İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

A NEW RULE - BASE MODIFICATION SCHEME FOR THE TIME DELAY SYSTEMS

M.Sc. Thesis by
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Department : **Elektrical Engineering**

Programme: **Control and Automation Engineering**

JUNE 2006

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to Mom & Dad

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CONTENTS

ABBREVIATIONS

FLC	: Fuzzy Logic Controller
PI	: Proportional Integral, Performance Index
I/O	: Input / Output
SF	: Scaling Factor
MF	: Membership Function
PID	: Proportional Integral Derivative
CDMA	: Code - Division Multiple - Access
ISF	: Input Scaling Factor
OSF	: Output Scaling Factor

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e	: Error
Δe	: Change of error
Δu	: Change of control signal
u	: Control signal
ke	: Input scaling factor for error
kde	: Input scaling factor for change of error
ko	: Output scaling factor for change of control signal
r	: Reference
y	: System output
e_{FLC}	: Normalized error
Δe_{FLC}	: Normalized change of error
Δu_{FLC}	: Normalized change of control signal
μ	: Membership functions
Δu_0	: Control signal magnitude when Δe is zero
T	: Time constant
L	: Time delay value
K	: System gain
τ	: Normalized dead time
mp	: Maximum overshoot
ts	: Settling time
tr	: Rise time
ess	: Steady state error

ÖLÜ ZAMANLI SİSTEMLER İÇİN YENİ BİR KURAL TABANI DEĞİŞTİRME YÖNTEMİ

ÖZET

Ölü zamanlı sistemlerde, sistemden gözlenen bilgi geçmiş bir ana aittir ve bu gecikmeli işareti kullanmak, kontrol sistemi uygulamalarında başarısız sonuçlara neden olabilir. Bu çalışma, ölü zaman bilgisinin sistem performansını artırmak adına kural tabanının yeniden düzenlenmesinde nasıl kullanılabileceği ile ilgilidir. Temel olarak, sistemin ölü zamanından kaynaklanan bilgi gecikmesinin kural tabanının uygun şekilde kaydırılması ile telafisi önerilmektedir. Kural tabanı kaydırma yöntemini etkileyen değiştirgeler (parametreler) detaylı bir biçimde incelenmiş ve kaydırma yöntemi, sistem model değiştirgelerine göre çizelgelenmiştir. Yeni yöntem birçok farklı sistemde denenmiş ve etkisi ortaya konmuştur. Yöntemin, ölü zaman değişimlerine, yapısal ve ayar değiştirgelerinin değişimlerine ve sistem model değiştirgelerindeki belirsizliklere karşı gürbüzlüğü tüm hatlarıyla ortaya konmuştur.

A NEW RULE - BASE MODIFICATION SCHEME FOR THE TIME DELAY SYSTEMS

ABSTRACT

In time delay control systems, the observed information is related to a past instant and using this delayed signal may cause unsatisfactory results in control system applications. This paper deals with how time delay information can be used in reorganizing the rule base so as to improve system performance. Basically, it proposes a new scheme of appropriate shifting of the rule base to compensate the information lag caused by time delay in the system. The parameters affecting the shifting scheme are discussed in detail and the shifting scheme is tabulated with respect to system model parameters. Applications of the new methodology in different systems are simulated and the effectiveness of the scheme is fully illustrated. Robustness in case of time delay changes, structural and design parameter variations and system model parameter uncertainties are also discussed intensively.

1. INTRODUCTION

1.1 Introduction

Following the first fuzzy control application carried by Mamdani [1], fuzzy logic is utilized quite often in control problems. During the past few decades, there are many successful applications with fuzzy logic controllers(FLCs) in industry. They have been reported to be successfully used for a number of complex and non-linear processes [2]. Moreover, the experience has shown that, fuzzy control may often be a preferred method of designing controllers for dynamic systems even if traditional methods can be used [3].

Between the various types of fuzzy logic controllers, just like the widely used conventional proportional integral (PI) controllers in process control systems, PI type FLCs are most common and practical [4].

The research for improving FLC performance spreads over number of areas. But simply, we can categorize the design parameters within two groups [5]:

a) Structural parameters

b) Tuning parameters.

Basically, structural parameters include input/output (I/O) variables to fuzzy inference, fuzzy linguistic sets, membership functions, fuzzy rules, inference mechanism and defuzzification mechanism. Tuning parameters include I/O scaling factors (SFs) and parameters of membership functions (MFs). Usually the structural parameters are determined during off-line design while the tuning parameters can be calculated during on-line adjustments of the controller to enhance the process performance, as well as to accommodate the adaptive capability to system uncertainty and process disturbance. Unfortunately we still do not have a well-formulated designing scheme that is globally acceptable.

Most of the practical processes under automatic control are nonlinear higher order systems and may have considerable dead time [4]. Higher order systems can be modeled by a first order counterpart [6] as soon as convenient approximations are carried, but control action is unavoidably delayed in a process with dead time. For this reason, dead time is recognized as the most difficult dynamic element naturally occurring in physical systems [7]. Therefore, any useful technique of designing a control system must be capable of dealing with dead time [4]. Conventional PI (or PID) controllers are frequently short in managing systems with dead time. To have a satisfactory performance the controller output or process input should be a nonlinear function of error and change of error. FLCs try to incorporate this nonlinearity by a limited number if – then rules [4]. As a result FLCs are used more commonly as the time delay or nonlinearity is the matter of concern.

For the time-delay process, the observed information comes later than desired for taking the control action. When used directly, the delayed information from the process gives wrong information to the rule base, and hence wrong control to the process [8]. To overcome this information lag, Li and Gatland [9] proposed shifting upper side of the rule base to left and bottom side to right for one cell. After this study Chang and Wang [10], in their Cellular CDMA System, used the same shifting strategy. Li and Tso [8] suggest that this method may not be accurate enough and requires larger rule bases. If there are too few rules, it is hard to provide proper compensation. Finally Zhuang and Roth [11] used the proposed method for their Laser Tracking System and find fairly good results for considerably small time delays.

This thesis work is devoted to enlighten the use of time delay information in shifting the rule bases. There exist many aspects to be considered in shifting operation and obtaining a better rule base. The shifting amount should be distinct for different time delays; it should even vary in between rows, where rows designate Δe. The time constant of the plant modeled by first order system should play a key role in designing the rule base shifting strategy. With all these in mind one may tabulate the shifting amounts of each row with respect to system model parameters: time delay value and time constant of the plant.

The rest of the thesis work is divided into 5 sections. In Section 2, the most common architecture of a FLC is given. The proposed rule base shifting strategy is detailed in Section 3. In Section 4, simulation results are presented. When the FLC structure deviates from the very generic structure given in Section 2 or in case of time delay and system model parameter uncertainties, the performance of the proposed shifting scheme is discussed in Section 5. Finally possible extensions and conclusions are given in Section 6.

2. ARCHITECTURE OF THE FUZZY LOGIC CONTROLLER

2.1 Feedback Control Structure

As it is mentioned in the Introduction section, the conventional PI type controllers are the most common controllers used in practical implementations. Among FLCs, PI types FLCs are also the best solution for the majority of problems. In all of the simulations done in this study, a PI type FLC is used having error (e) and change of error (Δe) as inputs and change of control signal (Δu) as output. Corresponding model of the overall control loop is shown in Figure 2.1.

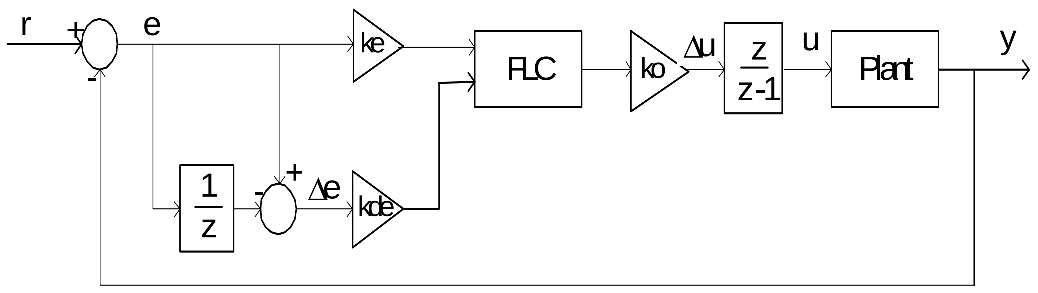


Figure 2.1: Basic control blocks illustration with PI type FLC

In the model of the widely used PI controller of Figure 2.1, e stands for error, Δe for change of error in the sampling interval, u is the control action, Δu is the change of control action in the sampling interval, r is the reference value, y is the output of the system and *ke, kde, ko* are the scaling factors.

2.2 Universe of Discourse and the Scaling Factors

The universe of discourse is chosen to be [-1, 1] for all membership functions. The input and output parameters are scaled to fit this range through the help of scaling factors.

Scaling factors can be divided into two groups as input scaling factors (ISFs) and output scaling factors (OSFs). ISFs normalize the real world inputs to the range membership functions are defined. OSF is used to change the normalized control effort to its practical value. The relation between real and normalized values of the parameters can be simply given as:

$$e_{FLC} = e * ke$$

$$\Delta e_{FLC} = \Delta e * kde \qquad (2.1)$$

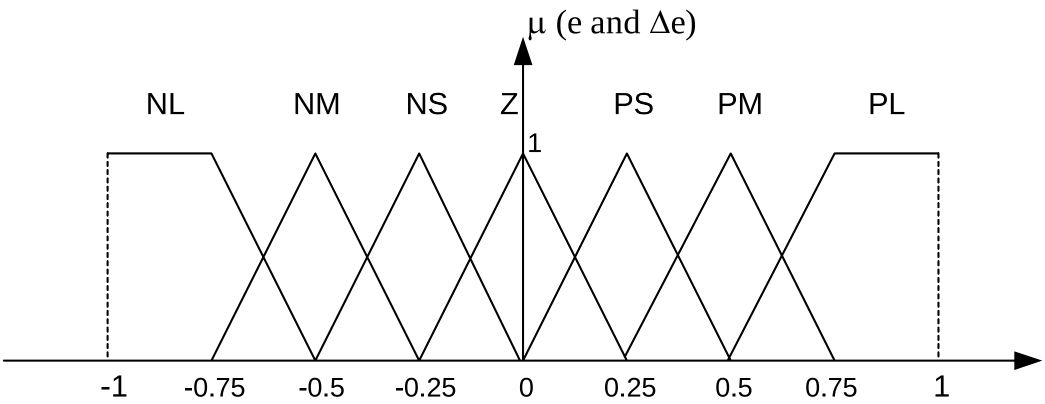
$$\Delta u = \Delta u_{FLC} * ko$$

where e_{FLC} and Δe_{FLC} are the normalized parameters entering FLC controller, Δu_{FLC} is the normalized FLC output; e, Δe and Δu are respective actual outputs, and *ke*, *kde*, *ko* are the error scaling factor, change of error scaling factor and the control effort change scaling factor, respectively.

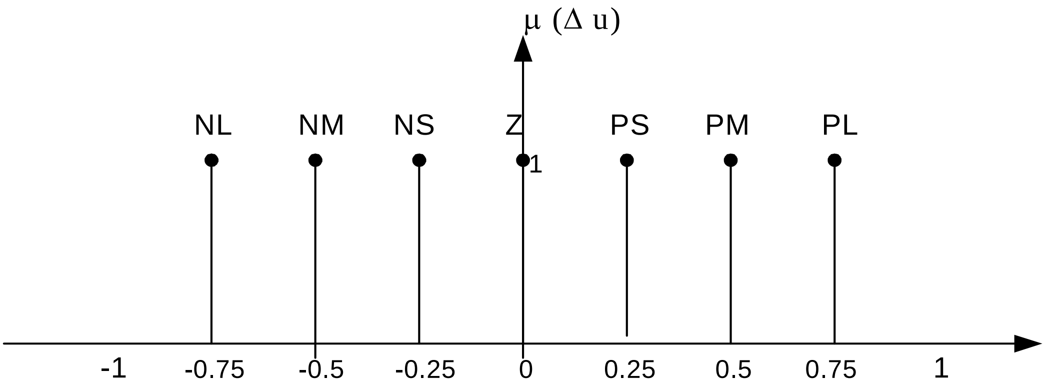
2.3 Membership Functions and the Inference Mechanism

For the development and simulation of the algorithm, throughout the report, 7 fuzzy regions are defined for each of the input and output parameters. This structure sums up to 49 rules. Actually that many rules is practically feasible and therefore widely used in fuzzy control applications. The fuzzy regions are named as NL (Negative Large), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium), PL (Positive Large). Figure 2.2 gives the MFs of input variables and the output variables. The inference mechanism is Takagi-Sugeno type and therefore the output membership functions are singleton. Singleton membership functions make calculations simpler and they are easier to implement in real world applications.

