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IMPLEMENTATION OF NONLINEAR FUZZY LOGIC FRACTIONAL ORDER PID CONTROLLER (NFL-FOPID) WITH FIRST ORDER TRANSFER FUNCTION

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Abstract
Today, the requirement of controllers in the field of engineering and process industries is going to be increased in order to control. Among all controllers, Proportional Integral Derivative (PID) controllers are widely used due to its easy implementation. The practical system is composed by the combination of sub-systems which exhibits the nonlinear behavior and conventional PID controllers are not so successful from stability point of view. In order to control those systems, in this paper, the Fractional Order PID (FOPID) controller has been used effectively instead of conventional PID controllers for those system which show the nonlinear behavior. Further, the control ability of the FOPID controller for the nonlinear environment has also been enhanced using Fuzzy Logic Control (FLC) concept with FOPID. Use of FLC concept with FOPID for nonlinear system has been abbreviated as NFL-FOPID (Nonlinear Fuzzy Logic- Fractional Order PID). Analysis and results verify that the proposed controller improves the efficiency as well as the stability of system.

Keywords:
PID Controller, Nonlinear, Fuzzy Logic Controller

1. INTRODUCTION

Despite the development of various modern or post-modern control theories, such as LQG or LQR, optimal control, control analysis and synthesis, classical proportional-plus-integral (PI) or proportional-plus-integral-derivative (PID) controllers. Because of the relatively simple structure, the industry is being widely used, hand-drawn implementation and perhaps easy understanding [1]. Therefore, it is often a matter of fact that PID controllers are considered for the first time in practical applications, unless the evidence shows that they are insufficient to meet the specifications. Due to the popularity of PID controllers in the real world, several methods have been developed to determine the parameters of PID controllers. In the early days of the 1940s, Ziegler and Nichols proposed the first systematic tuning method for PID parameters, then Cohen-Koon method, integral full error (IAE) optimal method, integral time-weighted full error (ITAE) Optimal method came in popular forms such as internal model control (IMC) method and relay auto-tuning method [2]. It was announced that all previous tuning methods were only suitable for linear systems and introduced a fuzzy modeling approach for non-linear characters, but some articles have presented a strong self-tuning PID controllers for non-static systems [3] - [5]. Control theory has been used for addressing the navigation and control of the unmanned aerial vehicle (UAVs). Globally several researches have focused their work on the design of the flight control systems for UAVs [5]. Fractional Order system is Partial order system which characterized by partial-order differential equations. Fractional calculus considers a real number for derivatives and unipairs. FOPID controller is an extension of traditional integer-order PID controller based on fractional calculus [6].

Fractional Order PID (FOPID) Controller is linear and especially symmetric; and has difficulties in the presence of non-linearity. To solve this problem using a fractional-order PID controller. A FOPID controller is presented below [2]:

$$G(s) = K_p + \frac{K_I}{S^\alpha} + K_D S^\beta = \frac{K_p S^\beta + K_I + K_D S^\alpha S^\beta}{S^\alpha} \tag{1}$$

There are several ways to calculate partial order and calculate a partial order PID controller [3] [4].

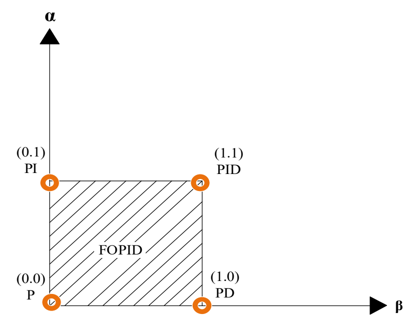

Fig.1. Generalization of the FOPID controller: from point to plane

Fractional Calculus is a branch of mathematics that is related to the actual number of differential or integral operator. It generalizes the general concepts of derivative and integral. In all the different definitions, the definition offered by the room and level is the most common. The definition is as follows [1]:

$$ {}_cD_x^{-n} f(x) = \int_c^x \frac{(x-t)^{n-1}}{(n-1)!} f(t)\,dt, n \in \Re \tag{2}$$

The general definition of D(derivative) is given by Eq.(2):

$$ {}_cD_x^{\upsilon} f(x) = \begin{cases} \int_c^x \frac{(x-t)^{-\upsilon-1}}{\Gamma(-\upsilon)} f(t)\,dt & if\ \upsilon < 0 \\ f(x) & if\ \upsilon = 0 \\ D^n\left[{}_cD_x^{\upsilon-n} f(x)\right] & if\ \upsilon > 0 \end{cases} \tag{3}$$

$$n = \min\{K \in \Re, K > \upsilon\}$$

where n is the well-known Euler's gamma function.

$$\text{Function } F(s) = s^\upsilon \tag{4}$$

The Function in Eq.(4) is not just a simple partial order transfer function which can be seen, but it is also very important for applications, as it will be seen later, we analyze our timing and frequency response.

