IAES International Journal of Artificial Intelligence (IJ-AI)
Vol. 1, No. 1, March 2012, pp. 31~44
ISSN: 2252-8938

Design and Implementation of Fuzzy Position Control System for Tracking Applications and Performance Comparison with Conventional PID

Nader Jamali Sufi Amlashi
Department of Electrical & Computer Engineering, University of Tabriz, Tabriz, Iran
E-mail: Jamali.tabrizu@yahoo.com

Article Info

Article history:

Received Feb 12th, 2012
Revised Mar 10th, 2012
Accepted Mar 24th, 2012

Keyword:

PID controller
Position control system
FLC
DC motors
Non-linear

ABSTRACT

This paper was written to demonstrate importance of a fuzzy logic controller in act over conventional methods with the help of an experimental model. Also, an efficient simulation model for fuzzy logic controlled DC motor drives using Matlab/Simulink is presented. The design and real-time implementation on a microcontroller presented. The scope of this paper is to apply direct digital control technique in position control system. Two types of controller namely PID and fuzzy logic controller will be used to control the output response. The performance of the designed fuzzy and classic PID position controllers for DC motor is compared and investigated. Digital signal Microcontroller ATMega16 is also tested to control the position of DC motor. Finally, the result shows that the fuzzy logic approach has minimum overshoot, and minimum transient and steady state parameters, which shows the more effectiveness and efficiency of FLC than conventional PID model to control the position of the motor. Conventional controllers have poorer performances due to the non-linear features of DC motors like saturation and friction.

Corresponding Author:

Nader Jamali Sufi Amlashi
University of Tabriz, Faculty of Engineering,
Department of Electrical & Computer Engineering, Tabriz, Iran
Email: Jamali.tabrizu@yahoo.com

1. INTRODUCTION

All control systems suffer from problems related to undesirable overshoot, longer settling times and vibrations and stability while going form one state to another state. Realworld systems are nonlinear, accurate modeling is difficult, costly and even impossible in most cases. The conventional digital control systems like classic PID solve the above problems approximately but we need to intelligent and precise control systems to acquiring desired response. It is necessary to know system’s mathematical model or to make some experiments for tuning PID parameters. However, it has been known that conventional PID controllers generally do not work well for non-linear systems, and particularly complex and vague systems that have no precise mathematical models. Moreover these control techniques produce more noise. Therefore, more advanced control techniques need to be used which will minimize the noise effects [1]. To overcome these difficulties, various types of modified conventional PID controllers such as auto-tuning and adaptive PID Controllers were developed lately [2]. There are three basic approaches to intelligent control: knowledge-based expert systems, fuzzy logic, and neural networks. All three approaches are interesting and very promising areas of research and development. In this paper, we present only the fuzzy logic approach. Fuzzy logic, proposed by Lotfi A. Zadeh in 1973. Zadeh introduced the concept of a linguistic variable [3].

Fuzzy Logic is a multivalued logic, that allows intermediate values to be defined between conventional evaluations like true/false, yes/no, high/low and emerged as a tool to deal with uncertain, imprecise, or qualitative decision-making problems. Fuzzy logic is a way to make machines more intelligent to reason in a fuzzy manner like humans. *Fuzzy control* is a control method based on *fuzzy logic*. The controller that use of this approach is called "Fuzzy Logic Controller (FLC)". Just as fuzzy logic can be described simply as "computing with words rather than numbers"; fuzzy control can be described simply as "control with sentences rather than equations"[4]. Fuzzy control successfully accomplish control tasks without knowing the mathematical model of the system , even if it is nonlinear, imprecise and complex. In other word, The fuzzy logic controller does not use mathematical models but mimics the skill and experience of a human operator. Today, fuzzy control applications cover a variety of practical systems, such as the control of cement kilns, train operation, parking control of a car, heat exchanger, robots, and are in many other systems, such as home appliances, video cameras, elevators, aerospace, etc. This paper is organized as follows: The formal framework of the theory of fuzzy sets and fuzzy controllers firstly presented. The Mathematical Modeling of experimental set-up and implement of model in act then studied. In the third part, The Simulink implementation related to two types of controllers is done with MATLAB software. Finally, the PID and fuzzy controllers is compared together.

2. FUZZY CONTROL SYSTEMS

For processes that are difficult to model but have straightforward control rules, fuzzy controllers are easy to design and implement. Moreover it can be noted that the controller design does not requires explicit knowledge of the motor and load characteristics[5]. Since the fuzzy controllers are designed directly from the properties of the process, the development time is often shorter than for conventional controllers [6]. The overall procedure for developing a fuzzy control system for a model DC motor is shown in figure 1**.** The system uses measured variables as inputs to describe the error or change of error from the DC motor. These inputs are then "fuzzified" using membership functions supplied by an expert operator to determine the degree of membership in each input class. The resulting "fuzzy inputs" are evaluated using a linguistic rule base and fuzzy logic operations to yield an appropriate output and an associated degree of membership. This "fuzzy output" is then defuzzified to give a crisp output response that can be applied to the drive motors.

