Design and Analysis of PID and Fuzzy Logic Controller for Simulation Performance

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Abstract

In this paper fuzzy logic controller (FLC) and proportional integral derivative (PID) controller are compared as for controlling the fixed armature current of direct current (DC) motor. The PID controllers are mostly used in factories for their powerful performance in the operating conditions and simple tuning methods. By using the Ziegler-Nichols method of frequency response to tune control parameters for the high order transfer function of fixed armature current of DC motor. Fuzzy logic has become the most popular and successful technologies for developing a sophisticated control system. FLC using smaller fuzzy control rules is proposed. By using MATLAB/SIMULINK to simulate high order transfer function, the simulation results and performance are analyzed, it shows the effectiveness of the proposed fuzzy logic controller is better than the designed ZN tuned PID controller and fine-tuned PID. To analyze the influence of membership function, three kinds of triangular membership functions and three types of membership functions are proposed to evaluate output responses. It suggests the intersection of boundary for triangular membership function is half. The performance of the triangular type membership function is better than the trapezoidal and Gaussian membership function in this study.

Keywords: PID controller, Fuzzy logic, Tune method, Simulation

1 Introduction

As the rapid development of technology, the intelligent system engineering is becoming more and more popular and interested in many fields. The controller is an important element in intelligent systems. The proportional integral derivative (PID) controller is adopted in most industrial control systems. PID controllers are widely employed for easy understanding and operating, simple structure, and powerful performance in many areas as DC motor, automotive, car control, intelligent robot and air flight control, etc. [1-5]. Some many algorithms and methods have been developed for the design and auto-tuning of PID parameters [6]. The principal of the PID controller is to calculate an error value of the difference between the measured process output variable and the desired set point. There are three separate constant parameters in a PID controller as proportional (P), integral (I), derivative (D). These three constant parameters are respectively interpreted in a team of time proportional (P) which is a term proportional to the error, integral (I) which is a term proportional to the integral of error concerning time, derivative (D) which is a term proportional to the derivative of error for a time. The quality of a control system mostly relies upon settling time (T_s), rise time (T_r), and overshoot (M_p) [7]. To have fine control of a system, we need to optimally adjust or tune these time variables to get lower overshoots, smaller settling time, and other variations. By finely tuned parameters, PID controllers will give strong and reliable function in the process of system control. There was much researches to explained tuning methods [8-9]. The Ziegler-Nichlos (ZN) technique was usually adopted in PID controls among these tuning methods. Ziegler-Nichlos introduced two methods to finely tune the parameters, a frequency response method and a step response method. The frequency response method is more reliable than the step response method [8-9].

In the design of control systems, there are problems related to undesirable overshoot, longer settling times, and vibrations that are needed to overcome during the process from one state to another state. Sometimes it is difficult to have accurate models for a nonlinear system in the real world. The conventional PID controllers usually need a numerical model and do not perform well for nonlinear systems in most cases. Therefore, we need further advanced control technologies to be utilized to minimize noise effects and overshoot. There are three techniques to an intelligent control system to overcome these difficulties: knowledge-based expert systems, fuzzy logic, and neural networks [10]. The fuzzy logic was firstly

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developed by Zadeh and has established the theory of fuzzy sets [11-14]. The advantage of fuzzy logic is different from the conventional logic system, it can deal with inaccurate or imprecise models. The fuzzy logic controller is a control method based on fuzzy logic. The fuzzy logic control system provides a simpler, quicker, and more reliable solution by being expressed with simple "if-then" rules. Fuzzy logic grants intermediate value to be explained between established evaluations such as true or false, yes or no, high or low and comes out as an instrument to handle with the uncertain, imprecise, or qualitative decision-making problems, at the same time, it is also a method to make machines more understanding to sense in a fuzzy character like a mortal. Therefore, fuzzy logic can be defined as "applying with words rather than numbers" or "control with sentences rather than formulas" and it is especially useful in an operation-controlled factory by empirical regulations.

Therefore, this study aims to analyze the performance of the PID controller and the FLC for the higher-order system. A designed PID controller that has been tuned by the Ziegler-Nichlos technique and a fuzzy logic controller with smaller fuzzy rules are proposed. Simulation results are demonstrated and the settling time, rise time, and overshoot are investigated to compare the performance. Three kinds of triangular membership functions are also carried to evaluate the influence of performance concerning the intersection of the boundary. The triangular, trapezoidal, and Gaussian membership functions have been analyzed for performance.

