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AUTOMATIC TUNING OF PID CONTROLLER USING FUZZY LOGIC

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Abstract *In this paper the new methodology for designing of PID controller is presented. PID controllers are the most widely used controllers in the industry. Although much architecture exists for control systems, the PID controller is mature and well-understood by practitioners. For these reasons, it is often the first choice for new controller design. There are many methods proposed for the tuning of PID controllers out of which Ziegler Nichols method is the most effective conventional method. In this paper, optimum response of the system is obtained by using fuzzy logic controllers. The method used here is fuzzy set point weighting. A comparison of the performance of fuzzy set point weighted controller is performed not only with the conventional methods of tuning but also with different shapes and numbers of designed membership functions.*
Keywords: *PID (proportional-integral-derivative), Fuzzy Logic (FL), Ziegler Nichols Method (ZN), Fuzzy Set Point Weighting Controller (FSPWC), Membership Functions (MF)*

1. Introduction

Tuning of PID controllers has always been an area of active interest in the process control industry. Ziegler Nichols Method (ZN) is one of the best conventional methods of tuning available now [1]. Though ZN tunes systems very optimally, a better performance is needed for very fine response and this is obtained by using Fuzzy Logic (FL) methodology which is highly effective. The FL methodology used in this paper is applied in the form of Fuzzy Set Point Weighting Controller (FSPWC) [1,7]. The idea of multiplying the set-point value for the proportional action by a constant parameter less than one is effective in reducing the overshoot but has the drawback of increasing the rise time. To achieve both the aims of reducing the overshoot and decreasing the rise time, a fuzzy module can be used to modify the weight depending on the current output error and its time derivative [7]. Thus by using FSPWC, which was suggested by Antonio Visioli and modifying it in accordance to our desired performance criteria, simulation of the FSPWC is performed in MATLAB to obtain desired results.

2.Tuning And Its Purpose

A PID may have to be tuned
When

a) Careful consideration was not given to the units of gains and other parameters.
b) The process dynamics were not well-understood when the gains were first set, or the dynamics have (for any reason) changed.
c) Some characteristics of the control system are direction-dependent (e.g. actuator piston area, heat-up/cool-down of powerful heaters).
d) You (as designer or operator) think the controllers can perform better.

Always remember to check the hardware first because there are many conditions under which the PID may not have to be tuned. These conditions are when
1) A control valve sticks. Valves must be able to respond to commands.
2) A control valve is stripped out from high-pressure flow where the valve's response to a command must have some effect on the system.
3) Measurement taps are plugged, or sensors are disconnected. Bad measurements may have you correcting for errors that don't exist. Once fix these hardware problems then depending on the responses we obtain an appropriate decision can be taken whether or not to tune a PID controller. [2]

2.1 Trial and error method

This process is a very time consuming process as a lot of permutations and combinations are involved. Though many iterations are performed the final result is not satisfactory. A balance is not obtained between the rise time and % overshoot even though a lot of possible combinations of the gains are incorporated. Continuous cycling may be objectionable because the process is pushed to the stability limit. Consequently, if external disturbances or a change in the process occurs during controller tuning, it results in unstable operation. The tuning process is not applicable to processes that are open loop unstable because such processes typically are unstable at high and low values of K_c but are stable at an intermediate range of values. It can be observed in Figure 1 that large overshoot is obtained as the program is written for faster rise time hence compromising with overshoot. All the time response specifications cannot be balanced using trial and error method.

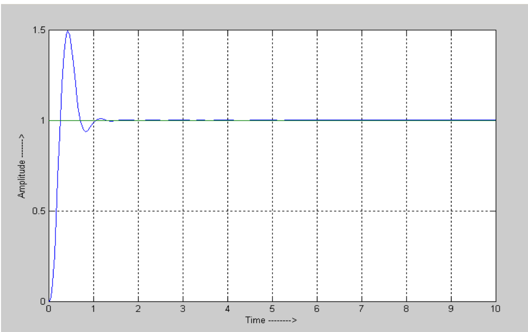


Figure 1 Unit step response of the system $G_1(s)$ tuned with trial and error method.

