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Speed control of DC motor using fractional order PID controller based on particle swarm optimization

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ABSTRACT

Due to the required different speeds and important role of direct current (DC) motors in laboratories, production factories and industrial application, speed controlling of these motors becomes an essential matter for proper operation with high efficiency and performance accuracy. This paper presents a new speed controlling technique that is based on particle swarm optimization (PSO) algorithm in the optimization process of the parameters for the fractional order proportional–integral–derivative (FOPID) controller. The FOPID is an advanced and modern controlling system in which the two more added parameters (the derivative μ and integral λ orders) are fractional rather than integer. Through the process of minimizing the fitness functions, the obtained results show that the designed controller system can excellently set the best controller parameters due to the fractions of these additional parameters. With respect to the PSO-PID controller, the simulation results for the proposed PSO-FOPID controller show performance improvements of 14%, 21%, 24.5%, 78%, and 19.3% in the values of the parameters Kp, Ki, Kd, Tr, and Ts respectively.

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1. INTRODUCTION

The most popular and useful control unit in the industrial fields is the proportional-integral-derivative (PID) controller due to its uniqueness in its simple structure and easy implementation in modern applications and complex industries. Despite the simplicity and ease of implementation of the PID controller, it needs continuous improvement to obtain the best performance results. The PID performance can be further enhanced through the process of making use of fractional order derivative and integrals. Therefor in fractional order controller not only the proportional (Kp) is tuned, however the additional two parameters (derivative mu μ and lambda λ) are optimized as well. This action adds flexibility and more robustness to the system, as a result dynamic system performance is enhanced in comparison with its counterpart integer system [1].

Therefore, when comparing the classic three-parameter control unit and the fractional order proportional–integral–derivative (FOPID) controller, the fractional order controller has two additional control parameters whose functions are employed as differentiation and integration commands to give the controller more opportunities for flexibility, control and stability. A proposal has been given by researchers for strong control by segmenting integer order integrals in the PID control system, also by using the near-optimal approximation of the arrangement transfer function [2]. Based on what was mentioned previously, the PID controller can be better optimized by using the so-called path theory of so-called proportional-integrative-derivative partial arrangement. The random optimization strategy from the evolutionary computation group is the principles of the particle swarm optimization (PSO) algorithm. The technology of this idea is inspired by a biological technique [3]. It has been vastly considered as a promising optimization algorithm because its low computation cost, good performance, and simplicity [4]. The PSO algorithms relies on collective actions through the various lines of research that have worked efficiently to solve most of the integrative optimization troubles.

The idea of PSO was suggested and based on the functions of birds on how to search for the best path and return home safety by building their own pathway formation. The aim of this paper is to optimize the FOPID controller parameters based on PSO algorithm. This algorithm is utilized to optimize the controller parametrs and it’s applied in the controlling the direct current (DC) motor [5].

The working principle of the DC motor is to convert electrical energy into kinetic energy. Due to their simplicity and constant control properties, the applications of DC motors have been most utilized in most industrial employment like a robotic maneuvers and electric leverage. DC motors provide adequate control of position and idle or acceleration speed. For these reasons, researchers have paid great interesting in the field of controlling the position and DC motor speed and they developed several methods for controlling its position and speed. One such method is the proportional-derivative-integrated controller (PID) which is commonly used to control velocity and position. Adjusting the parameters of the PID controller is very important because it has a great impact on the performance and stability of the control system [6]. There are many ways that can be used to control the DC motor speed and direction. One of these methods used is the conventional PI and PID controllers. We may face many dilemmas to gain perfect control results when using a conventional PID controller, especially in high-order systems where the conventional PID controller does not work well [7]. Therefore, durability of the device with good system performance is the main requirement when designing an efficient controlling system. As a result, many advanced control unit systems have been applied to ensure durability and non-rejectability working devices [8].

2. MTERIALS AND METHODS

2.1. Fractional calculus

The fractional order calculus (FOC) illustrates the idea of extension the derivative-integral factor that is derived from an integer “k” to an arbitrary order or to non-integer (fractional) order [9]. Differ-integral operator is denoted by D_t^{α} , it is a mixture of differential and integral processes that are frequently used in fractional calculus. So, the fractional calculus can be represented by ($d^k y/dt^k$), k-fold integrals where k is the irrational, fractional, or complex [10].

