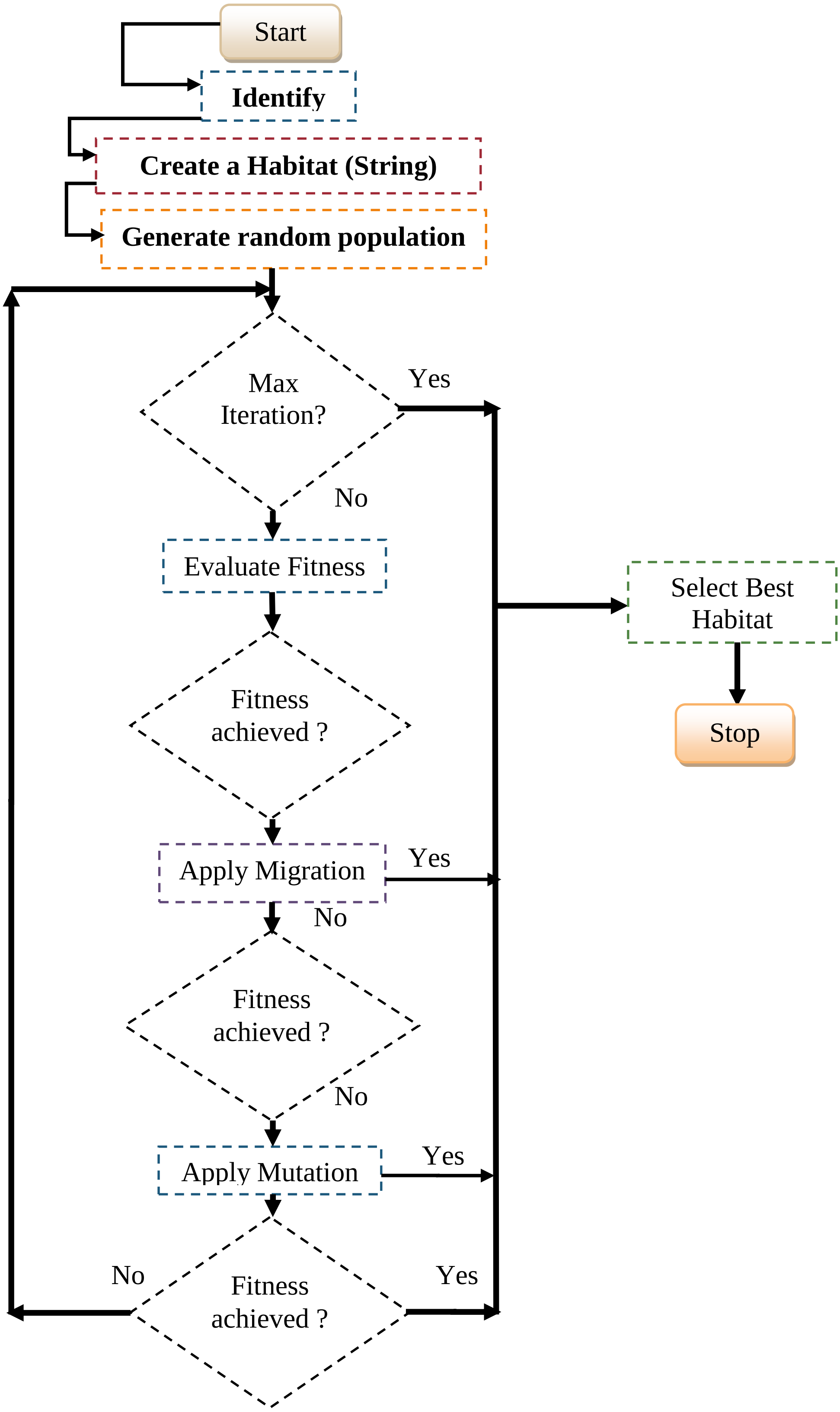


Figure 5 Flowchart of BBO

2.3. Fuzzy Logic Controller

FLC is used in a popular system for the time being [28]. FLC is based on the response, knowledge, and human experience in controlling systems. It can be used for modeling the behavior of linear/nonlinear or static/dynamic systems. Fuzzy controller has benefit over other techniques for deliver a greet consequence, better transparency and for having relative simplicity and agreeable results. The main idea of FLC is converting the linguistic variable based on the information of the operator into control actions applied to the system under control. A classical controller such as PID controller is efficient and offers powerful method to analysis linear systems. In case of nonlinear systems classical controllers does not produces satisfactory results due to the nonlinearities of these systems [10]. Therefore, FLC considers to be an efficient tool to control these nonlinear systems [11].

In closed loop control systems, the classical controllers have been replaced by the FLC. This means that the IF-THEN rules and fuzzy membership functions replaces the mathematical models to control the system. Both controllers are designed to enhance the system stability and to meet the requirement of the system behavior [18]. However, the main advantage of fuzzy logic when compared with classical controllers resides in the fact that, the fuzzy controller deals with the all system as a black box [31] because the mathematical model of the system may be too complex to be described; thus, it is difficult to be controlled with classical controllers. The control rules are depended essentially on the experience of the control engineer and knowledge of the system behavior.

Control engineer may be having idea about the characteristics system and good knowledge about controlling it. In designing a fuzzy control system, we typically express linguistic variable as a process of inputs and outputs in terms of linguistic values such as hot, warm, and cold. As an example, some people may classify 25 degrees Celsius as warm other may be classifying it as hot; hence, this relation between the temperature and its values is fuzzy.

2.3.1. Preliminaries on FLC

Through this section, as an introduction to fuzzy set theory, some definitions of fuzzy and fuzzy sets are briefly defined and discussed. The main idea in fuzzy set theory is that an element has a degree of membership to a fuzzy set. For more details, reader may be return to [30], [27] and [26**].** Assume U is a collection of all objects, members or elements of U denoted as u and U is referred to the universe of discourse. The element u represents any element in U.

2.3.2. Fuzzy sets, fuzzy subset, and null fuzzy set

For some objects u in U, a fuzzy set X in a universe of discourse U is defined as a set of ordered pairs u and μ_X , in which each element u of take a value $\mu_x(u)$ into the interval [0,1], and it is defined as $\{X = \left(\mathrm{u}, \mu_X\left(\mathrm{u}\right), \ \mathrm{u} \in \mathrm{U}\right)\}$, where $\mu_x \in$ [0, 1] is the MF for the fuzzy set X. The output of the membership function for a given input u is denoted as the membership degree or degree of the membership. It is clear that, there is an evident difference between fuzzy set and crisp set in defining the membership function $\mu_x(u)$, as shown in the next two equations for the temperature between 15 and 40 degrees.

In crisp set the membership function, is define as:

$$\mu_X\left(\mathrm{u}\right) = \begin{cases} 1 \ if \ \ temp \in [15, 40] \\ 0 \ if \ \ temp \notin [15, 40] \end{cases} \tag{2.31}$$

Furthermore, the membership function in fuzzy set defined as:

$$\mu_X\left(\mathrm{u}\right) = \mathrm{f\,n}\left(\mathrm{temp}\right)$$

In classical set theory, a set X is defined to be subset of set Y if and only if all element of set X are contained in set Y. This definition has extended to fuzzy set theory as follows:

For two fuzzy sets X and Y given in the universe of discourse U with two membership functions $\mu_X(u)$ and $\mu_Y(u)$ respectively. X is defined as a fuzzy subset in Y, defined as $X \subset Y$ if:

$$\mu_X(u) = 0 \qquad \forall\, u \in U$$

This means if X is a fuzzy set then no element in U has member in X.

2.3.3. Membership function features

A relation gives grades of membership for each element of a fuzzy number; this means that there is no sharp boundary between membership and non-membership. It takes values between 0 and 1. Figure 6 illustrates the membership function of fuzzy set cold, warm, and hot.

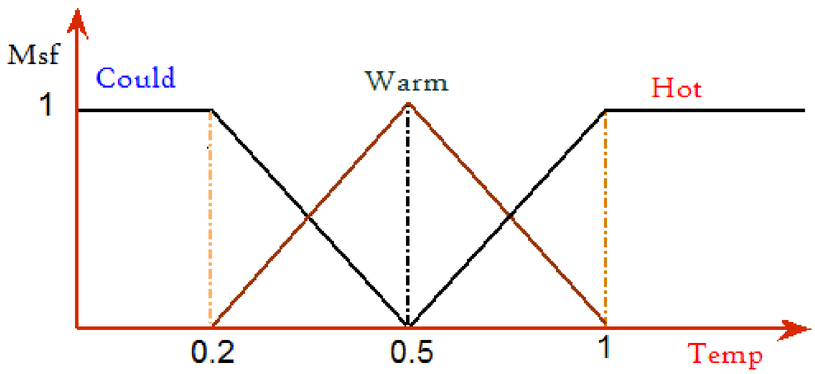


Figure 6 Triangular MFs

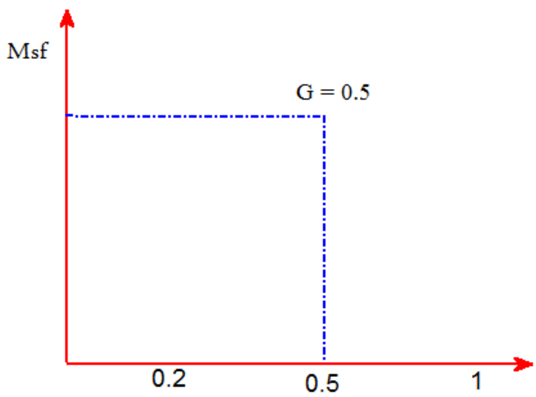


Figure 7 Singleton MFs

The universe of discourse *U* in the above figure is defined as temperature. There are three fuzzy sets cold, warm and hot with corresponding membership functions $\mu_{\text{cold}}(\text{u}), \mu_{\text{warm}}(\text{u})$ and $\mu_{\text{hot}}(\text{u})$. Some features of the MFs are discussed below such as core, boundary, support, singleton, symmetry, normality, center, and height. The core of a fuzzy set *X* is the crisp set of all points *u* in the universe of discourse *U* where $\mu_X(\text{u}) = 1$. The boundary of fuzzy set *X* is the crisp set of all points u in *U* where $0 < \mu_X(\text{u}) < 1$. The support of fuzzy set *X* is the crisp set of all points u in *U* where $\mu_X(\text{u}) > 0$. If the fuzzy set, whose support is single point in *U* it is referred to fuzzy singleton. Figure 6 shows single point $\text{u} = 0.5$ in *U*. A fuzzy set *X* is said to be a symmetric if $\mu_X(\text{u})$ is symmetric around a certain point $a = \text{u}$. Figure 5 shows the fuzzy set warm is symmetric around point = 0.5. The membership function is said to be normal if one element at least or more in the universe of discourse *U* has a value 1 as example $\mu_{\text{warm}}(\text{u} = 0.5) = 1$ The center of a fuzzy set X is the mean value of all points u in U that achieves the maximum value of $\mu_X(\text{u})$. The point *u* = 0.5 is the center of fuzzy set warm in Figure 6. The height of fuzzy set *X* is the largest value of $\mu_{\text{warm}}(\text{u})$ warm in Figure 6 is equal 1.

2.3.4. Linguistic variable

A linguistic variable is a variable, written in a natural language format, which considers imprecise information. For example, if we are studying the case of the room temperature. Using FL, temperature is linguistic variable that takes the fuzzy sets: cold, warm, and hot as shown in Figure 8 for the universe of course *U* defined on [0,50] . This means that the range of the temperature from 0 to 50 Celsius. Temperature below10 Co is interpreted as cold and temperature above 50 Co is considered as hot. Now, temperature between10 and 25 Co is cold with certain membership value and warm with another membership value. Similarly, the temperature between 25 and 40 Co may considered as hot with specified membership value and warm with another membership value.

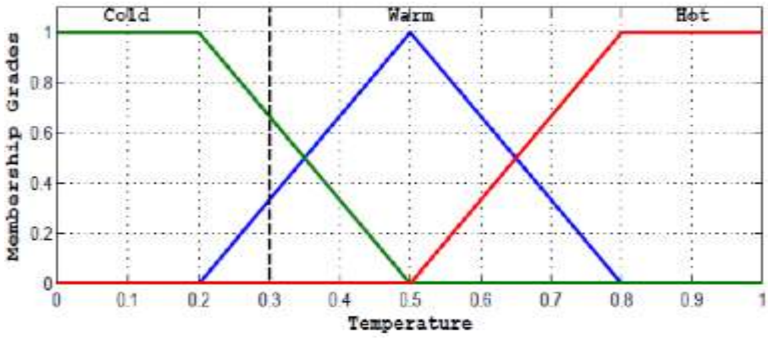


Figure 8 Example of fuzzy linguistic variable

Each element of Figure 8 is defined as a mathematical function, which normalized to the output range [0, 1] by multiplying scaling factor 1/50 from the discourse *U* defined on [0, 50]. In addition, this figure illustrates the idea of fuzzy partitioning. In fuzzy partitioning the transition or the moving from one set to another is easy. This means that the degree of a membership function for input u in a set warm increase while its membership function in a set cold decreases as the value of *u* moves from set cold to set warm. Many papers used the notation of linguistic variable in the form $\{G, \mathrm{T}(G), \mathrm{U}, \mathrm{S}_G\}$

Where G denoted as the linguistic variable name such as temperature, error, and error change, T(G) is the set of the names of the linguistic variable. In the case of temperature we have, T (temp) is {cold, warm, hot}. S_G, gives the meaning of the linguistic variable/label such as S_G take the label hot, this meaning returns to the linguistic variable temperature. Finally is the universe of discourse of the variables where G takes a crisp value.

2.3.5. Linguistic value

Let U_i^m denotes as a linguistic value of the linguistic variable *u* defined on the universe of discourse *U*, then the linguistic variable u is takes on elements from the set of linguistic values are denoted $\mathrm{U_i} = \{\mathrm{U_i^m}\}$, where m number of the linguistic values. For example, assume u denotes the linguistic variable temperature, then the linguistic values of the temperature variables are $U_i^1 = \text{cold}$, $U_i^2 = \text{warm}$, and $U_i^3 = hot$, so that $u \in U_i^m$ where $U_1^m = U_1^1, U_1^2, U_1^3$.

