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# Design of Bio-inspired Optimized Integer and Fractional PID Controller

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## Abstract

The proportional–integral–derivative (PID) controller are being widely used in almost every real-time engineering problem in accordance with the increasing demand for aquick and consistent response of the system. To justify the performance of PID controllers, a mathematical model of an electric motor is considered in this paper. The complete system is simulated on MATLAB/SIMULINK with an integer and fractional-order PID controller and analyzed in terms of control characteristics. A comparative study of the various closed-loop response of the system is also carried out to compare the performance of an integer and fractional-order PID controller. The controllers used in the system are modern optimized, i.e., the particle swarm optimization technique is used to acquire a more optimized system response. The simple concept of application of integer and fractional-order PID controllers is proposed in this research article. A similar approach can be applied to various real-time problems to obtain optimized results. However, other modern optimization techniques are also available and emerging regularly that can produce a stable and optimized response to satisfy the demand for system stability.

**Keywords:** Bio-inspired optimization method, Fractional and Integer order PID controller, Particle Swarm Optimization (PSO) method, Ziegler-Nichols tuning method.

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## Introduction

In the mid of 1950s, Ziegler and Nichols made use of PID controllers convenient to many industrial applications by proposing tuning rules for them. Since then, almost every industrial application consists the use of a PID controller. Due to their simple construction, the PID controllers are easy to understand and operate.[1] Initially, the PID controllers were tuned only using the Ziegler-Nichols tuning method, but later on, Cohen-Coon proposed another tuning rule for PID controllers.[2] The complexity and requirement of the system or plant increased over time, resulting in the emergence of new tuning technique that incorporates Self-tuning and Auto tuning, Robust and optimal tuning, Genetic and Intelligent control, Fuzzy and Adaptive tuning etc.[3-6] Also, the application of fractional-order PID controllers has become very popular as they have two extra degrees of freedom than integer-order PID controllers, enable the generation of more accurate system responses in the control characteristics context.[7]

The PID controllers have a very active role in the field of research as well that's why they always remain in discussion. To better understand the PID controllers, this article mainly focuses on the basics of integer and fractional order controller, their classical and modern optimization methods, and finally, applications to various industrial aspects. At the industrial level, the PID controllers feed into the domain of process control, robotics, electric drives and power systems, and biomedical engineering.[8,9] The performance of an electrical system is evaluated with an optimized PID controller after simulating it on MATLAB in this article. For the tuning of the controller, the Ziegler Nicholas method is used in classical tuning, and the Particle Swarm Optimization (PSO) method is implemented as a modern approach.

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## Material and methods

### Integer and Fractional order PID Controllers

The PID controllers have been successfully applied for many years due to their simplicity, robustness, and wide range of applicability. The PID controller involves three parameters; proportional (P), integral (I), and derivative (D).

The significance of these three parameters can observe in the performance of the system. The proportional action embraces proportional modifications in the system response as per the error signal. The integral term is responsible for the correctness of the output by reducing the offset after evaluating the process variable. Derivative term concerned the rate of change of process variables and changes output if any variations are present.[8]

Commonly, the parallel structure of the PID controller is in existence for the systems in which the terms proportional, integral, and derivative has individual equations, and their combined sum represents the overall mathematical equation for the PID controller.[9] The mathematical expression for integer order PID controllers is given in equation (1) below.

$$u(t) = K_p e(t) + K_i \int_0^t e(t)\,dt + K_d \frac{d}{dt} e(t) \qquad (1)$$

where KP is Proportional gain, Ti is Integral action time or reset time, Td is Derivative action time or rate time, e(t) is the error signal, and u(t) is the input signal. The desired response of the system is obtained by applying a PID controller to the system in terms of control characteristics such as stability, low settling time, less overshoot, fast rise time and almost null steady-state error, etc. But the recent advances in the field of control theory emphasize the application of fractional order PID controllers. A system having a fractional-order PID controller can generate a more stable response than an integer one.