1.1 TIME RESPONSE

The derivatives of the exponential function are given by,

$$ {}_cD_x^{\upsilon} t^{e^{at}} = E_t\left(-v,a\right), t > 0 \tag{5}$$

For negative orders, from definition Eq.(3) we have:

$$ {}_cD_t^{-\upsilon} e^{at} = \frac{1}{\Gamma(\upsilon)} \int_0^t \left(t-\xi\right)^{v-1} e^{a\xi} d\xi, \upsilon \in \Re^+ \tag{6}$$

By means of the substitution $x = t - \xi$, in the first place, and of the substitution $ax = y$, in the second place, we obtain [8] [9]

$$\begin{aligned} {}_cD_t^{-\upsilon} e^{at} &= \frac{1}{\Gamma(\upsilon)} \int_t^0 x^{v-1} e^{a(t-x)} dx \\ &= \frac{e^{at}}{\Gamma(\upsilon)} \int_t^0 x^{v-1} e^{-ax} dx \\ &= \frac{e^{at}}{\Gamma(\upsilon)} \int_0^{at} \left(\frac{y}{a}\right)^{v-1} e^{-y} \frac{dy}{a} \\ &= \frac{e^{at}}{\Gamma(\upsilon) a^{v}} \int_0^{at} y^{v-1} e^{-y} dy \\ &= E_t\left(\upsilon, a\right) \end{aligned} \tag{7}$$

For positive orders, the same definition gives [10] [12]:

$$\begin{aligned} {}_cD_t^{-\upsilon} e^{at} &= D^n o D_t^{\upsilon-n} e^{at} \\ &= \frac{d^n}{dt^n} E_t\left(n-\upsilon, a\right) \\ &= E_t\left(-\upsilon, a\right), \upsilon \in \Re^+ \wedge n \\ &= \min\left\{k \in N : k > \upsilon\right\} \end{aligned}$$

If $\upsilon = 0$, we have:

$$ E_t\left(0,a\right) = \sum_{k=0}^{+x} \frac{\left(at\right)^k}{\Gamma\left(k+1\right)} \tag{8}$$

which is the series development of e^{at}. Finally, the Laplace transform of E_t is [11]-[15]:

$$ \ell\left[E_t\left(\upsilon,a\right)\right] = \frac{1}{s^{\upsilon}\left(s-a\right)} \tag{9}$$

The Convolution theorem:

$$ \ell\left[\int_0^t f\left(t-\tau\right) g\left(\tau\right) d\tau\right] = \ell\left[f\left(t\right)\right]\ell\left[g\left(t\right)\right] \tag{10}$$

For negative orders, applying the convolution theorem Eq.(10) and Eq.(9) we obtain

$$ \ell\left[E_t\left(\upsilon,a\right)\right] = \frac{1}{\Gamma(\upsilon)} \ell\left[t^{\upsilon-1}\right]\ell\left[e^{at}\right] = \frac{1}{s^{\upsilon}\left(s-a\right)} \tag{11}$$

For positive orders, applying the Laplace transform and we have:

$$\begin{aligned} \ell\left[E_t\left(-\upsilon,a\right)\right] &= \ell\left[\frac{d^n}{dt^n} E_t\left(n-\upsilon,a\right)\right] \\ &= \frac{s^n}{s^{n-\upsilon}\left(s-a\right)} \\ &= \frac{1}{s^{-\upsilon}\left(s-a\right)} \end{aligned} \tag{12}$$

and when $\upsilon = 0$, we find [17] - [20]:

$$\begin{aligned} \ell\left[E_t\left(0,a\right)\right] &= \ell\left[e^{at}\right] \\ &= \frac{1}{s-a} \end{aligned} \tag{13}$$

Partial order derivatives and integral estimates have many different approaches to making such assumptions, but unfortunately it is not possible to say that one of these is the best, because in relation some characteristics are better than other characteristics, the relative qualities are based on the order of approximation discrimination.

Estimates are available in both S-domains and z-domains. In the past, now the frequency domain will be called constant estimates or estimates; Estimates of these estimated methods, discrete estimates, or partial sequence derivatives and integral in the field of time [7].

Between the integer high order periods, the integer dimension, the fractional amplitude, the Fractional Order Calculus (FOC) between the integer order spline, between the "partial order splices" between logic and fuzzy logic, there are non-integers between integers. FOC has created mathematical branches which work with discrimination and integration under the arbitrary order of operation, that is, there can be any real or complex numbers, not just an integer. Although contemporary theoretical research and its great results in real-world applications have been widely discussed relatively recently, the idea of non-integer derivation was first mentioned in the research of Lebanese in hospital in 1695 [10]. Later, the major works related to the FOC extend into personalities such as Euler, Fourier, Abel, Jewell or Riemann. Absence of simple geometric interpretation, absence of solution methods for partial order, *R* differential equation and most problems, the adequacy of the Integer Order Calculus (IOC) is visible, however, the situation is getting better now a days and FOC provides efficient equipment for many issues related to the fractional dimension, "eternal memory", chaotic behavior etc. In this way, FOCs are already available in engineering fields such as Bioengineering, Viscoelastic, Electronics, Robotics, Control Theory and Signal Processing [16]-[18].