2.3.6. Fuzzy conditional statement

For two inputs e, Δe and output u with a universe of discourses E, ΔE and respectively. The fuzzy conditional statement consists of two parts: antecedent that represents the condition in the application domain and the consequent represents the control action for the controlled system. The **IF-THEN** fuzzy control rule has the form:

R_1 : IF e is X_1 AND Δe is Y_1 THEN u is Z_1
R_2 : IF e is X_2 AND Δe is Y_2 THEN u is Z_2
… … … …
⋮
⋮
R_j : IF e is X_j AND Δe is Y_j THEN u is Z_j

Where, e, Δe and u are linguistic variable representing two process state and one control variable. , X, Y and Z are linguistic values of the linguistic variables, e, Δe and u in the universe of discourse , E , Δe and U respectively and, j = 1, 2, ……, n .

2.3.7. Operations on fuzzy sets

The following operations are suggested by Zadeh to establish the concept of the fuzzy set theory. Supposition X and Y are two fuzzy sets in U with MFs μ_X and μ_Y respectively. Fuzzy mathematics denoted as relation between the elements of X and Y described using $\mu_{X\alpha Y}(u_1, u_2)$, where, $u_1, u_2 \in XY$. The commonly used set operations are union, intersection, and complement. The union of X and Y means that all elements belong to X or Y. The intersection of X and Y is mean that, the collection of all elements belong to X and Y. The complement of X is the elements, which do not belong to X. Figure 9, Figure 10, and Figure 11 explains the basic operation of the fuzzy set respectively.

1. Union

The union of two fuzzy sets X and Y on the universe of discourse U is a fuzzy set Z is described in the relation $Z = X \cup Y$, and the membership function of the fuzzy set Z is described as following:

$$\mu_Z(u) = \mu_{X \cup Y}(u) = \max\{\mu_X(u), \mu_Y(u)\} \tag{2.32}$$

Moreover, it shown as:

$$\mu_Z(u) = \mu_X(u) \cup \mu_Y(u) \tag{2.33}$$

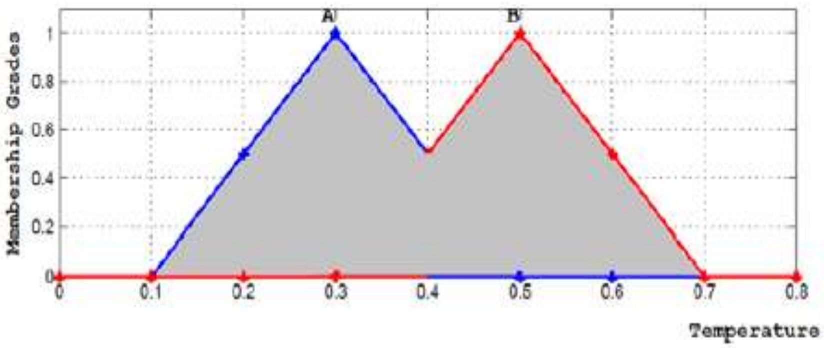


Figure 9 Union of fuzzy set X and Y

2. Intersection

The intersection of two fuzzy set X and Y on the universe of discourse U is a fuzzy set Z is described in the relation $Z = X \cap Y$, and the membership function of the fuzzy set Z is described as following:

$$\mu_Z(\mathrm{u}) = \mu_{X \cap Y}(\mathrm{u}) = \min\{\mu_X(u), \mu_Y(u)\} \tag{2.34}$$

Moreover, it shown as:

$$\mu_Z(\mathrm{u}) = \mu_X(\mathrm{u}) \cap \mu_Y(\mathrm{u}) \tag{2.35}$$

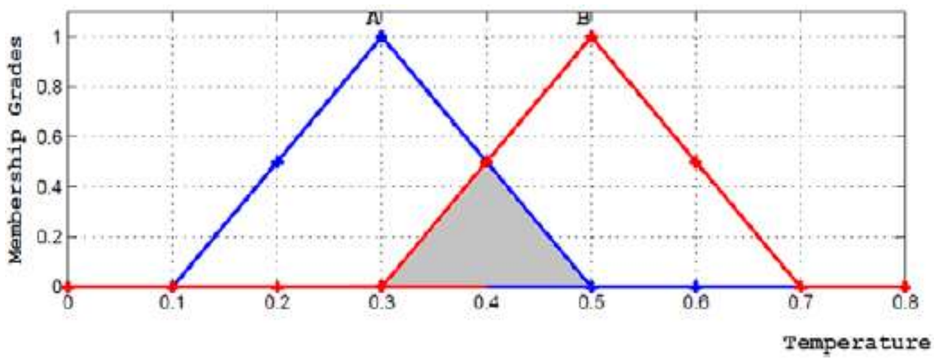


Figure 10 Intersection of fuzzy set X and Y

3. Complement

The complement of fuzzy set X is denoted by $\bar{X}$ and its membership function is defined as:

$$\mu_{\bar{X}} = 1 - \mu_X(Z) \tag{2.36}$$

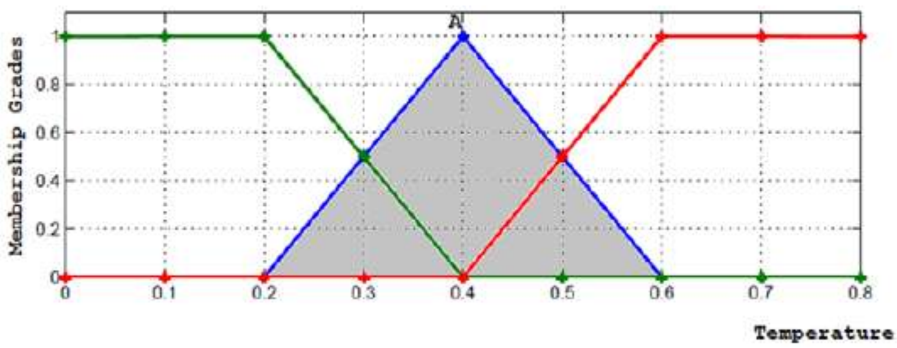


Figure 11 Complement of fuzzy set X

4. Cartesian product

If $X_1, X_2, X_3, \ldots\ldots X_n$ are fuzzy set in the universe of discourses

$U_1, U_2, U_3, \ldots\ldots U_n$ respectively, then the cartesian product is a fuzzy set denoted

by $U_1 \times U_2 \times U_3, \ldots\ldots U_n$ with membership function expressed as:

$$\mu_{X_1, X_2 \ldots\ldots X_n}(u_1, u_2, .., u_n) = \min\{\mu_{X_1}(u_1), \mu_{X_2}(u_2), \ldots.., \mu_{X_n}(u_n)\} \quad \text{Minimum}$$

(2.37)

$$\mu_{X_1, X_2 \ldots\ldots X_n}(u_1, u_2, .., u_n) = \{\mu_{X_1}(u_1) \times \mu_{X_2}(u_2) \times .. \times \mu_{X_n}(u_n)\} \quad \text{Product}$$

5. Algebraic product

The algebraic product of two fuzzy sets X and Y is defined as:

$$X\,Y = \left\{\left(u, \mu_X(u).\mu_Y(u)\right) | u \in U\right\} \tag{2.38}$$

6. Compositional rule of inference

If R is a fuzzy set relation $U \times V$ and X is a fuzzy set in U, then the fuzzy set Y in V includes A is given by

$$Y = X * R \qquad \{\text{X compsition R}\} \tag{2.39}$$

There are two cases in the compositional rule. The first case is maximum minimum (max-min) operation $\mu_X(u) = \max_{X \in U}\{\min(\mu_X(u), \mu_Y(v))\}$, and the second case is maximum-product (max-product) operation

$$\mu_X(u) = \max_{X \in U}\{(\mu_X(u) \bullet \mu_Y(v)\} \tag{2.40}$$

7. Fuzzy implication inference

The fuzzy implication inference rules:

A. The general modus ponens (GMP)

B. The general modus tollens (GMT)

Structure of the two methods as follows:

GMP *Premise* : $\text{a is } \overline{\text{X}}$

Rule: $if\ (a is X)\ then (b is X)$

Consequence: $\text{b is} \overline{\text{Y}}$

GMT *Premise*: $\text{b is} \overline{\text{Y}}$

Rule: $\text{if } (\text{a is X}) \text{then} (b \text{ is Y})$

Consequence: $\text{b is} \overline{\text{X}}$

The GMP method is closely to forward (data-driven) inference, which is used in FLC construction, while the GMT method is related to backward and it is widely used in expert systems. For two fuzzy sets X and Y, the fuzzy inference using GMP state: "If X is true and X implies Y, then Y is true". In this statement, X implies Y is the rule, where X is the antecedent and Y is the consequent. The rule base may be containing several implications as:

Premise: $a \text{ is} \overline{\text{X}} \text{and b is} \overline{\text{Y}}$

Rule: $\text{if } (\text{a is X}) \text{ and} (b \text{ is Y}) \text{ then} (c \text{ is Z})$

Consequence: $c \text{ is} \overline{\text{Z}}$

2.3.8. FLC structure

Figure 12 explains the basic arrangement of SISO fuzzy system, which comprises four main building components: fuzzification method, rule base, inference mechanism, and defuzzification method. As seen in the figure, the output and input data of FLC are crisp (non-fuzzy) values.

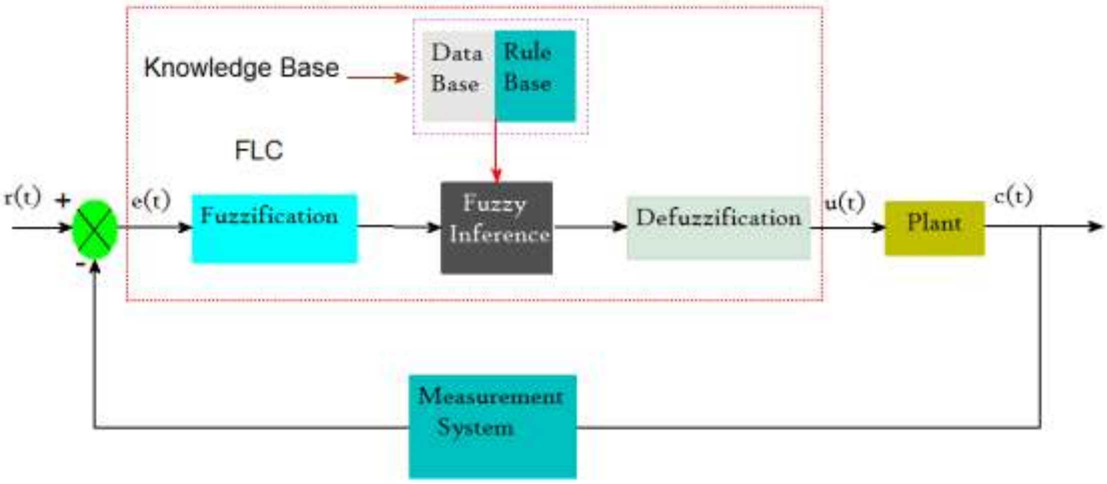


Figure 12 Fuzzy logic controller structure

Before illustrating FLC components, it is important to define the FLC input and output variables. The controller is used to correct the error signal then supply appropriate input to the plant. One input is used for FLC: the error that generated from the feedback loop. It may have a derivative of the error input for fuzzy like PD controller, or it may also have an integral input for fuzzy like PI controller. The two variables e and u of the FLC are the error and the output action, and the variables $e(t), u(t)$ are their fuzzy counterparts respectively, $c(t)$ is the output, and $r(t)$ is the set point.

2.3.9. Fuzzification

Fuzzification is the important block inside the controller structure, the purpose of fuzzifier is to transform the crisp input to fuzzy set defined in U and characterized by membership function $\mu_x(u):U \rightarrow [0,1]$ The input and output memberships overlaps, and they are scaled with respect to input-output of the fuzzy control. It is labeled by linguistic terms such as short, medium, and tall. For example, if the integer value 40 is the input, the fuzzification process converts the integer value into a linguistic variable. The number of the linguistic variables for the input output domains specified by the designer. In addition, they should be as small as possible because the large number of linguistic variables, the more complicated inference mechanism. The domain of the input variable e is chosen from the specification of the controlled system, similarly the domain of the output variable (control signal) u is chosen according to the desired output.

Figure 13 shows several types of membership functions [25], such as a triangular, trapezoidal, Gaussian, singleton, and the sigmoid membership functions. The most commonly used shapes are triangular trapezoidal, and singleton. As example, the triangular membership function can be characterized by a triple points (x, y, z) where the point (x = 0), (y = 1) and (z= 0) are vertices of triangle, while trapezoidal membership characterized by quadruple (x, y, z, w) points where the points ((x = 0), (w = 0)) and ((y = 1), (z = 1)).

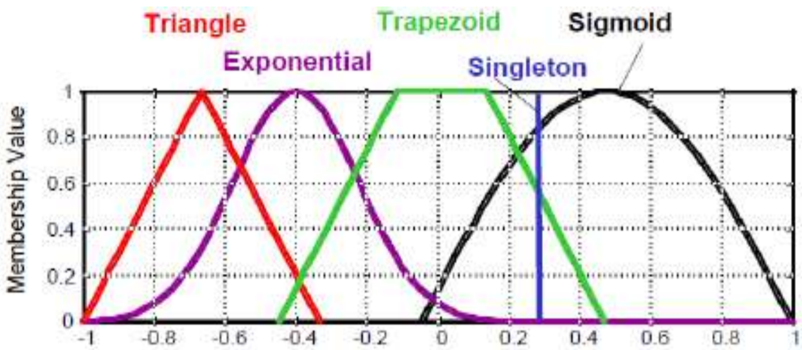


Figure 13 Membership functions shapes

In general, the width of each fuzzy set extends to the peak point of the adjacent fuzzy sets, and the peak value of the fuzzy set has a unity value. As an example in Figure 8 if u is a value between cold and warm fuzzy sets. The two fuzzy sets are active, and the membership functions of the two fuzzy sets are $\mu_{cold}(u), \mu_{warm}(u)$ depends on the intersection between the line of the input point and the two slops of the two fuzzy on the intersection between the line of the input point and the two slops of the two fuzzy sets. As example, the crisp input u = 0.3 has two membership functions $\mu_{cold}(u) = 0.7 and\ \mu_{warm}(u) = 0.3$. Summation of both membership functions is equal one.