2 PID Controller

2.1 Description

The PID controller is widely used in industry for its simple control structure, the typical continuous-time PID control equation in the time domain can be described as:

$$u(t) = K_p(e(t) + \frac{1}{T_i}\int_0^t e(t)d\tau + T_d \frac{de(t)}{d_t}) \quad \textbf{(1)}$$

Where $u(t)$ is the PID controller output, K_p is the proportional gain, T_i is the integral time, T_d is the derivative time, and $e(t) = ref(t) - y(t)$ is the error, $ref(t)$ is the reference input signal and $y(t)$ is the process output. The facts K_p, T_i, and T_d are the tuning parameters as shown in Figure 1.

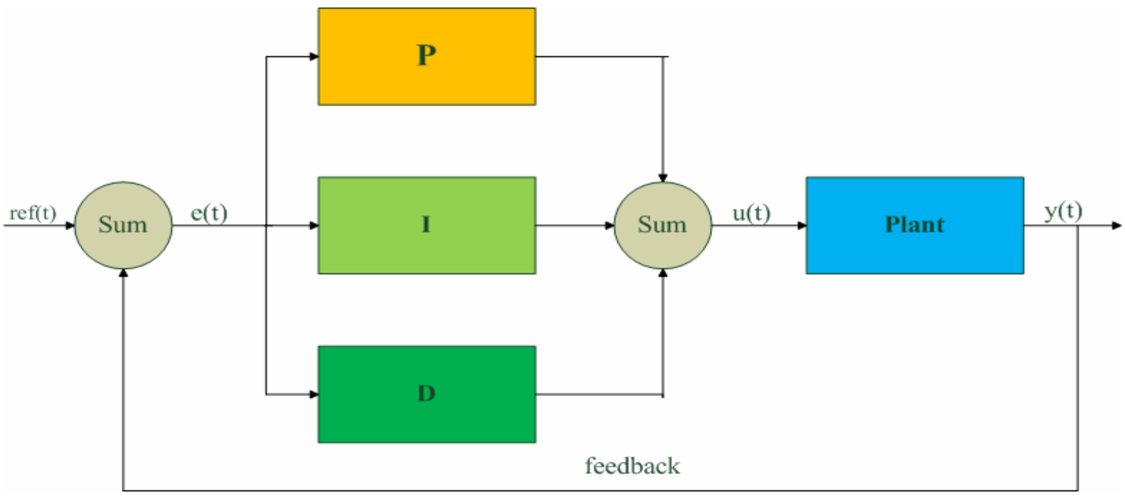


Figure 1. Block diagram of PID controller

When a PID controller is described by the following transfer function in the continuous s-domain

$$G_c(s) = K_p + \frac{K_i}{s} + K_d S \quad \textbf{(2)}$$

The equation can be arranged as follows

$$G_c(s) = K_p(1 + \frac{1}{T_i s} + T_d S) \quad \textbf{(3)}$$

here K_p is the proportional gain, K_i is the integration coefficient, and K_d is the derivative coefficient. There are three different adjustments (K_p, T_i, and T_d) in such a PID controller in which interacts with each other. To get the best performance according to the design specification of the system, we use the frequency response method by Ziegler-Nichlos to tune these parameters.

2.2 Design Process

A PID controller is designed for a field controlled with fixed armature current DC motor [15]. The transfer function between the output angular displacement of this motor shaft $\theta(t)$ and the input control action $U(t)$ is given as:

$$\frac{\theta(s)}{U(s)} = \frac{K_m}{s(T_f s+1)(T_m s+1)} \tag{4}$$

Here K_m is the constant oh motor gain, T_f is the constant of time of field circuit, and T_m is a time constant of an inertia-friction element. For a PID controller is being designed for a higher order system, we assume the values of variables as $K_m = 1\, rad/vol \cdot second$, $T_f = 0.2\, second$, and T_m = $1\, second$. Equation (4) can be expressed as:

$$G(s) = \frac{\theta(s)}{U(s)} = \frac{5}{s(s+5)(s+1)} \tag{5}$$

The Simulink model of the PID controller and the fixed armature current DC with transfer function G(s) is designed as Figure 2.