2. PID CONTROLLER

A closed loop control system with controller has been shown in Fig.2 in which $r(t)$ is the reference signal in time domain, $e(t)$ is the error signal, $u(t)$ is the controller's output or actuating signal, $c(t)$ is the controlled variable or actual output.

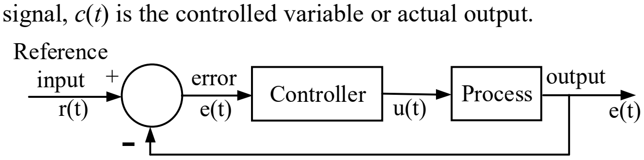

Fig.2. Closed loop system with single input and single output

The controller may be any type such as: PI, I, PI, PD, PID, FOPID, IDD, PIDD and many more. But among all controllers, PID controller is most widely applicable controllers in industries. The output of PID Controller $u(t)$ can be expressed in terms of $e(t)$; error signal as [9]:

$$u(t) = K_p \left[e(t) + \tau_d \frac{de(t)}{dt} + \frac{1}{\tau_i} \int_0^t e(\tau) d\tau \right] \tag{14}$$

The transfer function of the controller is given as:

$$C(s) = K_p \left(1 + \tau_d s + \frac{1}{\tau_i s} \right) \tag{15}$$

where, K_p = Proportional Gain, τ_d = Derivative Time, and τ_i = Integral Time.

For the sake of simplicity, the first order transfer function of the plant without delay in Fig.2 is defined as [17]:

$$P(s) = \frac{K}{1+\tau s} \tag{16}$$

The effect of K_P, K_I and K_D on the time response parameters, steady state error and stability have been shown in Table.1 [12]. In Table.1, the abbreviations are as follow: *RT* = Rise Time, *ST* = Settling Time and *SSE* = Steady State Error.

Table.1. Effect of K_P, K_I and K_D on the time response parameters, steady state error and stability

	RT	Overshoot	ST	SSE	Stability
Increase in K_P	Decrease	Increase	Small Increase	Decrease	Degrade
Increase in K_I	Small Decrease	Increase	Increase	Large Decrease	Degrade
Increase in K_D	Small Decrease	Decrease	Decrease	Minor Change	Improve

$$C(s) = K_p \left(1 + \tau_d s + \frac{1}{\tau_i s} \right) \tag{17}$$

An operator has to tune the parameters of PID controllers finely in order to achieve the enhance performance of the system otherwise it may cause instability in closed loop systems. The advantages and limitations of PID controller are given in Table.2.

Table.2. Advantage of different parameters of PID controller

Parameters	Advantages	Limitations
K_P	Adjustment of Controller output	May cause instability
K_I	Produces zero steady state error	Slow dynamic Response and Instability
K_D	Provides rapid system response	Sensitive to Noise and non-zero offset

3. FUZZY LOGIC CONTROLLER FOR PID

Apart from the freedom provided at partial rate of error in the design of traditional FLC-based PID controllers in the current study, it is logical that partial rate of error introduces some additional flexibility in PLC's input variable and is given input. The output scaling factor, such as the FLC, can also be increased in the size and membership function (MF) size. To prevent advanced loop performance, the better performance of the proposed Fuzzy FOPID controller is tested in comparison to classical PID, Fuzzy PID and FOPID. Controller in current study.

3.1 FUZZY FRACTIONAL ORDER CONTROLLER

Here the structure of fuzzy PID is a combination of Fuzzy PI and Fuzzy PD controllers (Fig.3). Fuzzy PID controller in integer order, error and error in the input are derived and the FLC output is multiplied by scaling factor and its integral unit multiplies with *B* and then the total controller is expressed to give output is. But in the current case, the FLC is replaced by the integer sequence rate of error on the input of its partial order equivalent (μ). In addition, the sequence of integral is replaced by a partial order (λ) on the output of the FLC, which represents a partial order conference (integration) of the FLC output [6].

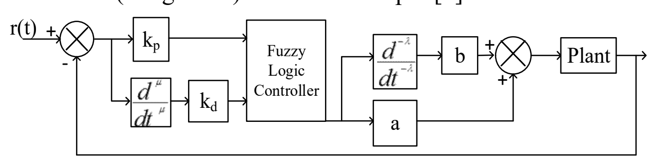

Fig.3. Structure of the Fuzzy Fractional Order PID controller

3.2 FUZZY MEMBERSHIP FUNCTION AND RULE BASE

The proposed FLC based FOPID controller uses two-dimensional linear rule base (Table.3) for error, and partial rate of change of error and FLC output and mammary type infringing with standard triangular membership functions [8]. Triangular membership work is chosen from other types such as Gaussian, trapezoidal, bell shaped, P-shaped etc. Because it is easy to implement in practical hardware. In Fig.4, fuzzy linguistic variables with NB, NS, Z, PS, and PB range Negative large, negative, small, zero, positive, small and positive respectively represent larger. The FLC output is determined by using the center of the gravitational method.