2.3.10. Knowledge base

In FC, it is important to define the state variable and the control variable of the FC. The good choice of these variables is important to have the desired behavior of the system. The function of the knowledge base is to model a human expert qualitative knowledge about the desired relationship between the input and the output of the fuzzy system [24]. Knowledge base includes three main parts as mentioned in Figure 12: rule base, fuzzy set and the fuzzy generator]; it is a set of rules in the form of **IF-THEN** statement that describe the state and the behavior of the system. It consists of all fuzzy implications that used to describe the relation between the input and the output. Selection of the rule base affects the performance of the FLC. In addition, it is used to provide and characterize the control goal and control policy of the controller into a set of linguistic rules. Rule base explains the relation between inputs; in general, it may use many variables in the form of conditional statements that have the following form:

$$\mathrm{R_j : IF\ e\ is\ E_j,\ AND\ \Delta e\ is\ \Delta E_j\ THEN\ u\ is\ U_j,\quad j = 1, 2, \ldots.., n}$$

Where e, Δe, and u are the input and output of fuzzy system $E_j, \Delta E_j$ and U_j are fuzzy variables with fuzzy membership function $\mu_E(e), \mu_{\Delta E}(\Delta e), \mu_U(u)$ respectively. The second term is the fuzzy set data. It contains of the information about the universe of discourse, number of the input and output and the number of the membership functions. It contains the fuzzy set, which quantify the statement of the input and the output such as: u is U and b is Y. Finally, fuzzy generating tends to access the fuzzy set and fuzzy implication to generate a fuzzy relation for each implication was defined in the rule base.

Many categories was proposed to form the **IF-THEN** statement. Two prevalent methods are Mamdani and Takagi-Sugeno [22].The first method, is considered as the most popular method is used to design FLC because it is simple to be implemented. The second is Takage-Sugeno (TS) method, which is called TS fuzzy rule. The two methods have a fuzzy antecedent part. The antecedent evaluation of the **IF-THEN** statement is the same for both methods, but the essential difference between them lies in the consequent part structure, where the consequent part of TS rule is a function of real value. The next two rules structure describes Mamdani and TS fuzzy method.

Mamdani style

$$\textbf{IF}\ \mathrm{e_i\ is\ E_i},\ \textbf{AND/OR}\ \Delta \mathrm{e_j\ is\ \Delta E_j}\ \textbf{THEN}\ \mathrm{u_{ij}\ is\ U_{ij}}$$

Sugeno style

$$\textbf{IF}\ \mathrm{e_i\ is\ E_i},\textbf{AND /OR}\ \Delta \mathrm{e_j\ is\ \Delta E_j}\ \textbf{THEN}\ \mathrm{u_{ij} = k_i u_j + k_j u_j}$$

In Mamdani fuzzy rule method, the knowledge of the system (antecedent) and the set of the action (consequent) depend on the human operator. Generally, for nonlinear systems the linguistic rule is one of four forms. Each one of these forms expressed linguistically as:

Single Input single output (SISO)

$$\textbf{IF} e\ is\ E\ \textbf{THEN}\ u\ \textbf{is}\ U$$

Multi input single output (MISO)

$$\textbf{IF}\ \mathrm{e_1\ is\ E_1},\ \textbf{AND}\ \mathrm{e_2\ is\ E_2}\ \textbf{THEN}\ u\ is\ U$$

Single Input multi output (SIMO)

IF e_1 is E_1 **THEN** u_1 is U_1 **AND** u_2 is U_2

Multi input multi output (MIMO)

IF e_1 is E_1 **AND**……**AND** e_r is E_r **THEN** u_1 is U_1 **AND**……**AND** u_r is U_r

In this thesis, the rule base is constructed as referred in the first case. This case will use in Chapter four. There are some techniques are used for generating rule base. These techniques may combine to construct an effective method to derive rule base [20] and [9]. Derivation rule base depends on using the antecedent (error) and the consequent (control signal) to describe the relation between the inputs and outputs of the fuzzy controller. First technique is based on the knowledge of the controlled system by analyzing the behavior of the system. We can use the input output relation that obtained from system identification to generate a set of fuzzy rules to achieve the optimal behavior of the system. Although this method does not effective for all systems due to complexity and nonlinearity, it gives good results. The second method is based on experienced human operator [24]. In many industrial control systems, the relation between the inputs and the output are not known with high precision to employ the control algorithms, so, human operator can generate a set of fuzzy **IF-THEN** rules to control the process. This method gives popularity for FLC in industrial fields because it does not require a mathematical model of the complex systems, but the main drawback of this method is it dependency on the knowledge of the human [32]. Another technique depends on the learning algorithm of the FC. It based on the ability to create fuzzy control rules and modifying them based on experience and system behavior [21].

2.3.11. Inference mechanism

Inference mechanism process is getting the pertinent control rule at the current time then decides what the output of the controller should be. The membership function value for each rule for controller input is calculated by using fuzzy inference mechanism. The following rule base R_1 is explained as [3]:

R_1 : **IF** e is E_1 **THEN** u is U_1

The fuzzy implication is expressed as a cartesian product of the antecedent and the consequent as $R_1 = E_1 \times U_1$. In addition, this is similarly done for all rules. Several ways are used to implement fuzzy inference methods, but the most commonly used in control field are Mamdani method (minimum-maximum) and Larsen method (product- maximum) [21].

$$\mu_{R_1}(e,u) = \min\{\mu_{E_1}(e),\ \mu_{U_1}(u)\} \qquad \text{Minimum}$$

$$\mu_{R_1}(e,u) = \{\mu_{E_1}(e).\mu_{U_1}(u)\} \qquad \text{Product} \tag{2.41}$$

To illustrate the operation of inference mechanism, this is given by the following example. Assume the FLC has two inputs E_1 and E_2 and output U, all of them have universe of discourse [-1,1] with peak points (-0.5,0,0.5),(-0.3,0,0.3),and (-0.5,0,0.5) respectively.

Before solving this example, the inference mechanism is divided into three steps first, specifying the inputs and determine the degree of its membership function. The second, applying the desired operation such as minimum or product operations. The final step aggregates, all the outputs, then combine them using maximum or sum aggregation method.

2.3.12. Defuzzification

Defuzzification is the last step of the FLC. The defuzzification method tends converts the resulting fuzzy set into a crisp values that can be sent to the plant as a control signal. In general, there are several methods used for defuzzification as shown in Figure 14.

In this thesis used centroid of area (COA) method. This method produces a control action that represents the center of the output of the fuzzy set. The weighted average of the membership function or the COA bounded by the membership function curve and it is converted to a typical crisp value. Figure 14 shows the various defuzzification methods.

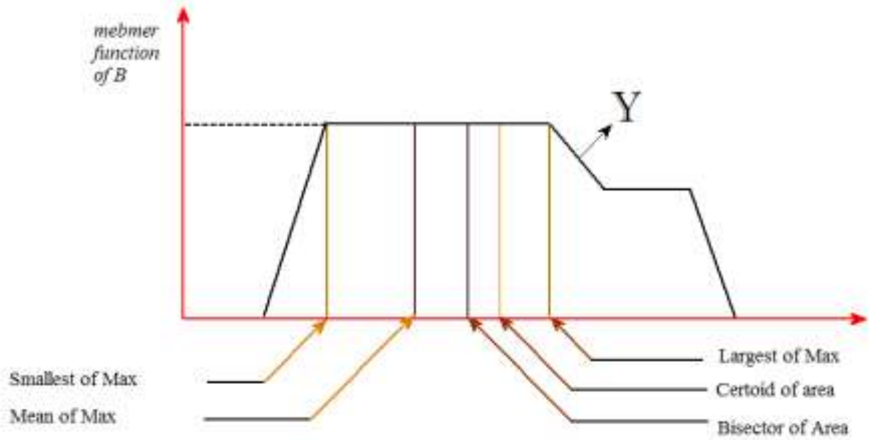


Figure 14 Defuzzification methods

The control action for the values, which obtained using Mamdani, using COA method, is determined as follows.

Mamdani Method

$$\text{Control action} = \frac{\sum_{i=1}^{m} \mu(a_i).a_i}{\sum_{i=1}^{m} \mu(a_i)} \tag{2.42}$$

2.3.13. Fuzzy control

Fuzzy PID controller has been applied successfully in many applications of control fields. Different design methods of fuzzy PID controller are used nowadays [10], [26] and [9] that present significant performance comparing to classical PID controller; moreover, designing and tuning Fuzzy PID controller with simple structure gives satisfactory results for the system. Fuzzy PID controller is good controller because its components help to provide convenient closed loop response characteristics. It combines the advantages of each term of PID controller individually, taking into account that the fuzzy PID terms are better than the classical PID terms [32]. Fuzzy proportional term reduces the rising time, while the fuzzy integral term precludes the steady state error, and the third fuzzy derivative term enhances the system stability by decreasing the overshoot and optimizing the transient response. Fuzzy controller consist of three main stages as shown in Figure 15,

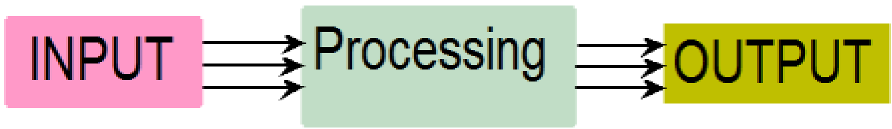


Figure 15 Fuzzy control system

CHAPTER THREE

MODELING OF FLUID SYSTEM

3.1. Introduction

A fluid system is widely used in many applications such as actuators and processes that involve mixing, heating, and cooling of fluids. Fluid system has extensive usage in industrial field; a lot of industrial applications of liquid level control are used now. A fluid is either a liquid or a gas. By taking into consideration the changes in the fluid pressure if the fluid's density remains constant a fluid is said to be incompressible. The fluid is compressible if the density changes with pressure. In the field of operation for industries applications the control of flow between two tanks and liquid level in tanks is a necessary matter. The flow between tanks has to be adjusted, also the level of fluid in the tanks has to be controlled. In particular, the liquid levels interact when the tanks are connected together and it should be controlled.

3.2. Flow Types

It is necessary in analyzing systems for the purpose of fluid flow splitting. The flow system is divided to two types:

3.2.1. The laminar flow

The laminar flow is a flow dominated by viscosity forces and it is characterized by a smooth parallel line motion of the fluid and low the Reynolds number (Re).

$$Re = \frac{\rho v D}{\mu} < 2000 \qquad (3.1)$$

Where

ρ : is the fluid mass

μ : is the fluid dynamic viscosity

v : is a flow average velocity

D : is the characteristic length

The frictional force is linearly proportional to velocity, Figure 16 shows the laminar flow in pipe in this type of flow

$$f_f = bv \qquad (3.2)$$

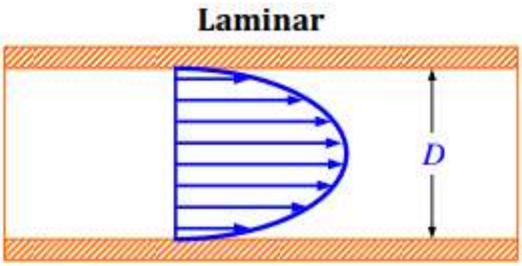


Figure 16 Velocity profile for laminar flow

3.2.2. The turbulent flow

The flow is called turbulent flow when inertia forces are dominated. The turbulent flow is characterized by an irregular and eddy like motion of the fluid and it has high Reynolds number Re greater than 4000.Friction force varies as a power of velocity. Figure 17 shows the Turbulent flow in pipe.

$$f_f = bv^a \qquad (3.3)$$

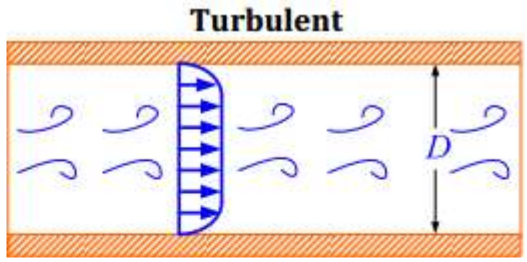


Figure 17 Velocity profile for turbulent flow

3.3. Resistance of Liquid - Level System

The resistance of liquid flow in the pipe can be calculated from:

$$Resistance\,(R) = \frac{Change\ in\ level\ difference}{Change\ in\ flow\ \ rate} \equiv \frac{m}{m^3/s} \qquad (3.4)$$

Figure 18 explains the flow of liquid through a short pipe connecting two tanks.