FOC is based on generalizing calculus in an arbitrary system, which can be irrational, complex, or even rational. This generalization led to the introduction of the fundamental continuous differ integral operator [11]. These mathematical operations can more accurately describe a real object than traditional integer ordering methods [12]. The operator aD_t^{α} is given by (1):

$$aD_t^{\alpha} = \left\{ \begin{array}{c} 1 \text{ for } \alpha = 0 \\ \frac{d^{\alpha}}{dt^{\alpha}} \text{ for } \alpha > 0 \\ \int_a^t (d\tau)^{-\alpha} \text{ for } \alpha < 0 \end{array} \right\} \tag{1}$$

where a, and t are the system limit conditions, and α ($\alpha \in \Re$) is the operation order.

There are three more famous definitions regarding to this method, these are Grünwald-Letnikov Riemann-Liouville, and Caputo definitions [13]. The three famous definitions are required in order to obtain the control algorithm. The Grunwald–Letnikov equation is:

$$aD_t^a f(t) = \lim_{h \to 0} \frac{1}{h^a} \sum_{j=0}^{\left[\frac{t-a}{h}\right]} (-1)^j \, j^a f(t - jh) \tag{2}$$

where the Riemann-Liouville definition is:

$$aD_t^a f(t) = \frac{1}{\Gamma(1-a)} \frac{d^k}{dt^k} \int_a^t \frac{f(\tau)}{(t-\tau)^{a-k+1}} d\tau \tag{3}$$

when the equation initial condition a is bounded by (k-1 <a <k), the integrals folding factor and the gamma function Γ (.) is given by:

$$\Gamma(y) = \int_0^{\infty} r^{y-1}\, e^{-r}\, dr \tag{4}$$

in the Laplace transform nutation the Differ-integral operator aD_t^{α} can be written as:

$$\mathcal{L}[aD_t^{\alpha} f(t)] = \int_0^{\infty} e^{-st}\, aD_t^{\alpha}\, f(t)dt \tag{5}$$

$$\mathcal{L}[aD_t^{a} f(t)] = s^{a}F(s) - \sum_{m=0}^{k-1} s(-1)^{j}\; {}^{0}D_t^{a-m-1} f(t) \tag{6}$$

the symbol α is between k-1 <α ≤ k.

2.2. Fractional order PID controller

The PID controller are almost used in the industrial processing system, specially, when close loop characteristics are considered. Mostly the interest lies in the four (overshoot, rise time, steady-state error, and settling time) major closed-loop step response characteristics [14], [15]. For the analyses and design of linear dynamic control system, the initial conditions of FO differential equations are zero assumed to determine the transfer function reactions of the system. The frequency domain s^{α} is usually represented in time domain operator as D^{α}, however, the FOPID or $PI^{\lambda} D^{\mu}$ controller can be illustrated as weighted sum of such operators with additional degrees of freedom for setting the weights (controller gains) alongside with the integro-differential order of the operators [16]. Figure 1 shows the block diagram for fractional order PID controller.

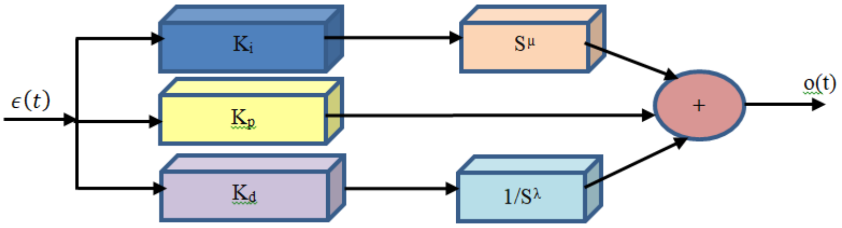


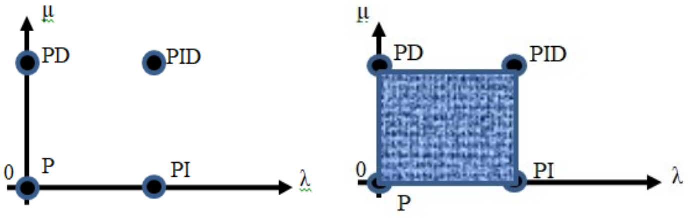
Figure 1. Block diagram of the fractional order PID controller