Although the very generic membership functions are chosen for the fuzzy controller, the extensions for these structural parameters are investigated in Section 5.



(a)



(b)

Figure 2.2: (a) MFs for e and Δe. (b) MFs for Δu.

2.4 Rule-Base

The rule-base for FLC has the most unbiased symmetric structure for the sake of generality. (Table 2.1) Basically, when change of error is 'Zero' ($\Delta e = Z$), the change of control effort (Δu) is in the same magnitude and direction with the error (e). This Δu value is abbreviated as Δu_0. In the other entries of the rule-base Δu is given by the following equation,

$$\Delta u = \Delta u_0 + \Delta e \tag{2.2}$$

Table 2.1: Rule-Base for Generic FLC

$\Delta e/e$	NL	NM	NS	Z	PS	PM	PL
PL	Z	PS	PM	PL	PL	PL	PL
PM	NS	Z	PS	PM	PL	PL	PL
PS	NM	NS	Z	PS	PM	PL	PL
Z	NL	NM	NS	Z	PS	PM	PL
NS	NL	NL	NM	NS	Z	PS	PM
NM	NL	NL	NL	NM	NS	Z	PS
NL	NL	NL	NL	NL	NM	NS	Z

3. PROPOSED RULE-BASE SHIFTING STRATEGY

When a delay is introduced in a system either by the nature of the system or by the external devices used, the observed information is from a past instant. Using this measured information may cause unsatisfactory results in time delay systems. But if we can guess the actual output information from process trend (from the information we have) then we can reorganize our rule base.

$\Delta e/e$	large N small	small P large
large P small	R_3	R_4
Z		
small N large	R_2	R_1

Figure 3.1: Regions for a rule base classified according to signs of (e, Δe).

In Figure 3.1, a regular rule base is divided into 4 regions besides Δe is equal to 'zero' row. In R_1 region, error is positive and decreasing in magnitude since change of error is negative. Therefore, for non-zero time delay, the actual (e, Δe) pair should lie somewhere in the left side of the measured one. To compensate this deviation, the rules corresponding to R_1 can be shifted to right. If shifting amount is correct, then the controller performs appropriate actions. In R_2, error and change of error are both negative and error magnitude has tendency to increase. Again the actual point is in the left of the observed one and shifting the rules to right may fit if it is in correct amounts. Similar arguments are valid for the upper side of rule base. In R_3 and R_4 the actual points are to the right of observed ones and rule base shifting should be to the left. When Δe is 'zero', than that row is unbiased and no shifting is needed.

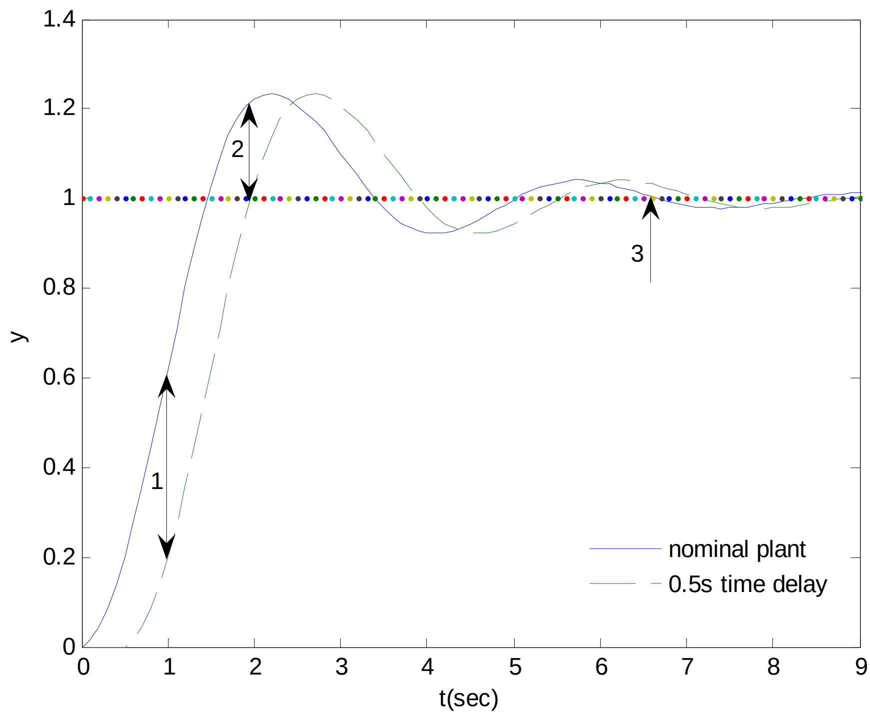


Figure 3.2: Arbitrary system step response in the absence of time delay (straight line) and the measured data with a delay of 0.5 seconds (dashed line)

In Figure 3.2, time delay effect is modeled as a shift in the plane for an arbitrarily chosen plant. At around t = 1s, the arrow labeled 1, shows the difference of error magnitudes. This point corresponds somewhere at R_1 region in Figure 3.1. A crisp error value of about 0.8 is measured, whereas, the actual error value around 0.4 which implies a deviation of %100 from the actual value. However, since it is known that the system has positive error and have tendency to overcome this (since Δe is negative), one can assume that the delayed system error must have been decreased. Then the question is how much is this decrease? Li and Gatland [9] shifted all the rules except for the ones in Δe equals to 'zero' row for one cell. This shifting scheme yields better performances for some systems but since it requires shifting even for small error changes (around the set point) it can cause oscillatory behavior and chattering. Also if the delay value is too high, this shifting amount may not be adequate.

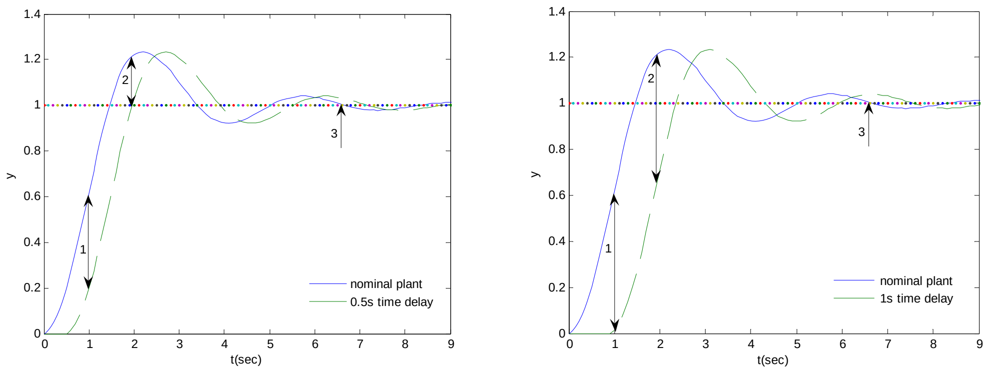
The proposed rule-base shifting strategy is a consequence of various parameters affecting the system response. As a matter of fact, the shifting amount depends on error magnitude, time delay magnitude, change of error magnitude and time constant of the (first order) plant under control. In this section these parameters are discussed in detail one by one. Next, tabulation will be given covering all the aspects touched.

3.1. Effect of Error Change Rate

It is easily seen that the difference of the two responses in terms of error magnitude is not same at each point if one carefully examines the points illustrated by the three arrows in Figure 3.2. At the arrow labeled as 1, error change rate is quite high and the response curve climbs up very rapidly to the set point in the delay time of 0.5s. At arrow labeled as 2, we measure to be at the set point value, but considering the time delay and interpreting change of error correctly we can feel that the actual system response value must be somewhere above that point. Similarly at arrow labeled as 3, as system response gets closer to the steady state region (very low change of error), the difference between the two graphs becomes nearly zero. Thus, as the error change (between sampling intervals) increases, does the difference of system responses between nominal and actual one. Therefore, the amount of shifting must be kept ‘low’ as system gets closer to the steady state region (when Δe is low) and it should be ‘high’ when the response rate of change of the system is high. No rule base shifting is appropriate for the small values of change of error to prevent oscillations and decrease chattering effect. Therefore, the shifting amount is, as it must be, not same for all the rows of the upper or lower halves of the rule base. In this study, the rows designate Δe changes.

3.2. Effect of Time Delay Magnitude

Time delay magnitude also plays an important role in predicting the actual response of the system. The two graphs of Figure 3.2 depart farther away from each other for higher delay values and thus the difference between the actual and measured values increases. Similarly, the two graphs get close to each other for a smaller time delay and the difference between the actual and measured values decreases. This is illustrated in Figure 3.3. In short, the shifting amounts must be adjusted in correlation with time delay values.



(a) (b)

Figure 3.3 (a) Arbitrary system step response in the absence of time delay (straight line) and the measured data with a delay of 0.5 seconds (dashed line). **(b)** Same system step response with time delay is increased to 1s.

3.3. Effect of Fuzzy Resolution

The resolution of the membership functions plays another key in rule base shifting. The non-linearity effect of the time delay process can be more precisely fit if more fuzzy regions are defined for each parameter. Figure 3.4 illustrates the variation of the shifting in infinite resolution case. That is impractical in real world applications and this can only be achieved by the use of limited number linguistic variables. It is obvious that adjusting the shifting amounts for Δe rows is more logical and efficient for higher resolutions. Naturally, on the other side of the argument, there lays computational complexity and this trade of should be handled by the designer. In this work 7 fuzzy regions are defined for each variable as discussed in detail in Section 2.

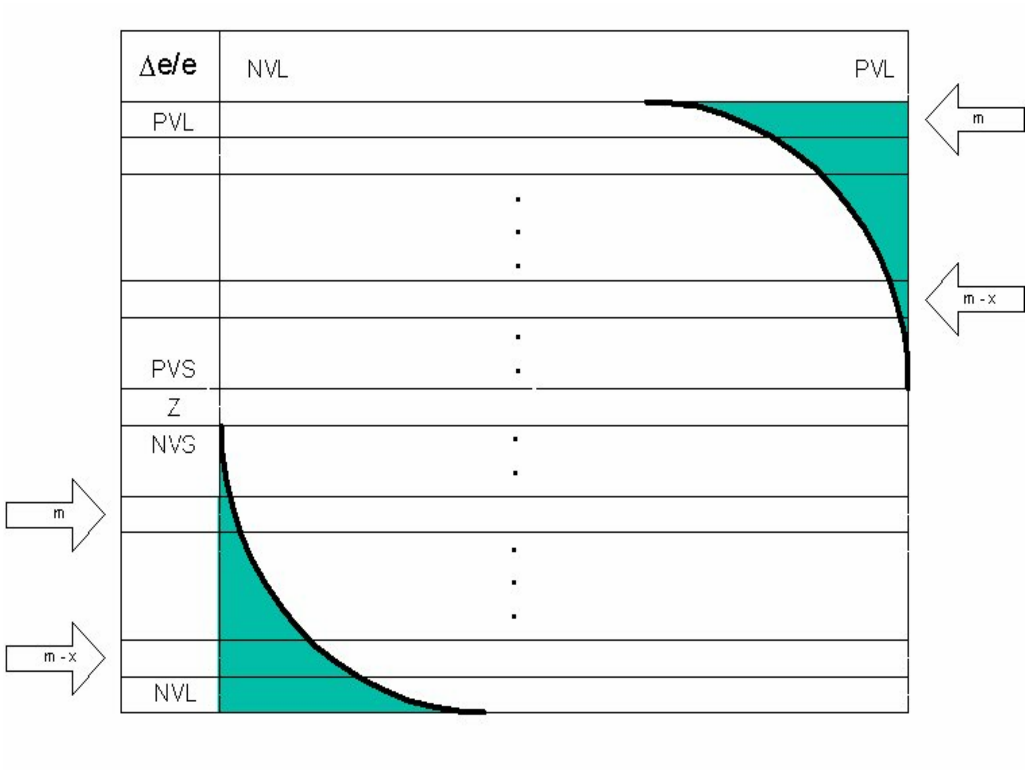


Figure 3.4: Ideal shifting mechanism for infinite resolution.