2.2 Pole placement method

If the process is described by a low-order transfer function, a complete pole placement design can be performed. Consider for example the process described by the second-order model.

$$G(s) = \frac{K_P}{(1+sT_1)(1+sT_2)} \quad (1)$$

This model has three parameters. By using a PID controller, which also has three parameters, it is possible to arbitrarily place the three poles of the closed loop system. The transfer function of the PID controller in parallel form can be written as

$$G_C(s) = \frac{K\left(1 + sT_I + s^2 T_I T_D\right)}{sT_I} \quad (2)$$

The characteristic equation of the closed loop system becomes

$$s^3 + s^2\left(\frac{1}{T_1} + \frac{1}{T_2} + \frac{K_P K T_D}{T_1 T_2}\right) + s\left(\frac{1}{T_1 T_2} + \frac{K_P K}{T_1 T_2}\right) + \frac{K_P K}{T_I T_1 T_2} = 0 \quad (3)$$

A suitable closed-loop characteristic equation of a third-order system is

$$(s + \alpha\omega)\left(s^2 + 2\zeta\omega s + \omega^2\right) = 0 \quad (4)$$

Which contains two dominant poles with relative damping (ζ) and frequency (ω), and a real pole at $-\alpha\omega$. Identifying the coefficients in these two characteristic equations determines the PID parameters K, T_I and T_D.

The solution is

$$K = \frac{T_1 T_2 \omega^2 (1 + 2\zeta\alpha) - 1}{K_P} \quad (5)$$

$$T_I = \frac{T_1 T_2 \omega^2 (1 + 2\zeta\alpha) - 1}{T_1 T_2 \alpha \omega^3} \quad (6)$$

$$T_D = \frac{T_1 T_2 \omega(\alpha + 2\zeta) - T_1 - T_2}{T_1 T_2 \omega^2 (1 + 2\zeta\alpha) - 1} \quad (7)$$

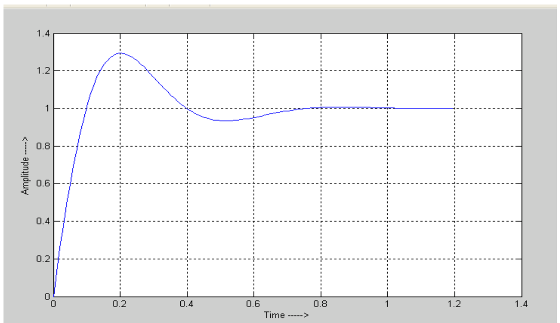


Figure 2 Response of a system tuned with Pole Placement Method.

2.3 Ziegler nichols method

$$u(t) = K_p\left[e(t) + T_d \frac{de(t)}{dt} + \frac{1}{T_i}\int_0^t e(\tau)d\tau\right] \quad (8)$$

Ziegler Nichols formula ensures good load disturbance attenuation, but it generally provides a poor phase margin and therefore it produces a large overshoot and settling time in the step-response. The overall control scheme for Ziegler Nichols Method is shown in Figure 3.

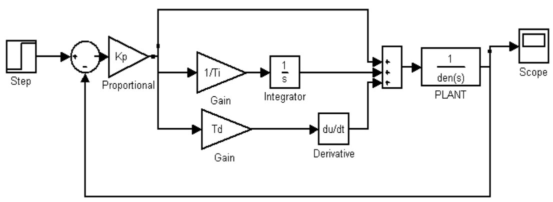


Figure 3. Control Scheme for Ziegler Nichols Method.

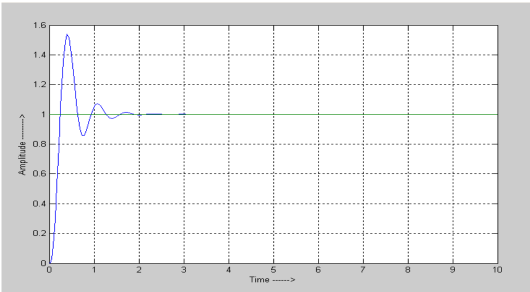


Figure 4. Unit step response of the system $G_1(s)$ tuned with ZL method.

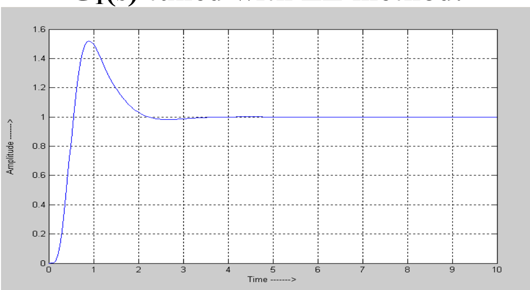


Figure 5. Unit step response of the system G2(s)tuned with ZL method.