The control procedure for the fractional order PID controller, can be presented by the integro-differential mathematic (7), given, and the transfer function of the such controller is illustrate by (8).

$$o(t) = K_p \in (t) + K_i\, D^{-\lambda} \in (t) + K_d\, D^{-\mu} \in (t) \tag{7}$$

$$G_{FOPID}(s) = K_p + \frac{K_i}{s^{\lambda}} + K_d\, s^{\mu} \tag{8}$$

Where the λ and μ parameters represent random real numbers. When μ = 1 and λ = 1, we can get a classic PID controller. Figure 2 shows the FOPID (μ and λ) parameters which generalize the classical PID controller, and expands it from point to plane. So, this awards us more tolerance for designing better PID controller, and it award a good chance for excellent setting of the control system dynamics [17]. The research suggested the method of particle swarm optimization (PSO) which can implement a number of optimization techniques to get the better parameters values of the controller [18], [19].



(a) (b)

Figure 2. Classical PID controller and (b) FOPID controller

2.3. Mathematical model

The block diagram of controlling the DC motor in which the armature is selected, is shown in Figure 3. In (9) gives the overall transfer function of this DC motor [20]. After applying the standard parameter values as shown in Table 1, to the DC motor, the final DC motor transfer function can be obtained as (10).

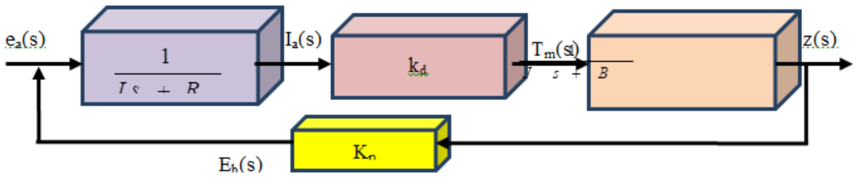


Figure 3. Block diagram system DC- speed motor

$$\frac{z(s)}{e_a(s)} = \frac{k_t}{[(r+Ls)(js+b)+k_t k_p]} \tag{9}$$

$$\frac{z(s)}{e_a(s)} = \frac{0.023}{0.005s^2+0.01s+0.000559} \tag{10}$$

Table 1. The values of the parameters DC motor

Standard specification of the DC motor		
Damping	B	0.00003 Nm*s/rad
Inductance	L	0.5 H
Moment of inertia	J	0.01 k.m2
Gain	K	0.023
Resistance	R	1 Ω

3. PARTICLE SWARM OPTIMIZATION SYSTEM

During previous years, the development of the particle swarm optimization (PSO) system was researched and developed by many scientists including J. Kenedy and R. Eberhart in 1995. The PSO theory depends on the intelligent movement principle of a swarm that moves in the search area, looking for the best solution for it. Therefore, each particle in the vacant region is treated as an N-dimensional point which attempts to optimize its position utilizing the existing location and its speed. The practical dimension between the existing site and the best site called "pbest", and its dimension between existing location and a global site called "gbest" [21].

PSO theory uses many numbers of swarm constituent particles looking for the best solution in the search space, so it is considered one of the algorithms that does not implement survival of the fittest [22]. For multi dimension problem as in PSO system, the velocity and position of the particles can be determined and updated according to the following equations [23];

$$u_j(t+1) = v.u_j(t) + k_1.\text{rand}.\left(\text{pbest}(t) - d_j(t)\right) + k_2.\text{rand}.\left(\text{gbest}(t) - d_j(t)\right) \tag{11}$$

$$d_j(t+1) = d_j(t) + u_j(t+1) \tag{12}$$

where,
uj(t+1) is the speed of the jth particle at (t+1) repetition.
dj(t+1) is the position of the jth particle at (t+1) repetition.
v is the inertial weight factor (weighting function).
k1 and k2 are acceleration constants and can be defined as cognitive learning rate and gregarious learning rate respectively.
rand is indiscriminate number between 1 and 0.
pbest is the personally best location for the particle.
gbest is the global best location for the particles swarm.