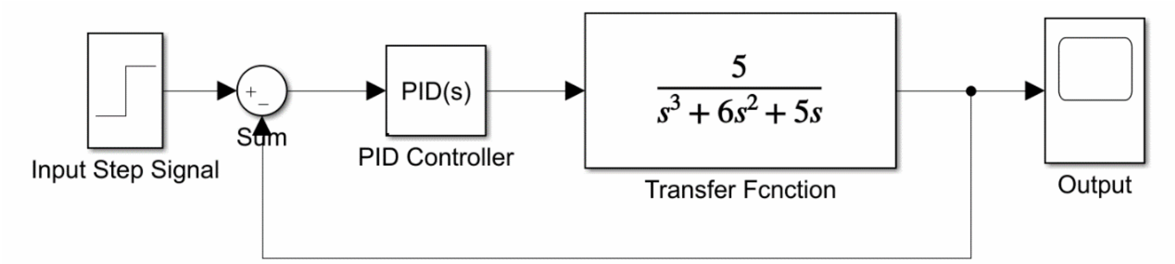


Figure 2. The plant with the designed PID controller

In the consideration of tuning technology, the procedure of the Ziegler-Nichlos frequency response method is adopted to be used here. The process of tuning steps as below:

(a) Let $T_i = \infty$ and $T_d = 0$.

(b) Using only the proportional gain K_p, we adjust the value of K_p from 0 to a critical value (K_u) as the output first exhibits oscillations.

(c) Read the time between peaks is T_u at this setting.

(d) As Table 1 shows, the approximate values for the controller gains can be given from K_u and T_u

Table 1. Ziegler-Nichlos tune method

Controller	K_p	T_i	T_d
P	$0.5K_u$		
PI	$0.45K_u$	$T_u/1.2$	
PID	$0.6K_u$	$T_u/2$	$T_u/8$

2.3 Simulation Process

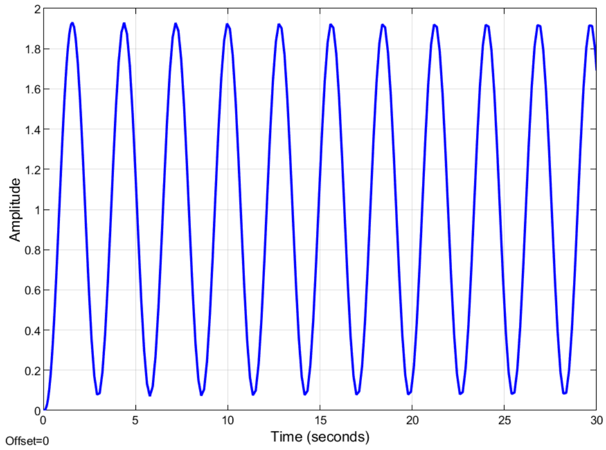
In the process of simulation of the PID controller, we use Matlab/Simulink to simulate the control. By using the Ziegler-Nichlos frequency response method, we set $T_i = \infty$, $T_d = 0$ and gradually increasing the proportional gain K_p until it reaches a stable oscillation as Figure 3 (a). The value of K_u is 5.976. The ultimate period T_u acquired from the time response is 2.817.Form Table 1, we have $K_p = 0.6 * K_u = 3.586$, $K_i = 1.2 * K_u / T_u = 2.564$, and $K_d = 3 * K_u * T_u / 40 = 1.263$. The unit step response of the closed-loop system PID controller with $K_p = 3.586$, $K_i = 2.564$ and $K_d = 1.263$ have investigated as showed in Figure 3 (b). As Figure 3 (b) showed, it is noted the overshoot $M_p = 62.2\%$, rise time $T_r = 0.57 sec$, and settling time $T_s = 9.97 sec$, both M_p and T_s are too large.

With the initial parameters obtained from the Ziegler-Nichlos frequency response method and the tools of MATLAB/ SIMULINK PID tune app, we can automatically tune the gain of a PID controller to achieve robustness and performance. It would specify the response process and have analysis plots to examine the controller performance in time and frequency domains. The unit step response of the closed-loop system with the fine-tuned PID parameters are $K_p = 2.190$, $K_i = 0.317$, and $K_d = 1.862$ is showed below in Figure 3 (c). It is observed that the overshoot is $M_p = 9.7\%$, rise time $T_r = 0.724 sec$ and settling time $T_s = 9.50 sec$. Both M_p and T_s are smaller as compare to the initial values obtained from the Ziegler-Nichlos frequency response method.