2.4 Ziegler nichols with fixed set-point weighting ‘b’

$$u(t)=K_p\left(by_{sp}(t)-y(t)\right)+K_d\frac{de(t)}{dt}+K_i\int_0^t e(\tau)d\tau \qquad \textbf{(9)}$$

An effective way to reduce overshoot is to weight the set-point for the proportional action by means of a constant b < 1 so that we get decreased overshoot with a slight increase in rise time as the proportional action is somewhat reduced. The overall control scheme is shown in Figure 6.

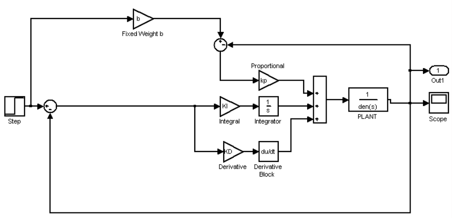


Figure 6. Control Scheme for Ziegler Nichols with fixed set-point ‘b’.

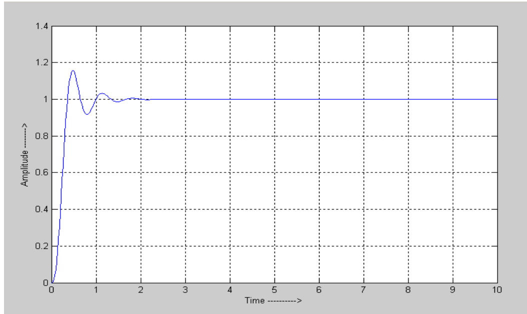


Figure 7. Response for system $G_1(s)$ tuned with fixed ‘b’ method.

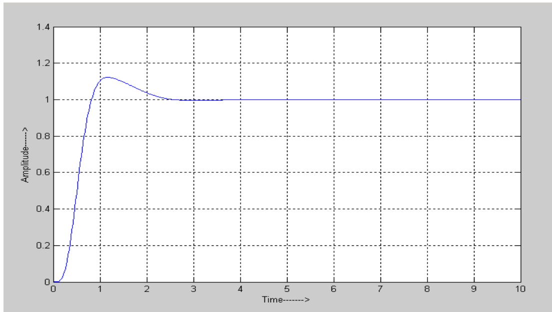


Figure 8. Response for system $G_2(s)$ tuned with fixed ‘b’ method.

3. Fuzzy set-point weighting:

3.1 PID tuning with fuzzy set-point weighting

The PID controller has the following well-known standard form in the time domain

$$u(t)=K_p\left[e(t)+T_d\frac{de(t)}{dt}+\frac{1}{T_i}\int_0^t e(\tau)d\tau\right] \qquad (10)$$

The typical tuning problem consists of selecting the values of these three parameters, and many different methods have been proposed in the literature in order to meet different control specifications such as set-point following, load disturbance attenuation, robustness with respect to model uncertainties and rejection of measurement noise. Using the Ziegler-Nichols formula generally results in good load disturbance attenuation but also in a large overshoot and settling time for a step response that might not be acceptable for a number of processes. Increasing the analog gain K generally highlights these two aspects.

An effective way to cope with this problem is to weight the set-point for the proportional action by means of a constant b <1 so that we get

$$u(t)=K_pe_p(t)+K_d\frac{de(t)}{dt}+K_i\int_0^t e(\tau)d\tau \qquad (11)$$

Where ep(t) = bysp(t)—y(t). In this way, a simple two-degree of freedom scheme is implemented; one part of the controller is devoted to the attenuation of load disturbances, and the other to the set-point following as shown in figure, where the following transfer functions are indicated:

$$G_{ff} = K_p\left(b + \frac{1}{sT_i} + sT_d\right) \qquad (12)$$

$$G_c = K_p\left(1 + \frac{1}{sT_i} + sT_d\right) \qquad (13)$$

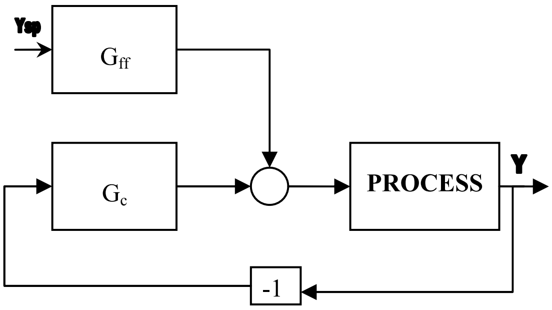


Figure 9. Two degrees of freedom implementation.