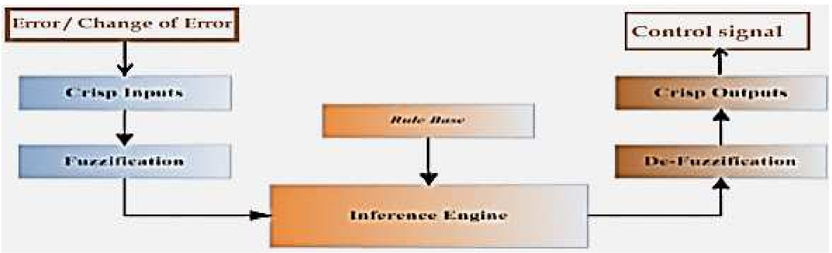


Figure 1. General structure of the fuzzy part

One of the most important problems with fuzzy controller is that the computing time is much more long that for PID, because of the complex operations as fuzzification and particularly defuzzification. Some optimization can be done if the defuzzification method is simplified. It means that it is recommended to avoid center of gravity method. Defuzzification is a mapping from a space of fuzzy control actions defined over an output universe of discourse into a space of non-fuzzy (crisp) control action. For this system, bisector of area (BOA) method is used for defuzzification. The method, finds the abscissa x of the vertical line that partitions the area under the membership function into two areas of equal size. For discrete sets, u_{BOA} is the abscissa x_j that minimizes

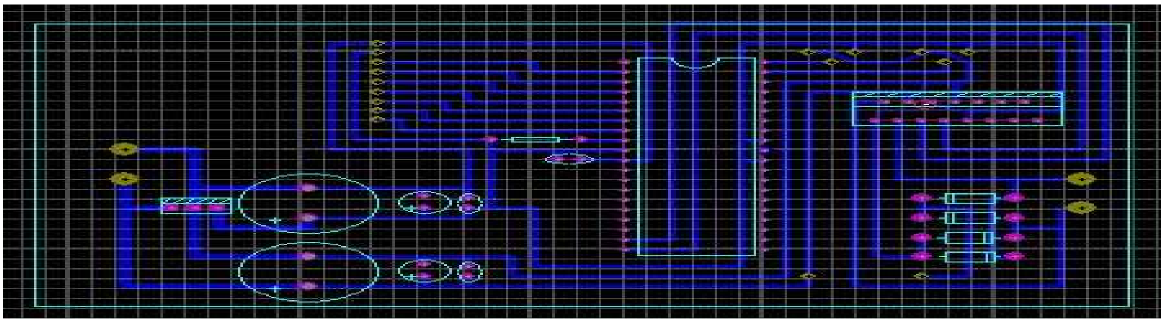
$$\left| \sum_{i=1}^{j} \mu_c(x_i) - \sum_{i=j+1}^{i_{max}} \mu_c(x_i) \right|, \quad i < j < i_{max} \tag{1}$$

Where x_i is a point in the universe $\boldsymbol{U}$ of the conclusion (i = 1,2, . . .), and $\mu_c(x_i)$ it's membership of the resulting conclusion set. Here $i_{\max}$ is the index of the largest abscissa $x_{i\max} \in \boldsymbol{U}$. It's computational complexity is relatively high. There may be several solutions x_j.

3. EXPERIMENTAL SETUP AND MODELING

3.1 Experimental setup

Software is the heart of the system that not only integrates the system components and control operations but define functionality and features using related techniques and methods [7]. Figure 2 shows a photo of Printed Circuit Board (PCB) and experimental set-up of DC motor position control using fuzzy Logic that is implemented in this paper. The total schematic diagram of this system including controller, motor, load, and potentiometer also is shown in Figure 3.



(a)

(b)

Figure 2. Experimental set-up of DC motor position control using fuzzy logic, a. PCB for synthesis section, b. experimental set-up section

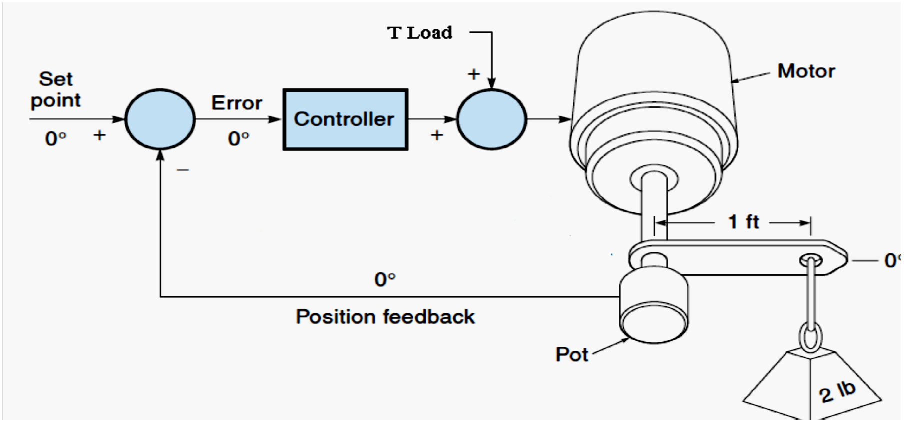


Figure 3. Schematic diagram of this system

3.2 Mathematical Modeling of experimental setup

Figure 4 shows a separately excited DC motor equivalent model

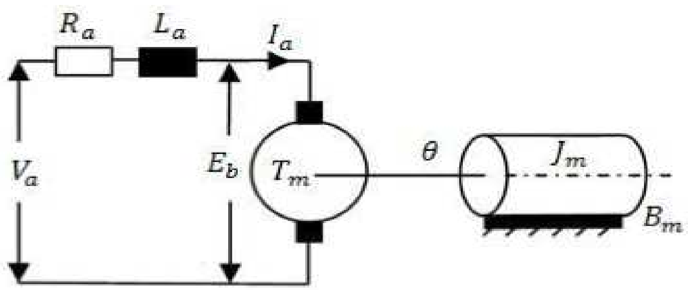


Figure 4. DC motor model

$v_a(t)= R_a .i_a(t)+ L_a . \frac{dia(t)}{dt} + e_b(t)$ (2)

$e_b(t)=K_b .w(t)$ (3)

$T_m(t)=K_T .i_a(t)$ (4)

$T_m(t)=J_m .\frac{dw(t)}{dt} + B_m .w(t)$ (5)

where v_a= armature voltage (v), R_a= armature resistance (Ω), L_a= armature inductance (H), *ia* = armature current (A), E_b= back emf (V), $\omega(t)$= angular speed (rad/s), T_m= motor torque (Nm), Θ = angular position of rotor shaft (rad), J_m = rotor inertia (kgm^2), B_m = viscous friction coefficient (Nms/rad), K_T = torque constant (Nm/A) and K_b = back emf constant (Vs/rad). Eventually, the transfer function between shaft position and armature voltage at no-load is:

$$\frac{\theta(s)}{V_a(s)} = \frac{K_T}{L_a.J_m.s^3 + (R_a.J_m + L_a.B_m).s^2 + (K_T.K_b + R_a.B_m).s} \quad (6)$$

Figure 5 shows the DC motor model built in Simulink. Motor model was converted to a 2-in 2-out subsystem. Input ports are armature voltage (V_a) and load torque (T_{load}) and the output ports are angular speed in (w) and position (teta).