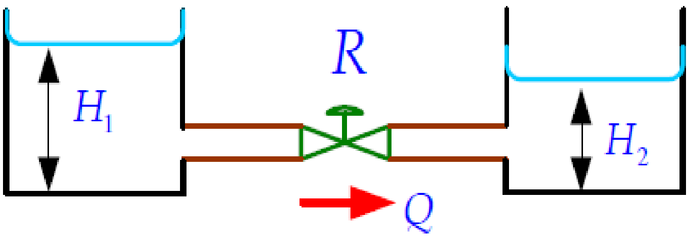


Figure 18 Two tanks connected by a short pipe with a valve

3.3.1. Resistance in laminar flow

In laminar flow, the relationship between steady state head at the level of restriction and steady-state flow rate is

$$Q = K_L H \qquad (3.5)$$

The resistance of laminar flow R_L is determined by:

$$R_L = \frac{dH}{dQ} = \frac{1}{K_L} = \frac{H}{Q} \tag{3.6}$$

3.3.2. Resistance in turbulent flow

In turbulent flow, the steady-state flow rate is calculated from:

$$Q = K_t \sqrt{H} \tag{3.7}$$

From Eq. (3.7), we can differentiate Q with respect to H as follows:

$$dQ = \frac{K_t}{2\sqrt{H}} dH \tag{3.8}$$

Rewrite Eq. (3.8) into

$$\frac{dQ}{dH} = \frac{K_t}{2\sqrt{H}} \tag{3.9}$$

By plotting the head-versus-flow-rate curve, the resistance can be determined based on measuring the slope of the curve at the operating condition and experimental data. Figure 19shows an example of such a plot, where point P is the steady-state operating point. The tangent line to the curve at point P intersects the coordinate at $(0, -\overline{H})$ point .Thus, the slope of this tangent line is $2\overline{H}/\overline{Q}$. Since the resistance R_t at the operating point P is given by $2\overline{H}/\overline{Q}$, the resistance R_t is the slope of the curve at the operating point. Consider the operating condition in the zone of point P and define a small deviation of the head from the steady-state value as h and the corresponding small change of the flow rate as q .Then , the curve slope at point P could be given by :

$$\text{slope of curve at point P} = \frac{h}{q} = \frac{2\overline{H}}{Q} = R_t \tag{3.10}$$

From Figure 19,the equation of the resistance R_t for turbulent flow is given by:

$$R_t = \frac{dH}{dQ} \quad (3.11)$$

From Eq. (3.7), Eq. (3.6) and Eq. (3.11), R_t will be:

$$R_t = \frac{2H}{Q} \quad (3.12)$$

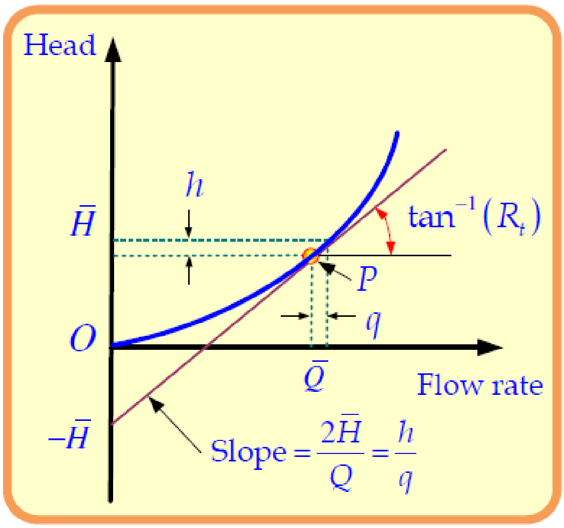


Figure 19 Head versus - flow-rate curve

3.4. Capacitance of Liquid - Level System

The capacitance of a tank is the relationship between the changes in liquid stored to the change in the head.

$$Capacitance\ (C) = \frac{Change\ in\ liquid\ stored}{Change\ in\ head} \equiv \frac{m^3}{m} \quad (3.13)$$

Where Capacitance (C) is cross- sectional area (A) of the tank

$$\frac{dV}{dt} = q_{in} - q_{out} \quad (3.14)$$

$$V = A \times h \tag{3.15}$$

Substitute Eq. (3.15) in Eq. (3.14),

$$\frac{d(A \times h)}{dt} = q_i - q_o \tag{3.16}$$

Simplify Eq. (3.16) into

$$A\frac{dh}{dt} = q_i - q_o \tag{3.17}$$

Hence,

$$C\frac{dh}{dt} = q_i - q_o \tag{3.18}$$

3.5. Mathematical Modeling of Single Tank

The single tank system is shown in Figure 20. If the operating condition is adjusted to head value and the flow rate varies slightly for the specified period, a mathematical model can easily be found in terms of capacitance and resistance. This type of flow is known as turbulent flow value.

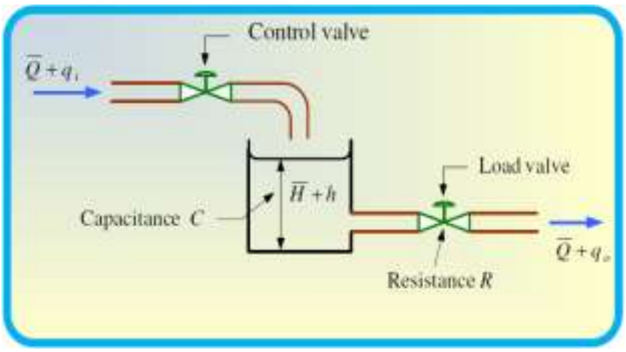


Figure 20 Single tank system

In Figure 20, the rate of change in liquid stored in the tank is equal to the flow in minus flow out

$$C\frac{dh}{dt} = q_i - q_o \quad (3.19)$$

Or

$$C\,dh = \left(q_i - q_o\right)dt \quad (3.20)$$

In the present system, we define h and q_0 as small deviations from steady state head and steady state outflow rate, respectively.

Thus

$$dH = h \quad (3.21)$$

$$dQ = q_o \quad (3.22)$$

The resistance R can be written as:

$$R = \frac{dH}{dQ} \quad (3.23)$$

Substitute Eq. (3.21) and Eq. (3.22) in Eq. (3.23), we get

$$R = \frac{h}{q_o} \quad (3.24)$$

Rewrite Eq. (3.24) into

$$q_o = \frac{h}{R} \quad (3.25)$$

Putting Eq. (3.25) in Eq. (3.19)

$$C\frac{dh}{dt} = q_i - \frac{h}{R} \quad (3.26)$$

Rewrite Eq. (3.26) as follows:

$$RC\frac{dh}{dt} + h = R\,q_i \quad (3.27)$$

Taking the Laplace transforms for both sides of Eq. (3.27), supposing the zero initial condition, we get

$$(RCs+1)H(s)=RQ_i(s) \tag{3.28}$$

Where

$H(s)=L[h]$ and $Q_i(s)=L[q_i]$

Rewrite Eq. (3.29) into

$$\frac{H(s)}{Q_i(s)}=\frac{R}{RCs+1} \tag{3.29}$$

Taking the Laplace transforms for both sides of Eq. (3.25).

$$Q_o(s)=\frac{H(s)}{R} \tag{3.30}$$

Rewrite Eq. (3.30) into

$$H(s)=\frac{Q_o(s)}{R} \tag{3.31}$$

Substitute Eq. (3.29) in Eq. (3.27), we obtain

$$\frac{Q_O(s)}{Q_i(s)}=\frac{1}{RCs+1} \tag{3.32}$$

Eq. (3.32) represents the transfer function of single tank system.

3.6. Mathematical Modeling of Double Tanks System

The liquid level system is shown in Figure 21, where the two tanks are interacted to each other. Using the same ideas as employed in the single tank model .This will give a second order transfer function equation. If the variations of the variables from the irrespective steady state values are small, the resistance R_1 stays constant. Hence, at steady-state.

$$\bar{Q} = \frac{\bar{H}_1 - \bar{H}_2}{R} \tag{3.33}$$

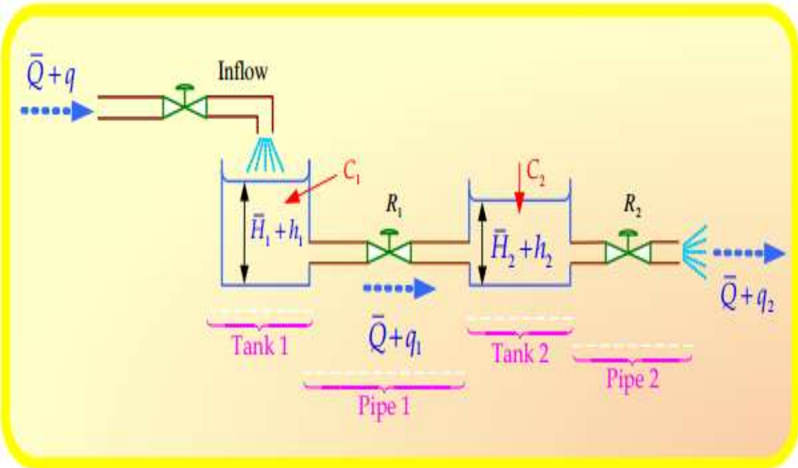


Figure 21 The implement of double tanks fluid system

After small changes have occurred, we have

$$\bar{Q} + q_1 = \frac{\bar{H}_1 + h_1 - \left(\bar{H}_2 + h_2\right)}{R_1} \tag{3.34}$$

Simplify Eq. (3.35) into

$$\bar{Q} + q_1 = \frac{\left(\bar{H}_2 + \bar{H}_1\right)}{R_1} + \frac{\left(h_1 - h_2\right)}{R_1} \tag{3.35}$$

Supposition that variations of the variables from their respective steady-state values are small. After that, use the symbols defined in Figure 21, we may get the following four equations:

For the first tank :

$$C_1 \frac{dh_1}{dt} = q - q_1 \tag{3.36}$$

For the first pipe :

$$q_1 = \frac{h_1 - h_2}{R_1} \tag{3.37}$$

Putting Eq. (3.37) in Eq. (3.36) , we obtain

$$C_1 \frac{dh_1}{dt} + \frac{h_1}{R_1} = q + \frac{h_2}{R_1} \tag{3.38}$$

For the seconed tank:

$$C_2 \frac{dh_2}{dt} = q_1 - q_2 \tag{3.39}$$

For the second pipe :

$$q_2 = \frac{h_2}{R_2} \tag{3.40}$$

Substitute Eq. (3.40) in Eq. (3.41)

$$C_2 \frac{dh_2}{dt} + \frac{h_2}{R_2} + \frac{h_2}{R_1} = \frac{h_1}{R_1} \tag{3.41}$$

Take Lablace Transfer function for the two sides of Eq. (3.38),using $I.C^{/}sh_1(0) = h_2(0) = 0$, we get

$$\left(C_1 s + \frac{1}{R_1} \right) H_1(s) = Q(s) + \frac{1}{R_1} H_2(s) \tag{3.42}$$

Simplify Eq. (3.42) into;

$$H_1(s) = \frac{R_1Q(s) + H_2(s)}{(R_1C_1s + 1)} \quad (3.43)$$

Take Lablace Transfer function for the two sides of Eq. (3.41),using $I.C^{/}sh_1(0) = h_2(0) = 0$

We get ;

$$\left(C_2s + \frac{1}{R_2} + \frac{1}{R_2}\right)H_2(s) = \frac{1}{R_2}H_1(s) \quad (3.44)$$

Simplify Eq. (3.44) into;

$$\left(\frac{R_2R_1C_2s + R_1 + R_2}{R_2R_1}\right)H_2(s) = \frac{1}{R_1}H_1(s) \quad (3.45)$$

Putting Eq. (3.43) in Eq. (3.45), the resultant equation will be

$$\left(\frac{R_2R_1C_2s + R_1 + R_2}{R_2R_1}\right)H_2(s) = \frac{1}{R_1}\left(\frac{R_1Q(s) + H_2(s)}{(R_1C_1s + 1)}\right) \quad (3.46)$$

Substitute $H_2(s) = R_2Q_2(s)$ in Eq. (3.46) as follows :

$$\left(\frac{R_2R_1C_2s + R_1 + R_2}{R_2R_1}\right)R_2Q_2(s) = \frac{1}{R_1}\left(\frac{R_1Q(s) + R_2Q_2(s)}{(R_1C_1s + 1)}\right) \quad (3.47)$$

Simplify Eq. (3.47) in to;

$$(R_2R_1C_2s + R_1 + R_2)R_2Q_2(s) = \left(\frac{R_1Q(s) + R_2Q_2(s)}{(R_1C_1s + 1)}\right) \quad (3.48)$$

Simplify Eq. (3.48) into;

$$((R_2R_1C_2s + R_1 + R_2)R_2Q_2(s))(R_1C_1s + 1) = R_1Q(s) + R_2Q_2(s) \quad (3.49)$$

Simplify Eq. (3.49) into;

$$\left(\left(R_2R_1C_2C_1\right)s^2+\left(R_1C_1+R_1C_1+R_2C_2\right)s+1\right)Q_2(s)=Q(s) \tag{3.50}$$

From Eq. (3.50)

$$\frac{Q_2(s)}{Q(s)}=\frac{1}{\left(\left(R_2R_1C_2C_1\right)s^2+\left(R_1C_1+R_1C_1+R_2C_2\right)s+1\right)} \tag{3.51}$$

By dividing Eq. (3.51) on ($R_2R_1C_2C_1$), we will observethe double tank system transfer function as shown in Eq. (3.52).

$$\frac{Q_2(s)}{Q(s)}=\frac{1/R_2R_1C_2C_1}{\left(s^2+\left[\frac{R_1C_1+R_1C_1+R_2C_2}{R_2R_1C_2C_1}\right]s+1/R_2R_1C_2C_1\right)} \tag{3.52}$$

We can get Eq. (3.52) in another way by block diagram reduction as shown in Figure 22, Figure 23, and Figure 24.