A fractional-order controller proposed by Podlubny in 1999 is a joint outcome of a traditional integer-order and a non-integer controller based on fractional-order calculus.[10] The fractional-order calculus has evolved by its contributors and applied in many fields extensively in the specialization of control theory for the previous two decades. There is no doubt about the effectiveness of fractional-order controller performance due to the differentiation and integration of non-integer order equations. It has attracted the attention of researchers because it has two additional parameters than the integer-order controller resulting in more accurate system response. They also provide greater flexibility to the system organization, resulting in system performance that is more stable.[10]

The transfer function of the fractional-order PID controller is given in equation (2) below.

$$uf(t) = Kpf\, e(t) + Kif\, \{aD\lambda\, t\, e(t)\} + Kdf\, \{aD\mu t\, e(t)\} \qquad (2)$$

where, uf(t) is the fractional-order PID controller response, e(t) is the error signal, and the parameters λ and μ are positive real numbers associated with the integral and derivative terms. Both these parameters λ and μ are responsible for the fractional-order control scheme that generalizes the integer-order control. Kpf, Kif, Kdf are the proportional, integral, and derivative gains. The aDqt is a different integral operator which combines the effect of differentiation and integration in a single notion. This operator is commonly used in fractional calculus and is given in equation (3) below.[11]

$$aDqt = \begin{cases} \frac{d}{dt} & q > 0 \\ 1 & q = 0 \\ \int(dt) & q < 0 \end{cases} \qquad (3)$$

where, q is a complex number representing the fractionalorder, while the operation's limitations are a and q.

## Tuning Schemes

The tuning process involves the evaluation of control parameters before applying the controller to any system or plant. The tuning choice is determined by the system's behavior and open-loop response to giving some disturbance, such as a step signal at the input side. The Ziegler-Nichols and Cohen-Coon tuning rule comes under the classical tuning methods. While in modern tuning methods, there are numerous optimization algorithms to choose from. The electrical system in this study is controlled using a traditional and modern optimized PID controller.[12]

## Classical Tuning Methods

The Ziegler-Nichols process of tuning is dependent on the system performance operating without any controller. They proposed two tuning rules: process reaction curve (PRC) and ultimate gain method. In the PRC method, the system is simulated in an open-loop manner with a step signal at the input terminal. This method applies to the system that

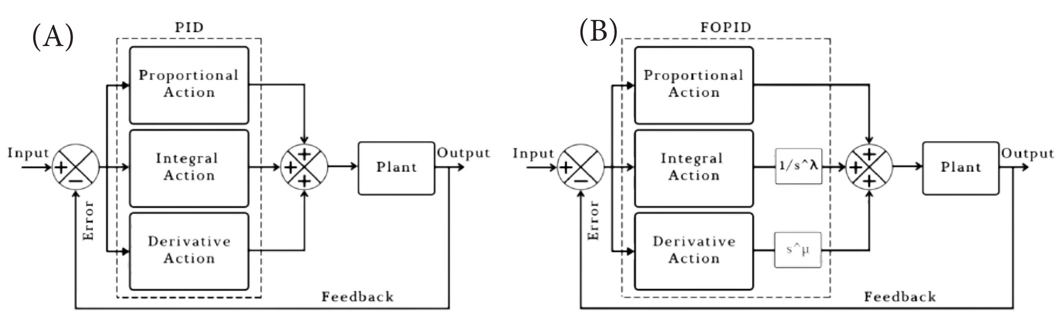


**Figure 1:** Parallel structure of PID controller, (A) Integer order, (B) Fractional order.

displays the S-shape response "sigmoid". The sigmoid assist to evaluate the parameters such as time delay, time constant, and dc gain, as suggested in the tuning method. The user can utilize all these parameters to find the PID parameters (Kp, Ki, and Kd).[13]

The systems which do not exhibit the "sigmoid", are accessed through the ultimate gain method. With the help of ultimate gain and period, the controller parameters are retrieved in this method. However, proportional gain or root locus plot assists the findings of the ultimate gain and period.The method proposed by Cohen-Coon is also based on Ziegler-Nichols first method. This method also uses the notion of time delay, time constant, and dc gain to evaluate the controller parameters using a different formula approach than Ziegler-Nichols method.

Valerio and Costa have proposed tuning rules for fractional-order PID controllers, similar to the Ziegler-Nichols tuning rule. These tuning rules apply to the systems with 'Sigmoids'. To tune the fractional-order PID controller, a suitable rule-set can be selected based on the delay time and lag value.[13]

## Modern Optimization Methods

In recent years, there have been numerous optimization approaches evolved that function conceptually different from the classical tuning methods, regarded as the modern optimization methods. These modern optimization techniques involve various methods such as Genetic Algorithm, Simulated Annealing, Bio-inspired Optimization, Neural network, Fuzzy based Optimization, etc.[14] These all methods depend on certain phenomena and behavior of their components. In this paper, the Particle Swarm Optimization method is considered to optimize the PID controller that lies under the domain of the bio-inspired optimization method.