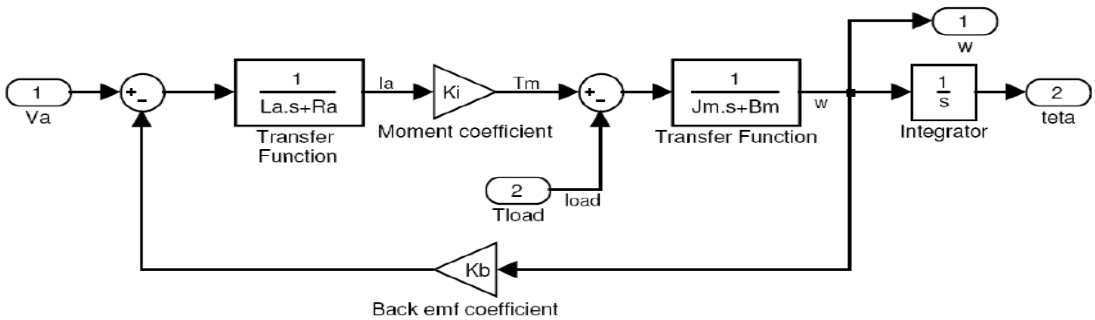


Figure 5. Simulink model

Servo motors are special category of motors, designed for applications involving position control, velocity control and torque control. These motors are special in the following ways:

1. Lower mechanical time constant.
2. Lower electrical time constant.
3. Permanent magnet of high flux density to generate the field.
4. Fail-safe electro-mechanical brakes.

For applications where the load is to be rapidly accelerated or decelerated frequently, the electrical and mechanical time constants of the motor plays an important role. The mechanical time constants in these motors are reduced by reducing the rotor inertia. Table 1 shows the DC motor specification. In this study, a DC motor with the below spesifications was used:

Table 1. DC Motor Specifications

Type	DC Motor
Moment of intertia of the rotor	1e-3
Rated motor voltage	6 V(DC)
Armature inductance	0.01 (H)
Armature resistance	0.005(Ω)
Electromotive force constant	0.22
Back E.M.F. Constant	1.5
Damping ratio	1.91

4. PROPORTIONAL-INTEGRAL-DERIVATIVE (PID) CONTROLLER DESIGN

Figure 6 shows the schematic model of a control system with a PID controller.

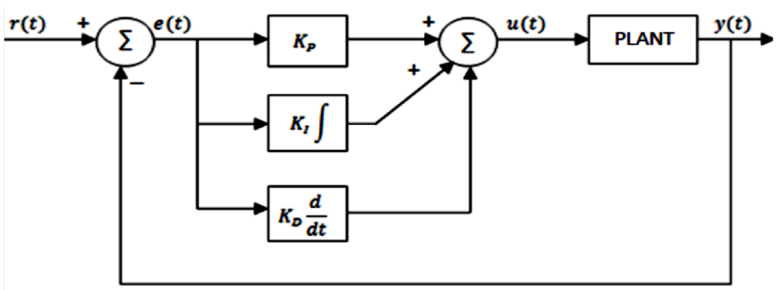


Fig. 6: Schematic model of a PID controller

Control signal u(t) is a linear combination of error e(t) , it's integral and derivative.

$$u(t) = K_P e(t) + K_I \int e(t)dt + K_D \frac{de(t)}{dt} \quad (7)$$

$$u(t) = K_P \left(e(t) + \frac{1}{T_I} \int e(t)dt + T_D \frac{de(t)}{dt} \right) \quad (8)$$

where K_P = proportional gain, K_I = integral gain, K_D = derivate gain, T_I = integral time and T_D = derivate time.

If the controller is digital, then the derivative term may be replaced with a backward difference and the integral term may be replaced with a sum. For a small constant sampling time u(t) can be approximated as:

$$u(n) = K_P \left(e(n) + \frac{1}{T_I} \sum_{j=1}^{n} e(j)T_s + T_D \frac{e(n) - e(n-1)}{T_s} \right) \quad (9)$$

4.1 Tuning PID parameters

PID controllers are usually tuned using hand-tuning or Ziegler-Nichols methods[8]. Hand-tuning is generally used by experienced control engineers based on the rules shown in Table 2. But these rules are not always valid. For example if an integrator exists in the plant, then increasing K_P results in a more stable control.