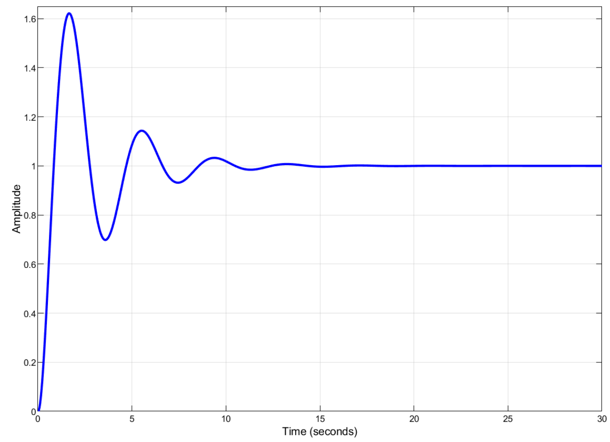
3 Fuzzy Logic Controller

3.1 Description

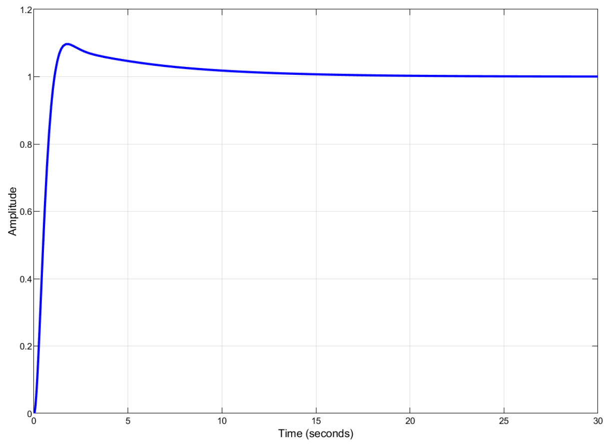
The concept of fuzzy logic was firstly proposed by Zadeh in 1965. Mamdani and his research group had designed a controller with fuzzy variables and fuzzy rules, this controller has successfully simulated reason of human and also achieved better control result [16]. Sugeno has reviewed key points in applying fuzzy control and shows successful results in industrial applications [17]. Fuzzy logic is a control algorithm which is based on a linguistic control strategy. The basic performance of a fuzzy logic control system is depending on good knowledge about the system to be



(a) Step response for $K_p = 5.976$



(b) The step response for $K_p = 3.586$, $K_i = 2.564$, and $K_d = 1.263$



(c) The step response for $K_p = 2.190$, $K_i = 0.317$, and $K_d = 1.862$

Figure 3.

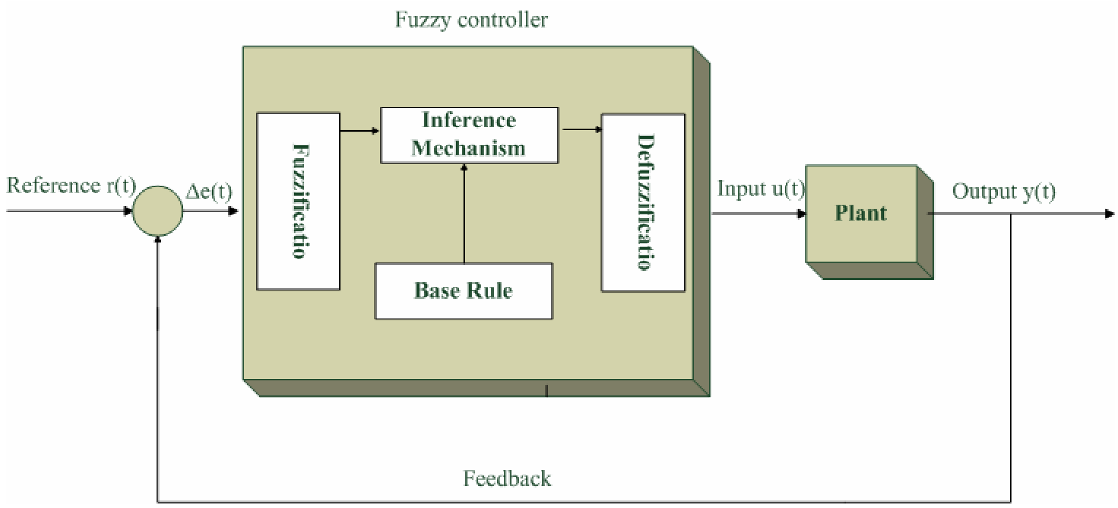


Figure 4. The block diagram of fuzzy controller

controlled, the design of the controller will allow machines more intelligent to think logically in a fuzzy pattern like humans. Fuzzy control can successfully implement control jobs when the system doesn't have a mathematical model, even the system is nonlinear, ill-defined, and complex. The block diagram of fuzzy controller is shown in Figure 4. The fuzzy controller is makeup with the following four modules: fuzzification, inference mechanism, rule base, and defuzzification.

(a) A rule-base holds the knowledge, in the form of a set of rules, of how best to control the system.

(b) An inference mechanism evaluates which control rules are relevant at the current time and then decides what the input to the plant should be.

(c) A fuzzification interface simply modifies the inputs so that they can be interpreted and compared to the rules in the rule-base.

(d) A defuzzification interface converts the conclusions reached by the inference mechanism into the inputs to the plant.