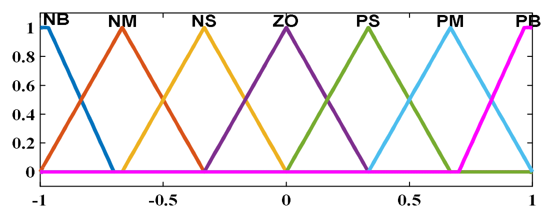

Fig.4. Membership functions for error, fractional rate of error and FLC output

Table.3. Rule base

DE \ E	NB	NS	Z	PS	PB
NB			NB	NS	
NS		NB	NS	Z	
Z	NB	NS	Z	PS	PB
PS		Z	PS	PB	
PB		PS			

4. MODELLING OF PROPOSED SYSTEM

The proposed system is designed MALAB or Simulink and programming. Initially, the proposed system is validated using programming output waveforms for different parameters of P-I-D through comparison.

The Eq.(19) corresponds in time domain to the fractional differential equation of the form [9]:

$$u(t) = K_P e(t) + T_i\, {}_0D_t^{-\lambda} e(t) + T_d\, {}_0D_t^{\delta} e(t) \tag{19}$$

where, λ =1 and δ =1 for obtaining a classical PID controller.

After the traditional structure of non-linear PID controller, well known in literature, it can write a new formula for non-linear Fractional order $PI^{\lambda}D^{\delta}$ Controller (NFOC):

$$u(t) = f(e)\left[K_P e(t) + T_i\, {}_0D_t^{-\lambda} e(t) + T_d\, {}_0D_t^{\delta} e(t)\right] \tag{20}$$

where $f(e)$ is nonlinear function of variable e. various definitions of the nonlinear function $f(e)$ can be used, for instance [10]:

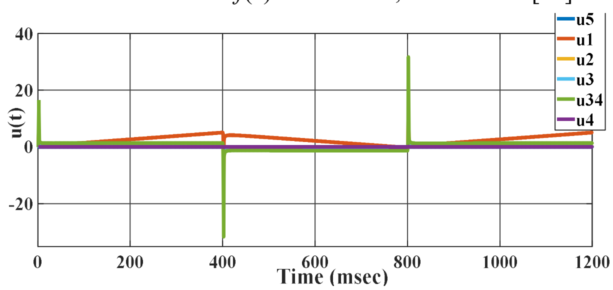

Fig.5. Output analysis of non-linear PID controller with parameters from Table.4

A widely used nonlinear function can have the form:

$$f(e) = K_0 + (1-K_0)|e(t)|,\ K_0 \in \langle 0,1\rangle \tag{21}$$

When K_0 =1 in Eq.(21) obtain a classical form of the linear fractional-order controller Eq.(19). For K_0=1 we have a 6 degrees of freedom controller.

For K_0 = 0 within interval (e_l, e_h) the output of the controller does not change and therefore the actuator behavior is much more smooth. The Eq.(19) and Eq.(20) are used for analysis for linear and nonlinear systems with variable values of PID as shown in Table.3. In addition, output waveforms for comparison are represented in Fig.5 and Fig.6.

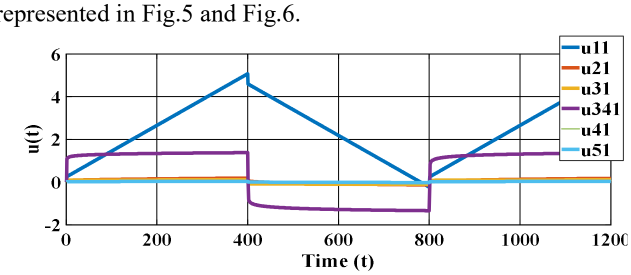

Fig.6. Output analysis of non-linear PI controller with parameters from Table.4

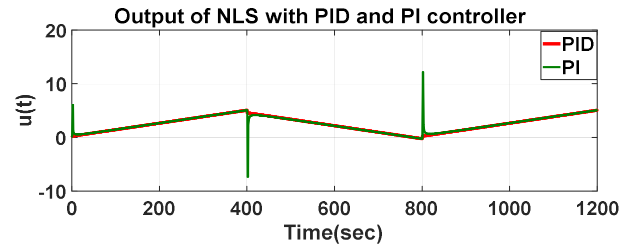

Fig.7. Output of NLS with PID and PI controller for data of u1

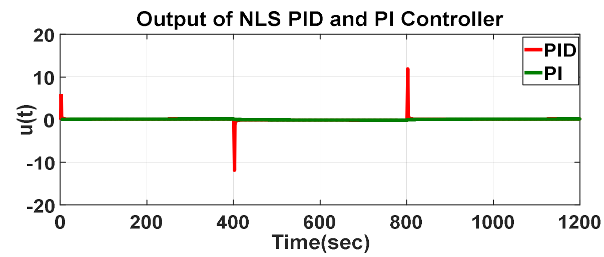

Fig.8. Output of NLS with PID and PI controller for data of u2

Dataset used for analysis are shown in Table.3 taken for comparison [9]-[16].