The Particle Swarm Optimization (PSO) is a bio-inspired population-based search algorithm that provides a solution to complex and non-linear systems. The PSO algorithm was initially proposed by Dr. Kennedy and Dr. Eberhart in 1995. The basic concept of PSO was motivated by the social behavior of animals like bird flocking and fish schooling etc. In PSO, each member of the animal's group or population is called a particle, and the whole population is called a swarm. The PSO involves the group communication of particles regarding the food search or migration from their original position in search space, although they all do not have the perfect solution. But the information collected by the experience of the individual and group particles they all be able to discover the best technique that made the particles constantly change their position and velocity from previous points.[15]

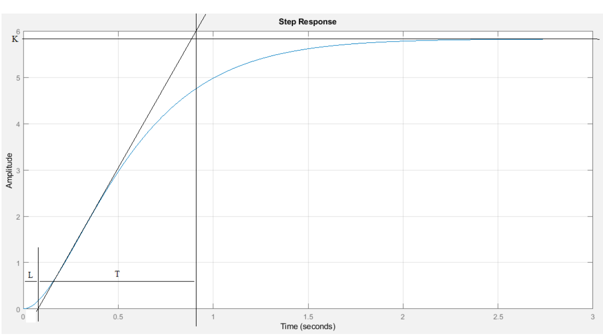


**Figure 2:** Sigmoid on applying step input to the open-loop system

# Result and discussion

## Simulation of Real-Time Application

To better understand the performance of integer and fractional-order controllers, let us consider a real-time application of an electric motor driving a fan with a huge diameter through anelastic coupling with torsional stiffness constant Kr as shown in figure 4. Thevenin equivalent source with ideal angular velocity in series with virtual rotary damper Bm can be used to represent the electric motor.The electric motor, on the other hand, is not an ideal source, although it has a torque-speed characteristic.The load is regarded an analogous rotary damper Br, and the fan has inertia J related to the bearing.[16]

To examine the system performance, the mathematical model of the electric motor is simulated in a close loop manner on MATLAB.The closed-loop speed response of the electric motor exhibits a high overshoot, settling-time, and rise-time. Also, throughout the operation, the electric motor fails to achieve the rated speed. Therefore, it is required to control the speed by applying an optimized PID controller. As a result, both integer and fractional-order PID controllers are included in the proposed paradigm. Initially, the Ziegler-Nichols classical method is applied to tune the integer-order PID controller. Finally, the particle swarm optimization technique is applied to tune both integer and fractional-order controllers.[17, 18]Figure 5 shows the complete comparative simulated model of an electric motor.