3.2 Design Process

The Simulink model of the fuzzy logic controller with unity feedback is given in Figure 5 for the plant of a fixed armature current DC motor with a transfer function. There are two inputs for the fuzzy logic controller, one is the error (error) and the other one is the rate of change in error (derror). The difference between the reference value and the output is the error. The rate of change in error is the difference between the error at time t and (t-1). The parameter of output is the control variable. We usually use 3, 5, 7, 9, or 11 membership functions for input and output variables in the two inputs fuzzy logic controller [18]. In this paper, 2 membership functions are first employed for the input and output variables. The linguistic variables are named Negative (N) and Positive (P) in membership function as showed in Figure 6 for inputs and output. The type of membership function is a trapezoidal membership function (trapmf).

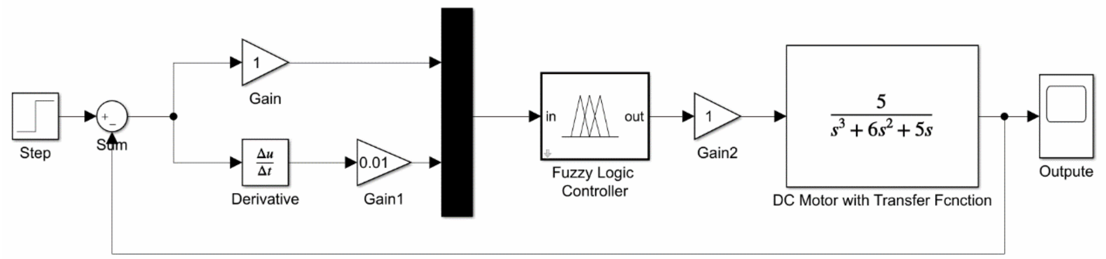


Figure 5. The Plant with fuzzy logic controller

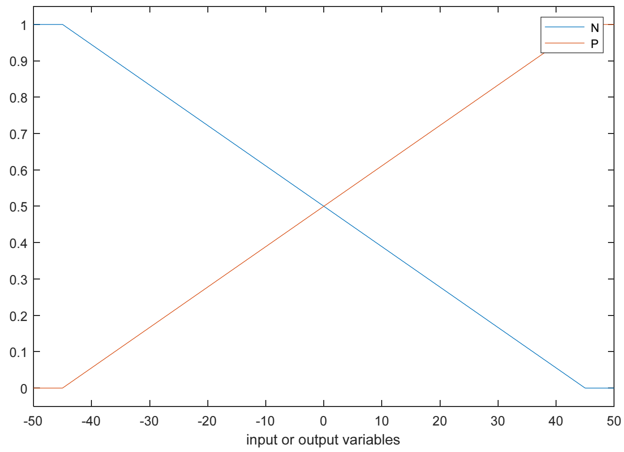


Figure 6. Membership function distributions for input and output variables

After the membership functions have choired for two inputs and one output, then a rule base for a fuzzy logic controller is created. As fuzzy logic controllers are the knowledge base control system, it is the main requirement to know what type of time response is designed for the system. The rule table is showed as in Table 2 where Neg means Negative, Pos means Positive.

Table 2. Rule table for output variable

error/derror	Neg	Pos
Neg	N	N
Pos	P	P

By applying these requirements, a set of linguistic rules has established as enlisted in Table 2. Then fuzzy rules can be expressed with If ... and …. Than …. statements as below

If error is Neg and derror is Neg than output is N

If error is Neg and derror is Pos than output is N

If error is Pos and derror is Neg than output is P

If error is Pos and derror is Pos than output is P

The step response for the fuzzy logic controller for DC motor higher-order transfer function is presented in Figure 7. As the result showed, there is no overshoot $M_p = 0\%$, rise time $T_r = 5.304\,sec$, and settling time $T_s = 7.665\,sec$, the step response of output is a smooth curve and reaches the steady state at 7.665sec.