Table.4. Dataset used for Analysis for PID Controller

S.No.	T_s	K_p	T_i	T_d	*Lambda*	*delta*	*K*
u1	0.01	20.5	100	11.31	1	0.82	1200
u2	0.01	5.1	4.6	7.8	0.5	0.9	1200
u3	0.01	6.2359	1.785	1.964	0.1236	0.924	1200
u4	0.01	1.148	0.936	0.683	0.962	0.438	1200
u5	0.01	1.5193	0.483	0.337	0.798	0.987	1200
u34	0.01	50.4	55.6	18.20	0.070	0.922	1200

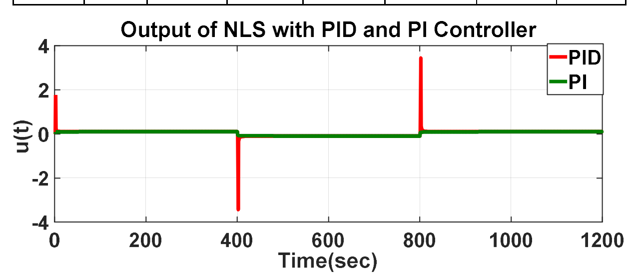

Fig.9. Output of NLS with PID and PI controller for data of u3

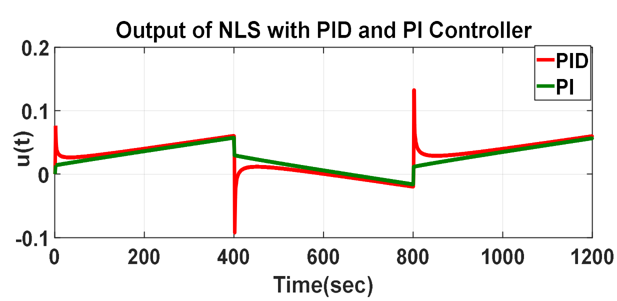

Fig.10. Output of NLS with PID and PI controller for data of u4

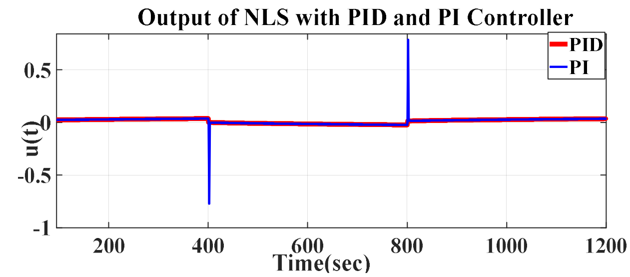

Fig.11.Output of NLS with PID and PI controller for data of u5

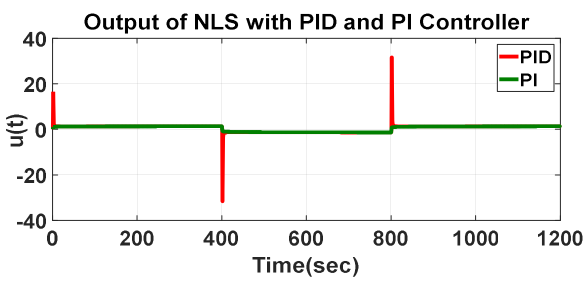

Fig.12. Output of NLS with PID and PI controller for data of u34

As per Fig.7 to Fig.12, the output on non-linear controller gives better output gain with PI controller by ignoring derivative component for specified equation of $u(t)$.

4.1 MODELLING OF NONLINEAR FRACTIONAL ORDER PID CONTROLLER

The nonlinear fractional order PID controller is designed from Eq.(20) as shown in Fig.13, where K_o is taken unity and varies as feedback gain varies.

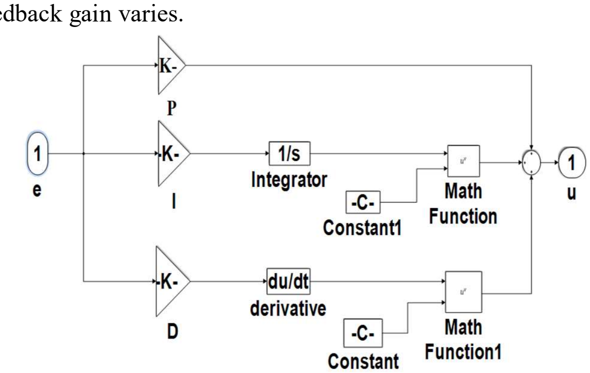

Fig.13. Matlab model for fractional order $PI^{\lambda}D^{\delta}$ controller

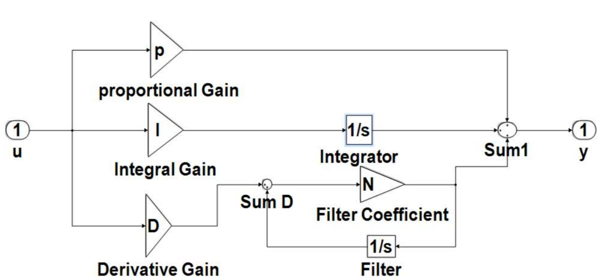

Fig.14. Matlab model for conventional PID controller

The input for PID controller as P-I-D are given from output generated from FLC. Input to FLC are error and error % and output are K_p, K_d and *alpha*, using these parameters K_I is designed and given as input signals to PID controller.