3.4. Effect of System Time Constant

For a generic tabulation of the shifting amounts, information from the structure of the plant under control should also be used. Since a first-degree counterpart can model systems, the plants in this study are chosen or approximated to be first order for the ease of calculations. The transfer function can be given as follows,

$$G(s) = \frac{K}{1 + Ts} e^{-sL} \tag{3.1}$$

where L is delay time, K is the gain and T is the time constant for the process model.

Then, the time constant is the sole parameter determining the system characteristics. For a fair judgment about the magnitude of the time delay, it must be evaluated in conjunction with the time constant. That is, for a system having 0.05 seconds as time constant, 1 second of time delay is rather big, whereas, for a slower system having 3 seconds as time constant, same value of time delay has much smaller deterioration effect on the system performance. To combine time constant and time delay information the following proportion τ is used, to normalize time delay value,

$$\tau = \frac{L}{L+T} \tag{3.2}$$

The new parameter τ also normalizes the time delay value to the range defined on the interval [0, 1]. This quantity is called the normalized dead time or controllability ratio. It has generally and roughly been found out that processes with small τ are easy to control and the difficulty in controlling the system increases as τ increases. [15]

3.5. The Rule-Base Shifting Scheme

For the controller developed in Section 2, several shifting schemes are investigated for many time delay values and performance indexes. Some of the shifted versions of the rule-base of Table 2.1 are given in Table 3.1. The shifting amounts are equal and opposite in direction in lower and upper sides of Δe = Z (zero) row. For instance, in Table 3.1.b., all the rows are not shifted equally; that is, the neighbouring rows of Δe equals to 'Zero' are not shifted, and the others are shifted for one cell in appropriate directions. This shifting scheme is coded as 011(shifted number of cells from low values to high values of Δe) and the corresponding controller is abbreviated as FLC_011. Table 3.1 includes four shifting schemes for FLCs that will be compared throughout the paper.

Table 3.1: Different Shifting Schemes For Rule - Base of Generic FLC (a) FLC_001 (b) FLC_011, (c) FLC_023(d)FLC_033

Δe/e	NL	NM	NS	Z	PS	PM	PL
PL	PS	PM	PL	PL	PL	PL	PL
PM	NS	Z	PS	PM	PL	PL	PL
PS	NM	NS	Z	PS	PM	PL	PL
Z	NL	NM	NS	Z	PS	PM	PL
NS	NL	NL	NM	NS	Z	PS	PM
NM	NL	NL	NL	NM	NS	Z	PS
NL	NL	NL	NL	NL	NL	NM	NS

(a)

Table 3.1 (CONTINUED)

Δe/e	NL	NM	NS	Z	PS	PM	PL
PL	PS	PM	PL	PL	PL	PL	PL
PM	Z	PS	PM	PL	PL	PL	PL
PS	NM	NS	Z	PS	PM	PL	PL
Z	NL	NM	NS	Z	PS	PM	PL
NS	NL	NL	NM	NS	Z	PS	PM
NM	NL	NL	NL	NL	NM	NS	Z
NL	NL	NL	NL	NL	NL	NM	NS

(b)

Δe/e	NL	NM	NS	Z	PS	PM	PL
PL	PL	PL	PL	PL	PL	PL	PL
PM	PS	PM	PL	PL	PL	PL	PL
PS	NM	NS	Z	PS	PM	PL	PL
Z	NL	NM	NS	Z	PS	PM	PL
NS	NL	NL	NM	NS	Z	PS	PM
NM	NL	NL	NL	NL	NL	NM	NS
NL	NL	NL	NL	NL	NL	NL	NL

(c)

Δe/e	NL	NM	NS	Z	PS	PM	PL
PL	PL	PL	PL	PL	PL	PL	PL
PM	PM	PL	PL	PL	PL	PL	PL
PS	NM	NS	Z	PS	PM	PL	PL
Z	NL	NM	NS	Z	PS	PM	PL
NS	NL	NL	NM	NS	Z	PS	PM
NM	NL	NL	NL	NL	NL	NL	NM
NL	NL	NL	NL	NL	NL	NL	NL

(d)

In the light of all these results given up to now, the proposed shifting amounts with respect to τ are given in Table 3.2. The performance index used for the tabulation is in very generic form having a weighting factor for each performance measure,

$$PI = \frac{1000}{100mp + 3ts + 6tr + 100ess} \quad (3.3)$$

where m_p is the maximum overshoot, t_s is the settling time (%2 settle band is used), *tr* is the rise time (time passing between the response reaches %10 to %90 of its final value) and e_{ss} is the steady state error.

The proposed shifting scheme is consistent with our presumptions. Actually, these regions are not crisp for all cases, but changes slightly for different configurations of the membership functions and rules. Moreover, when a biased performance index specialized for improving either of the performance measures is used, the borders may change too.

Actually, since the extreme rules are rarely fired, a change made in the shifting scheme related to the small and medium values of Δe will naturally make the most important effect on the system performance. Moreover, for Δe is equal to NS or PS, no shift is convenient to prevent oscillatory behavior. One can easily observe these two criteria in Table 3.2.

Table 3.2: Proposed Shifting Schemes

τ	Appropriate shift
$\tau < 0.05$	001
$0.05 <= \tau < 0.15$	011
$0.15 <= \tau < 0.7$	023
$\tau >= 0.7$	033

4. SIMULATION RESULTS

In this section, simulation results are given. The most commonly used controller given in Section 2 is used for the simulations. The scaling factors shown in Figure 2.1 are tuned for each case separately. The input scaling factor *ke* is chosen to be unity in all cases since reference is unit step and error is already normalized to [-1, 1]. Unfortunately there is no commonly accepted method for choosing the other scaling factors. Therefore, they are usually found by trial error techniques. In this study, the scaling factors maximizing the performance index of Eq. 3.3 is used:

$$PI = \frac{1000}{100\,mp + 3ts + 6tr + 100\,ess}$$

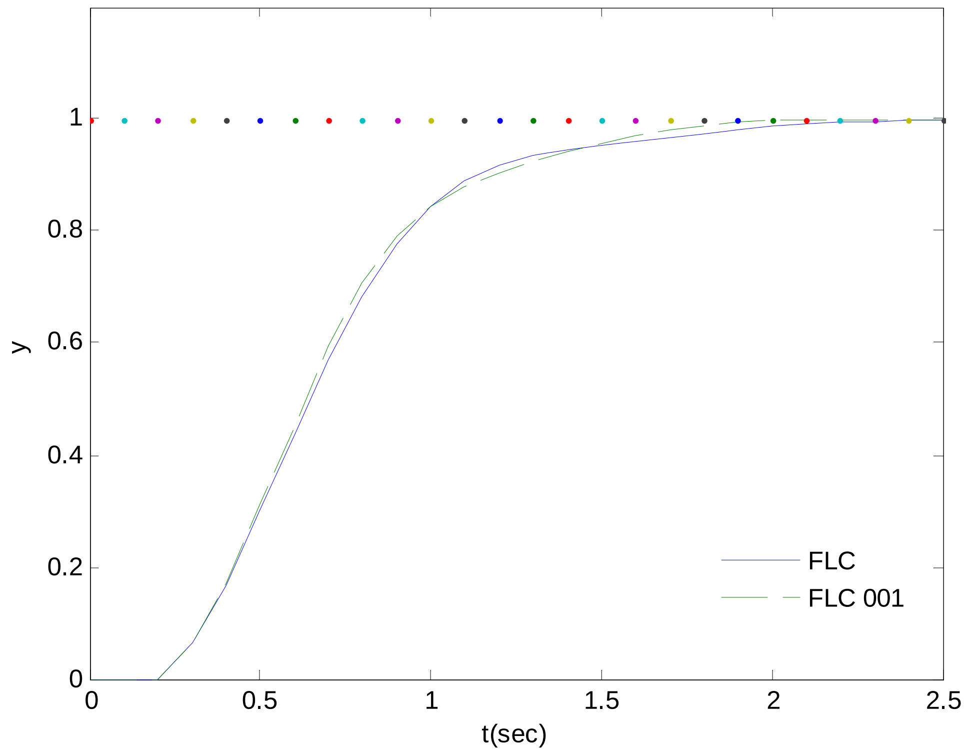


Figure 4.1: Effect of rule base shifting for a time delay value of 0.05s. τ is 0.047 in this case.

In Eq. 3.1, using K equal to 1 (compensated through output scaling factor) and choosing T = 1s to simplify the simulations, the equation becomes:

$$G(s) = \frac{1}{1+s} e^{-sL} \qquad (4.1)$$

In all simulations, sampling time is 0.1s. For systems having 1s as time constant, this value is fair enough to reveal system characteristics. Simulation time varies for the specific example in order to fully justify controller performance.

In the first example (Figure 4.1), the delay time is small in comparison to the time constant. As Table 4.1 reveals, 001 shift slightly improves the performance index value. Since the extreme rules have little influence on the controller this result seems to be reasonable.

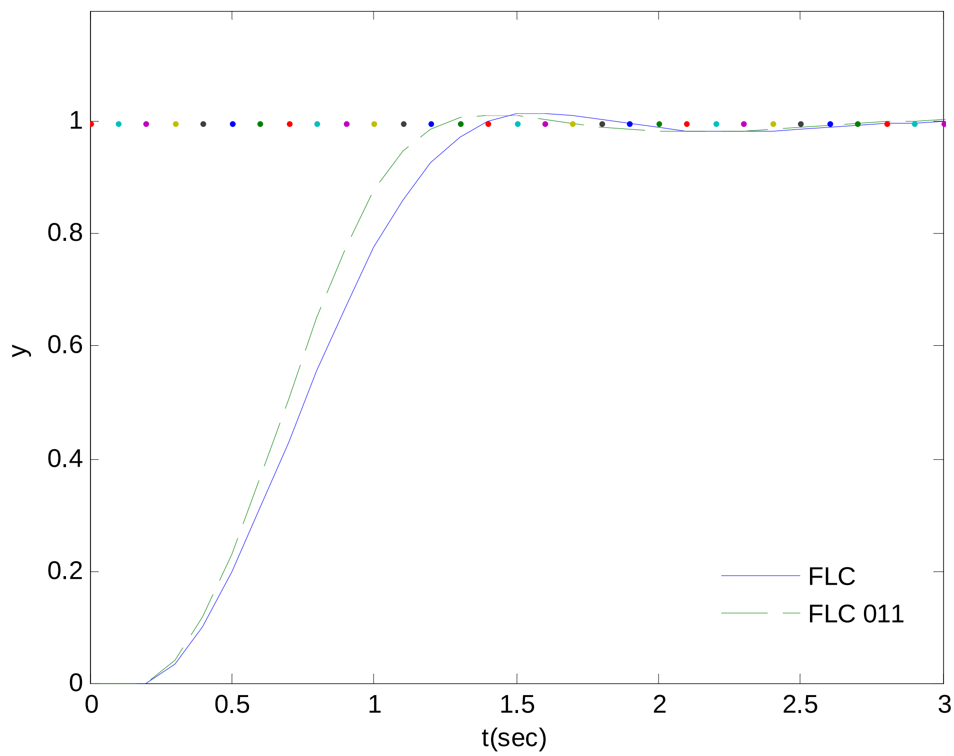


Figure 4.2: Effect of rule base shifting for 0.1s delay time.

Figure 4.2 illustrates the case when 0.1s delay is introduced to system. This corresponds to a normalized dead time (τ) of 0.09 and the proposed shifting scheme is 011. As a result shorter rise time yielded about 20% improvement.

Table 4.1: Performance Results for Generic FLC (Eq. 3.3)

Delay time	τ	Controller	Performance Index
0.05s	0.046	FLC	111.11
		FLC_001	123.00
0.1s	0.09	FLC	93.00
		FLC_011	109.97
0.2s	0.17	FLC	65.18
		FLC_011	84.24
		FLC_023	90.78
0.9s	0.47	FLC	26.83
		FLC_023	37.02
1.75s	0.64	FLC	17.33
		FLC_023	23.08
		FLC_033	22.97
3s	0.75	FLC	11.76
		FLC_033	15.72

If time delay value is 0.2s, then τ becomes 0.17 and Table 3.1 proposes 023 shift. It provides 40% improvement in the performance index. However, since these borders are not crisp and not discontinuous from one another, 011 shift gives also good results. This is illustrated in Figure 4.3. The performance index values for the three rule bases are given in Table 4.1.