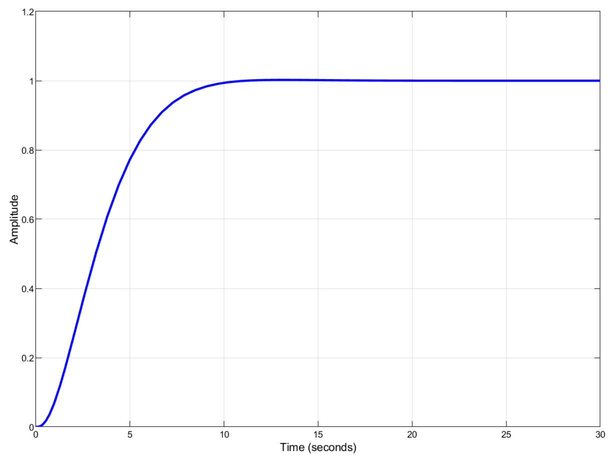
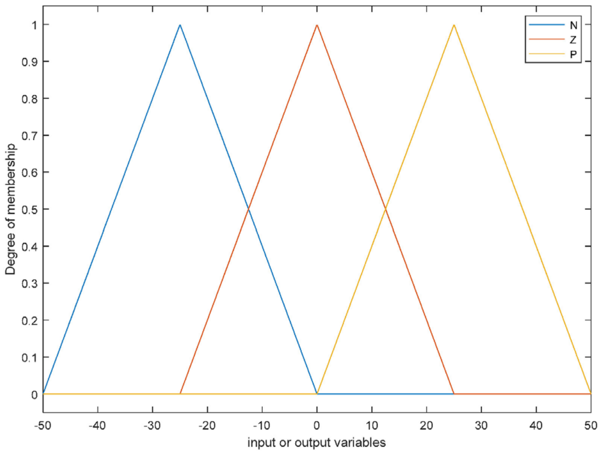


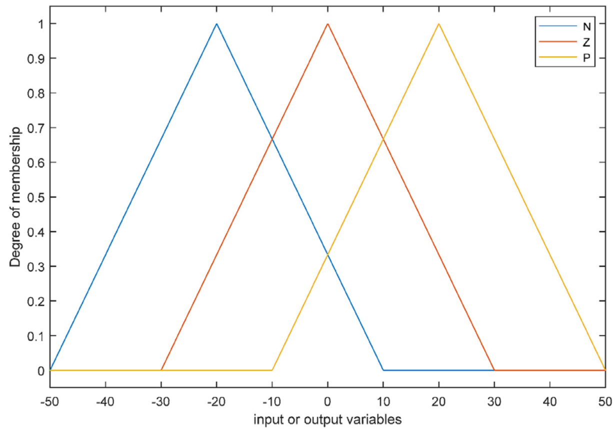
Figure 7. The step response for fuzzy logic controller

3.3 Membership Function

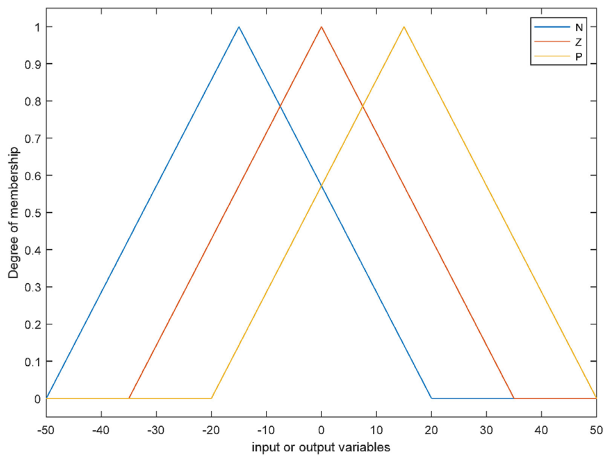
The membership function is used to specify the degree to which a given input belongs to a set. It is used in the fuzzy logic system in the steps of the fuzzification and defuzzification that map the non-fuzzy input values to fuzzy linguistic terms and vice versa. To analyze the affection of the intersection of boundary for the same type of membership function, three kinds of triangular membership functions are used for input and output variables in Figure 8(a), Figure 8(b), and Figure 8(c). All of these three kinds of membership functions have intersected at their boundary in different degrees of an intersection. The rule table for membership functions in Figure 8 is showed in Table 3 for input and output variables, and the step response for FLC for the higher-order transfer function of equation (5) is presented in Figure 9. The overshoot M_p are 0%, 5.5% and 36.5% for kind 1, 2, and 3, the rise time T_r are 9.154sec, 3.134sec, and 1.167sec, the settling time T_s are 13.826sec, 4.490sec, and 7.004sec respectively.



(a) Boundary intersection kind 1 for triangular membership function



(b) Boundary intersection kind 2 for triangular membership function



(c) Boundary intersection kind 3 for triangular membership function

Figure 8.