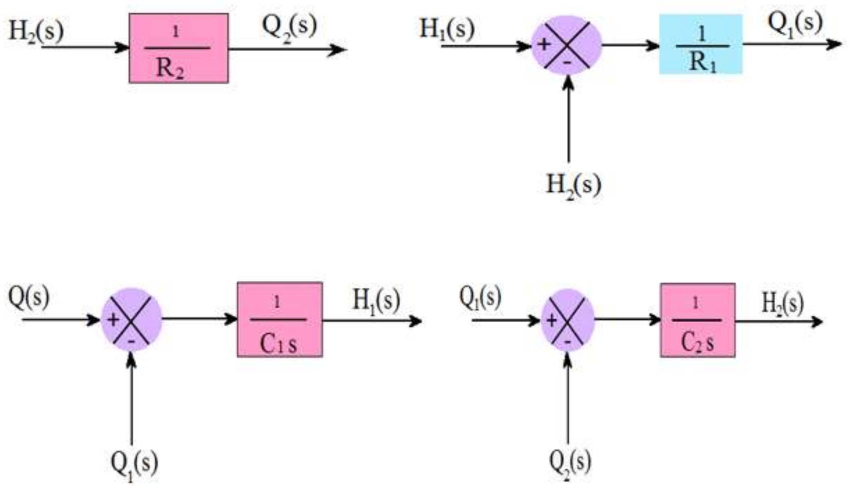


Figure 22 Elements of the system block diagram

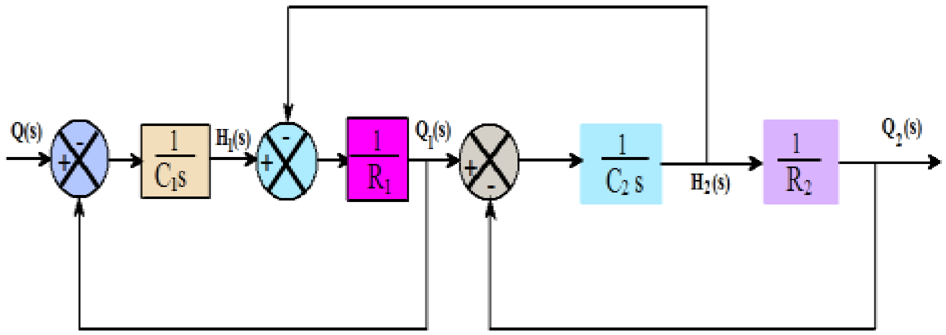


Figure 23 Structure of the system block diagram

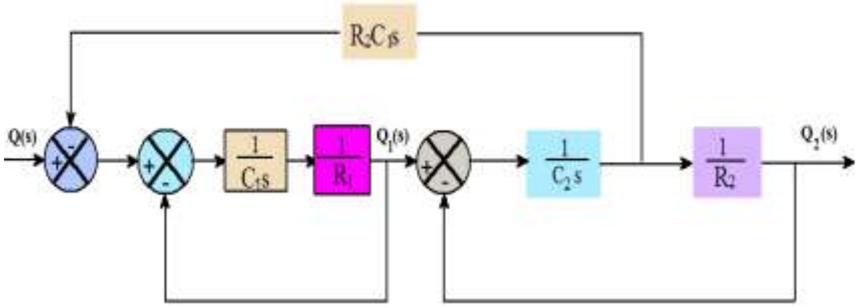


Figure 24 Successive reductions of the block diagram

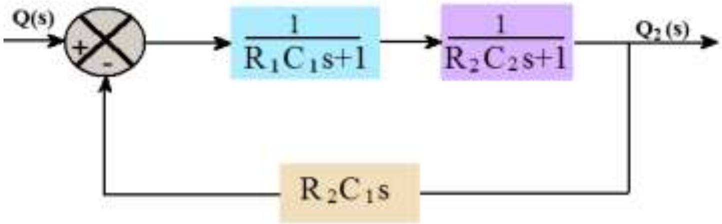


Figure 25 Successive reductions of the block diagram

Finally, the transfer function of the interacted system will be:

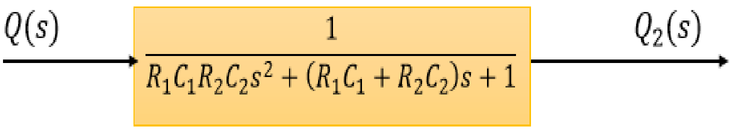


Figure 26 Successive reductions of the block diagram

3.7. Parameters

We described the parameters of the double tank system in previous section. In this section, the height of the first tank (H_1) is 2 m and the height of the second tank (H_2) is 1.99 m, the square cross-section area of each tank ($C_1 and C_2$) is 9 m^2.The circular cross-section area of the connection pipes (pipe1, pipe2) for the double tanks system is $a_1 = a_2 = 0.0125\pi m^2$, the value of the gravitational acceleration is $9.81 m/\sec^2$.

$$R_1 = a_1(\sqrt{2.g}).\frac{1}{2.\sqrt{H_1 - H_2}} \tag{3.53}$$

Substitute the values of $(H_1, H_2, C_1, C_2, a_1)$, we will get

$R_1 = 0.8697$

$$R_1 = a_2(\sqrt{2.g}).\frac{1}{2.\sqrt{H_2}} \tag{3.54}$$

Substitute the values of (H_2, C_1, C_2, a_2), R_2 will be

$R_2 = 0.0617$

Substitute the values of the parameters (R_1, R_2, C_1, C_2) in Eq. (3.52),

$$\frac{Q_2(s)}{Q(s)} = \frac{0.2302}{s^2 + 2.058s + 0.2302}$$

By using Matlab program, the system step response has been concluded as shown in Figure 27. In Figure 27, the characteristics of the output response are very poor, where the settling time and the rise time is very high that make the response of the output system slower. In other word, this response is not desirable in industrial processes.

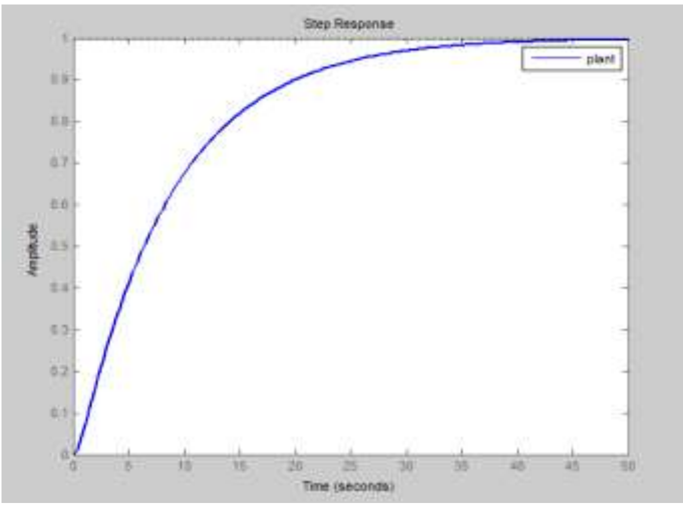


Figure 27 Output response of the double tanks system

CHAPTER 4

SIMULATION RESULTS AND DISCUSSION

4.1. Introduction

The PID controller model has been designed in three methods which are root locus design method, symmetrical optimum design method and magnitude optimum design method. The output response characteristics for each method has been simulated and tested. All of these methods are compared graphically and numerically. Furthermore, we optimized the parameters of PID controller by using a new evolutionary algorithm BBO. In addition, a comparison between the characteristics of output responses of PID controller design methods and the characteristics of output response of BBO is also made.

In spite of the diversity in using PID controller, more time is needed for the trial and error tuning to find suitable PID parameters. Moreover, it is hard to achieve the desired control performance when applying PID controllers to some application and time varying systems because of the dynamic nature of these systems. Therefore, control techniques has been designed to limit the drawback in the PID controller. One of these techniques is the FLC that will be applied in this thesis.

In addition to that, the response enhancement by using Fuzzy Logic Controller has been simulated. Furthermore, graphically and numerically comparison with PID controller, BBO and Fuzzy logic controller will also be introduced. The design of PID controller will be presented in this chapter.

4.2. Design of PID Controller

In chapter three, PID controller was discussed. In this section, a description of the design of PID controller is presented. The main equation of PID controllers is:

$$u(t) = K_P e(t) + K_I \int_0^t e(t)dt + K_D \frac{de(t)}{dt} \tag{4.1}$$

Figure 28 explains the basic structure of PID controllers

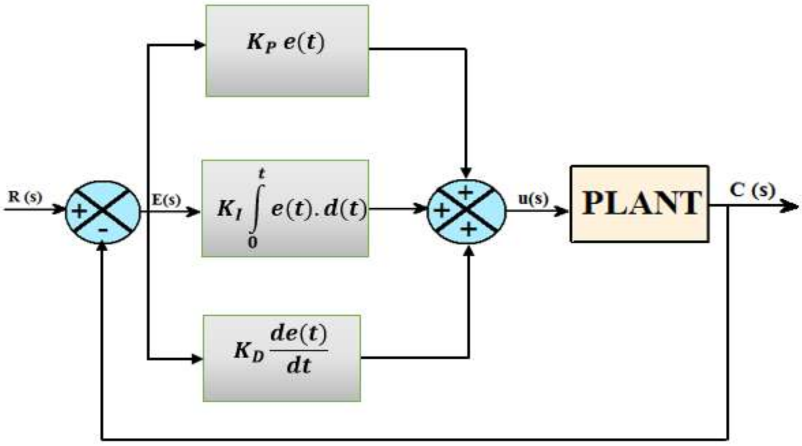


Figure 28 The structure of PID controller

As discussed earlier, there are several techniques for tuning PID controllers, These techniques can be summarized as follows:

- **Magnitude optimum design method**
- **Symmetrical optimum design method**
- **Root locus design method**

4.2.1 Magnitude optimum design method

The magnitude optimum design method is previously mentioned in Chapter two which is applied it in this section to find a controller for double tank system. The system transfer function can be represented as:

$$G(s)=\frac{0.2302}{s^2+2.058\ s+0.2302} \tag{4.2}$$

Rewrite the Eq. (4.2) in to Eq. (4.3)

$$G(s)=\frac{1}{4.34404\ s^2+8.94005\ \ s+1} \tag{4.3}$$

Note that the transfer function in Eq. (4.2) is second order, so the type of the resulting controller must be PI- controller. This is satisfied in the magnitude optimum design method. Through the transfer function of the system in Eq. (4.3), we can determine the parameters $a_0 = 1$, $a_1 = 8.94005$, $a_2 = 4.34404$

Hence, we can compute the parameters of PI- controller (P_0 and P_1) in Eq. (4.4) and Eq. (4.5)

$$P_0 = a_0 \frac{a_1^2 - a_0 a_1}{a_1 a_2 - a_0 a_3} \tag{4.4}$$

$P_0 = 1.9461$

$$P_0 = 1.9461 P_1 = a_1 \frac{a_1^2 - a_0 a_2}{a_1 a_2 - a_0 a_3} - a_0 \tag{4.5}$$

$P_1 = 16.3987$

Substitute the parameters of PI-controller in Eq. (4.6)

$$C(s)=\frac{P_0+P_1 s}{2s} \tag{4.6}$$

Rewrite the Eq. (4.6) with the value of P_0 and P_1 into the Eq. (4.7)

$$C(s)=\frac{1.9461+16.3987\ s}{2s} \tag{4.7}$$

Figure 29 shows the closed loop system by using magnitude optimum design method. This figure is given by Eq. (4.7) as PI-controller and Eq. (4.2) as plant of the system.

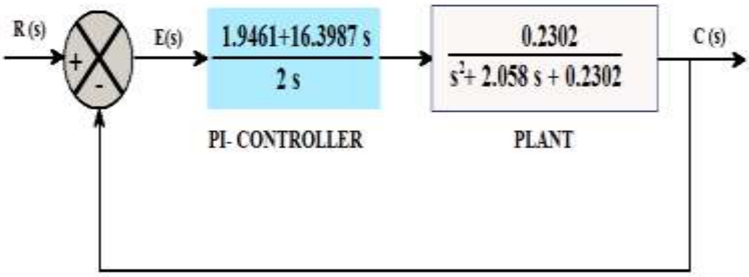


Figure 29 Structure of the system with magnitude optimum design

The simulink model of magnitude optimum design method

The design of the system is shown in Figure 30 implemented by using Matlab – Simulink using Eq. (4.7) and Eq. (4.2). Eq. (4.7) represents the block PID controller while Eq. (4.7) stands for the block of plant .By running this model, we have been obtained the following response as shown in Figure 31.

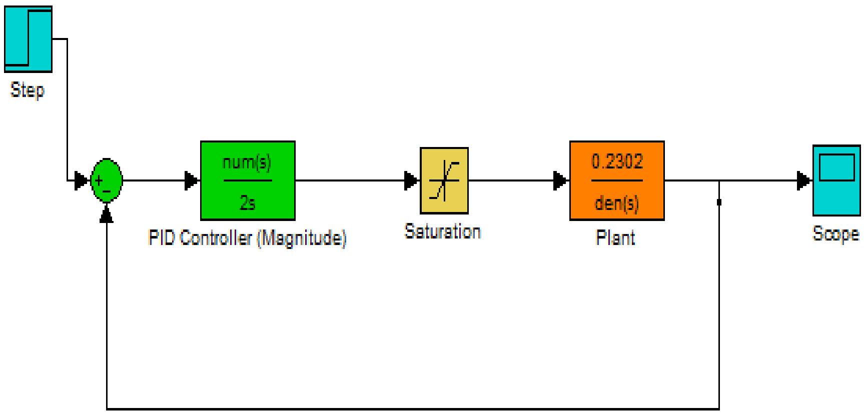


Figure 30 Simulink model of the magnitude optimum design for PI controller

Figure 31 represents the simulation result of the output response of a PI controller by using magnitude optimum design method with settling time $(t_s = 4.34sec)$ and rise time of 1.56 sec.

The simulated curve explains that the overshoot begins at 3.43 *sec* and becomes maximum at (4.3 *sec*), then decreases gradually until 6.64 *sec*. At 6.64 sec, the steady state error becomes zero.