However, the use of set-point weighting generally leads to an increase in the rise time since the effectiveness of the proportional action is somewhat reduced. This significant drawback can be avoided by using a fuzzy inference system to determine the value of the weight b(t) depending on the current value of the system error e(t) and its time derivative è(t). The idea, in a few words, is simply that b has to be increased when the convergence of the process output y(t) to ysp(t) has to be speeded up, and decreased when the divergence trend of y(t) from ysp(t) has to be slowed down. For the sake of simplicity, the methodology is implemented in such a way that the output f(t) of the fuzzy module is added to a constant parameter w, resulting in a coefficient b(t) that multiplies the set-point. The overall control scheme is shown in Figure 10.

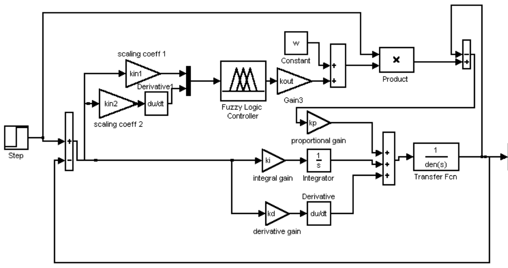


Figure 10. Simulink Block Diagram for FSPWC scheme.

The two inputs of the fuzzy inference system, the system error e and its derivative è, are scaled by two coefficients, Kin1 and Kin2 , respectively, in order to match the range [-1, 1] on which the membership functions are defined. Five triangular membership functions are defined for each input while nine triangular membership functions over the range [-1, 1] are defined for the output, which is scaled by a coefficient Kout .The rule matrix is based on the Macvicar Whelan matrix . The meaning of the linguistic variables is explained in the table.

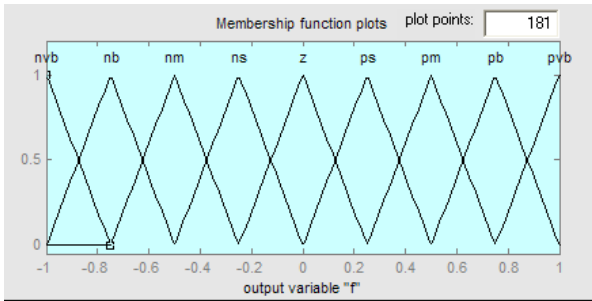


Figure 11. Membership functions for e and è.

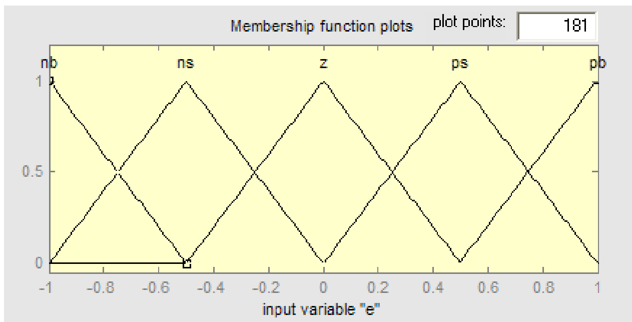


Figure 12. Membership functions for output function.

Table 6.1 Basic Rule Table for Fuzzy Inference System

e \ Δe	NB	NS	Z	PS	PB
NB	NVB	NB	NM	NS	Z
NS	NB	NM	NS	Z	PS
Z	NM	NS	Z	PS	PM
PS	NS	Z	PS	PM	PB
PB	Z	PS	PM	PB	PVB

Table 6.2 Meaning of the linguistic variables in the Fuzzy Inference System

NVB	Negative Very Big
NB	Negative Big
NM	Negative Medium
NS	Negative Small
Z	Zero
PS	Positive Small
PM	Positive Medium
PB	Positive Big
PVB	Positive Very Big

In the case of the fuzzification of the set-point weight, having fixed the value of K_{in1} equal to the inverse of the amplitude of the step of the set-point, we search for the values of K_{in2} , w and the position of the membership functions in order to minimize the value of the integrated absolute error

$$IAE = \int_0^\infty |e(t)| dt \quad (14)$$

Finally, it is worth stressing that by choosing other objective functions, different design specifications can be satisfied, e.g., a step response with the minimum overshoot can be obtained.