Table 3. Rule table for output variable

error/derror	Neg	Zeo	Pos
Neg	N	N	Z
Zeo	N	Z	P
Pos	Z	P	P

As mentioned before, the type or number for the input and output variables could be choired by the experience or knowledge. In Figure 10, we have compared three different types of triangular membership function (trimf), trapezoidal membership function (trapmf), and Gaussian membership function (gauessmf) with Table 3 rule table. The step response for the three types of membership functions is shown in Figure 11. As we find from Figure 11, the overshoot

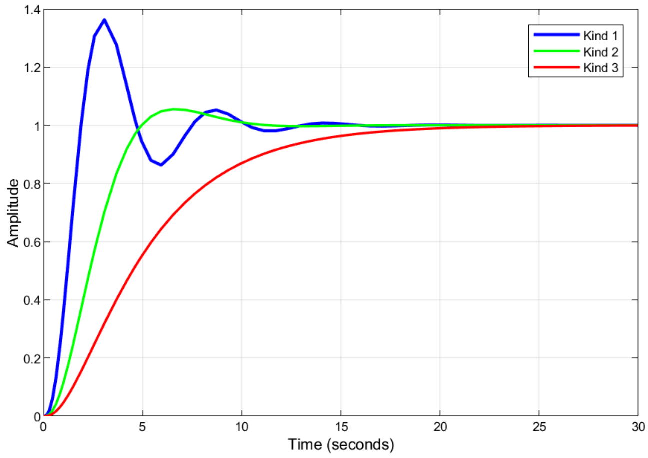
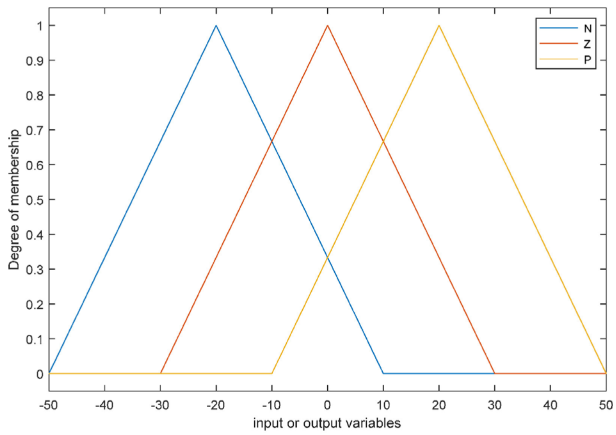


Figure 9. The step response for the three kinds of boundary intersection for triangular membership functions

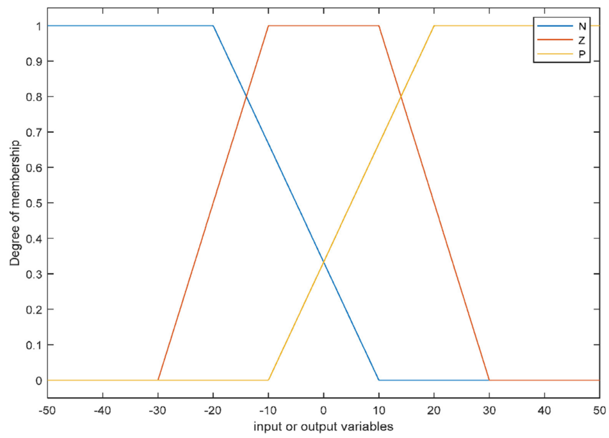
M_p are 5.5%, 11.3%, and 0%, the rise time T_r are 3.134sec, 2.237sec, and 19.085sec, the settling time T_s are 4.490sec, 7.164sec, and 27.051sec, for trimf, trapmf, and gaussmf respectively.

4 Results and Discussion

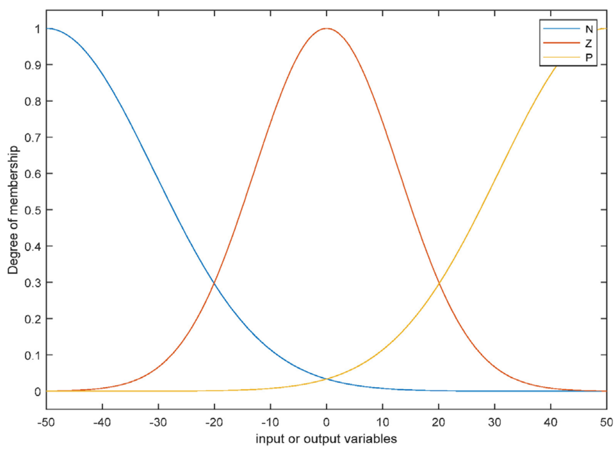
The results of step response simulation for the ZN tuned PID controller (ZNPIDC), fine-turned PID controller (FTPIDC) by MATLAB/SIMULINK and FLC are analyzed and compared in Table 4. The FTPIDC has a small overshoot (M_p) and settling time (T_s) as compared with ZNPIDC. As observed from Figures 3(b) and Figures 3(c), there are shorter rise time and overshoot to PID controllers, hence the performance of FTPIDC is better than the ZNPIDC. A proposed FLC using smaller fuzzy rules and expert knowledge to have effective performance in overshoot and settling time. As shown in Figure 7 and Table 4, there is no overshoot in the step response curve and the setting time is faster than FTPIDC and ZNPIDC. Although the rise time of FLC is slow than FTPIDC and ZNPIDC, however, FLC has better control performance than PID due to its lack of vibration and fast stability.