Table 2. Hand-tunning rules

Operation	Rise Time	Overshoot	Stability
K_P	Faster	Increases	Decreases
T_d	Slower	Decreases	Increases
$1/T_i$	Faster	Increases	Decreases

The disadvantage of this method is that it should take a long time to find the optimal values. Another method to tune PID parameters is Ziegler-Nichols frequency response method. The procedure is as follows:
1. Increase Kp until system response oscillates with a constant amplitude and record that gain value as Ku (ultimate gain)
2. Calculate the oscillation period and record it.
3. Tune parameters using Table 3

Table 3. Zeigler-Nicoles rules

Controller	K_P	T_i	T_d
P	$0.5\,K_u$	……	……..
PI	$0.45\,K_u$	$T_u/1.2$	………
PID	$0.6\,K_u$	$T_u/2$	$T_u/8$

The PID controller model is hand-tuned by first increasing the value of the proportional gain, Kp, until the a desirable response is obtained. The derivative gain Kd and the integral gain Ki, are then adjusted to improve and optimize the response of the system [9]. In this paper, Zeigler-Nichols (Z-N) tuning method is used to find the controller parameters or coefficients of classic PID. The transfer function of classic PID parameters is following:

$$G_C(s)= 8.108\,\frac{1+0.25S}{1+1.9\ S} \qquad (10)$$

4.2 Simulink implementation

Figure 7 shows the PID control system designed in MATLAB/Simulink where controller coefficients were adjusted using (Z-N) tuning method. Also, figure 8 presents a comparison between output response in tunned and unturnned parameters conditions.

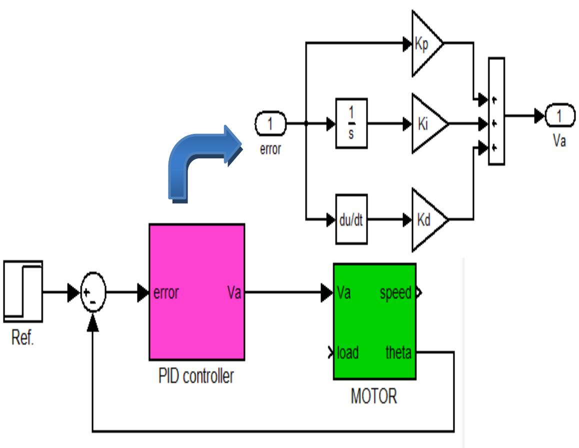


Figure 7. Crisp PID control system

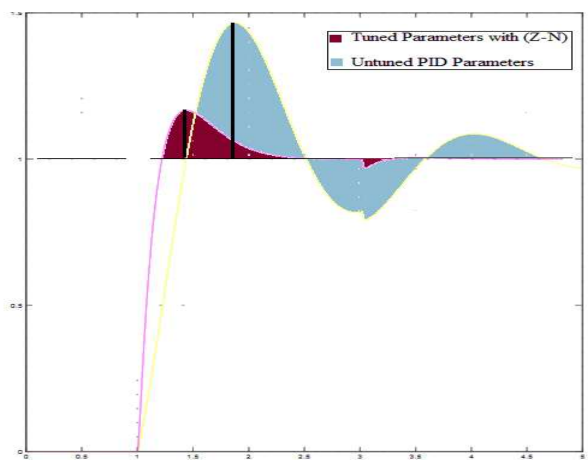


Figure 8. Comparison between output response in tunned and unturnned parameters conditions.

Overshoot is not desired especially in position control systems. Table 4 shows the values of the performance criteria obtained with the adjusted controller parameters.

Table 4. Performance specifications for crisp PD control system.

Variable	Value
T_r	0.641
T_s	5.49
overshoot	12.4%
e	0

5. FUZZY LOGIC CONTROLLER

A fuzzy logic controller has four main components as shown in Figure 1: fuzzification interface, inference mechanism, rule base and defuzzification interface. Implementation of an FLC requires the choice of four key factors [10]: number of fuzzy sets that constitute linguistic variables, mapping of the measurements onto the support sets, control protocol that determines the controller behaviour and shape of membership functions. Thus, FLCs can be tuned not just by adjusting controller parameters but also by changing control rules, membership functions, etc.

Rule base, inference mechanism and defuzzification methods are the sources of nonlinearities in FLCs. But it's possible to construct a rule base with linear input-output characteristics. For an FLC to become a linear controller with a control signal where is "error" and is "change of error", some conditions must be satisfied [11]:

a Support sets of input linguistic variables must be large enough so that input values stay in limits.
b Linguistic values must consist of symmetric triangular fuzzy sets that intercept with neighbouring sets at a membership value of so that for any time instant, membership values add to 1 condition.
c Rule base must consist of combinations of all fuzzy sets.
d Output linguistic variables must consist of singleton fuzzy sets positioned at the sum of the peak positions of input fuzzy sets.
e Should be multiplication and defuzzification method must be "Centre of Gravity" (COG).

5.1 Fuzzy PI+D controller design

MATLAB/Fuzzy Logic Toolbox is used to simulate FLC which can be integrated into simulations with Simulink. The FLC designed through the FIS editor is transferred to Matlab-Workspace by the command "Export to Workspace". Then, Simulink environment provides a direct access to the FLC through the Matlab-Workspace in servomotor drive simulation [12]. We would like to apply a similar analysis to FPD+I control in order to accommodate integral action. Figure 9 shows a FPD controller.

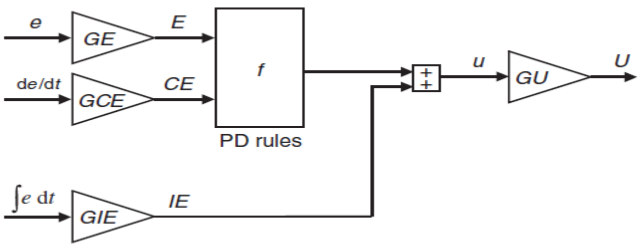


Fig. 9: FPD controller

But the integrator creates problems by increasing the order of the closed loop system, which calls for three-dimensional plots, or multi-dimensional ones in the general case. That will be cumbersome. From an engineer's point of view, it may suffice to give up on completeness and make do with two-dimensional plots. Control signal *U(n)* is a nonlinear function of "error" and "change of error". Thus,

$$U(n) = f\,(\,GE\ \ x\ \ e(n))\,,\,GCE\ \ x\ \dot{e}(n)\,)\ \ x\ \ GU \qquad (11)$$