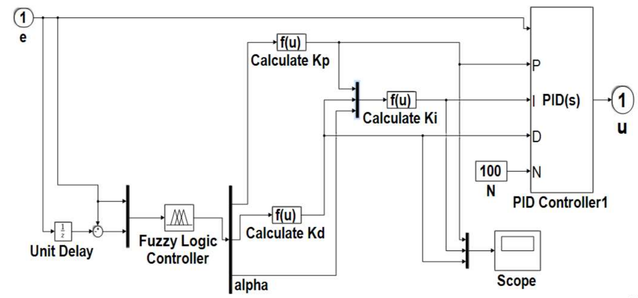

Fig.15. Matlab model for nonlinear FOPID controller with fuzzy logic controller

4.2 FUZZY LOGIC CONTROLLER DESIGN

There are three components of FIS controller as:

- Input membership functions
- Output membership functions
- Rules

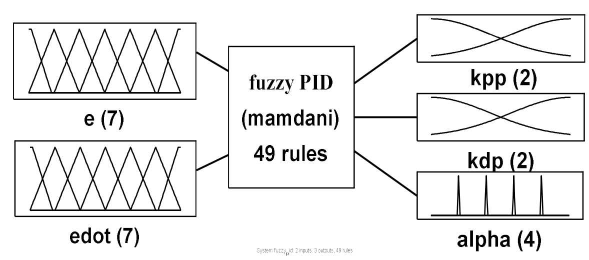

Fig.16. Fuzzy Logic Controller design bock diagram

Input membership function:

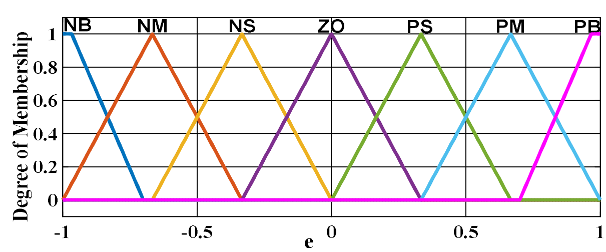

Fig.17. Input membership function for error input

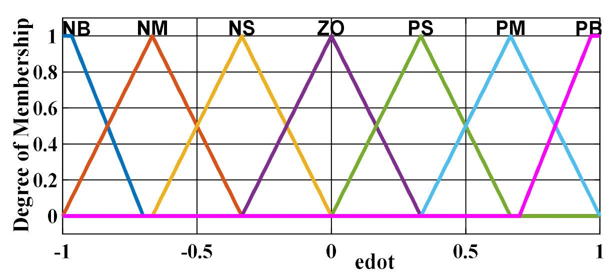

Fig.18. Input membership function for error percentage input

Output membership Functions:

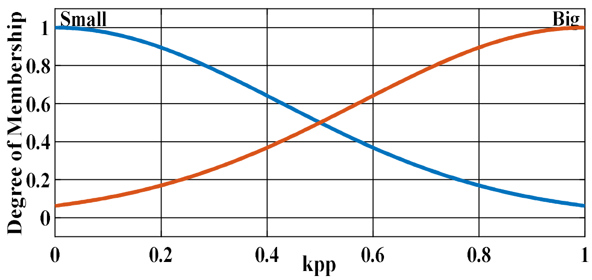

Fig.19. Output membership function for K_p

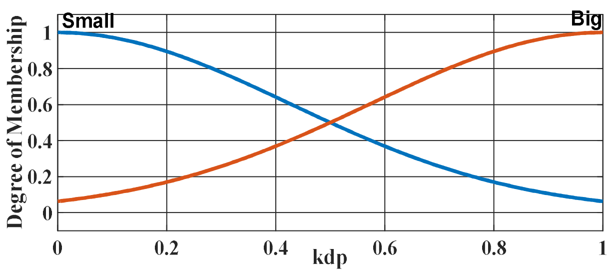

Fig.20. Output membership function for K_d

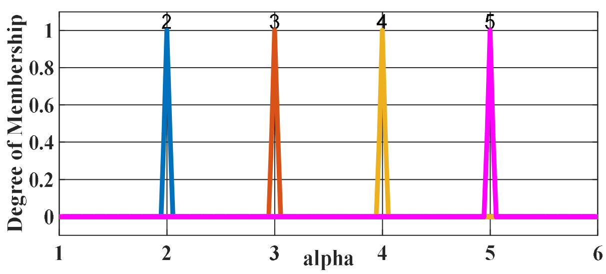

Fig.21. Output membership function for *alpha*

5. RESULTS AND ANALYSIS

This section describes the results and their analysis with nonlinear fractional order PID controller. Analysis is conducted with FOPID, conventional PID and Fuzzy implemented PID controller.

