Communications on Applied Nonlinear Analysis
ISSN: 1074-133X
Vol 31 No. 1 (2024)

Design of Fuzzy Fractional Order-based PID Controller for Higher Order Systems

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Article History:

Received: *25-09-2023*

Revised: *05-11-2023*

Accepted: *30-11-2023*

Abstract:
The conventional Integer Order-based Proportional Integral Derivative (IO-PID) control is mostly used in process control and manufacturing industries. However, it has been analyzed after an in-depth review of the literature that traditional IO-PID control is not worthwhile for non-linear and higher-order applications. The Controlling of higher-order systems is a critical issue in many industrial plants. The foremost objective of Controllers in complex systems is the reduction of settling time, overshoot, etc for higher-order systems. A novel Fuzzy fractional order-based PID (FFOPID) controller is designed to resolve all the significant issues of control systems. The traditional controller and the novel controller are given the same unit step input and the simulation had been done using MATLAB. The comparison between the output response of the two controllers revealed that the designed novel controller works better than the traditional IO-PID controllers.

Keywords: Optimization, Artificial Intelligence (AI), Fuzzy Logic Control (FLC), Higher order System, Integer Order based PID (IO-PID), Fuzzy Fractional-order based PID (FFOPID).

Significant Statement

The traditional IO-PID controllers are widely used for the tuning of process control loops. However, the IO-PID is not able to tune the feedback loop in case of major load disturbances and non-linearities and the working of the IO-PID controller is questionable in higher-order systems. Recently, the Fuzzy Fractional-order PID (FFOPID) has been recently applied in diverse fields of science and engineering and it has been found that this newly designed controller in fact provides better results and extra adjustments over all the existing techniques.

Compliance with Ethical Standards

Funding: No funding is provided for the preparation of the manuscript.

Conflict of Interest: The author declares that there is no conflict of interest.

Ethical Approval: This article does not contain any studies with human participants or animals performed by any of the authors.

Consent to Publish: The author involved in this manuscript gives full consent for publication of this submitted article.

Data Availability Statement: Data sharing is not applicable to this article.

1. INTRODUCTION

The flaws in the performance of IO-PID for complex systems led to the design of many innovative hybrid controllers in the past. The traditional IO-PID had been limited to integers only for the tuning purposes of the control loops. However, the conventional fifty years old integer-based IO-PID controller was augmented with two fractional-order parameters integrator (I^{λ}) and differentiator (D^{α}) in which values of λ and α are some non-integers. The fraction-order-based PID controller is proving to be superior to conventional integer-based controllers while handling uncertainties and non-linearities in diverse applications [1,2]. It has been realized that technological innovations are required to get better control to be more effective [3]. The process control systems are divided into two categories called linear and non-linear systems. The linear control systems can be easily handled with the existing conventional technologies. However, Non-linear systems lead to large settling times, higher overshoots, etc. The world is full of measurement and control systems that are non-linear in nature like diverse motors, resistive and inductive loads, etc. There is a lack of absolute systems to get the anticipated output and this always motivate researchers to evolve new systems and further refinement of current systems. [4].

2. PID CONTROLLER

The IO-PID algorithm is so far the most suitable technique for the control purpose in the industry. The only shortcoming of this controller is that tuning is done on hit and trial basis and needs abundant expertise and technical skills. The most suitable method to obtain the optimum settling time and lesser overshoots is the help of Ziegler-Nichols.

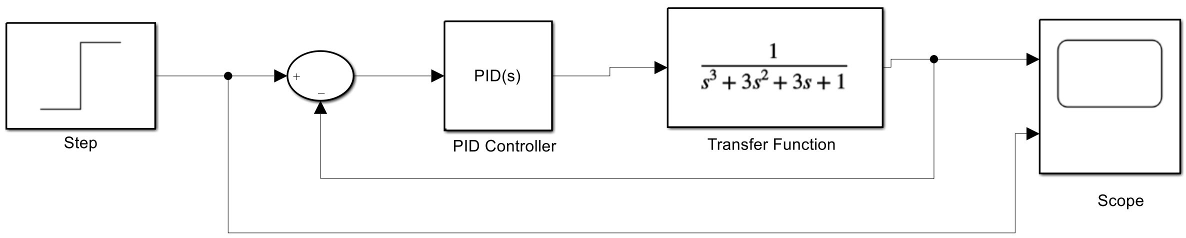

Figure 1: Design of IO-PID Controller for a Third-Order System

Tuning of IO-PID is done with the help of the Ziegler-Nichols method

$K_p = 0.60 * K_u = 4.80$,

$K_i = 2.0 * K_u / T_u = 2.56$,

$K_d = (K_u * T_d) / 8.0 = 2.25$.