Where *f* represents the control algoritm. A linear function approximately should be obtained with a suitable choice:

$$f\,(GE\ x\ e(n))\,,\,GCE\ x\ \dot{e}(n))\ x\ GU \approx GE\ x\ e(n))\,,\,GCE\ x\ \dot{e}(n) \qquad (12)$$

Then

$$U(n) = (GE \times e(n)+ GCE \times \dot{e}(n)) \times GU \quad (13)$$

$$U(n) = GE \times GU \times (e(n)+\frac{GCE}{GE} \times \dot{e}(n)) \quad (14)$$

When we compare this equation with the control signal of a crisp PID controller, the relationship between gains of a PID controller and of an fuzzy PD controller is:

$$GE \times GU=K_P \quad and \quad \frac{GCE}{GE} =T_D \quad (15)$$

Consequently, parameter values of a linear FPD controller may be determined from a tunned PID controller. Figure 10 shows the control system with an FPD controller.

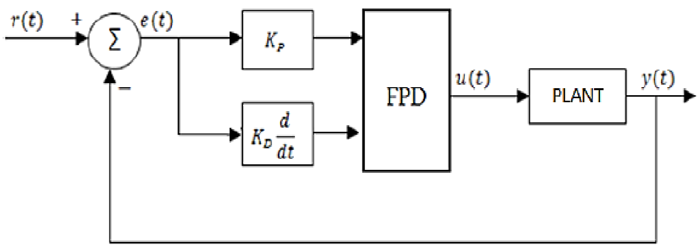
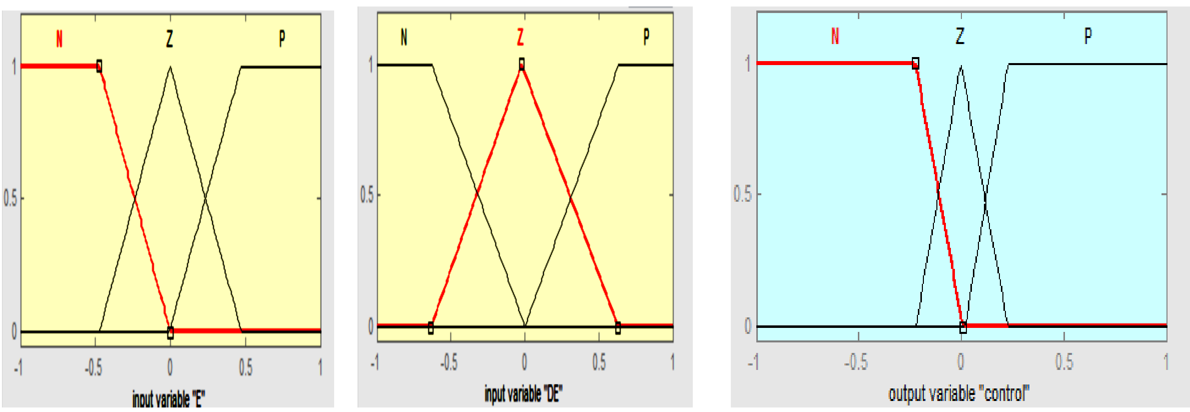


Figure 10. Control system with an FPD controller

5.2 Simulink implementation

Takagi-Sugeno fuzzy inference system can be used to design the fuzzy controller and the membership functions for the inputs and output of variable are shown in figure 11 (a) and (b). In this paper, inputs of FPD are “Error (E)” and “Derivate of Error (DE)” where the output is “control”. Input and output variables of FPD consist of three fuzzy sets namely N (negative), Z (zero), P (positive) as shown in Figure 11 (a) and (b). Table 5 shows the form of the DC motor's fuzzy rules base that used in design of controller.



(a) Fuzzy input variables “error” and “derivate of error”. **(b)** Fuzzy output variable “control”.

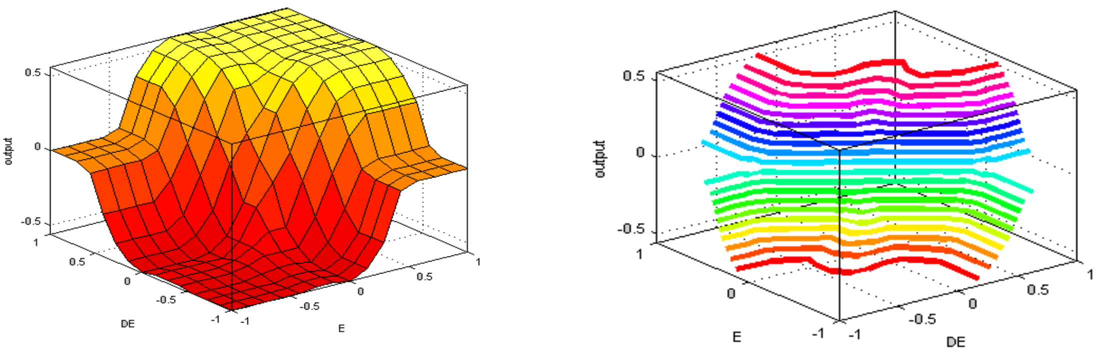
Figure 11. Fuzzy input-output variables.

Control surface and contour of fuzzy controller with considering to fuzzy rules is shown in figure 12 (a) and (b). Figure 13 shows the fuzzy PD control system designed in Simulink.