5.1 IMPLEMENTATION OF PID

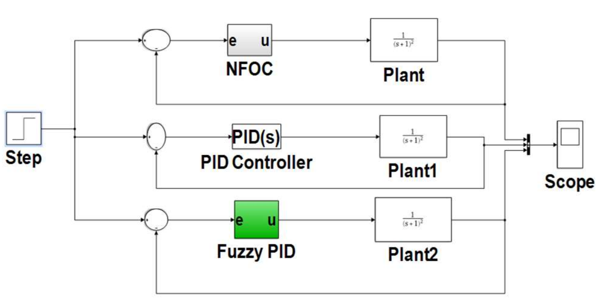

Fig.22. Matlab model of comparison implemented on first system

The proposed system with first order transfer function system is shown in Fig.22. In this system comparison of three modules can be seen as NFOC (Nonlinear Fractional order controller), PID (Conventional) and Fuzzy PID controller.

First transfer function taken for analysis is:

$$G(s) = \frac{1}{(S+1)^2} \tag{22}$$

Table.5. Dataset used for analysis on First System for Fuzzy Input of K_p, K_i and K_d

S.No.	K_u	T_u	K_{pmin}	K_{pmax}	K_{dmin}	K_{dmax}
u1	45	3.1	14.4	27	11.16	20.925
u2	2.2	3	0.704	1.32	0.528	0.99
u3	9	6	2.88	5.4	4.32	8.1
u4	11	1.2	3.52	6.6	1.056	1.98
u5	2.8	1.3	0.896	1.68	0.2912	0.546
u34	84	1.5	26.88	50.4	10.08	18.9

For the calculation of K_{pmin} and K_{pmax}:

$K_{pmin} = 0.32*K_u$;

$K_{pmax} = 0.6*K_u$;

$K_{dmin} = 0.08*K_u*T_u$;

$K_{dmax} = 0.15*K_u*T_u$;

where K_u and T_u are equality constants.

Comparison of three modules according to the Table.5 dataset shown in Fig.(3)-Fig.(28):