This balance between local and global research, which is within the responsibility of the weighting function (v), is also responsible for the dynamic adjustment of particle velocities, the weighting function v is calculated as:

$$v = v_{max} - \frac{(v_{max} - v_{min}).iter}{iter_{max}} \qquad (13)$$

where;
v max and v min are defined as premier and eventual weights
iter is known as a time of the repetition current
itermax is the maximum number of repetitions.
The definition is a suggested fitness function to optimize PID controller parameters:

$$F = v_{max} \times (1 - e^{-1}) \times (Mp + Ess) + v_{min} \times e^{-1} \times (Ts - Tr) \qquad (14)$$

where;
MP: is the Maximum Overshoot,
Tr: is the Rise Time,
Ts: is the Settling time

The optimization steps of the parameters of the PSO-PID controller for controlling the DC motor speed are implemented according to the PSO algorithm. These steps are implmented in MATLAB–Simuink program. The main steps include a model for DC motor speed so that the Mp, Tp & Ts parameters of the motor model step response are calculated. As a result, the fitness function assignment and comparison between pbest and gbest can also be calculated. Finally, the partical speed and location can be followed and these steps are illustrated in the flow chart as shown in Figure 4.

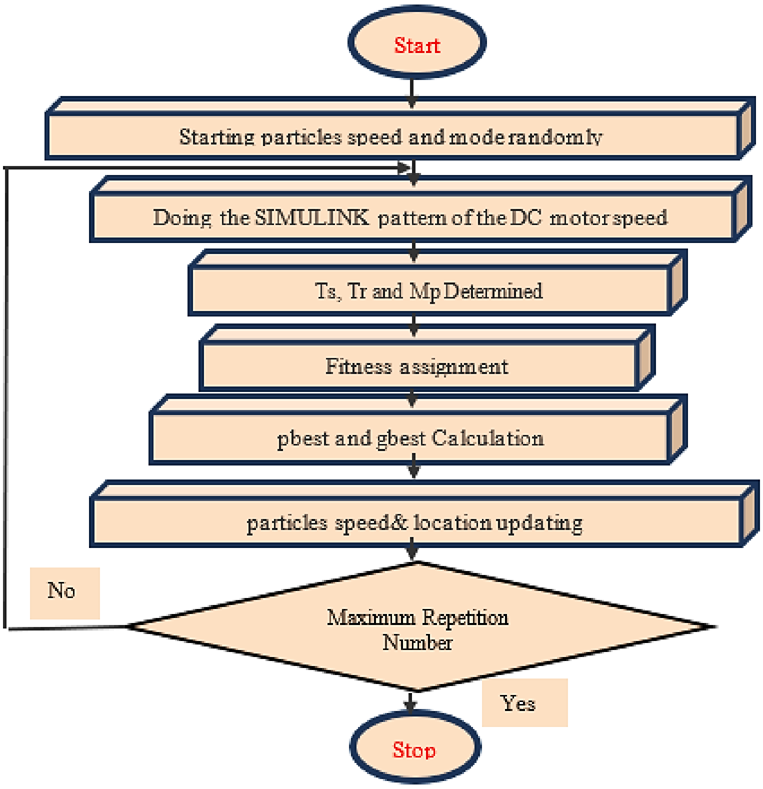


Figure 4. The basic PSO algorithm chart

4. PSO-FOPID CONTROLLER SYSTEM

In this paper, the PSO algorithm is applied to search for the best or optimized FOPID controller parameters. The PSO is a researching system based on the idea of the social behavior of fish and bird schooling. PSO exploits a swarm of particles that explore promising regions of the D-dimensional search space with adaptive speed. It works until the stop condition is met. Better particle placement gives optimum parameters selection for the controller [1]. Therefore, the PSO system, which was developed in 1995 can be defined as an improvement method based on evolutionary calculation, and the inertial weight was added in 1998 [24], [25].