Table 5. Fuzzy rules

Δe \ e	N	Z	P
N	N	N	Z
Z	N	N	P
P	Z	P	P

\



The control surface and contour of the fuzzy PID controller, (a). control surface, (b). contour fuzzy controller

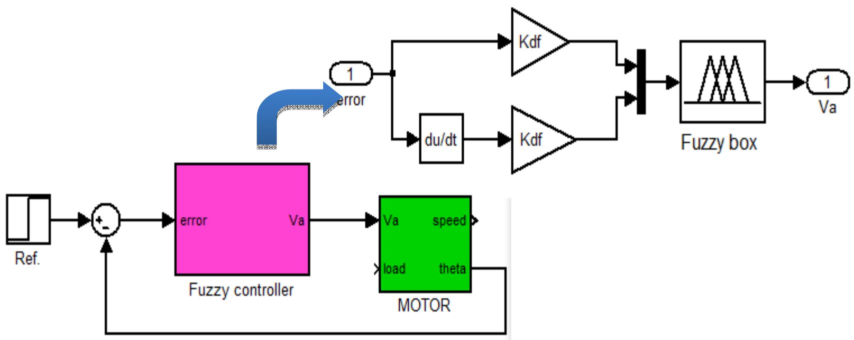
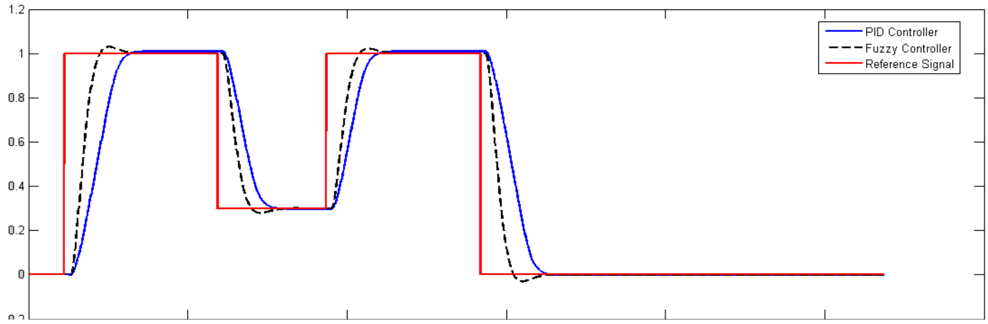


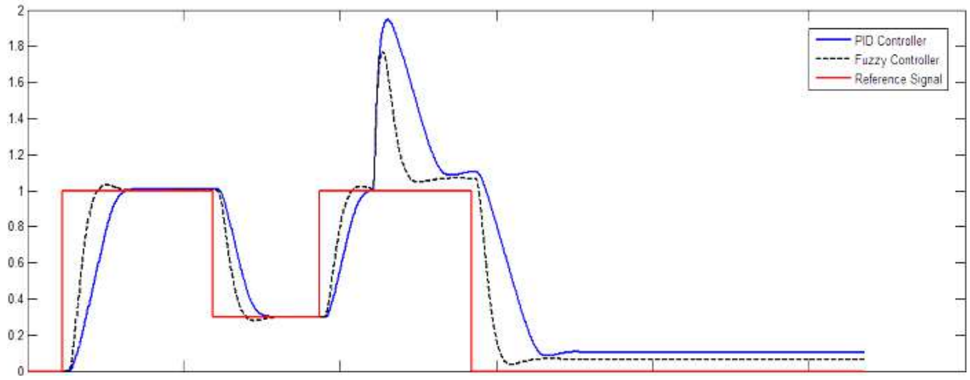
Figure 13. Fuzzy PD control system

6. SIMULATION RESULTS

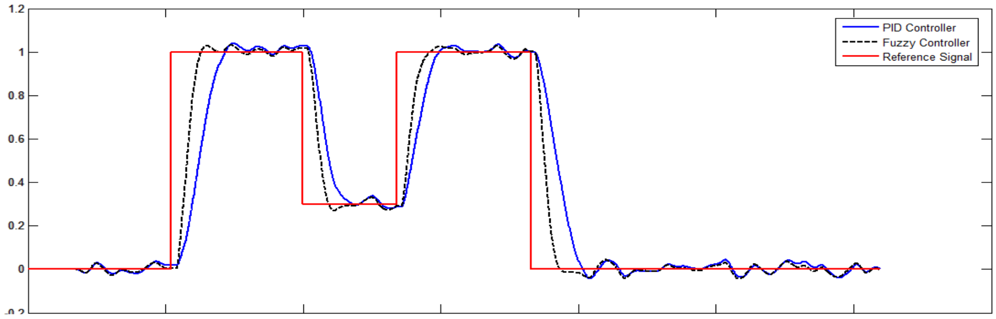
Simulation results show that incorporating the linguistic fuzzy information into controllers clearly results in superior tracking performance. Therefore, the proposed control method provides a tool for making use of the fuzzy information in a systematic and efficient manner. The output response of both the PID and Fuzzy logic were compared. Table (7) and (8) shows the comparison between the output response for the PID and Fuzzy logic controller for main parameters and changed parameters. From the analysis and comparison of both controllers, the FLC performs like PID controller for when we have not any load or changed parameters or noise or disturbance. But, when comparing both of these controllers with considering injection load or changed parameters or noise or disturbance, the fuzzy logic controller performs better. Response output for all controllers with and without considering injection external load, step changes and noise was shown in figures (14) and (15).



(a) Output response without load



(b) Output response for step changes of load



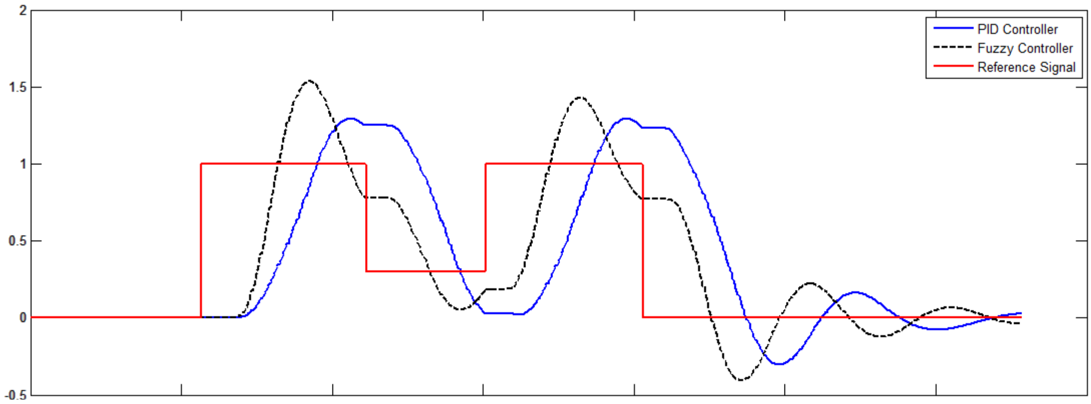
(c) Output response for Gaussian noise

Figure 14. Output response for two controllers with considering applied different loads .(a) without load. (b) step changes of load. (c) Gaussian noise instead of load.