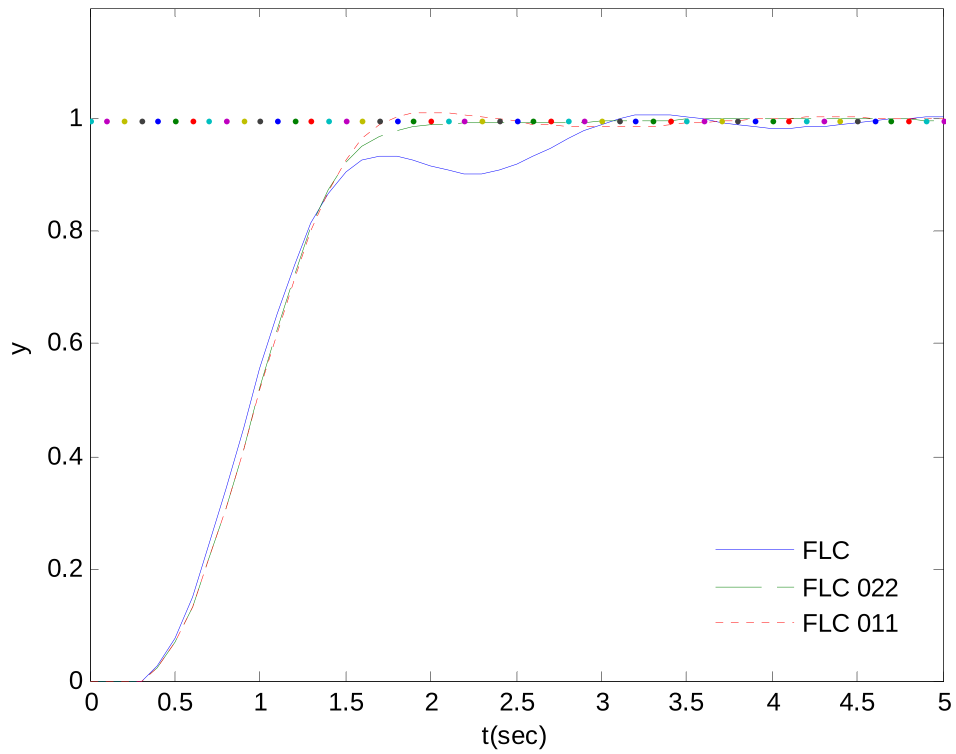


Figure 4.3: Effect of rule base shifting for 0.2s delay time.

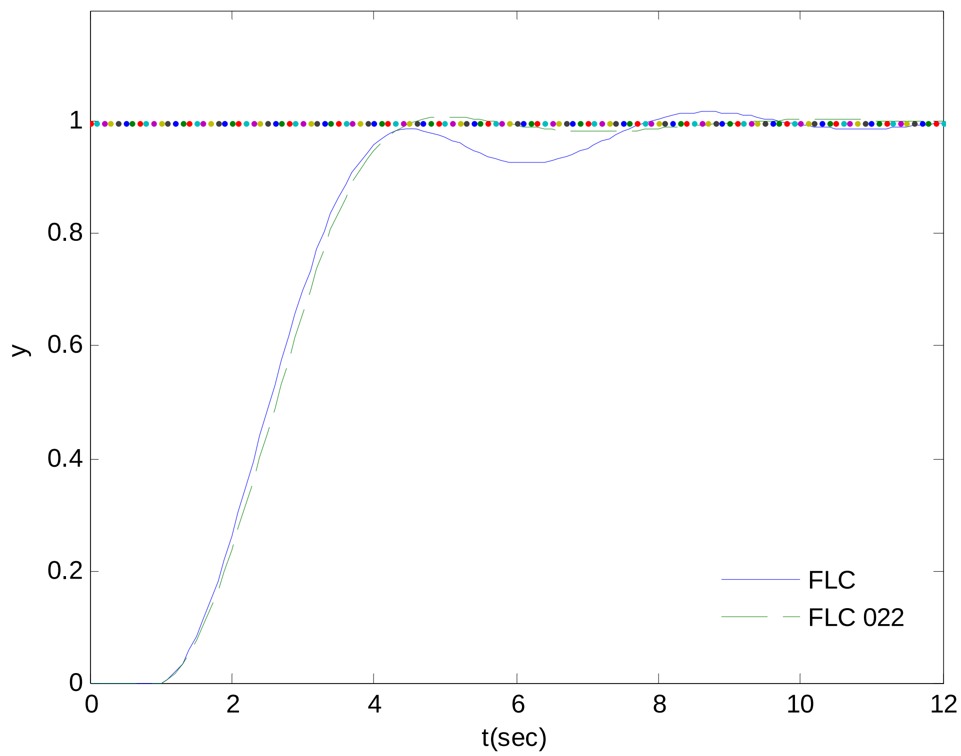


Figure 4.4: Effect of rule base shifting for 0.9s delay time.

Figure 4.4 shows the case when delay value and time constant are close to each other. In that case normalized dead time is 0.47. Once more, the proposed shifting scheme yields improved results. Especially the settling time of the proposed rule-based system is fairly good. Overall, the improvement is 38%. Actually, as in most of the cases, for this case rise time seems to be deteriorated a little, too. This is expectable since the new structure assumes that the system 'rose' more than the observed and so the control action is somehow softer than that of the nominal controller's, in region R_1 of Figure 3.1.

For a time delay value of 1.75 seconds, τ is 0.64. This case is illustrated in Figure 4.5. The rule-base shifting tabulation proposes 023 shift, but since τ is close to 0.7 (where the shifting scheme switches to 033), 033 shift gives almost same results.

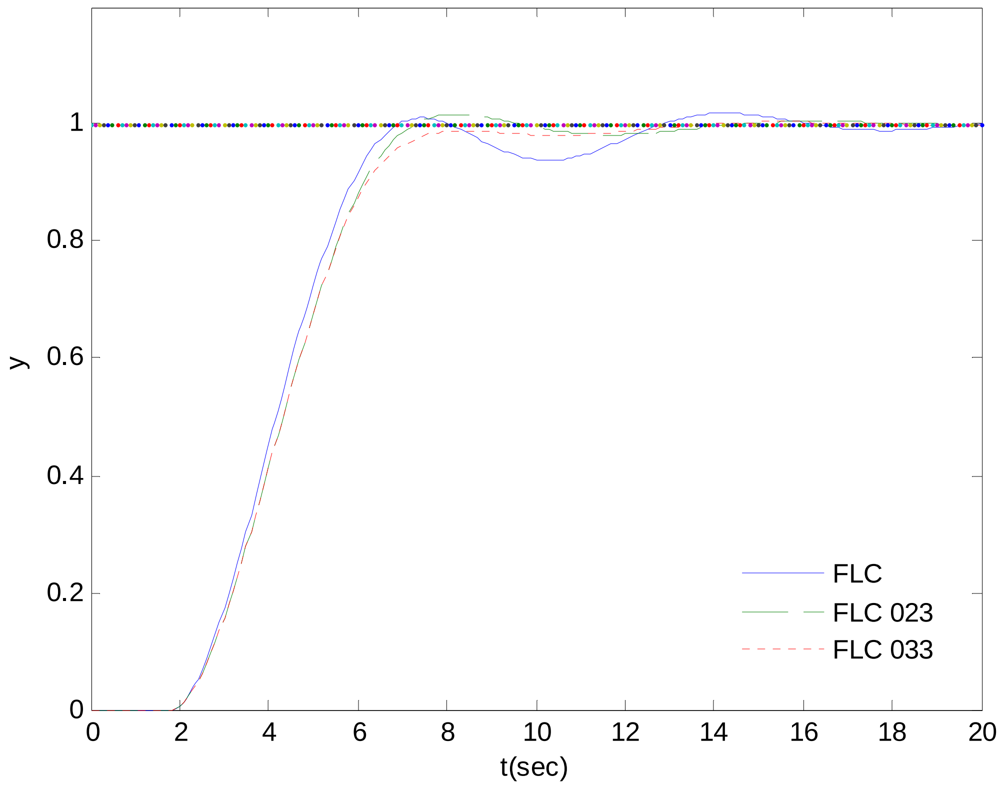


Figure 4.5: Effect of rule base shifting for 1.75s delay time.

Increasing the time delay far beyond the time constant of the plant is simulated in Figure 4.6.

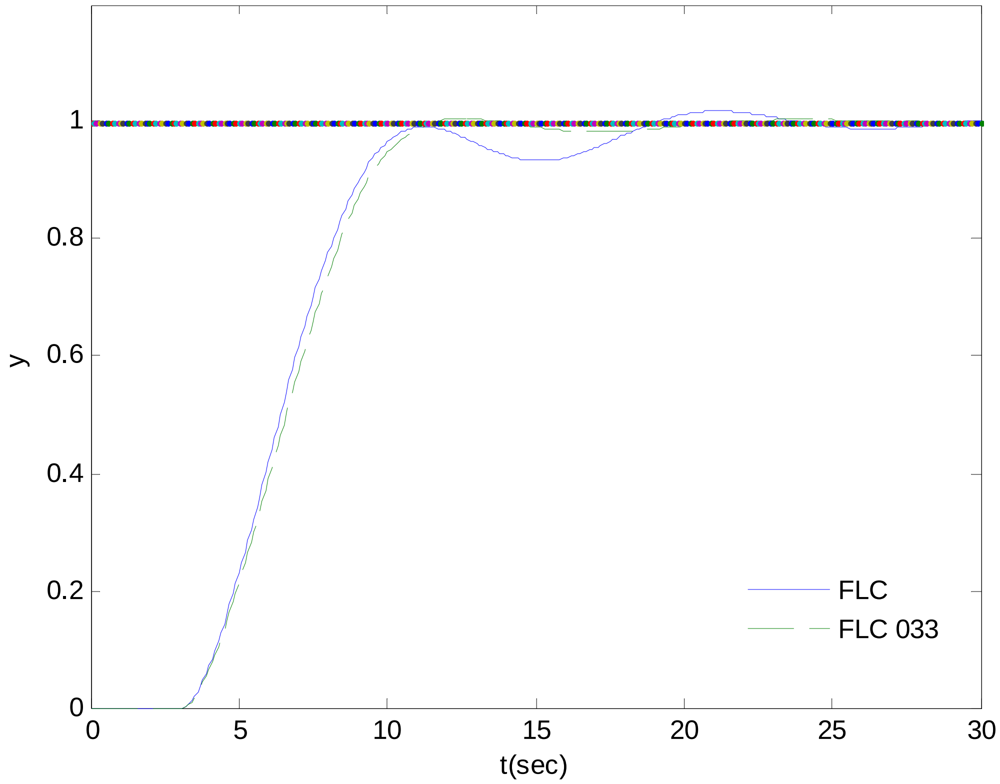


Figure 4.6: Effect of rule base shifting for 3s delay time.