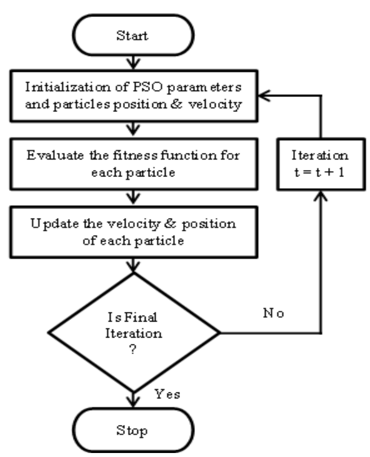


**Figure 3:** PSO flowchart

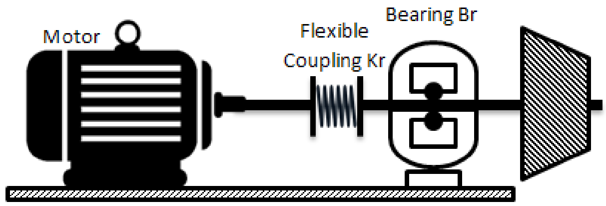


**Figure 4:**Electric motor driving a fan with a huge diameter16.

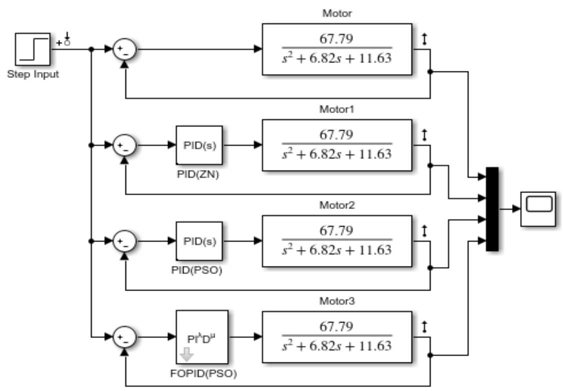


**Figure 5:** Comparative Simulink model of electric motor.

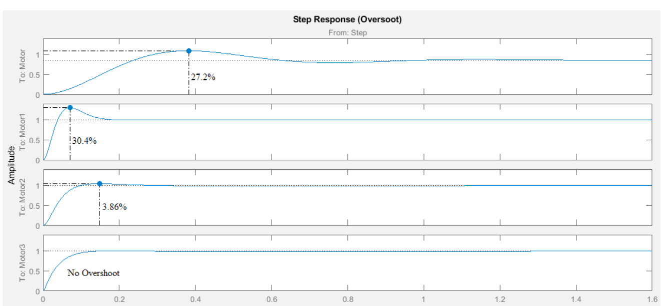


**Figure 6:** System's comparative response curve as a function of overshoot.

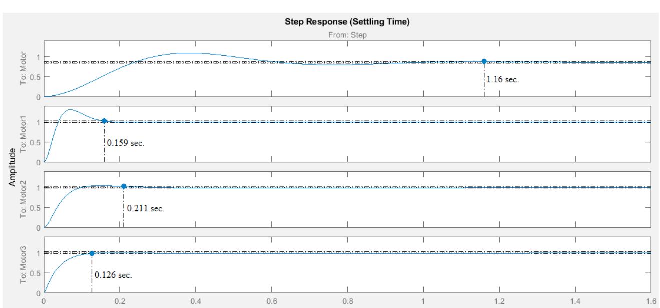


**Figure 7:** System's comparative response curve as a function of settling time.

After applying the optimized integer and fractional-order PID controller to the electric motor, its performance can be understood by analyzing the control characteristics individually. Figure 6 and figure 7depict the relative reaction as a function of overshoot and settling time,respectively.

**Table 1:**Comparative analysis of control characteristics

| *System* | *Characteristics* | | | |
|---|---|---|---|---|
| | Overshoot | Settling-time | Rise-time | Final Value |
| Without PID | 27.2% | 1.16 sec. | 0.161 sec. | 0.854 |
| PID (ZN) | 30.4% | 0.159 sec. | 0.03 sec. | 1 |
| PID (PSO) | 3.86% | 0.211 sec. | 0.06 sec. | 1 |
| FOPID (PSO) | No overshoot | 0.126 sec. | 0.07 sec. | 1 |

Form both the responses shown in figure 6 and figure 7, it is clear that the system having optimized PID controller has improved overshoot and settling time. The response with fractional-order PID controller is extremely optimized than the integer-order PID controller, due to its two extra degrees of freedom.

Refer to table 1 for a more succinct description of the system's performance.

## Conclusion

Table 1 clearly justifies the application of integer and fractional-order PID controllers tuned by classical and modern optimization techniques, as the system with an optimized controller has better control characteristics such as peak overshoot, settling-time, rise-time, and final value (steady-state error). Although the classical tuning approach has a shorter settling time and a quick rise time, the overshoot has increased, indicating that there is a possibility of improvement. As a result, both modern optimized integer-order and fractional-order PID controllers are employed in the system.The modern optimized integer-order PID controller improved the response than classical one. However, when compared to other proposed control strategies for an electric motor, the deployment of modern optimized fractional-order PID controller offers a better response pursuantly of control characteristics.

A simple concept of the application of integer and fractional-order PID controller to the electric motor is proposed in this paper, which justifies the application of PID controller. The most fundamental types of controllersare the integer ones and may be utilized in any system; the emergence of fractional-order controllers has enhanced the utility of PID controllers even more.Both the integer and fractional-order PID controllers can be applied especially to bio-medical engineering applications due to the vast range of possibilities for research in this domain. Also, the modern optimization techniques such as genetic algorithms, bio-inspired optimization techniques, neural and fuzzy logic etc. can also be applied to tune the PID controllers.

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