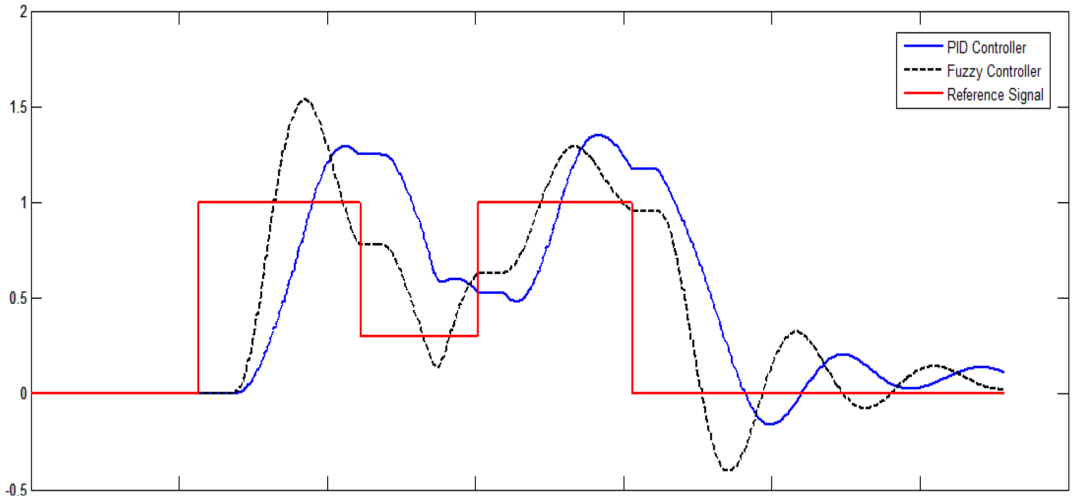
When we have a imprecise model of our plant or even if exist mistakes in modeling, simulation results show that the fuzzy logic controller in terms of performance is better than conventional PID. In other word, in the test, we intentionally make a imprecise modelling of DC motor with false parameters to study the behavior of these two types of controller in this conditions: As an illustration to substantiate the applicability of this approach, the following test manipulated parameters have been chosen according to Table 6.

Table 6. Test manipulated parameters

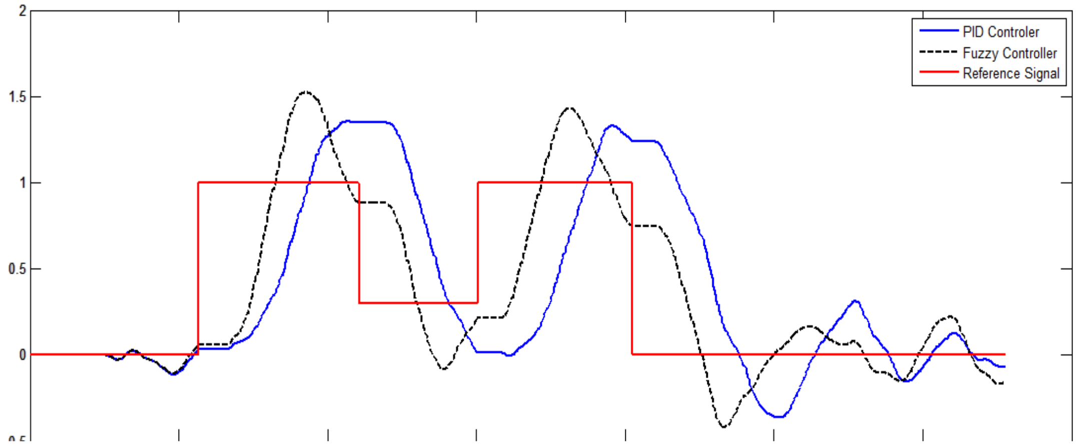
Type	DC Motor
Moment of intertia of the rotor	1e-1
Rated motor voltage	6 V(DC)
Armature inductance	0.1 (H)
Armature resistance	0.05(Ω)
Electromotive force constant	0.22
Back E.M.F. Constant	1.5
Damping ratio of the mechanical system	10.91



(a) Output response without load



(b) Output response for step changes of load



(c) Output response for Gaussian noise

Figure 15. Output response for two controllers with considering applied different loads .(a) without load. (b) step changes of load. (c) Gaussian noise instead of load.

Table 7. comparison between the output response for all controllers

Comparison	PID Controller			Fuzzy Controller		
	T_r	T_s	OS(%)	T_r	T_s	OS(%)
No load	2.87	5.49	4	2.76	5.57	15.43
Step Changes	3.42	6.34	4.67	3.12	6.28	12.2
Noise	8.65	none	18.7	4.36	7.48	16.3

Table 8. comparison between the output response for all controllers for changed parameter

Comparison	PID Controller			Fuzzy Controller		
	T_r	T_s	OS(%)	T_r	T_s	OS(%)
Step Changes	14.4	none	46.5	11.3	none	52.2
Noise	20.6	none	56.78	14.6	none	66.33

6. CONCLUSIONS

Fuzzy controllers have the advantage that can deal with nonlinear systems and use the human operator knowledge. Here we test it with a linear system of second order with known parameters. In order to compare it with one classical controller we simulated the same system controlled by PID. The fuzzy controlled system is very sensitive to the distribution of membership functions but not to the shape of membership functions. Fuzzy controlled system doesn‘t have much better characteristics in time domain than PID controlled system, but its advantage is that it can deal with nonlinear systems.