The input to the third order system is given as a step having $K_p = 4.80$, $K_i = 2.56$, $K_d = 2.25$. Hence, the overshoot obtained is $M_p = 38.3\%$, and Settling time (t_s) = 9.03 sec.

It is worth mentioning here that although higher-order complex systems can be handled with Ziegler Nichols to some extent. However, this method fails miserably when it faces large load changes and high errors in the closed loop. The fuzzy control overcomes nonlinearities easily and enhances the control loop's overall performance. It is inferred that controlling an uncertain load variation can be done easily with the help of fuzzy control [5,6].

Fuzzy Logic is a technique of Artificial Intelligence (AI) in which nonlinear systems are handled by control experts. Fuzzy Logic Control (FLC) has the capability of resolving the issue of non-linearities in higher-order systems very well as compared to conventional control. Fuzzy logic, Unlike Boolean logic, provides greater flexibility to handle the concept of partial truth rather than only 0 and 1 for complex systems [7]. There is a rising focus on fractional-order calculus in the field of control systems in recent times [8]. It has been used widely in process control applications, signal processing, etc. The main benefit of fraction-based calculus is that it can easily be combined with diverse controllers to have better performance and effectiveness.

The latest FOPID is found to be highly effective in higher-order nonlinear control systems in comparison to conventional PID controllers [9]. It is disclosed that the latest FOPID controllers are highly advantageous in comparison to conventional IO-PID controllers while handling non-linearities. It can easily be said that FOPID involves a higher level of complexity as there are five parameters than three parameters of IOPID [10].

FOPID also written as $PI^{\lambda}D^{\alpha}$, is much superior to conventional IOPID and the former uses fractional order integral along with derivative actions [11]. It is extremely astonishing to investigate from the available literature that FOPID is still confined to simulations and educational kits only where similar to plant-like conditions are created[12].

Conventional control (IO-PID) is basically a combination of three gains which are proportional, Integral, and Derivative. They are also called K_p, K_I, and K_d respectively.

The transfer function of the IO-PID controller as a function of error is given in Eqs. (1) and (2), respectively:

$$u(t) = K_P\, e(t) + K_I \int_0^t e(t)\, dt + K_D\, de(t) / dt \tag{1}$$

$$U(s)/E(s) = K_P + K_I / s + K_D\, s \tag{2}$$

There is an addition of fractional order derivative and integral terms in Laplace frequency, s, to implement fractional order values rather than only integers.

The fractional order-based PID (FOPID) finally takes the shape of equation 3

$$U(s) / E(s) = K_P + K_I / s^{\lambda} + K_D s^{\alpha} \tag{3}$$

Whereas both the λ and α are non-integers.

The IO-PID is fully represented when the values of $\lambda = 1$ and $\alpha = 1$. However, in the case of the FOPID controller, there is an addition of two fractional-order parameters which are represented as λ and α. These two parameters provide much larger liberty and additional modifications to the users for handling higher-order complex systems [13]

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3. FUZZY FRACTIONAL ORDER-BASED PID (FFOPID) CONTROL

The Fuzzy Logic Control (FLC) is also being used to handle non-linearities which is based on fuzzy set theory. It is considered a multi-value logic due to its numerous industrial applications, especially in nonlinear control systems. There are several applications where there was a significant reduction of offset with the use of the fusion models of Fuzzy Control Logic with Neural Networks and Genetic Algorithms etc.

This present work is an attempt to draw the attention of researchers working in this field toward the advantages of hybrid Fuzzy Fractional Order based PID (FFOPID) Controller [10][14][17]. The FFOPID can be easily comprehended with the help of the MATLAB toolbox named FOMCOM. The author of this paper has designed a novel FFOPID controller for a unit step input which is a conglomerate of fuzzy Logic and a fractional-order-based Proportional Integral Derivative (FOPID) controller. The results obtained are much better due to the fact that both techniques are utilized at the same time in this novel controller. The diverse fuzzy membership functions are formed finally depending on the error and change of error to get the optimum output response.