Principles of macvivar whelan matrix

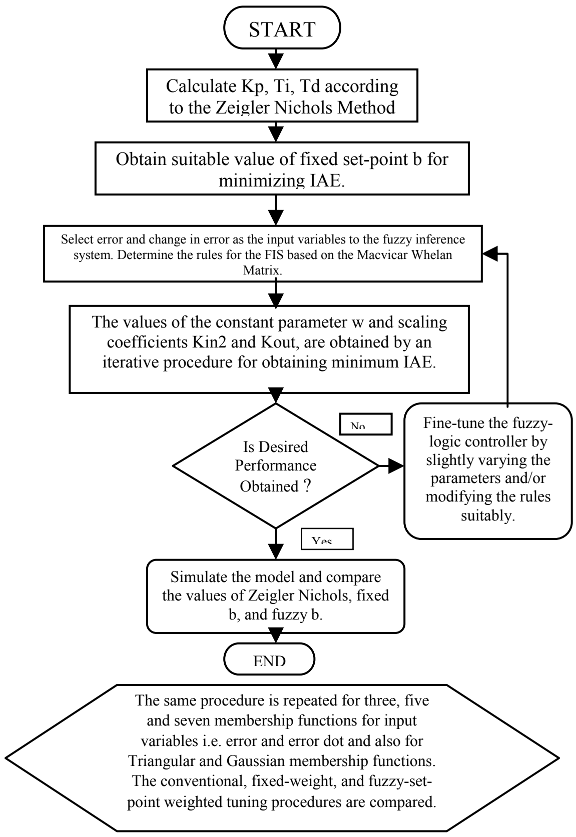
1. If the output has the desired value and the error derivative is zero we then keep constant the output of the controller.
2. If the output diverges from the desired value our action then depends on the signum and the value of the error and its derivative. If the conditions are such that error can be corrected quickly by itself we then keep the controller output constant or almost constant otherwise we change the controller output to achieve satisfactory results

3.2 Practical tuning procedure

Having determined the value of the three parameters *K, Ti,* and *Td* by means of the Ziegler—Nichols step response or frequency response method, it remains to assign the values of the other parameters and subsequently to modify the peak values of the membership functions and the rules according to the typical practical procedure for the fuzzy controllers . The value of K_{in1} can simply be chosen as the inverse of the amplitude of the step of the set-point. For the others, a practical procedure is to set w = 1 and then keep increasing the value of *Kout* (starting from *Kout* = 0), while accordingly modifying the value of K_{in2} in order to normalize the input *è,* as long as the performance improves. Then, this procedure can be iterated with decreasing values of w until better results are achieved. At the end, the peak values of the membership functions have to be tuned, especially to limit oscillations of the system output, by increasing the action of the fuzzy module when the output of the system is close to the set-point but its derivative is still high. Finally, the rules may also be modified to improve the system response

3.3 A flowchart for tuning PID

The procedure to tune the PID controller using fuzzy logic is shown below



4. Simulation results

4.1 System $G_1(s)$

The system under consideration is

$$G_1(s) = \frac{1}{0.008s^3 + 0.04s^2 + 0.5s + 1} \quad (15)$$

To verify the full potentialities of the investigated methodologies, it will be assumed that no saturation levels are present for the control variable. After the tuning phase, accomplished using the various techniques, the unit step responses have been simulated. The resulting values of the time domain specifications and performance criteria are reported in Table 7.1.1

To compare the control laws, tuned by fuzzy logic methodologies with classical industrial methodologies, it also shows a PID tuned with Ziegler Nichols method both without 'ZN' and with 'ZN-b', a fixed set-point weight.

Table 7.1.1 Comparison Table Of Time Domain Specifications And Performance Criteria

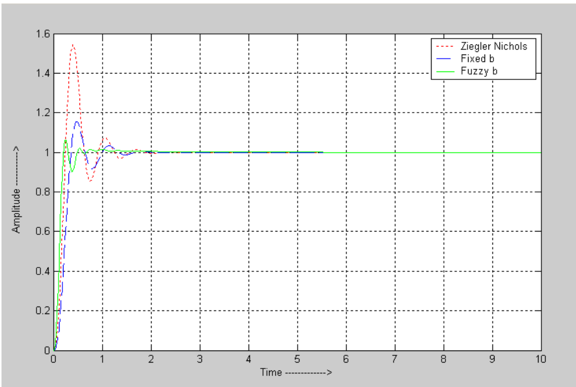


Figure 13. Step responses of $G_1(s)$ with different controllers.