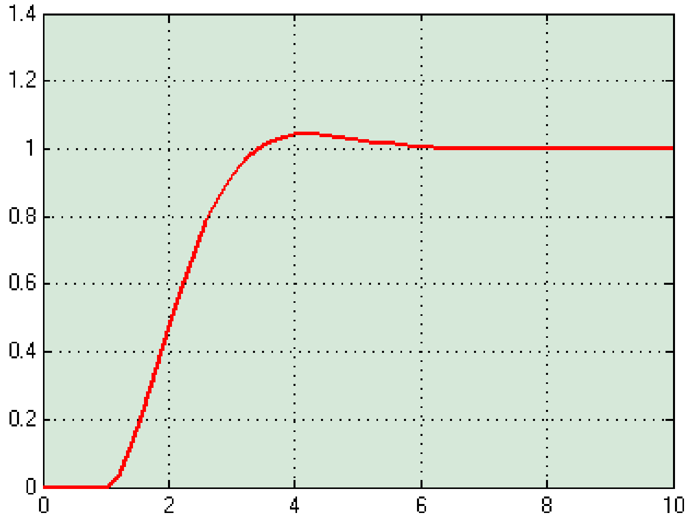


Figure 31 Magnitude optimum design for PI controller response

4.2.2. Symmetrical optimum design method

In Chapter two, the symmetrical optimum design method has been explained, which is applied it in this section. The plant transfer function is:

$$G(s) = \frac{0.2302}{s^2 + 2.058\,s + 0.2302} \tag{4.8}$$

Rewrite Eq. (4.8) into Eq. (4.9)

$$G(s) = \frac{0.2302}{(s + 1.9377)(s + 0.1203)} \tag{4.9}$$

In order to design the symmetrical optimum method, we must set poles of Eq. (4.9) that represents plant transfer function G(s). From Eq. (4.9) the poles are:

$P_1 = 1.9377,\ P_2 = 0.1203$

By simplify Eq. (4.9) into:

$$G(s) = \frac{0.987536}{(0.51607\ s + 1)(8.3125\ s + 1)} \tag{4.10}$$

Observe that G(s) in Eq. (4.10) is stable and contains one small time constant (τ) which equals to:

$\tau = -1/P_1 = 0.51607$, and larger time constant (T_1) which is equivalent to $T_1 = 1/P_2 = 8.3125$

By the way, $K\ =\ 0.987536$, the number of large time constants is one, this is given by $n = 1$.

According to these values, we calculated the controller parameters of K_P and T_P by using Eq. (4.11) and Eq. (4.12).

$$K_P = \frac{T_1}{2 * K * \tau * 4 * \tau} \tag{4.11}$$

Put the values of K and τ in Eq. (4.11),

$K_P = 3.9506$

Substitute the values of τ in Eq. (4.12),

$$T_P = 4.\ n.\ \tau \tag{4.12}$$

$T_P = 2.06428$

Putting the values of K_P and T_P in Eq. (4.13)

$$C(s) = K_P \frac{1 + T_P s}{s} \tag{4.13}$$

This will lead to controller transfer function as in Eq. (4.14)

$$C(s) = 3.9509 \ \frac{1 + 2.06428\ s}{s} \tag{4.14}$$

Simplify Eq. (4.14) into

$$C(s) = \frac{8.1558s + 3.9509}{s} \tag{4.15}$$

Figure 32 shows the closed loop system by using symmetrical optimum design method. In this Figure, the block of PI controller is represented by the Eq. (4.15) and the plant of the system represented by Eq. (4.8).

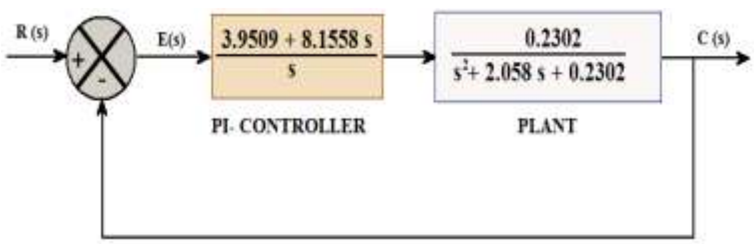


Figure 32 Structure of the system with symmetrical optimum design

The simulink model of symmetrical optimum design method

The Simulink model for Matlab program of symmetrical optimum design is shown in Figure 33. This model is designed by using Eq. (4.15) as a controller and Eq. (4.8) as a plant. After running the Simulink model as shown in Figure 33, we obtained the output response as shown in Figure 34.

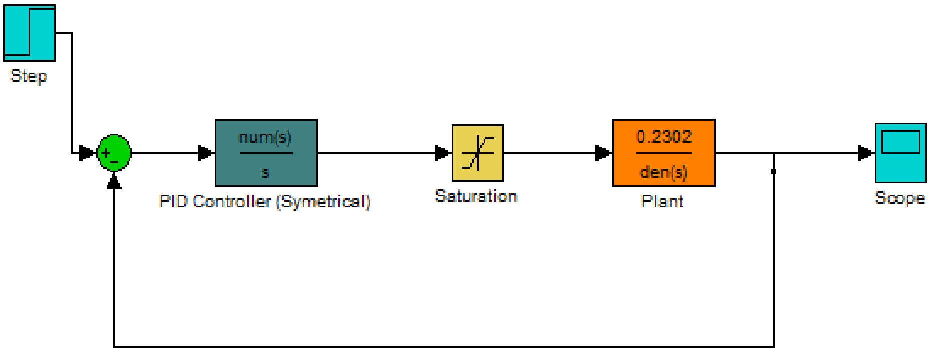


Figure 33 Simulink model of the symmetrical optimum design for PI controller

Figure 34 explains the output response of the PI controller by using symmetrical optimum design method. In this figure, the characteristics of Symmetrical output response has settling time $(t_s = 9.35 sec)$ and rise time $(t_r = 1.17 \text{ sec})$. Notice that the overshoot begins at 2.7 sec and becomes maximum at 3.92 sec, then decreases gradually until zero at 7 sec. The resultant undershoot in the response between the period from (7 sec) to (9.95sec) .After that, it will be zero at 9.95 sec.

Figure 34 Symmetrical optimum design for PI controller response.

4.2.3. Root locus design method

We used root locus design method to design a PID controller for the double tank system. The requirements in this method are zeros and poles of the open loop transfer function. Finally, the choice of a suitable structure of the controller is as shown below:

The double tank system transfer function is

$$G(s) = \frac{0.2302}{s^2 + 2.058\, s + 0.2302} \tag{4.16}$$

Simplify Eq. (4.16) into

$$G(s) = \frac{0.2302}{(s + 0.1187)(s + 1.9393)} \tag{4.17}$$

The transfer function of the PI controller is:

$$C(s) = K_P \frac{s + 0.1187}{s} \tag{4.18}$$

We propose to choose the pole of G(s) at $P = 0.1187$ .Hence, the resulting root locus plot for C(s) G(s) is as in Figure 35.

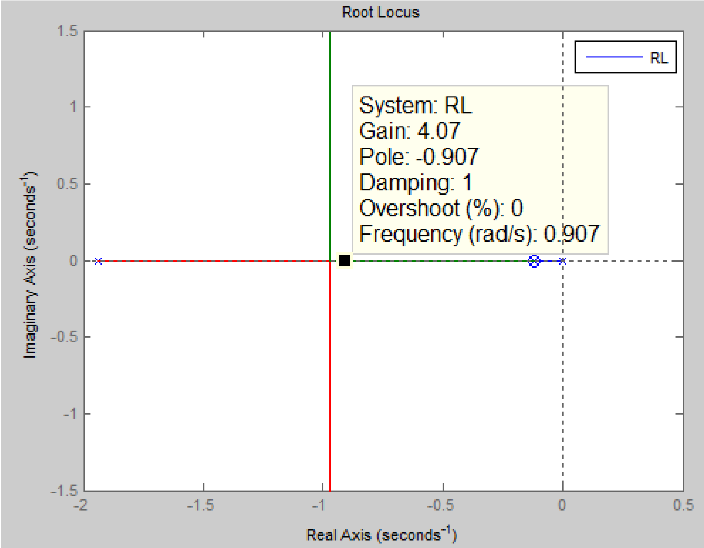


Figure 35 Root locus plot for PI controller

In order to achieve a closed loop that is not too fast and without overshoot, we choose $K_p = 4.07$ in the case of PI controller transfer function. Rewrite Eq. (4.16), after putting the value of K_P, we will obtain:

$$C(s) = 4.07\,\frac{s + 0.1187}{s} \tag{4.19}$$

Simplify Eq. (4.19) into

$$C(s) = \frac{4.07s + 0.4831}{s} \tag{4.20}$$

Figure 36 shows the closed loop system by using root locus design method. This model is dependent on Eq. (4.20) as controller and on Eq. (4.16) as plant.

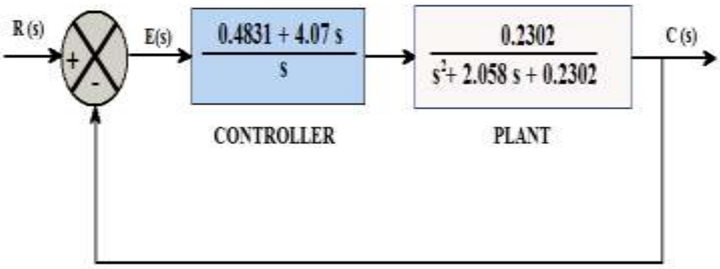


Figure 36 Structure of the system with root locus design

The simulink model of root locus design method

The Simulink model of root locus design is shown in Figure 37.This model is designed by using Eq. (4.20) as controller and Eq. (4.16) as plant. After that, by running the Simulink model as shown in Figure 37, we got the output response as shown in Figure 38.

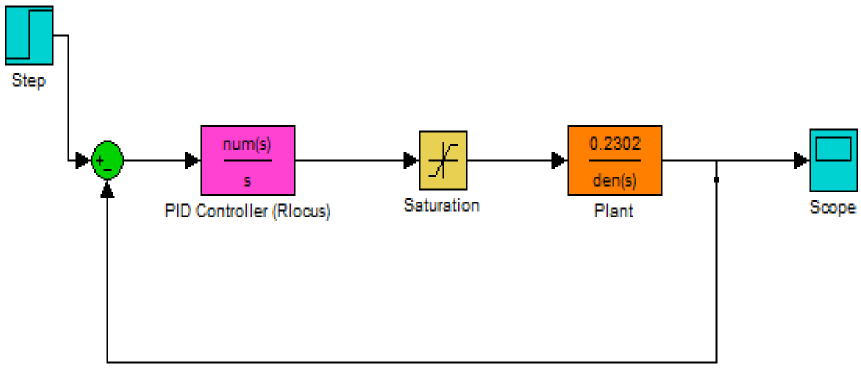


Figure 37 Simulink model of the root locus design for PI controller

Figure 38 shows the output response of PI controller by using root locus design method with rise time $(t_r = 4.02 \text{ sec})$, settling time $(t_s = 7.99 \text{ sec})$.It is very slow and the output response takes large time up to zero steady stat error. This response is considered undesirable in industrial applications because of its disadvantageous characteristics.

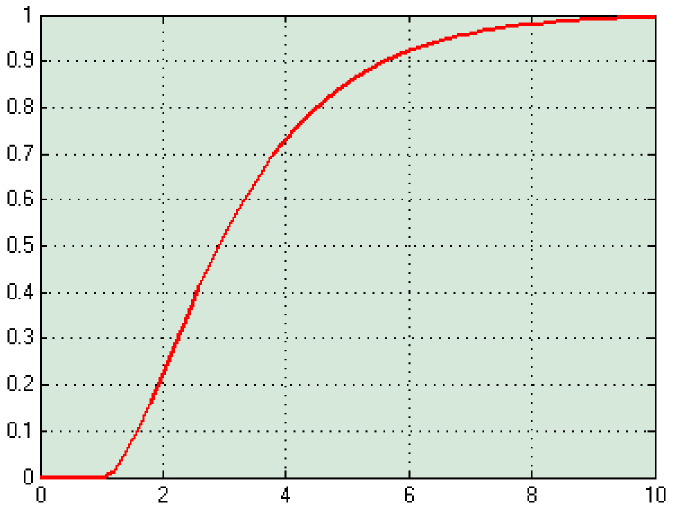


Figure 38 Root locus design for PI controller response

To determine the best method according to the resulting outputs responses for these methods. In order to facilitate a comparison, table 1 has been made to display the characteristics of each response.

Characteristic / Methods	Settling time	Overshoot	Rise time
Magnitude optimum design	**5.34 sec**	**4.37 %**	**1.56 sec**
Symmetrical optimum design	**9.35 sec**	**31.1%**	**1.17 sec**
Root locus optimum design	**7.99 sec**	**zero**	**4.02 sec**

Table 1 Characteristics of PID Controller Design Methods

Table 1 explains the characteristics of output responses for PID controller design methods: magnitude optimum design, symmetrical optimum design and root locus design. From table 1, notice that the rise time of the root locus optimum design response is very large that makes the output response of closed loop system very slow and the settling time very large. This makes the response with larger time up to zero steady state error. These characteristics are considered very bad and undesirable in industrial applications. The output response of the symmetrical optimum design is faster than the output response of the two other methods because the output responses of root locus design method and magnitude optimum design have got rise time less than their rise time but they have an overshoot of more than 31% and larger settling time .

Hence, the characteristics of output response of symmetrical optimum design is very bad and unacceptable in practical applications. The settling time of the magnitude optimum method is less than settling time of the symmetrical optimum design and root locus design .This makes it reach to zero steady state error before them. The over shoot of the magnitude optimum design method is very small and the difference is very small between its rise time and the rise time of the symmetrical optimum design. This leads to the difference between its speed and the speed of the output response of the symmetrical optimum design is very small.

Finally, the properties of optimum design output response are better than symmetrical optimum design output response and root locus design output response. For practical applications in industry these values are too high to be tolerated. An output response having a minimum overshoot and fastest response is required .We will optimize the output responses by using the BBO algorithm in the next section.

4.3. Using BBO for Tuning PID Controllers

In this study, optimizing the parameters of PID controller $\left(K_P, K_I, K_D\right)$ considers the main goal from using BBO as shown in Figure 39. Setting the parameters of PID could be seen as an optimizing problem where one tries to get on the optimal solution inside a predefined search space to fulfill a desired reference of a system. In this context, the biogeography based optimization algorithm could be used to find the optimal values for K_P, K_I and K_D. The variables of islands in this problem are the three gains as in Eq. (4.21).

$$\begin{aligned} K_P &\in [\, K_{P\,min},\ K_{P\,max} \,] \\ K_I &\in [\, K_{I\,min},\ K_{I\,max} \,] \\ K_D &\in [\, K_{D\,min},\ K_{D\,max} \,] \end{aligned} \tag{4.21}$$

To evaluate the habitats, we used the function in Eq. (4.22)

$$HIS = \int e^2(t)\,dt \tag{4.22}$$

Figure 39 explains the structure of the BBO for tuning PID parameters.