In the normal controlling system has three (K_p, K_i, and K_d) essential parameters, however, according to the proposed FOPID controller another parameters λ (integer order) and μ (derivative order) are added, these two parameters are determined through the application of the PSO algorithm, so that the best output response for the control system is obtained. The "personality" is used to substitute the "particle" and the "inhabitance" is used to specify the "group". Assume that these parameters (K_p, K_i and, K_d) and the parameters λ (integer order) and μ (derivative order) are personality, so the personality contains the five members, and assigned as real value. Now assume that there are n personalities in the inhabitance, so the n x 5 is the inhabitance dimension. Using a set of good control parameters K_p, K_i, K_d, λ, and μ can achieve good results and fine-tuned values to achieve a good system output response, as a result of this action the value performance parameters is reduced in the time domain, these parameters include rise time (Tr), settling time (Ts), steady-state error (ess), and maximum overshot (mp%). Figure 5 illustrates system of the block diagram the PSO-FOPID controller for the DC motor [26].

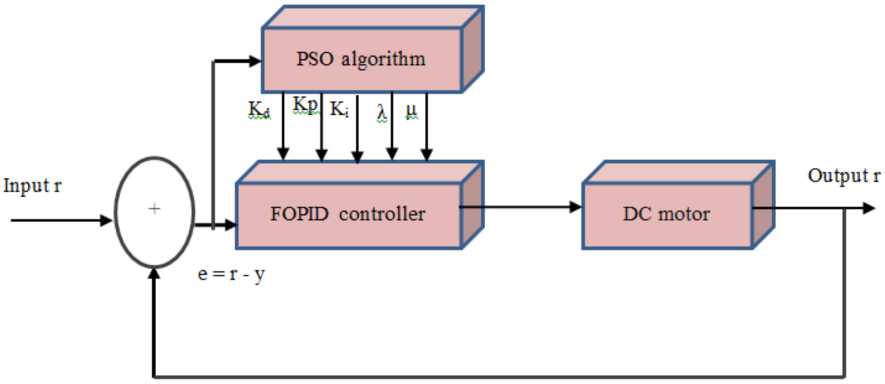


Figure 5. Block diagram system of the PSO-FOPID controller

5. RESULTS AND DISCUSSION

In this study the parameter values taken for running the PSO algorithm in MATLAB environment is give in Table 2. The unit step response of speed control of DC-motor using PSO-FOPID and PSO-PID controller are shown in Figures 6 and 7 respectively. The PSO-FOPID controller parameters are shown in Table 3. The obtained results illustrate the performance of the PSO algorithm in choosing the best average parameters values for the performance of the proposed PSO-FOPID controller. The convergence curve for each gain is called as particle for Kp, Ki ,Kd, λ and μ are plotted to give an idea how the PSO Algorithm converged to its final value has been illustrated in Figures 8 and 9 is the outcome of convergence curve for output response.

Table 2. The values of the particle swarm parameters

Name of Parameter	The Values
Cognitive Component k_1	2
Minimum Inertia Weight	0.4
Maximum Speed	10
Maximum No. of Iterations	100
Number of Particles	20
Maximum Inertia Weight	0.9
Social Component k_2	2

Table 3. Comparison parameter values for the various components of μ and λ

Controller Parameter	Kp	K_i	K_d	mp %	Tr	Ts	Lamda(λ)	Mu(μ)
PSO-FOPID values	10.4795	1.68142	8.46935	0	0.00383	0.00693	0.716997	0.0122554
PSO-PID values	9.12192	1.37863	5.94026	0.0329	0.0177	0.00857		