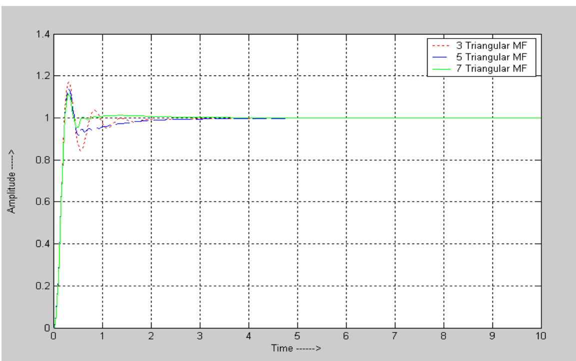


Figure 14. Step responses of $G_1(s)$ with different Triangular MFs.

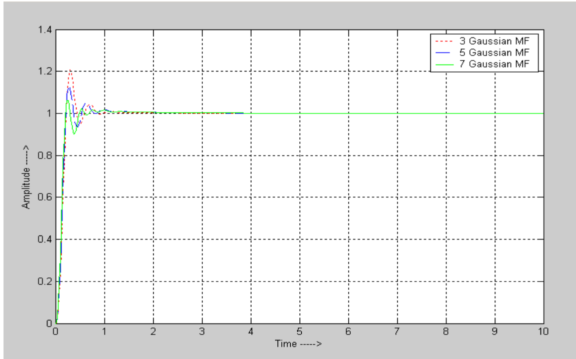


Figure 15. Step responses of $G_1(s)$ with different Gaussian MFs.

Applying the proposed optimal tuning methodology, the resulting values of PID parameters are reported in Table 7.2.1. Plots of the system for unit step response are plotted in figures 13, 14 and 15. A comparison of the below mentioned tuning techniques has also been performed.

Table 7.2.1 Comparison Table Of Time Domain Specifications And Performance Criteria for $G_2(s)$

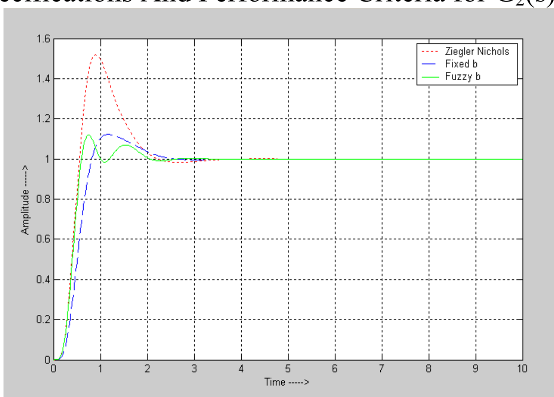


Figure 16. Step responses of $G_2(s)$ with different controllers.

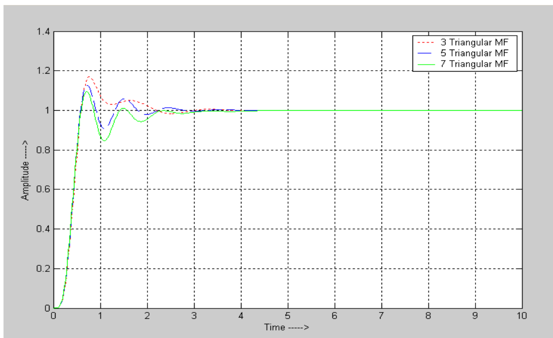


Figure 17. Step responses of $G_2(s)$ with different Triangular MFs.