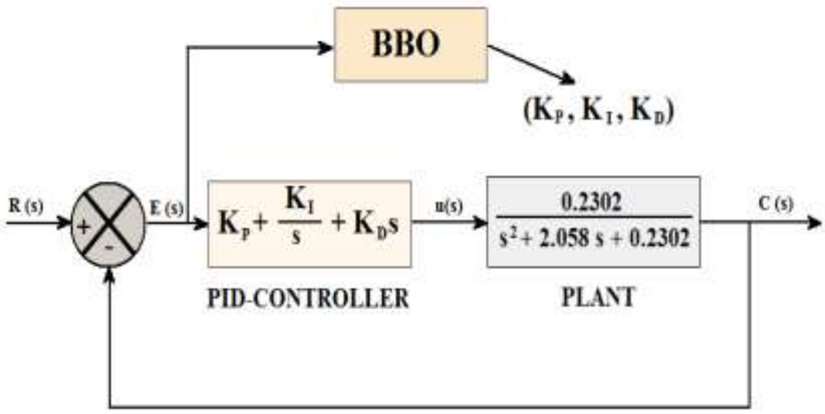


Figure 39 Structure of BBO

The initial variables of the BBO algorithm are shown in table 2

Population size	50
Number of generations	50
Mutation	0.04
(K_P, K_I, K_D)	[0,50]

Table 2 The variable of BBO Algorithm

After operating the BBO algorithm with the HIS in Eq. (4.22), the optimal gains are shown below in table 3:

K_P	44.7297
K_I	1.45
K_D	16.9999

Table 3 The parameters of PID Controllers

The simulink model of BBO

Figure 40 shows the Simulink model of BBO, in this Figure, the values of the resulting parameters by using BBO after the optimization are shown in table 3 for PID controller (BBO) block and plant block based on Eq. (4.14) in. After running Simulink model in Figure 40, we obtained the output response as in Figure 41.

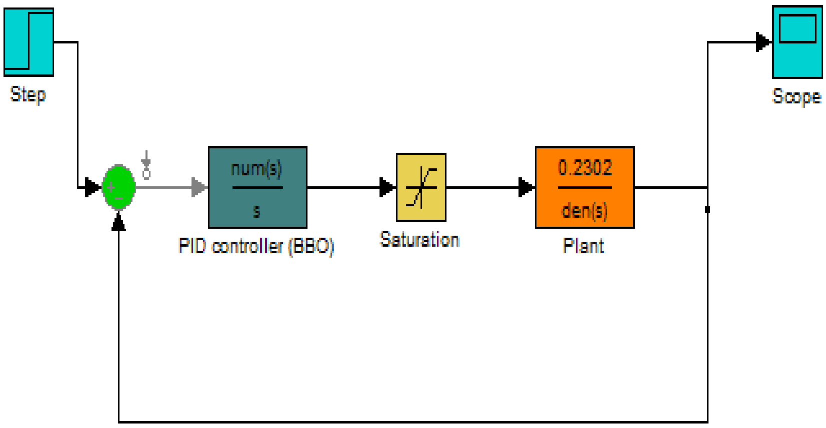


Figure 40 Simulink model of BBO

At the 17^{th} run, BBO could give better results for tuning PID controller for double tank system and reached the optimal combination of (K_P, K_I, K_D). Figure 41 shows the output response of BBO for tuning PID controller. From this Figure, notice that the output response of BBO has zero overshoot, settling time of 2.718 sec and rise time of 1 sec.

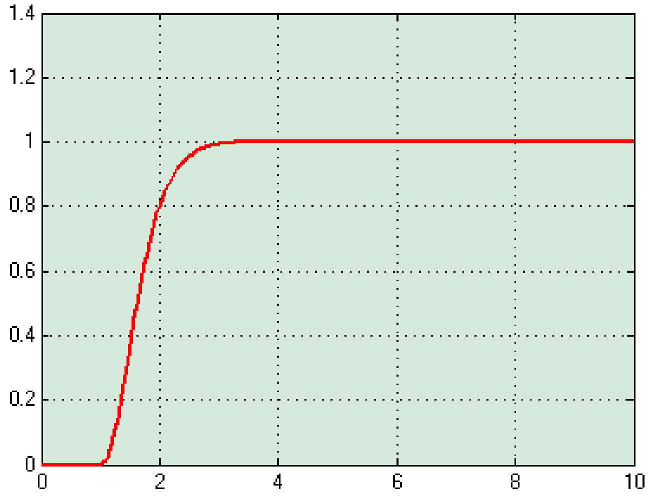


Figure 41 BBO step response.

Table 4 shows the characteristics of output responses for each method used for designing a PID controller as shown in Figure 31, Figure 34 and Figure 38.The properties of output response of BBO are shown in Figure 40. From table 4, note that the output response of BBO has reached to zero overshoot and small rise time less than the rise time of the other output responses, which makes it is faster than the output response of PID controller design methods. Moreover, it is reached to zero steady stat error before symmetrical, magnitude and root locus output response because it has settling time less than their settling time as it is clear from table 4. The performance of BBO is good and enabled optimizing the parameters of PID controller and could give results better than the results of PID controller design methods.

.

characteristics / methods	Settling time	Max Over shoot	Rise time
BBO	**2.718 sec**	**0**	**1 sec**
Magnitude optimum design	**5.34 sec**	**4.37 %**	**1.56 sec**
Symmetrical optimum design	**9.35 sec**	**31.1%**	**1.17 sec**
Root locus Design	**7.99 sec**	**zero**	**4.02 sec**

Table 4 The Characteristics of BBO Algorithm and PID Controller Design Methods Output Response

4.4. Fuzzy PID Controller

Fuzzy PID controller has been applied successfully in many applications of control fields. Different design methods of fuzzy PID controller are used nowadays that present significant performance comparing to classical PID controller; moreover, designing and tuning fuzzy PID controller with simple structure gives satisfactory results for the system. Fuzzy PID controller is good controller because its components help to provide convenient closed loop response characteristics. It combines the advantages of each term of PID controller individually as mentioned in Chapter 2, taking into account that the fuzzy PID terms are better than the classical PID terms. We will show that in the simulation results of Fuzzy PID controllers. Fuzzy proportional term reduces the rising time, while the fuzzy integral term removes the steady state error, and the third fuzzy derivative term enhances the system stability by decreasing the overshoot and optimizing the transient response. Generally, the number of rules which cover all possible inputs equal to number of fuzzy sets of first input multiplied by the number of the fuzzy sets of the second input in this thesis, in the case of FC with one input (error), the input has 9 fuzzy sets. The possible rules are 9 rules that cover all possible input variation. Similarly if number of the inputs are (increased / decreased), the number of the rules will (increased/decreased). Fuzzy PID controller is considered as the third step in this thesis**,** where we worked fuzzy for the resulting parameters from the optimization of PID controller by using (BBO)**.** As mentioned in chapter two, there are several types of fuzzy PID controller. Through this thesis, we are used Fuzzy Proportional Control as shown in Figure 43.

4.4.1 Fuzzy proportional control

The Input to a FP controller represents error and the output is the control signal u as in Eq. (4.23) .The block diagram of fuzzy proportional controller is shown in Figure 42.

$$u = f(e_n) \tag{4.23}$$

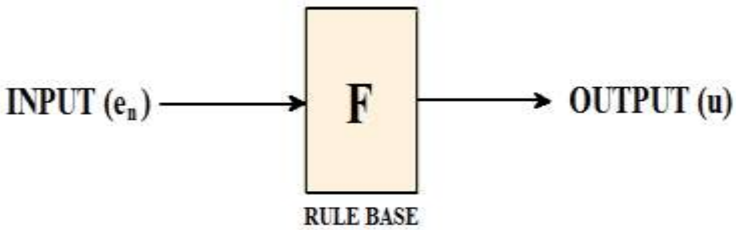


Figure 42 Fuzzy proportional controller (FP)

The structure of Fuzzy Proportional control is shown in Figure 43.

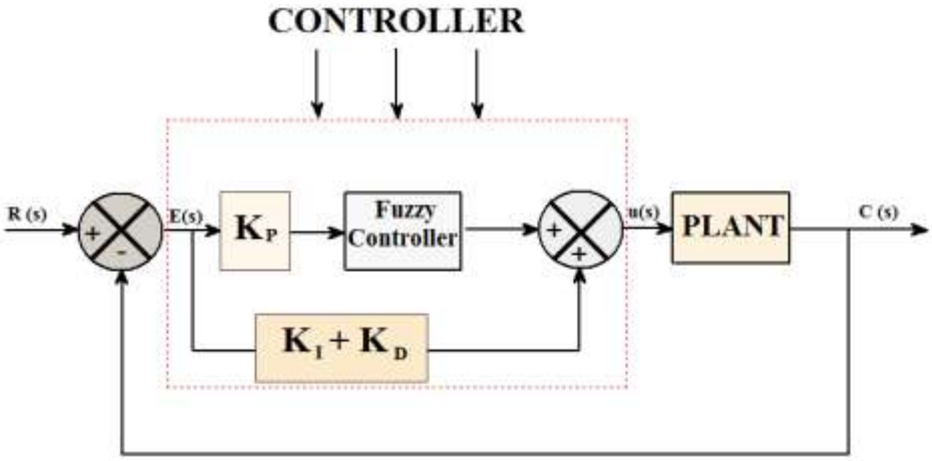


Figure 43 Structure of fuzzy proportional controller (FP)

4.4 2. Fuzzification

In this thesis, we have used one input (e) and one output (u) for the simplicity. We have used triangular fuzzy set with nine linguistic terms for both input and output variables of FLC. The universes of discourse for the inputs e and output u are partitioned into nine fuzzy sets as shown in Figure 44 and Figure 45 respectively. The universe of discourse of the error and the output are defined as e = [-1.25, 1.25], and u = [-57.5, 57.5] respectively.

Table 5 shows the ranges of linguistic variable input error and nine member function are used with ranges between -1.25 and 1.25.

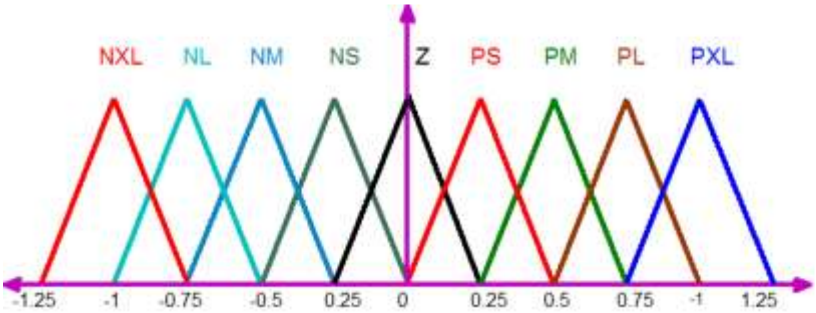


Figure 44 Membership function for input (e)

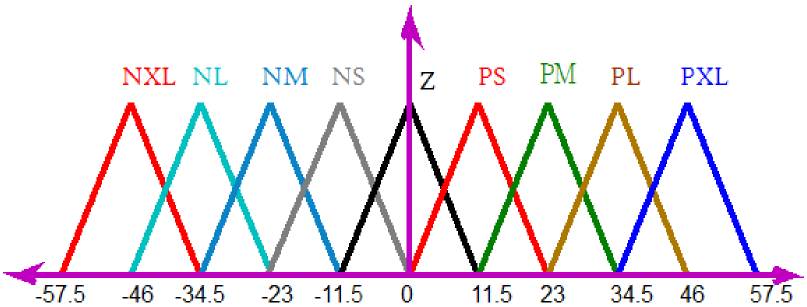


Figure 45 Membership function for output (u)

Table 5 show the ranges of linguistic variable input error e (t) and nine member function are used with ranges from -1.25 to 1.25.

Linguistic	Notation	Numerical Range
Negative X large	NXL	[-1.25 -1 -0.75]
Negative large	NL	[-1 -0.75 -0.5]
Negative Medium	NM	[-0.75 -0.5 -0.25]
Negative Small	NS	[-0.5 -0.25 0]
Zero	Z	[-0.25 0 0.25]
Positive X Large	PXL	[0.75 1 1.25]
Positive Large	PL	[0.5 0.75 1]
Positive Medium	PM	[0.25 0.5 0.75]
Positive Small	PS	[0 0.25 0.5]

Table 5 Input Linguistic Variable Error

Table 6 show the ranges of linguistic variable output control signal (u) and nine member function are used with ranges from -57.5 to 57.5

Linguistic	Notation	
Negative X large	NXL	[-57.5 -46 -34.5]
Negative large	NL	[-46 -34.5 -23]
Negative Medium	NM	[-34.5 -23 -11.5]
Negative Small	NS	[-23 -11.5 0]
Zero	Z	[-11.5 0 11.5]
Positive X Large	PXL	[34.5 46 57.5]
Positive Large	PL	[23 34.5 46]
Positive Medium	PM	[11.5 23 34.5]
Positive Small	PS	[0 11.5 23]

Table 6 Linguistic Output Variable (u)

4.4.3 Rule base

Rule base is main part in the FLC, there are four methods to derive rule base. Deriving fuzzy rule base is an important part in FLC design and implementation. Two approaches for deriving rule base: heuristic and deterministic approaches. Heuristic approach is depended on the qualitative knowledge of the system behavior. The rule is designed by analyzing the behavior of the process such as the convergence from the proposed output that may be correct. The second approach can systematically determine the parameters and the linguistic structure of the rules which satisfy the desired control. Through this thesis, Mamdani fuzzy rule is adopted to build the fuzzy model of the system. This method was constructed with one output as the consequence and one input as antecedent with variables (e, *u*) as error, output, and rules respectively. All rules are shown in table 7. Generally, there are many forms from the linguistic rule. Each one of these forms expressed linguistically in chapter two. In this thesis, the rule base is constructed as shown below:

SISO

IF e is E **THEN** *u* is *U*

Table 7 explains all the rules base of FLC, which are used in this study.