5. ROBUSTNESS AND PERFORMANCE ANALYSIS

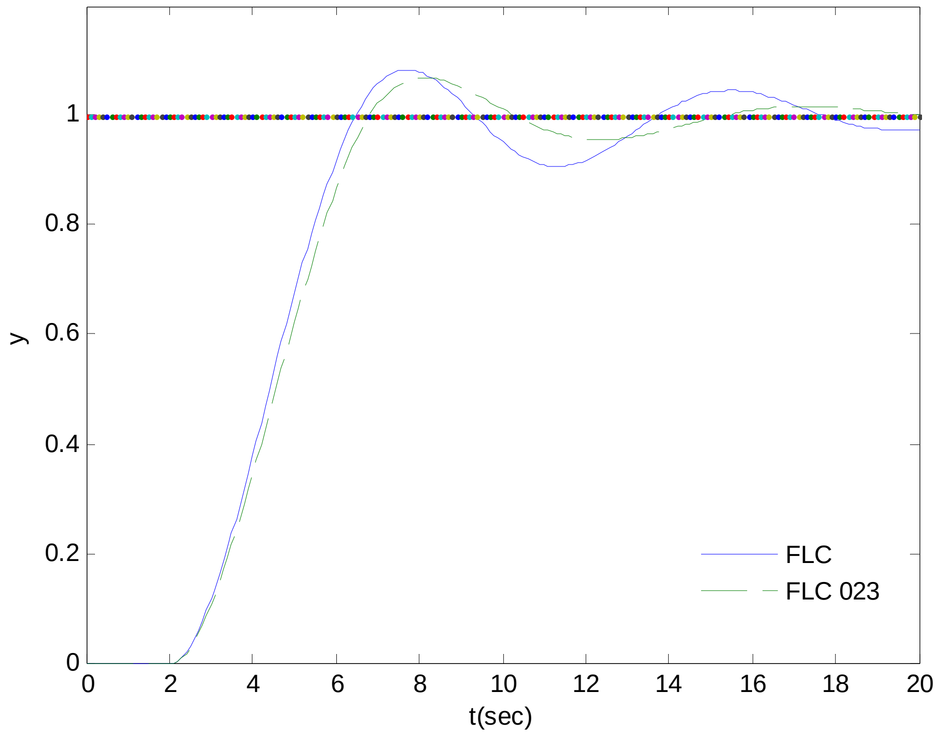
5.1. Robustness

Although, it is derived for the most commonly used and unbiased design parameters for the sake of generality, the idea behind the proposed shifting scheme is valid even for the deviations in design parameters, imprecision in system model parameters and changes in the performance index measures. That is not to say the tabulation given in Table 3.1 is the best for all cases, instead, the point is, that the proposed scheme is better even if the design parameters vary. The designer should work with his \ her own parameters and own performance index in order to optimize shifting scheme and tuning parameters.

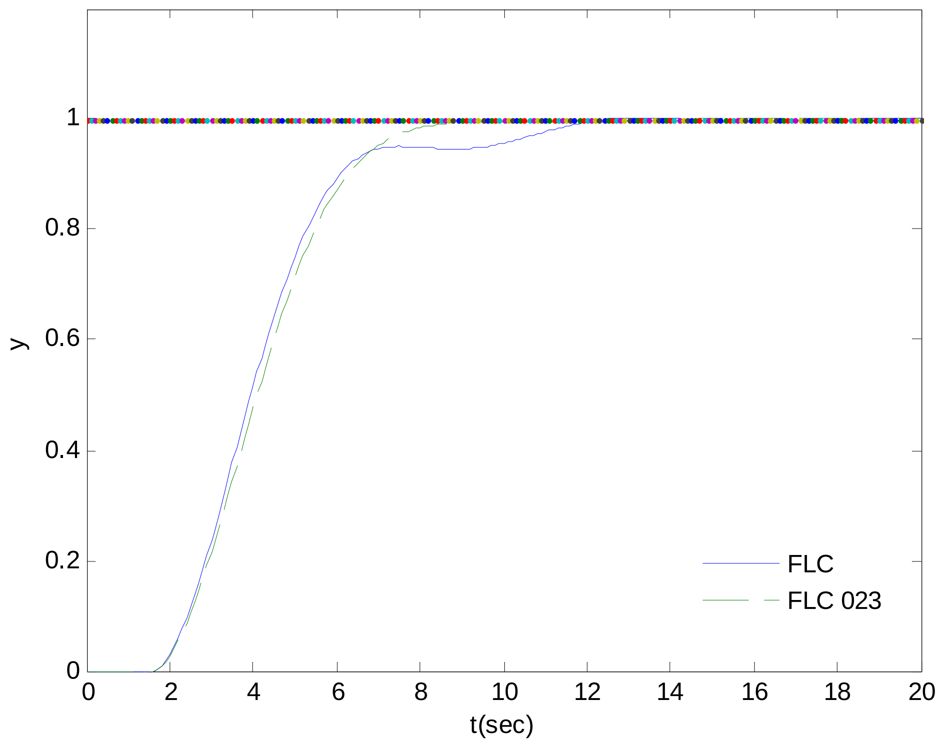
In this section, all these aspects in a controller system design will be covered and the rule-base shifting scheme is shown to be robust for all the fluctuations in parameters. In all scenarios the other parameters affecting the design are assumed to be constant. For each case one or two examples are simulated.

5.1.1. Robustness to Changes in Time Delay (L)

Because of the external devices used or nature of the system, the time delay magnitude in the system model can change. Using the shifted rule-base in the controller yields improved results even in case of time delay variations. In Figure 5.1, for a time delay of 1.75 seconds, responses of the system to variations on the time delay are simulated. The system response and performance index is given in Figure 4.5 and Table 4.1, respectively. In Figure 5.1.a, after the optimization of the parameters for L = 1.75s, time delay is increased 15% (2 seconds) with no parameter retuning. Normally, both system responses corrupted. However, the result of the proposed method still outperforms its nominal counterpart in the same amount (33%). In a similar but opposite manner, if the time delay is decreased to 1.5 seconds, with other parameters remaining the same, proposed method gives better system responses. (Figure 5.1.b and Table 5.1)



(a)



(b)

Figure 5.1: Effect of time delay variations (All SFs are optimized for L = 1.75s) **(a)** L = 2s, **(b)** L = 1.5

Table 5.1: Performance Results for Changes in Time Delay Magnitude (Eq. 3.3)

Delay time	Controller	Performance Index
1.75s	FLC	17.33
	FLC_023	23.08
2s	FLC	10.92
	FLC_023	14.51
1.5s	FLC	18.03
	FLC_023	21.60

5.1.2. Robustness to Imprecision in Time Constant (T)

Time constant is the sole model parameter for a first order plant. Time constant of the real world plant can deviate from the model because of the measurement errors or physical constraints. A control algorithm should be robust to these parameter uncertainties. As illustrated by Figure 5.2 and Table 5.2, the proposed shifting scheme has robustness in terms of time constant fluctuations. In the plant simulated in Figure 5.2, time constant is increased to 1.1 seconds causing the normalized dead time, τ , to decrease to 0.61. Therefore, as suggested by Table 3.1, again 023 shifting scheme is used for the simulations.

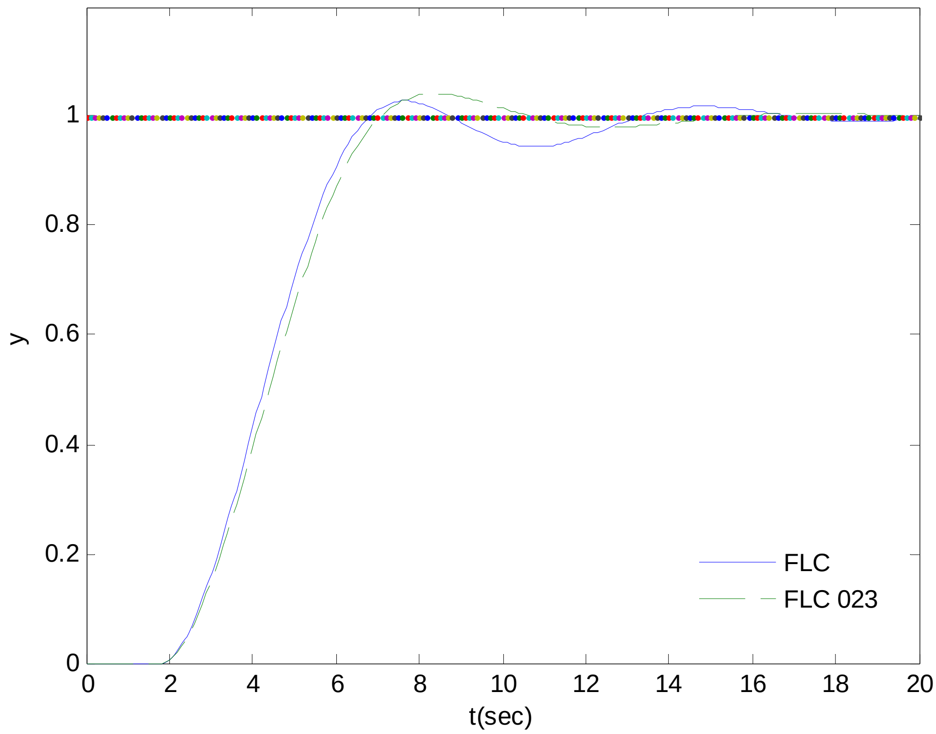


Figure 5.2: Effect of time constant increment (T is increased by 10% for L = 1.75s case)

Table 5.2: Performance Results for Time Constant Increment (Eq. 3.3)

Delay Time	Time Constant	Controller	Performance Index
1.75s	1.1s	FLC	16.47
		FLC_023	18.53

5.1.3. Robustness to Changes in Knowledge Base of the Controller

In the simulations of Section 4, the FLC has the most general structure. The rule-base and MFs are chosen to be in most unbiased manner. In this section robustness of the shifting scheme in terms of MFs and rule-bases will be illustrated.

5.1.3.1. Changes in Membership Functions

In this part, instead of the membership functions given in Figure 2.2, for input and output variables, symmetric triangles with equal base and 50% overlap with neighboring MFs are used. (Figure 5.3) The inference mechanism is Mamdani type. The other parameters, including the rule-base, remain the same.

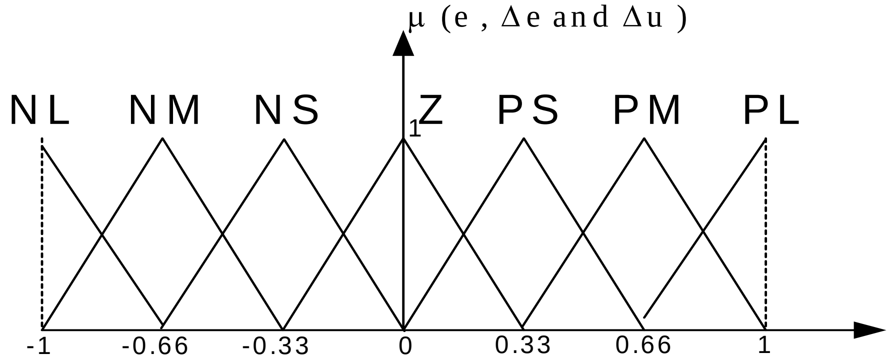


Figure 5.3: Another set of MFs for e, Δe and Δu.

The borders of the tabulation given in Table 3.1 may change slightly for different structural parameters, but the sequence is the same. The comparison to show the improvement with rule base shifting for a delay of 1.75 seconds is given in Figure 5.4. In this illustration the parameters are optimized for each controller by using the new MFs and the same performance index given in equation 3.3. The improvement in terms of the performance index is about 10%. The system with the shifted controller has better rise time compared to nominal one. The other measures seem to be close to each other.