2 System $G_2(s)$

As an illustrative example regarding delay processes, consider the transfer function

$$G_2(s) = \frac{e^{-0.3s}}{(1+0.2s)(1+0.6s)} \qquad (16)$$

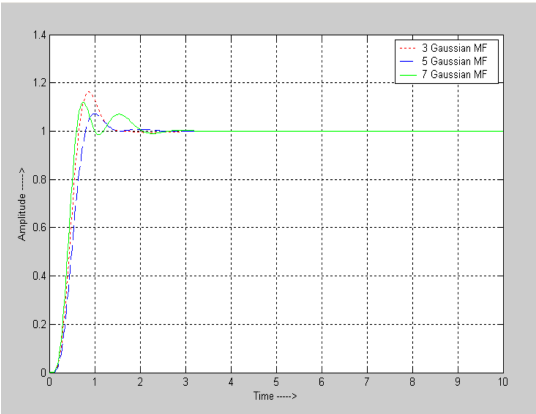


Figure 18. Step responses of G_2(s) with different Gaussian MFs.

8. Conclusion

In this paper, comparison between different methodologies regarding the tuning of PID controllers using FL has been presented. The results have clearly emphasized the advantages of fuzzy inference systems, in this context. The main benefits in the use of FL appear when process non-linearities such as saturation are significant. The main benefits in the use of FL are evident as a balance is obtained between both rise time and overshoot in the response i.e lesser overshoot and smaller rise time are obtained simultaneously by using FL methodologies which is almost impossible using conventional methodologies. The designing of Fuzzy logic controller and study analysis of number of membership functions and their shapes were the main area of concentration in our paper and the results obtained clearly determine that as the change in number of membership functions and their shape obtained the finer is the tuning and optimal is the response. The ease of tuning of fuzzy mechanism parameters plays a key role in the practical applicability of the methodologies, since it determines the improvement in the cost per benefit ratio with respect to standard methods. In this context, Fuzzy Set Point Weighting Controller appears superior to others, as it guarantees, in general, very good performances in the set point and load disturbance step responses and it requires a modest implementation effort; therefore its practical implementation in industrial environments appears to be very promising

6. References

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Table 7.1.1 Comparison Table of Time Domain Specifications and Performance Criteria

	TUNING METHOD	DELAY TIME	RISE TIME	SETTLING TIME	% OVERSHOOT	IAE	ISE	ITAE	ITSE
CONVENTIONAL METHODS	ZIEGLER NICHOLS	0.25	0.28	1.65	52.14	0.39	0.22	0.16	0.02
	ZIEGLER NICHOLS WITH FIXED 'b'	0.24	0.32	1.24	15.56	0.28	0.18	0.07	0.00
FUZZY LOGIC SET POINT WEIGHTING	3 TRIANGULAR MF	0.16	0.26	1.22	14.06	0.22	0.12	0.10	0.00
	5 TRIANGULAR MF	0.16	0.24	1.62	13.96	0.23	0.12	0.13	0.00
	7 TRIANGULAR MF	0.16	0.24	0.54	11.54	0.18	0.12	0.06	0.00
	3 GAUSSIAN MF	0.16	0.22	0.78	20.61	0.18	0.12	0.04	0.00
	5 GAUSSIAN MF	0.14	0.21	0.72	13.15	0.18	0.11	0.05	0.00
	7 GAUSSIAN MF	0.14	0.20	0.54	06.22	0.16	0.10	0.05	0.00

Table 7.2.1 Comparison Table of Time Domain Specifications and Performance Criteria for $G_2(s)$

	TUNING METHOD	DELAY TIME	RISE TIME	SETTLING TIME	% OVERSHOOT	IAE	ISE	ITAE	ITSE
CONVENTIONAL METHODS	ZIEGLER NICHOLS	0.40	0.28	2.06	51.94	0.80	0.47	0.57	0.18
	ZIEGLER NICHOLS WITH FIXED 'b'	0.52	0.44	2.18	12.22	0.62	0.42	0.31	0.05
FUZZY LOGIC SET POINT WEIGHTING	3 TRIANGULAR MF	0.42	0.32	2.02	16.85	0.51	0.34	0.23	0.03
	5 TRIANGULAR MF	0.40	0.30	2.00	12.96	0.47	0.33	0.19	0.02
	7 TRIANGULAR MF	0.40	0.30	2.00	9.18	0.49	0.33	0.23	0.03
	3 GAUSSIAN MF	0.44	0.34	1.30	16.16	0.50	0.37	0.18	0.03
	5 GAUSSIAN MF	0.44	0.34	1.70	16.00	0.57	0.36	0.16	0.03
	7 GAUSSIAN MF	0.38	0.28	1.80	11.39	0.44	0.32	0.16	0.02