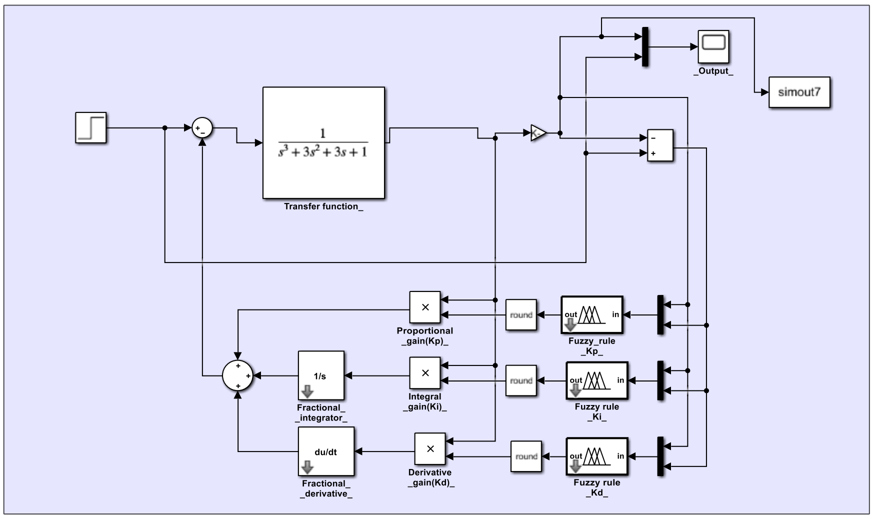

Figure 2: Designed Simulink model for Fuzzy fractional-order-based PID (FFOPID) Controller

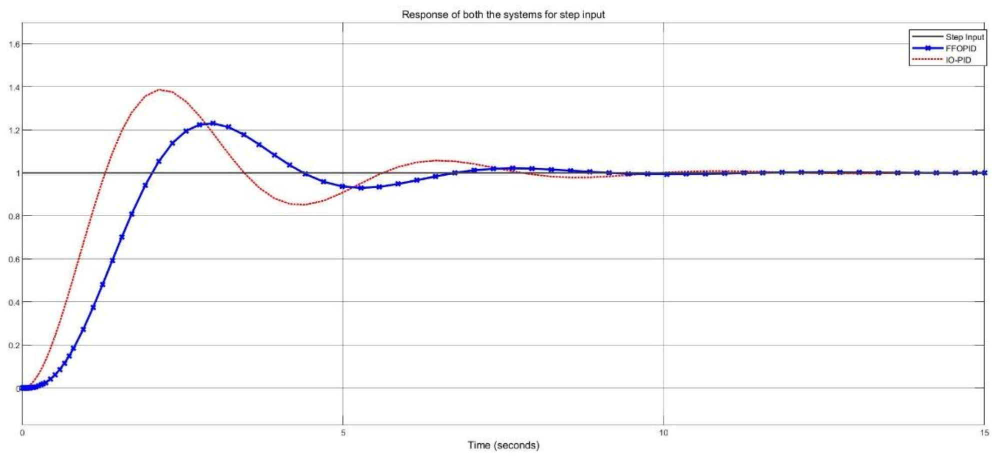

Figure 3: Output Response of IOPID and FFOPID systems after a step input

4. RESULTS & DISCUSSION

The overshoot ($M_{p)}$ and Settling time (t_s) obtained from both controllers are compared [15, 16] when a step input is given. The values measured are shown in Table 1. However, the present work has proved that the proposed novel-designed FFOPID has given a much better output response having a lesser settling time and overshoot, etc.

Table 1: Time Response of both the controllers

Controller/ Parameters	**Conventional IO-PID Controller**	**Proposed FFOPID Controller**
Overshoot Mp (%)	38.6099	22.9768
SettlingTime Ts (sec)	9.0897	7.9240

The table depicts that novel FFOPID control is giving lesser settling time measured in seconds and overshoot which is measured in percentage than conventional IO-PID Control

5. CONCLUSIONS

A third-order complex transfer function is being taken in this work to analyze the performance of the newly designed FFOPID. A comparison is made in this paper between traditional IO-PID and FFOPID after the tuning of K_p, $K_{i,}$ and K_d along with two fractional order parameters: γ and µ.

It is concluded from the work after a systematic comparison that the FFOPID controller has an edge over the IO-PID controller with respect to the overshoot M_p in (%) and settling time T_s (in seconds), etc. The author can summarize that in the near future, the performance of diverse non-linear systems can be easily improved with the help of the projected designed hybrid controller.

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