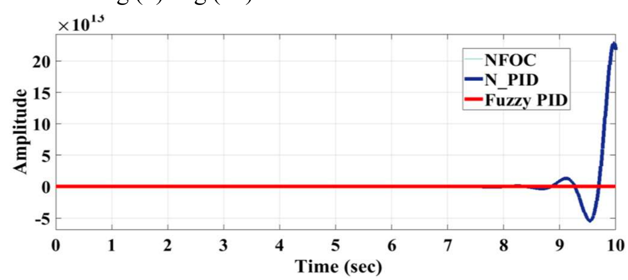

Fig.23. Comparative waveform for u1 dataset with first system

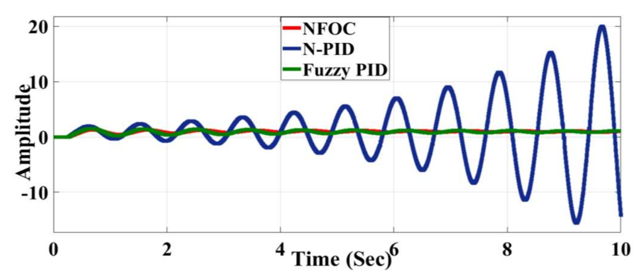

Fig.24. Comparative waveform for u2 dataset with first system

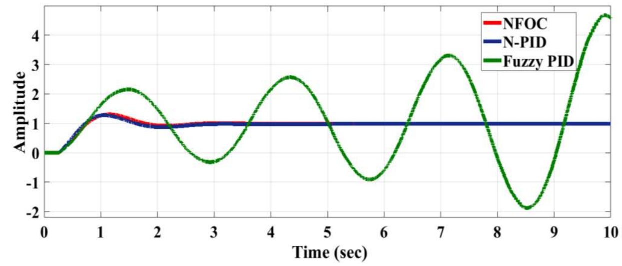

Fig.25. Comparative waveform for u3 dataset with first system

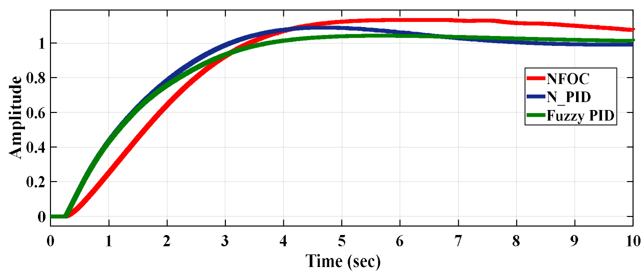

Fig.26. Comparative waveform for u4 dataset with first system

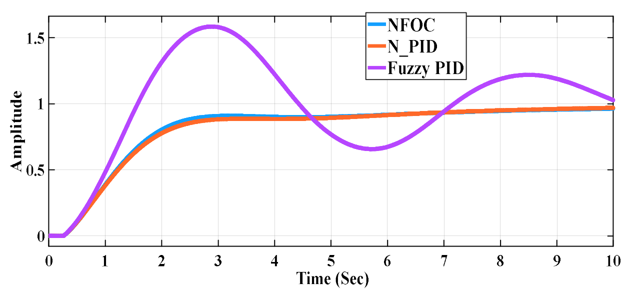

Fig.27. Comparative waveform for u5 dataset with first system

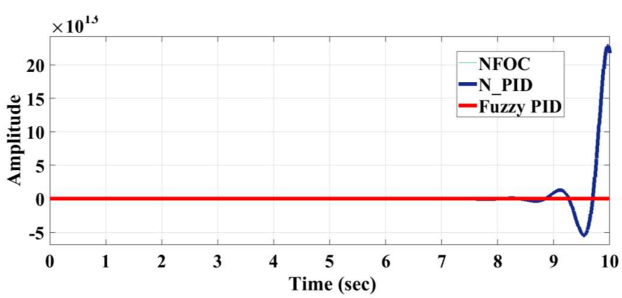

Fig.28. Comparative waveform for u34 dataset with first system

Different analysis of nonlinear fractional order controller and fuzzy controller on basis of Table.5 dataset which shown in Fig.(29)-Fig.(32) :

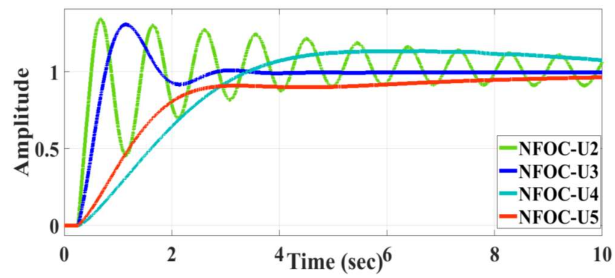

Fig.29. Comparative waveform for NFOC dataset with first system

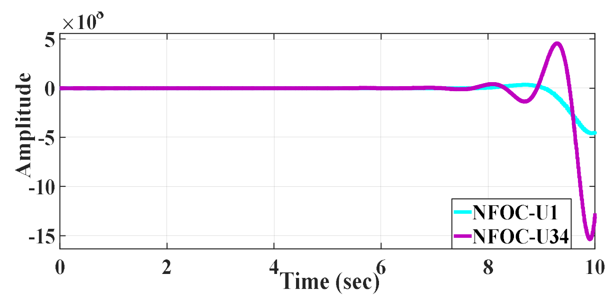

Fig.30. Comparative waveform for NFOC dataset with first system

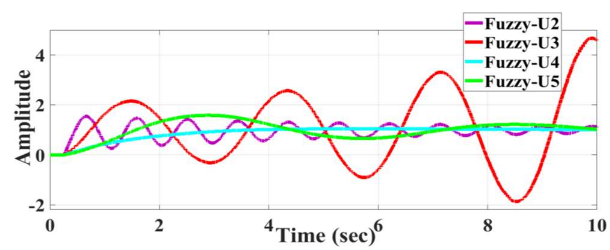

Fig.31. Comparative waveform for Fuzzy dataset with first system

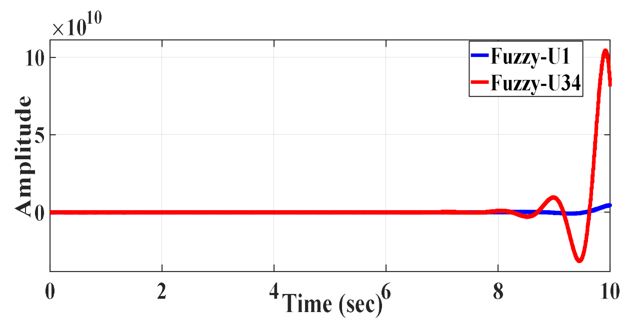

Fig.32. Comparative waveform for Fuzzy dataset with first system

Comparison shows the result that fuzzy PID gives better responses and stability in the system than conventional PID and NFOC. This comparison also shows that stability and system's linearity depends on values of K_p, K_i and K_d.

6. CONCLUSION

For the solution of nonlinearity controlling controllers, fractional order PID controllers are used in this work. In FOPID a stability coefficient with integrator and differentiator is used to gain stability. These coefficients are lambda (λ) and delta (δ) as $PI^{\lambda}D^{\delta}$. These factors are used as multiplication factors. To improve the efficiency of this fractional order PID controller, this is further controlled with fuzzy logic controllers (FLC). Implementation of FLC improves the efficiency as well as the stability of system. In the propose work nonlinear fractional order PID controller(FOPID) is compared with conventional PID and Fuzzy Logic controller by implementing six conditions of K_p, K_i and K_d for first order transfer system (journal system). This validate the use of fuzzy logic controller for better quality output conditions and gives alternate method for non-linear system of controlling.

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