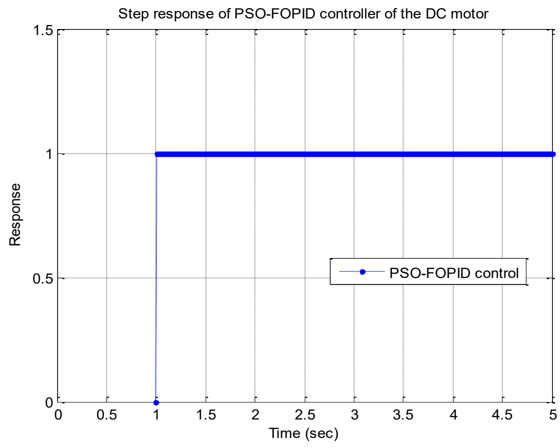


Figure 6. The DC motor unit step response for the PSO-FOPID controller

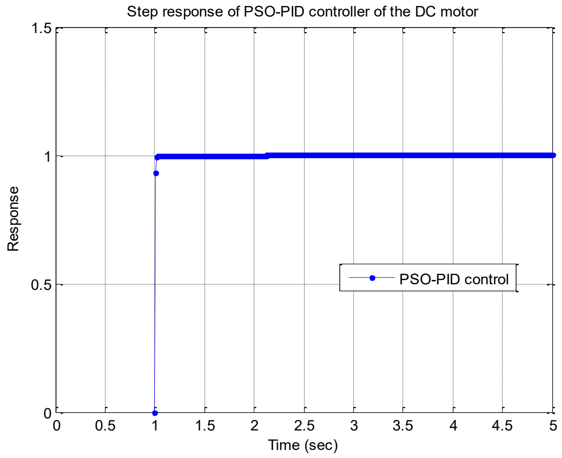


Figure 7. The DC motor unit step response for the PSO-PID controller

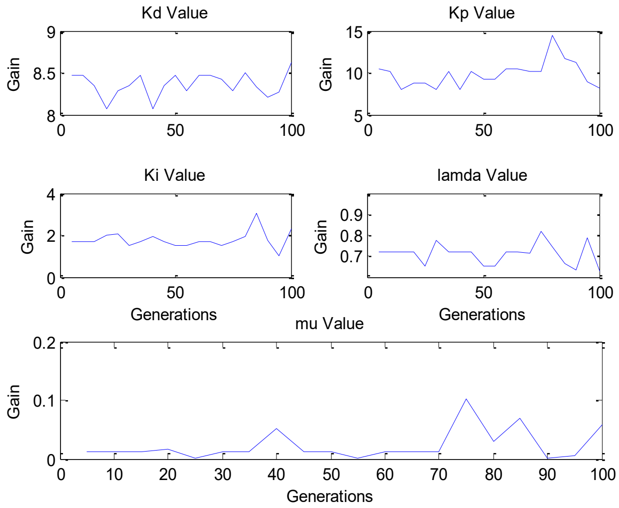


Figure 8. Generating the values of the Kp, Ki, Kd, λ and μ of the PSO- FOPID controller

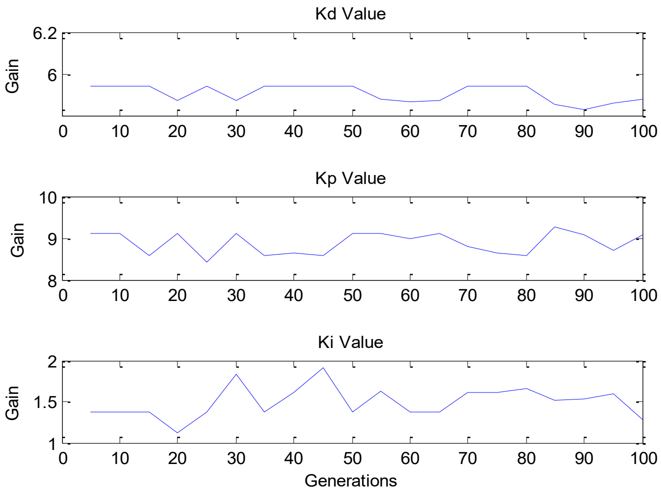


Figure 9. Generating the values of the Kp, Ki, Kd of the PSO- PID controller

6. CONCLUSIONS

In this paper the PSO algorithm is conjugated with the FOPID controller to control the speed of DC motor. The controlling system which based on the PSO algorithm is modelled and simulated using MATLAB (Simulink version 15) software. Simulation results show that the role of such algorithm is obvious in choosing the optimum controller performance parameters. Due to the fractional values of the added parameters (integral order λ and derivative order μ) for the proposed controller, the system performance is enhanced. In comparison with the PSO-PID controller, the obtained results of the PSO-FOPID controller show performance enhancement of 14%, 21%, 24.5%, 78%, and 19.3% in the values of the parameters K_p, K_i, K_d, Tr, and Ts respectively. These improvements in the proposed controller parameters clarify the high flexibility and robustness of the designed system.

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