(a) Triangular membership function (Trimf)



(b) Trapezoidal membership function (Trapmf)



(c) Gaussian membership function (Guassmf)

Figure 10.

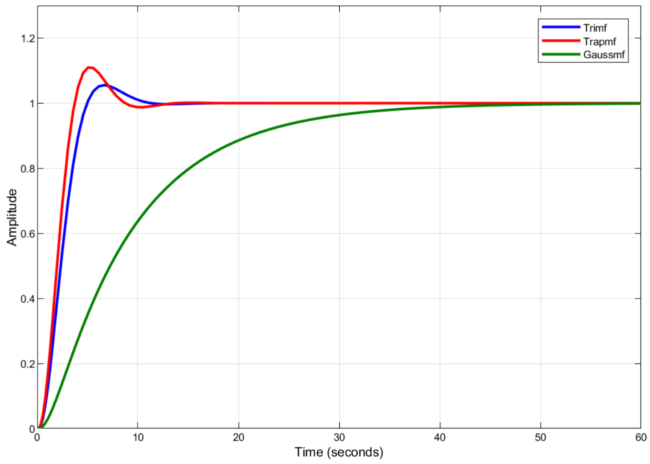


Figure 11. The step response for three different types of membership functions

Table 4. Performance of output responses for PID and FLC controllers

Controller	M_p(%)	T_r(sec)	T_s(sec)
FLC	0	5.304	7.655
FTPIDC	9.7	0.724	9.50
ZNPIDC	62.2	0.570	9.97

The affection of the intersection of membership has analyzed in Figure 9, they are all triangular membership functions, except for different kinds of the intersection at the boundary. From Table 5, the overshoot of kind 1 is 0%, but the rise time and setting time are too slow than kind 2 and 3. The rise time of kind 3 is better than kind 1 and 2, but the settling time and overshoot are higher than kind 2. The performance of kind 2 is better due to its ability to reach a stable state quickly with some overshoot.

Table 5. Performance of output responses for three kinds of triangular membership function in FLC

Triangular membership function	M_p(%)	T_r(sec)	T_s(sec)
Kind 1	0	9.154	13.826
Kind 2	5.5	3.134	4.490
Kind 3	36.5	1.167	7.004

In Figure 11, the performance of different types of membership functions has been simulated with the same rule table. From Table 6, gaussmf has 0% overshoot, but the rise time and settling time are the worst among these three types of the membership function. Although the rise time of trapmf is fast than the other two membership functions, its overshoot is higher than trimf and gaussmf. The control performance of trimf is better than trapmf and gaussmf for its shorter setting time and a litter overshoot. Although the rising time of trimf is greater than trapmf, its overshoot and setting time are better than trapmf, so its control performance is the best among these three membership functions.

Table 6. Performance of output responses for three types of membership function in FLC

Type of membership function	M_p(%)	T_r(sec)	T_s(sec)
Trimf	5.5	3.134	4.490
Trapmf	11.3	2.237	7.164
Gaussmf	0	19.085	27.051

5 Conclusion

This study has investigated the design of PID controller and FLC. Firstly, two membership functions for input and output variables of FLC are compared to two kinds of PID controllers, and it can be observed that the FLC offers a better dynamic and steady response compare to FTPIDC and ZNPIDC. To evaluate the effect of the intersection at the boundary of the membership function for performance. Three kinds of triangular membership functions have been designed to analyze the parameters of overshoot, rise time, and settling time. It is shown that the half intersection of boundary gives better with lesser setting time. Fuzzy logic is defined by membership functions. We propose three types of membership functions to analyze step output responses with the same rule table. The trigonometric membership function has the characteristics of short setting time, immune overshoot, and so on.

By using MATLAB/SIMULINK to design and simulate ZNPIDC, FTPIDC, and FLC in this paper. The output response results are presented and discussed. The results show the overshoot, rise time, settling time, and control performance have been enhanced for using the proposed FLC. Also, three kinds of triangular membership functions and three types of membership functions have evaluated for the output responses. Triangular membership function for FLC in this study case has more benefits, such as smaller fuzzy rules, higher flexibility, simple control, and static performance.

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