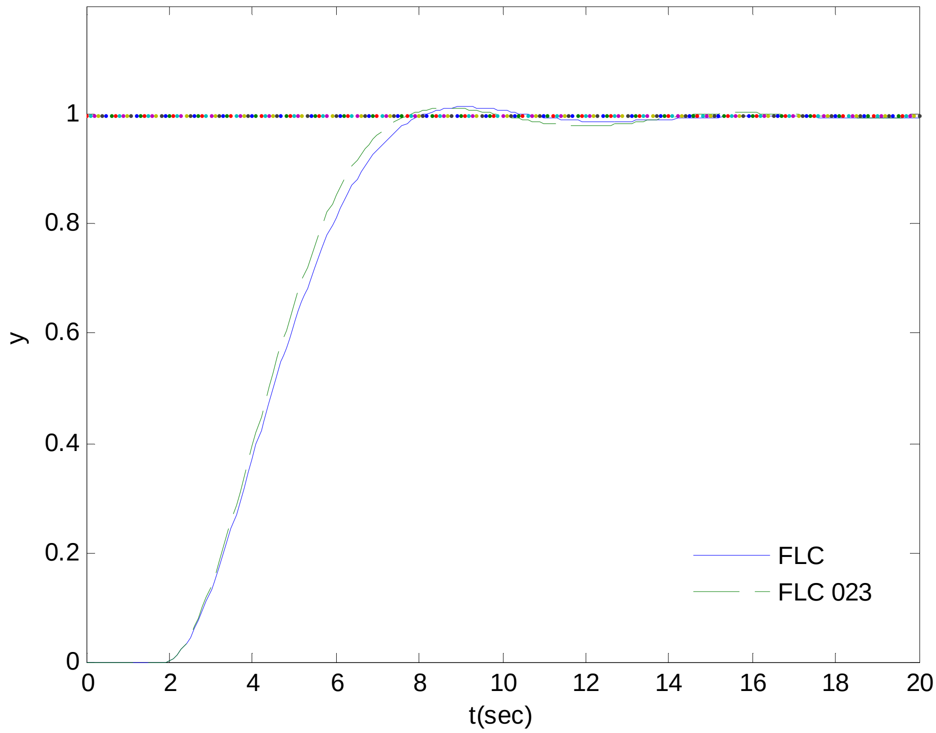


Figure 5.4: Effect of change MFs (The MFs of Figure 5.3 are used) (L = 1.75s)

Table 5.3: Performance Results for Different MFs (Eq. 3.3)

Delay Time	Controller	Performance Index
1.75s	FLC	20.74
	FLC_023	22.24

5.1.3.2. Changes in Rule-Base

5.1.3.2.1. Variation of Rules

The rule- base of Table 2.1 is structured in a most unbiased manner. Though, most of the time, the rule-base is reorganized for different design purposes. In this part, shifting scheme will be simulated in two different rule – bases. The first one will be the rule-base that Li and Gatland [9] used for their thermal process is given in Table 5.4. The response of the system is divided in regions according to signs of e and Δe (as in Figure 3.1) and the sign of the control increment is proposed directly or in terms of signs of e or Δe. [9, 10, 13, 14] Control signal magnitude is given as,

$$\Delta u = \Delta u_0 + \Delta e + C \quad (5.1)$$

where Δu is the change of control signal (output of the FLC), Δu_0 is the control magnitude when Δe is equals to zero (Z), and C is the compensation term. Δu_0 has the same fuzzy value as e. (i.e. if e is PM and Δe is Z, then Δu_0 is PM, if e is NL and Δe is Z, then Δu_0 is NL)

Table 5.4: Rule-Base of Li&Gatland [9] a) FLC , b) FLC_023

Δe/e	NL	NM	NS	Z	PS	PM	PL
PL	Z	PS	PS	PM	PM	PL	PL
PM	NS	Z	PS	PS	PM	PL	PL
PS	NM	NS	Z	PS	PS	PL	PL
Z	NL	NM	NS	Z	PS	PM	PL
NS	NL	NL	NS	NS	Z	PS	PM
NM	NL	NL	NM	NS	NS	Z	PS
NL	NL	NL	NM	NM	NS	NS	Z

(a)

Δe/e	NL	NM	NS	Z	PS	PM	PL
PL	PM	PM	PL	PL	PL	PL	PL
PM	PS	PS	PM	PL	PL	PL	PL
PS	NM	NS	Z	PS	PS	PL	PL
Z	NL	NM	NS	Z	PS	PM	PL
NS	NL	NL	NS	NS	Z	PS	PM
NM	NL	NL	NL	NL	NM	NS	NS
NL	NL	NL	NL	NL	NL	NM	NM

(b)

The compensation term C is chosen zero (Z) for most cases, but there are exceptions:

i. when the magnitude of error (for both negative and positive values) is large, then C can be chosen to speed up the response [9]. In this example this modification is not carried and C is assumed to be Z for the corresponding cases.

ii. when the magnitude of error (for both negative and positive values) is small, then C can be chosen to decrease |u| to prevent intolerable overshoot [9]. This is a precaution for chattering and oscillatory behavior.

In Table 5.4, the entries with non-zero compensating terms (C) are shaded.

The simulations results show that proposed shifting scheme performs well for this modification, too. (Figure 5.5 and Table 5.5) Although the improvement in terms of performance index (Equation 3.3) appears to be decreased, one must remember that the shifting scheme is developed for the very generic structure given in Section 2. In this part, the shifting algorithm is shown to be robust to changes in both structural and tuning parameters. For a fair judgment, one should check the maximums (or minimums) of the own performance index used with the own design parameters.

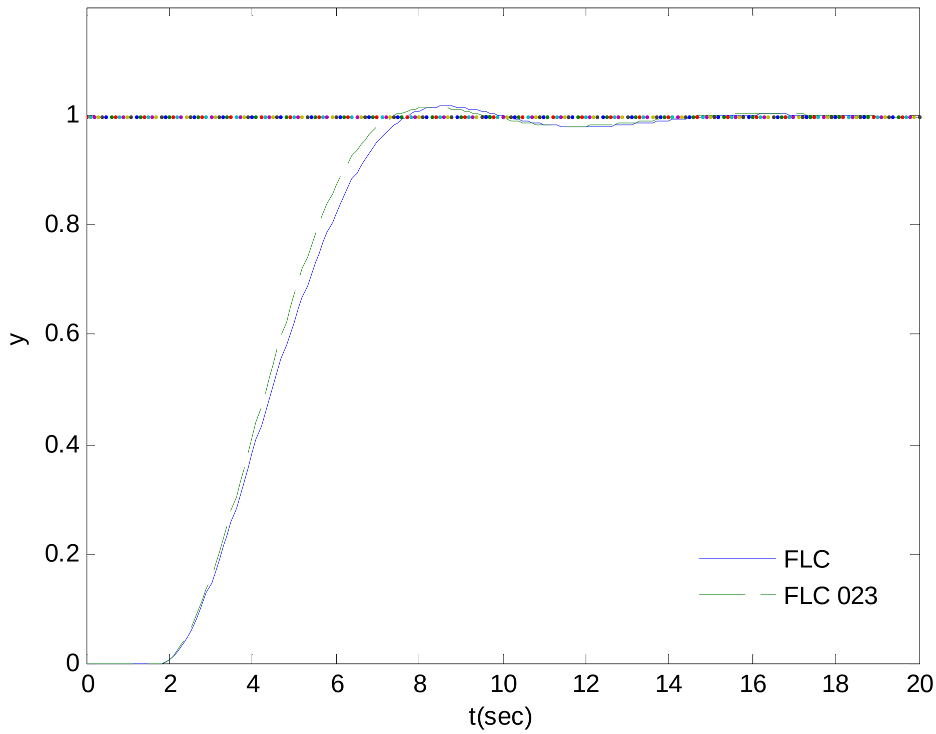


Figure 5.5: Results for rule-base of Table 5.4 (L = 1.75s)

Table 5.5: Performance Results for Rule-Bases of Table 5.4 (Eq.3.3)

Delay Time	Controller	Performance Index
1.75s	FLC	19.70
	FLC_023	21.33

Table 5.6: Rule-base of Chopra *et all.* [15]   a) FLC , b) FLC_023

Δe/e	NL	NM	NS	Z	PS	PM	PL
PL	Z	PS	PS	PM	PL	PL	PL
PM	NS	Z	PS	PM	PM	PM	PL
PS	NM	NS	Z	PS	PS	PM	PL
Z	NL	NM	NS	Z	PS	PM	PL
NS	NL	NM	NS	NS	Z	PS	PM
NM	NL	NM	NM	NM	NS	Z	PS
NL	NL	NL	NL	NM	NS	NS	Z

(a)

Δe/e	NL	NM	NS	Z	PS	PM	PL
PL	PM	PL	PL	PL	PL	PL	PL
PM	PS	PM	PM	PM	PL	PL	PL
PS	NM	NS	Z	PS	PS	PM	PL
Z	NL	NM	NS	Z	PS	PM	PL
NS	NL	NM	NS	NS	Z	PS	PM
NM	NL	NL	NL	NM	NM	NM	NS
NL	NL	NL	NL	NL	NL	NL	NM

(b)

The second rule base is from Chopra *et al.* [15] (Table 5.6). The simulation is for a considerably small amount of delay time, 0.2 seconds, and the results revealed by Figure 5.6 and Table 5.7 are extremely satisfactory. (Shaded entries of Table 5.6 designates the different cells from Table 2.1)

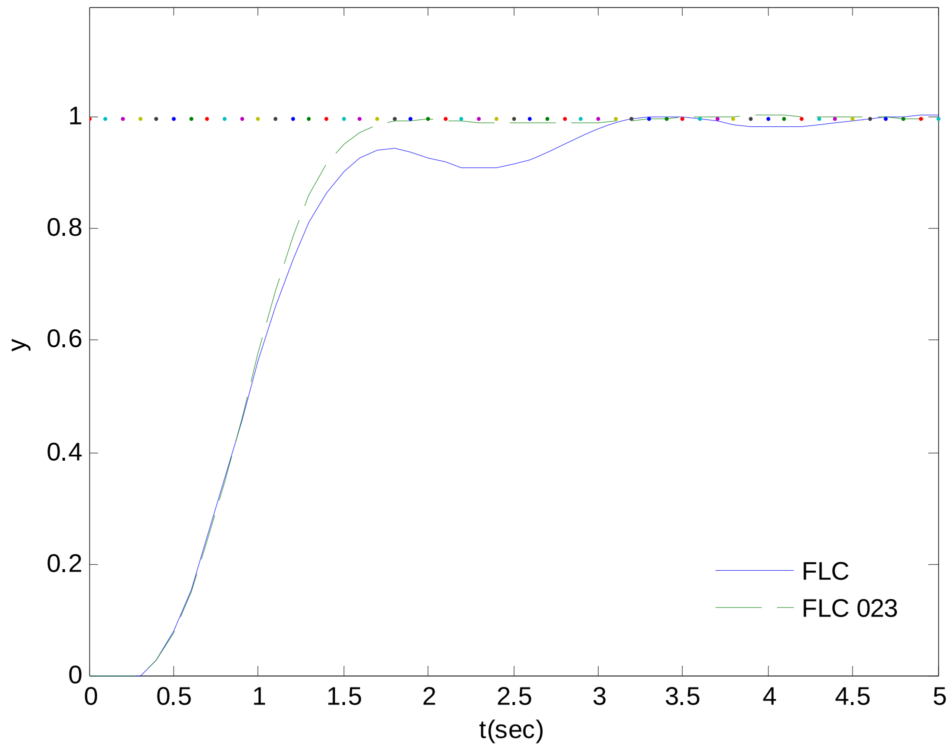


Figure 5.6: Results for the rule-base of Table 5.6. (L = 0.2s)

Table 5.7: Performance Results for Rule-Base of Table 5.6 (Eq. 3.3)

Delay Time	Controller	Performance Index
0.2s	FLC	67.44
	FLC_023	95.60

5.1.3.2.2. Variation of the Size of the Rule-Base

Rule-base shifting scheme has more effect as the variables are defined on more fuzzy regions. This is because of the fact that with more resolution, non-linear structure of the shifting scheme can be fit more precisely. However, this work is based on the case where 7 fuzzy regions are defined for each parameter. Actually, the improvement achieved by increasing the number of fuzzy regions may not compensate the computational complexity. In Figure 5.7, for a FLC having 81 rules (9 fuzzy regions for each input and output parameter), 1.75 seconds of delay is simulated. 0233 shift yields the best results in terms of performance index of Equation 3.3. The improvement, as seen numerically in Table 5.8, is not so much in comparison with 49 – rule counterpart. (Table 4.1)

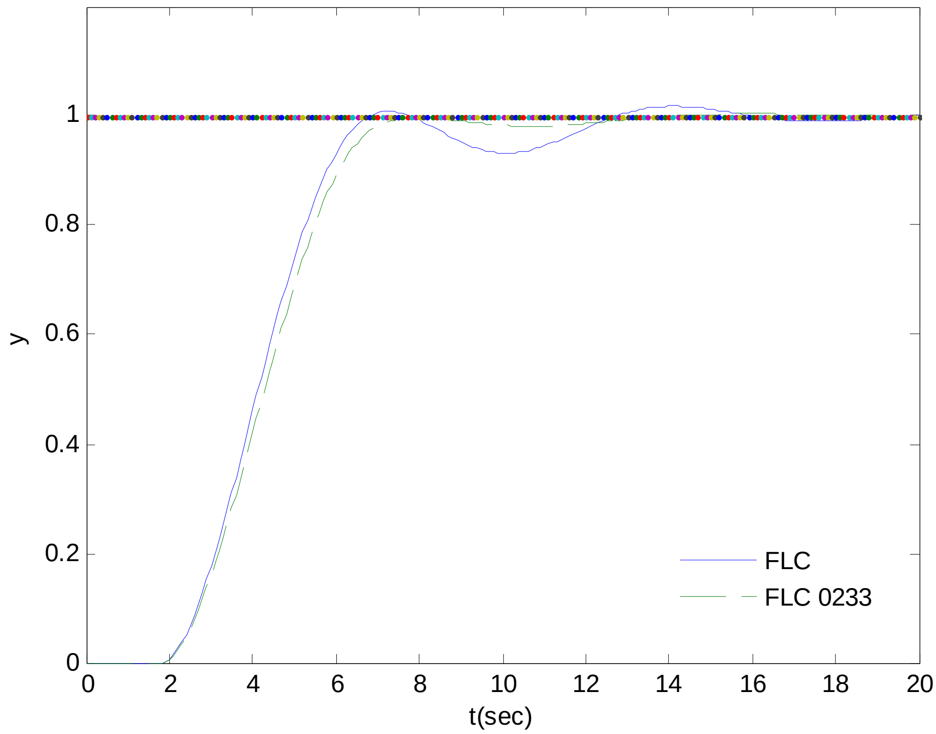


Figure 5.7: Comparison of the controllers with 9 fuzzy region for L = 1.75s.