Error (e)	Output (u)
NXL	NXL
NL	NL
NM	NM
NS	NS
Z	Z
PS	PS
PM	PM
PL	PL
PXL	PXL

Table 7 Rules base

4.4.4. Inference mechanism

In general, the inference process includes two steps:

1-The premise of all rules are compared to the crisp inputs to determine which rules apply to the current situation. This matching process determines the certainty for each rules uses $\mu_{premise}$ which is calculated by minimum and product ways as shown in Eq. (4.24) and Eq. (4.25) respectively:

A- minimum way as:

$$\mu_{premise} = \min\left(\mu(\alpha_1), \mu(\alpha_2)\right) \quad (4.24)$$

B- product way as:

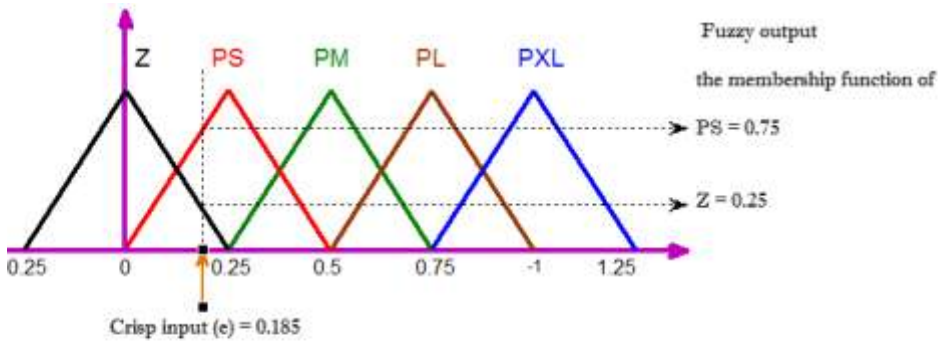
$$\mu_{premise} = \left(\mu(\alpha_1), \mu(\alpha_2)\right) \quad (4.25)$$

Where a_1, a_2 are the crisp inputs.

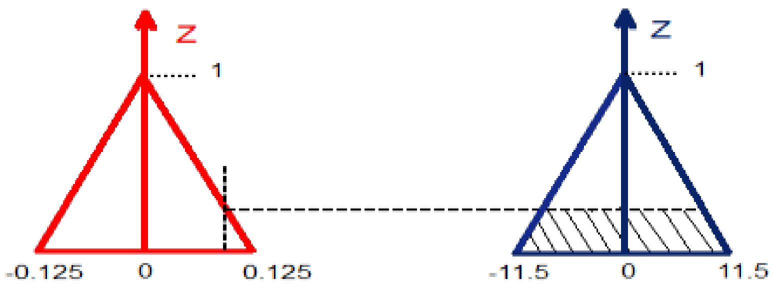
In this thesis, we used one input only. So, Eq. (4.25) will be as follows:

$$\mu_{premise} = \mu\left(a_1\right) \quad (4.26)$$

2- Clipping the fuzzy set as shown in Figure 45 that involves the meaning of the rule consequent to the degree to which the rule antecedent has been matched by the crisp input. Finally, the clipped values of the output of each rule are aggregated.



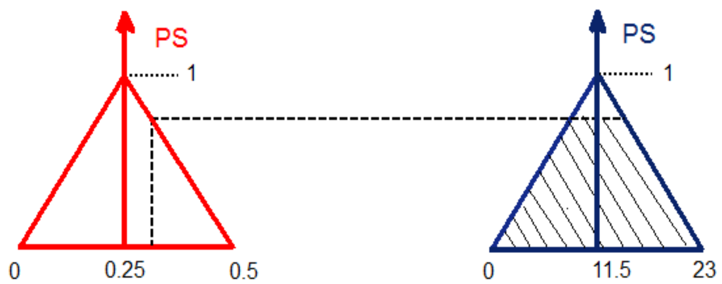
(a)



Control signal error (e)

If error is zero then control signal is zero

(b)



Error (e) **control signal (u)**

If error is PS then control signal is PS

(c)

Figure 46 All operations of inference mechanism

From Figure 46, the values of the membership functions of the proposed fuzzy sets are: $\mu_Z(e) = 0.25$, $\mu_{PS}(e) = 0.75$ .In this thesis the formula in Eq. (4.26) used to calculate the membership function of the output control signal. The membership function of control signal can be observed from:

$\mu_Z(u) = \mu_Z(e) = 0.25$ and $\mu_{PS}(u) = \mu_{PS}(e) = 0.75$

The control action of both rules will be determined using a centroid of area defuzzification method in the next section.

4.4.5. Defuzzification

Defuzzification method is the last step of the FLC**,** as indicated in chapter two. There are many methods for defuzzification. COA method is used in this thesis. This method produces a control action that represents the center of the output of the fuzzy set. The weight average of the membership function or the COA bounded by the membership function curve and it is converted to a typical crisp value.
The crisp control signal value can be determined by:

$$\text{Crisp control signal}(u) = \frac{\text{Sum of first moments of area}}{\text{Sum of areas}} \tag{4.27}$$

Or alternatively, it can be expressed as:

$$u = \frac{\sum_{i=1}^{m} \mu(a_i).a_i}{\sum_{i=1}^{m} \mu(a_i)} \tag{4.28}$$

When the value of input (e = 0.185), as a result of the formula in Eq. (4.26), the fuzzy output in Figure 46 (a) is clipped and taken the form in Figure 47.The area of trapezoid is calculated based on Eq. (4.28) and Figure 47.

$$Area_Z = \frac{0.25 * (23 + 17.25)}{2} = 5.03125$$

$$Area_{PS} = \frac{0.75*(23+5.75)}{2} = 10.78125$$

From Eq. (4.27), u will be

$$u = \frac{(5.03125\times 0)+(10.78125\times 11.5)}{5.03125+10.78125} = 7.8409$$

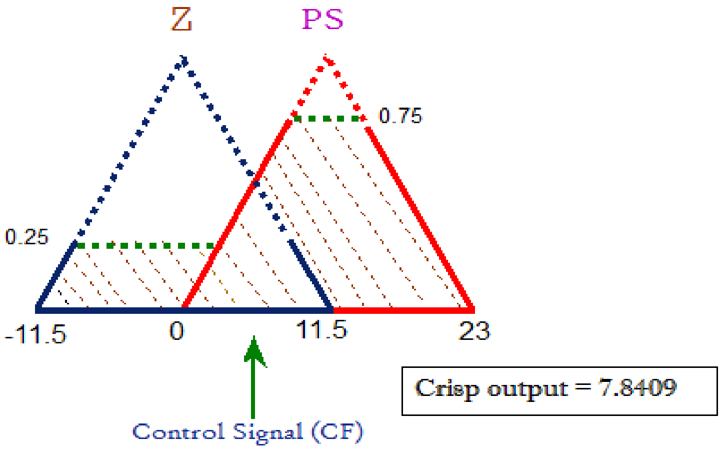


Figure 47 Operation of defuzzification

The simulink model of fuzzy controller

In FC, the measurement of error can be calculated from Eq. (4.29):

$$E(s) = R(s) - Y(s) \qquad (4.29)$$

Figure 48 shows the Simulink model of fuzzy proportional controller by using Matlab Simulink. The system design is shown in Figure 48 by using Eq. (4.16) based on block of plant which is substituted in block of PID controller. The values of K_D *and* K_I are shown in table 4 .The block diagram of FLC has been implemented with one input and one output. The membership functions for input and output are shown in Figure 44 and Figure 45.

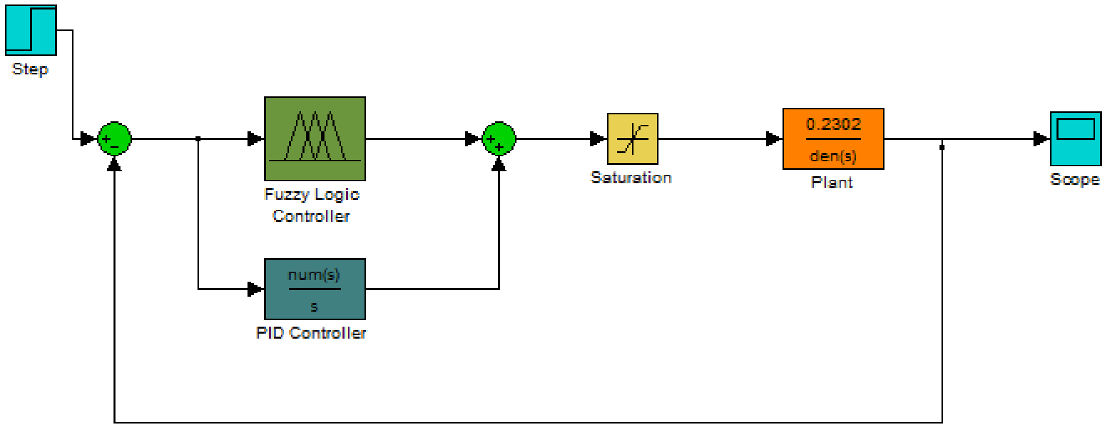


Figure 48 Simulink model of fuzzy proportional

By running the Simulink model of fuzzy proportional controller, we will produce the step response as shown in Figure 49. Figure 49 shows the output response of Fuzzy PID controller with settling time $(t_s = 2.62\,sec)$ and rise time $(t_r = 0.96\,sec)$. From this figure, note the output response has got better dynamic properties and steady-state properties. It has reached to zero overshoot and zero steady state error.

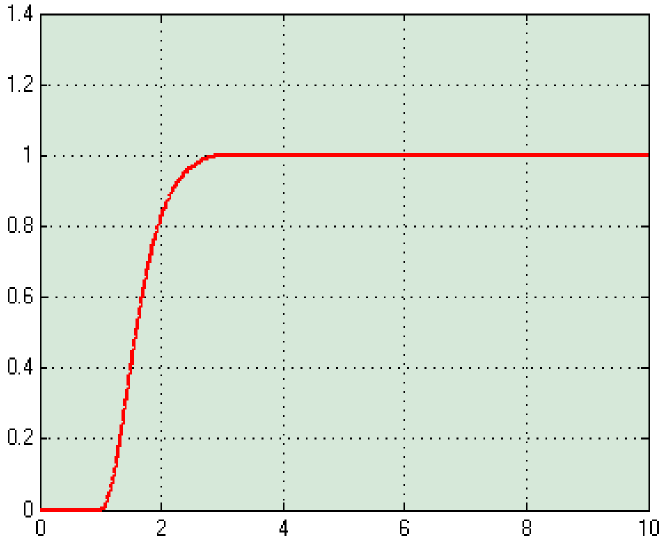


Figure 49 Fuzzy proportional controller step response

According to the characteristics of the output response, we can determine the performance for PID controller, BBO and fuzzy PID controller. A comparison between their output response characteristics is made. To summarize the comparison between the performance for PID controller, BBO and fuzzy PID controller, table 8has been constructed to explain the characteristics of the output responses as shown in Figure 49, Figure 31, Figure 34, Figure 38and Figure 41.

From this table, we can observe that the characteristics of the Fuzzy PID controllers output response is better than the output response of BBO and the output response of PID controller design methods. It has reached to zero overshoot and the rise time is less than the rise time of the four other responses. So, it is faster than them, also it is reached firstly to zero steady state error because it has the least rise time between the responses.

characteristics / methods	Settling time	Max Over shoot	Rise time
Fuzzy proportional	**2.62 sec**	**0**	**0.96 sec**
BBO	**2.72 sec**	**0**	**1 sec**
Magnitude optimum design	**3.29 sec**	**4.37 %**	**1.56 sec**
Symmetrical optimum design	**9.35 sec**	**31.1%**	**1.17 sec**
Root locus optimum design	**7.99 sec**	**zero**	**3.65 sec**

Table 8 The Characteristics of Fuzzy PID Controller, BBO Algorithm and PID Controller Design Methods Output Response.

CHAPTER FIVE

CONCLUSION AND FUTURE WORK

5.1. Conclusion

The desired tasks were accomplished using three stages: the first stage was to control on flow rate for the liquid through the pipes between the two tanks. Then, analyzing the mathematical model of the double tank system. In the second stage, used the new evolutionary algorithm BBO and designed the control techniques. Appling a control techniques is important to guarantee high efficiency, lower error, lower settling time, lower over shoot and lower rise time for the output response of the system. PID controller was applied to control flow rate for double tank system. Then, BBO algorithm was implemented to optimization the parameters of PID controller. The second controller was Fuzzy Logic Controller (FLC). In this thesis, we applied Mamdani method in FLC. This was applied using 9 rules. FLC controller used the center of area (COA) defuzzification method, and min max inference mechanism. In the third stage, we compared the results of using the BBO algorithm and the two Controllers PID and FLC. First, we compared the results of the PID and the BBO algorithm in terms of overshoot, settling time, rise time, transient response and steady state error. Second, we compared the results of PID controller and BBO algorithm and FLC. All simulations were presented by using MATLAB Software version 2011 and SIMULINK, which are used widely in control applications. The numerical results and output step responses for PID controller and BBO algorithm showed that the Biogeography Based Optimization could be find the optimal values for the parameters of PID controller and gives satisfactory results in tuning PID parameters**.**

To Summarize, the obtained results for the BBO algorithm achieved the desired performance in terms of reducing settling time, overshoot and rise time response expected. Finally, the simulations and numerical results of BBO algorithm, PID controller and Fuzzy logic controller were presented in this thesis. We proved that the FLC is more efficient in the time response behavior than the PID controller and BBO algorithm. The rising time for the FLS was less than the rising time of the BBO algorithm and the PID controller, also the settling time for FLC was less than the settling time of BBO algorithm and the PID controller. In other words, the simulation results and the output response of the FLC is better than the simulation results and the output response of PID controller and BBO algorithm.

5.2. Future Work

The field of producing double tank system for different control systems, using different concepts is still growing and much can be done in this field.
Several suggestions can be recommended in this issue for future work summarized as a follows:

1. Relating to the work presented in this thesis, additional studies can be performed to achieve more experimental measurements for the modeled designs.

2. Changing the fuzzy controller by neural fuzzy one and compare the results to find the best one.

3. The control system in this study can be implemented with FPG

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APPENDICES A

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