PID controller can not be applied with the systems which have a fast change of parameters, because it would require the change of PID constants in the time. It is necessary to further study the possible combination of PID and fuzzy controller. It means that the system can be well controlled by PID which is supervised by a fuzzy system . Fuzzy logic controllers are relatively new and use a completely different approach than traditional controllers. Fuzzy logic controllers are not based on a mathematical model of the system but instead implement the same control rules that a skilled human operator would. Fundamental in the concept of fuzzy logic is the recognition that rules and conditions come in degrees, as specified in linguistic terms, for example, negative, zero, and positive.

7. CLOSING THOUGHTS

It seems certain that fuzzy logic controllers will be used in more and more products and systems. On the consumer side, they are already being used in automobiles, camera focusing, air conditioners, and microwave ovens, to name a few. For industrial systems, they are being used in process control for temperature and flow control, and servomechanism for speed control and helicopter autopilots. Also, fuzzy logic controllers are being used in conjunction with traditional PID controllers, where the job of the fuzzy controller is to adapt the PID parameters to changing conditions. In many cases, the fuzzy controller is a traditional microcontroller, such as the Intel 8051 or Motorola 68HC11 or AVR, which has been programmed to implement fuzzy logic. Also, new fuzzy logic control ICs that are designed specifically for this application are becoming available. In practice, utilities may use conventional controllers such as automatic voltage regulator (CAVR), Power System Stabilizers (CPSS) or fuzzy logic based controllers like automatic voltage regulator (FLAVR), conventional fuzzy logic based power system stabilizer (FLPSS) [13].

A final word: Although fuzzy logic controllers have repeatedly performed better than their traditional control system counterparts, these improvements do not come without effort. Finding the right rule set and specifying the nature and range of the fuzzy variables can be very time-consuming. Arriving at the right set of inputs for the subway train in Sendai took engineers months of tuning.

ACKNOWLEDGEMENTS

The author would like to express his sincere thanks to Mr Lotfi A. Zadeh , professor for computer science at the University of California in Berkeley for his truly's services and valuable works to sciencific social.

REFERENCES

[1] Vikas S. Wadnerkar, Mithun M. Bhaskar, Tulasi Ram Das and A.D. RajKumar, "*A New Fuzzy Logic based Modeling and Simulation of a Switched Reluctance Motor*", Journal of Electrical Engineering & Technology Vol. 5, No. 2, pp. 276~281, 2010.

[2] Y. heidari, A. R. Noee, H. Ali Shayanfar,S. Salehi, "Robust Control of DC Motor Using Fuzzy Sliding Mode Control with Fractional PID Compensator", TJMCS, Vol .1 No.4 (2010) pp.238-246 .

[3] Zadeh L. A., "*Outline of a New Approach to the Analysis of Complex Systems and Decision Processes*", *IEEE* Transactions Systems, Man and Cybernetics, SMC-3, 1973, pp. 28-44.

[4] Essam Natsheh and Khalid A. Buragga, "*Comparison between Conventional and Fuzzy Logic PID Controllers for Controlling DC Motors*", International Journal of Computer Science Issues, Vol. 7, pp. 128-134 ,Issue 5, September 2010.

[5] N.Senthil Kumar, C.Senthil Kumar, "*Design and Implementation of Adaptive Fuzzy Controller for Speed Control of Brushless DC Motors*", International Journal of Computer Applications, Volume 1-No.27*, pp. 36-41, 2010*.

[6] Pérez Claudia,Strefezza Miguel, "*Speed Control of a DC Motor by Using Fuzzy Variable Structure Controller*", Proceedings of the 27th Chinese Control Conference, July 16-18, 2008, pp. 311-315.

[7] Roop Pahuja, H.K Verma, and Moin Uddin, "*Design and Implementation of Fuzzy Temperature Control System for WSN Applications*," IJCSNS International Journal of Computer Science and Network Security, VOL.11 No.2, February 2011.

[8] Ziegler J and Nichols, "*Optimum settings for automatic controllers*". Transactions of the American Society of Mechanical Engineers (ASME) 64, 759–768.

[9] Sheroz Khan, Salami Femi Abdulazeez, Lawal Wahab Adetunji, AHM Zahirul Alam, Momoh Jimoh E. Salami, Shihab Ahmed Hameed, Aisha Hasan Abdalla and Mohd Rafiqul Islam, "*Design and Implementation of an Optimal Fuzzy Logic Controller Using Genetic Algorithm*", Journal of Computer Science 4 (10): 799-806, 2008, pp. 799-806.

[10] Mamdani, E. H., "Application of Fuzzy Logic to Approximate Reasoning Using Linguistic Synthesis". *IEEE* Transactions on Computers, 26 (12), pp. 1182-1191, 1977.

[11] Jantzen, J., Foundations of Fuzzy Control, WS: John Wiley & Sons, Ltd., 2007.

[12] Mehmet Cunkas and, Omer Aydoğdu, "*Realization of Fuzzy Logic Controlled Brushless DC Motor Drives Using Matlab/Simulink*", Mathematical and Computational Applications, Vol. 15, No. 2, pp. 218-229, 2010.

[13] K. Prasertwong and, N. Mithulananthan, " Conventional and Fuzzy Logic Controllers at Generator Location for Low Frequency Oscillation Damping", International Journal of Electrical and Electronics Engineering, (2009) pp. 656-664.