Table 5.8: Performance Results for controller with 9 fuzzy regions (Eq. 3.3)

Delay Time	Controller	Performance Index
1.75s	FLC	17.64
	FLC_023	23.08
	FLC_0233	24.18

5.1.4. Robustness to Imprecision in Scaling Factor (SF)

The tuning parameters are optimized with global search algorithms or exhausted search. Because of the incapability of the search methods, the scaling factors can be found in the vicinity of the optimum values or, rather, limitations of physical constraints to implement number precisions can lead small deviations from the ideal values. A robust design should compensate such little number imprecision. To test the proposed shifting scheme, all the optimum scaling factors are increased by 10% (Figure 5.8) and the performance index results are given in Table 5.9.

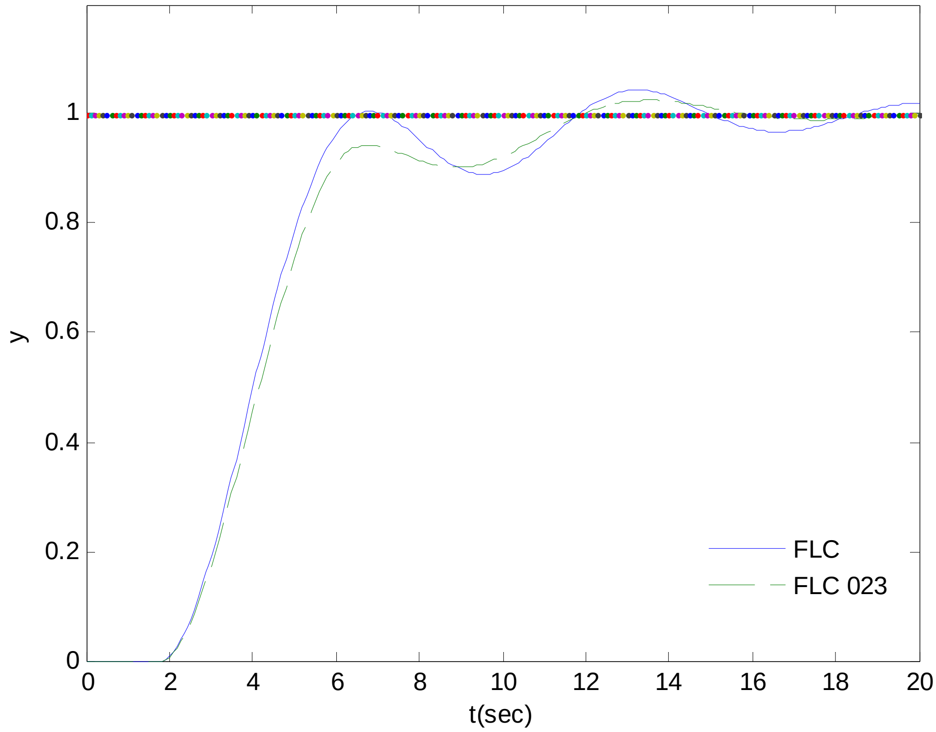


Figure 5.8: Performance Results for 10% increased SFs for L = 1.75s case

Table 5.9: Performance Results for 10% increased SFs (Eq. 3.3)

Delay Time	Controller	Performance Index
1.75s	FLC	13.35
	FLC_023	15.27

5.2. Performance Analysis

Up to this point in all simulations, the performance index given by Equation 3.3 is used. This performance index is widely used and accepted. However, one may change the weightings of the parameters for design purposes. Moreover it is possible to use a completely different performance index. For example, if one tries to design a controller for a system in which total error and overshoot are critical, then he / she may use a performance index utilizing integral absolute error, integral time square error and maximum overshoot:

$$PI_2 = \frac{1000}{IAE + ITSE + 100 \times mp} \qquad (5.2)$$

In this part, modified versions of Equation 3.3 and new performance index PI_2 will be used in simulations. The simulations are held for L = 0.2, and as Table 3.1 says, 023 shift is used. Actually for different rule-bases the borders may move or even the shifting schemes can change. Here these exceptions are neglected but the designer need to know that for different performance indexes, reorganization of Table 3.1 can be crucial.

5.2.1. Modifications in the Performance Index

5.2.1.1. Effect of Changing the Weighting Factor of the Settling Time

The settling band for Equation 3.3 was 2%. One may not need it to be so tight. In Figure 5.9 and Table 5.10, the case with the same performance index of Equation 3.3 only having 5% as settling band is used.

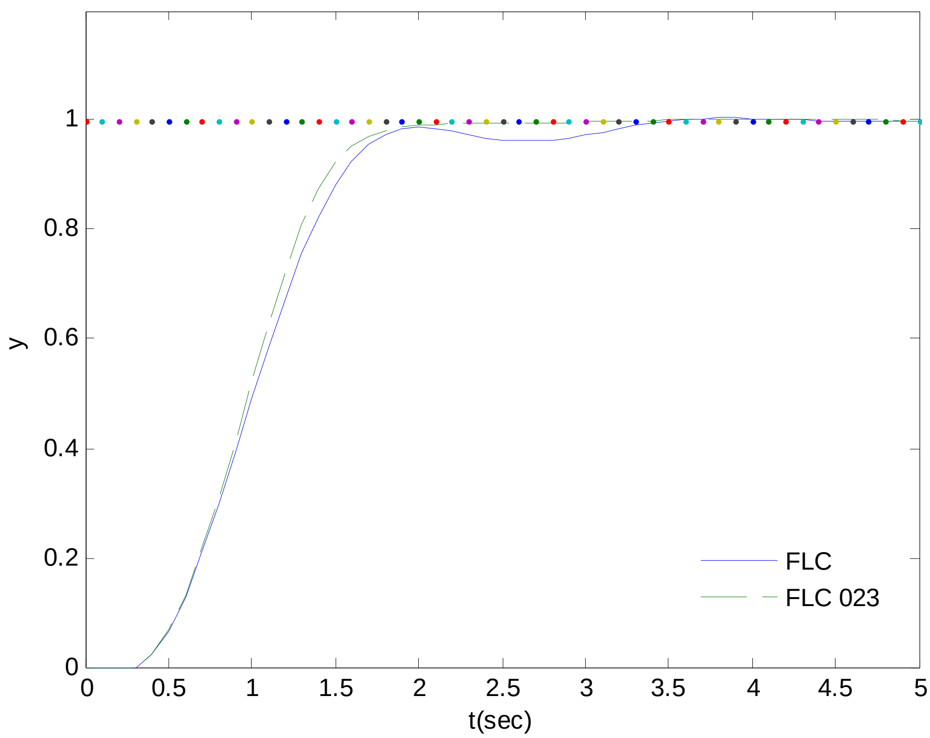


Figure 5.9: Comparison of the controllers for 5% settling band.

Table 5.10: Performance Results for 5% Settling Band (Eq. 3.3)

Delay Time	Controller	Performance Index
0.2	FLC	83.80
	FLC_023	96.00

5.2.1.2. Effect of Changing the Weighting Factor of the Rise Time

To improve the rise time criterion for design purposes, the designer must increase the weighting factor of the rise time. The following is a illustration of the weighting factor of rise time increased by 50%. (Figure 5.10 and Table 5.11) Then the performance index function becomes,

$$PI = \frac{1000}{100\,mp + 3\,ts + 9\,tr + 100\,ess} \tag{5.3}$$

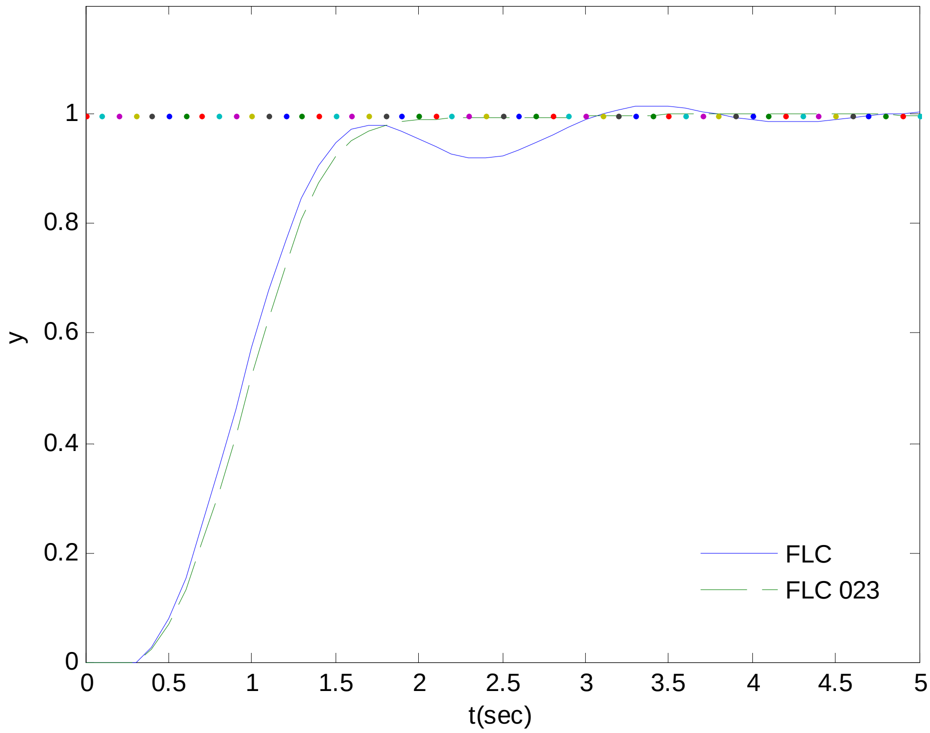


Figure 5.10: Comparison of the controllers. (Scaling factors are optimized with respect to Equation 5.3.)

Table 5.11: Performance Results for Equation 5.3

Delay Time	Controller	Performance Index
0.2s	FLC	56.09
	FLC_023	72.91

5.2.1.3.Effect of Changing the Weighting Factor of the Steady - State Error

If steady state error is fatal to the design, one must increase the penalty factor for steady state error value. To simulate this, in the performance index of Equation 3.3, weighting factor of steady state error is multiplied by three,

$$PI = \frac{1000}{100\,mp + 3\,ts + 6\,tr + 300\,ess} \tag{5.4}$$

The results for simulations are given in Figure 5.11 and Table 5.12.

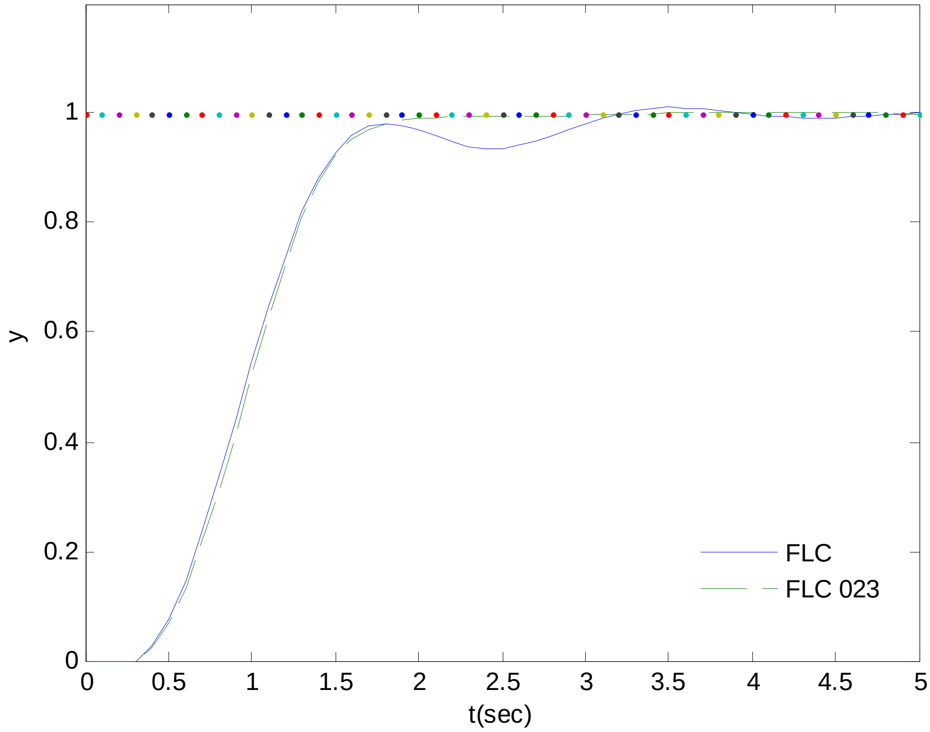


Figure 5.11: Comparison of the controllers. (Scaling factors are optimized with respect to Equation 5.4)

Table 5.12: Performance Results for Equation 5.4

Delay Time	Controller	Performance Index
0.2s	FLC	64.28
	FLC_023	90.40

5.2.1.4.Effect of Changing the Weighting Factor of the Overshoot

For less overshoot, Equation 3.3 can be modified as,

$$PI = \frac{1000}{200\,mp + 3ts + 6tr + 100\,ess} \tag{5.5}$$

The results for simulations are given in Figure 5.12 and Table 5.13.

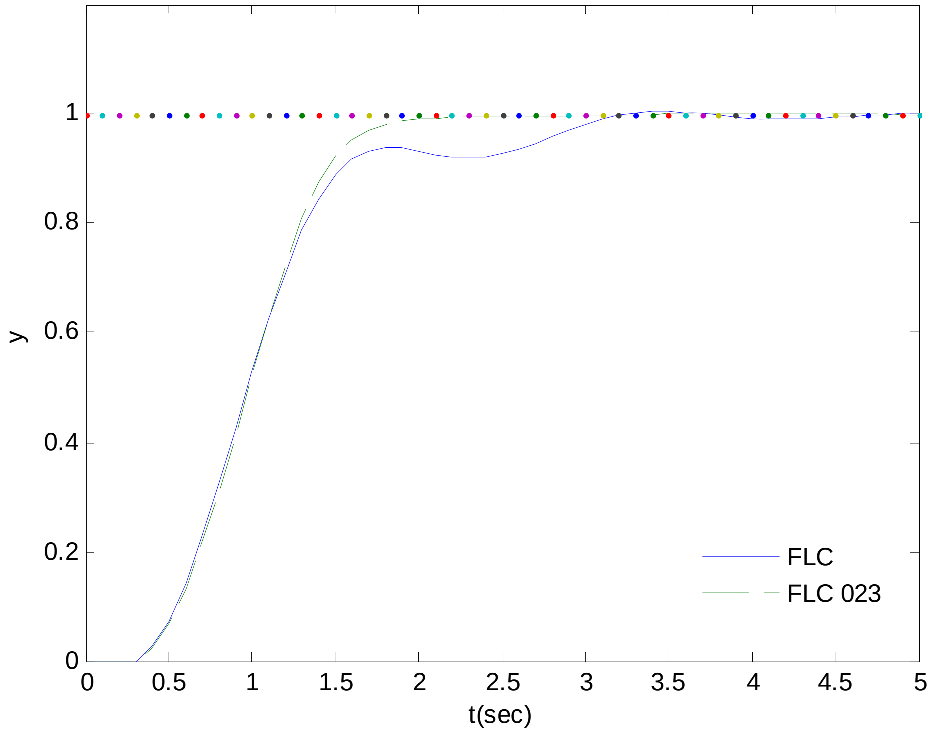


Figure 5.12: Comparison of the controllers. (Scaling factors are optimized with respect to Equation 5.5)

Table 5.13: Performance Results for Equation 5.5

Delay Time	Controller	Performance Index
0.2s	FLC	63.50
	FLC_023	89.21

5.2.2. Performance Index Utilizing Errors

If the performance index of Equation 5.2 is used to optimize scaling factors, (Figure 5.13 and Table 5.14) the improvement seems to be limited compared to others.

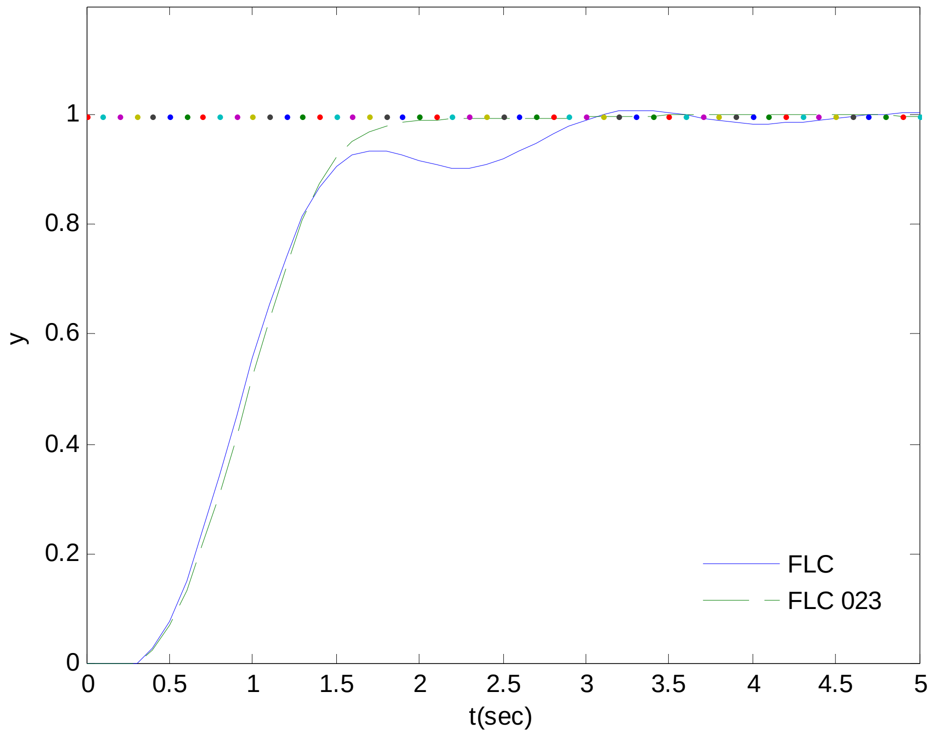


Figure 5.13: Comparison of controllers. (Scaling factors are optimized with respect to PI_2 (Equation 5.2))

Table 5.14: Performance Results for PI_2 (Eq. 5.2)

Delay Time	Controller	Performance Index
0.2s	FLC	61.96
	FLC_023	66.02

6. CONCLUSIONS AND DISCUSSIONS

A fuzzy rule-base shifting scheme in the presence of time delay is proposed. The effects of the time delay value, the system time constant, and the magnitude of error change are discussed for time delay systems in detail. Combining all of these aspects, the shifting scheme is tabulated with respect to the normalized dead time. The simulation results show that proposed rule-base shifting scheme improves system performance in considerable amounts.

Although, it is derived for the most commonly used and unbiased design parameters for the sake of generality, the idea behind the proposed shifting scheme is valid even for the deviations in structural parameters. At the transitions of Table 3.1, reasonable performance indices give continuous results from one shifting scheme to another. Moreover, these borders can be moved for design purposes or different performance indexes.

Shifting all rows by one cell (Li and Gatland [9]) yields improved results rarely. Still, their results are not as good as the ones tabulated in Table 3.1. In fact, when no manipulation on the FLC structure is executed, it generally worsens the results. Therefore, Li and Gatland [9] proposed two sets of scaling factors (for transient and steady state responses) and changing some entries of the rule base by utilizing a compensation term over equal shifting of all rows and then some more performance ameliorations are observed. However, the new controller produced simply by using the tabulation in Table 3.1 provides better results even in very generic form.

Rule-base shifting scheme has more effect as the variables are defined on more fuzzy regions. This is because of the fact that with more resolution, non-linear structure of the shifting scheme can be fit more precisely.

The main idea of rule base shifting is predicting the actual information of the plant by using the delayed one. Actually, rule-base shifting is not the only way to achieve this. In the light of the investigations done in this paper, one may study on the structure and position of MFs and / or tuning of the scaling factors.

REFERENCES

[1] **E. H. Mamdani**, 1974. Application of Fuzzy Algorithm for Simple Dynamic Plant. *Proc. IEE*, 1585–1588.

[2] **M. Sugeno**, 1985. Industrial Applications of Fuzzy Control, Elsevier, Amsterdam.

[3] **E.H. Mamdani**, 1993. Twenty Years of Fuzzy Control: Experiences Gained and Lessons Learnt. *Proc. 2nd IEEE Int. Conf. Fuzzy Systems*, San Francisco, CA, 339–344.

[4] **R.K. Mudi and N.R. Pal**, 1999. A robust Self-tuning Scheme for PI and PD Type Fuzzy Controllers, *IEEE Trans. Fuzzy Systems,* **7**, **1**, 2–6.

[5] **B.Hu, G.K.I.Mann and R.G.Gasine**, 1999. New Methodology for Analytical and Optimal Design of Fuzzy PID Controllers, *IEEE Trans. Fuzzy Systems,* **7**, **5**, 521-539.

[6] **S. Skogestad**, *2002.* Simple Analytic Rules for Model Reduction and PID Controller Tuning, *J. Process Control,* **13**, **4**, 291-309.

[7] **F. G. Shinskey**, 1998. Process Control Systems—Application, Design, and Tuning, McGraw-Hill, New York.

[8] **Han-Xiong Li and S. K. Tso**, 1999. Higher Order Fuzzy Control Structure for Higher Order or Time-Delay Systems, *IEEE Trans. Fuzzy Systems,* **7**, **5**, 814- 829.

[9] **H. X. Li and H. B. Gatland**, 1995. A New Methodology for Designing a Fuzzy Logic Controller, *IEEE Trans. Syst., Man, Cybern.*, **25**, **3**, 505–512.

[10] **Po-Rong Chang and Bor-Chin Wang**, 1996. Adaptive Fuzzy Proportional Integral Power Control for a Cellular CDMA System with Time Delay, *IEEE Journal on Selected Areas in Communications*, **14**, **9**, 1818-1829.

[11] **Y.Bai, H. Zhuang, and Z. S. Roth,** 2005. Fuzzy Logic Control to Suppress Noises and Coupling Effects in a Laser Tracking System, *IEEE Transactions on Control Systems Technology*, **13**, **1**, 113 – 121.

[12] **Y. Song and A.T. Johns**, 1997. Applications of Fuzzy Logic in Power Systems, *IEEE Power Engineering Journal***, 11, 5**, 219-222.

[13] **Han-Xiong Li and H. B. Gatland**, 1996. Conventional Fuzzy Control and Its Enhancement, *IEEE Transactions on Systems, Man, and Cybernetics-Part B: Cybernetics*, **26**, **5**, 791 – 797.

[14] **C.C.Lee**, 1990. Fuzzy Logic on Control Systems: Fuzzy Logic Controller, *IEEE Transactions on Systems, Man, ans Cybernetics*, **20**, **2**, 404-435.

[15] **K.J.Astrom and T.Hagglund**, 1995. PID Controllers: Theory, Design, and Tuning, Instrument Society of America, North Caroline.

[16] **S. Chopra, R. Mitra and V. Kumar**, 2005. Fuzzy Controller: Choosing an Appropriate and Smallest Rule Set, International Journal of Computational Cognition, **3**, **4,** 73 – 79**.**

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