Design Optimal Fractional Order PID Controller Utilizing Particle Swarm Optimization Algorithm and Discretization Method

Abdelelah Kidher Mahmood, Bassam Fadel Mohammed

Abstract**—*In this paper particle swarm optimization algorithm has been applied todesign fractional order PID (FOPID)controllerwhich has five unknown parameters to be tuned anddetermined by minimizing a given integral of timeweightedabsolute error (ITAE) as a fitness function. The FOPIDcontroller is a special kind of PID controller whose derivative andintegral order are fractional rather than integer which has fivetuned parameters.The closed loop systemfor a plant cascadedwith the fractional order PID ($PI^{\lambda}D^{\mu}$) controller has been builtutilizing a MATLAB/Simulink with applicationof intelligentoptimization algorithm (PSO) asa sub program. The parameters of the $PI^{\lambda}D^{\mu}$controller found and injected to the controller structure. Themain specification of this method is that the all five parameters of $PI^{\lambda}D^{\mu}$controller have been found directly without spreading the steps ofcomputation. The results showperformance of the closed loopsystem with FOPID controller is much better than integer orderPID controller for the same system and with better robustness.ThePI$^{\lambda}D^{\mu}$controller converted to z domain and programing toPIC microcontroller using new PIC Development Board.***

Index Terms**—*Fractional calculus,fractional order controller, fractional order toolbox for MATLAB, MATLAB Simulink, PSO algorithm, continued fractionexpansion(CFE), programing in C,PIC microcontroller.***

I. INTRODUCTION

Theimportant requirementsfor a closed loopcontrol systemincludingthe controller is to maintain the stability and robustness through the rejection of the disturbance andelimination of noise. The most popular controllers is the PID controllers which has parameters to be tuned to get a wellspecifications for the system both in time domain andfrequency domain.

The PID controller that are significantly used in theindustries and manufactures and in other domesticequipment's, which has three parameters to be tuned. Tuning PIDcontroller is most importunate issue in industrial and process controllers due to its ability to tune the few parameters likeproportional, integral and derivative manually or self-tune automatically. According to the Japanelectricmeasuring instrument manufacture's association in 1989, PID controller is used in more than 90% of the control loop. As anexample for the application of PID controller in industry,slow industrial process can be pointed, low percentageovershoot and smallsettling time can be obtained by usingthis controller. In feedback control systems the controllerfunction has ability to eliminate steady state offsets throughderivative action.

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The derivative action in the control loopwill improve the damping and therefore accelerating thetransient response. Many theoretical and industrial studieshave been done in PID controller setting rules like Ziegler andNichol's in 1942 proposed a method to set the PID controllerparameter Hägglund and Åström in 1955 and in 1999changing in the technique have been introduced by them. By generalizing the derivative and integer orders, from theinteger field to non-integer numbers, the fractional order PIDcontrol is obtained [1]. The performance of the PID controllercan be improved by making the use of fractional orderderivatives and integrals. This flexibility helps the designmore robust system. The most important advantages of the $PI^{\lambda}D^{\mu}$ controller is the better control of dynamical systemsand less sensitive to changes of parameters of a control system[2]. Before using the fractional order controller in design anintroduction to the fractional calculus is required. The firsttime, calculus generation to fractional, was proposedLeibniz and Hopital for the first time after words, the systematicstudies in this field by many researchers such as Liouville1832, Holmgren 1864 and Riemann 1953 were performed[1]. Due to widespread usage ofPID controller in industriesand product manufactures so researchers always motivated tolook for abettor and suitable design method or alternativecontroller[3]. For example, the fractional order algorithm forthe control of dynamic systems has been introduced byutilization of CRONE (French abbreviation for CommandRobusted'Ordre Non Entier), over the PID controller, whichhas been demonstrated by Oustaloup [4]. Podlubny hasproposed a generalization of the PID controller as $PI^{\lambda}D^{\mu}$ controller which is known as fractional order PID controller,where λ is the non-integer order of integrator and μ is thenon-integer order of the differentiatorterm. He alsodemonstrated that the $PI^{\lambda}D^{\mu}$ controller has better responsethan classical PID controller [5]. Frequency domainapproaches of $PI^{\lambda}D^{\mu}$ controller are studiedin [6]. Also many valuable studies have been done forfractional order controllers and their implementations in[7].Crucial importance of tuning of the controllers cannot beunderestimated.Thus, many tuning techniques for obtainingthe parameters of the controllers were introduced during lastfew decades. Tuning methods of $PI^{\lambda}D^{\mu}$ controllers are recent research subject. Most of the researchers orientedto theclassical optimization and intelligent methods [8].Sometuning rules for robustness to plant uncertainty for PI^{λ}controller are given in [9].However in order to achieve betterresults, there are still needs for new methods to obtain theparameters of $PI^{\lambda}D^{\mu}$ controllers.

In this paper the Particle Swarm Optimization (PSO)algorithm has been used to tune the parameter of $PI^{\lambda}D^{\mu}$controller in order to get an optimum time domainspecifications in which integral of time weighted absoluteerror (ITAE) has been minimized and the results comparedwith conventional PID and with some other methods like theproposed method by (Vineet Shekher, Pankaj Rai and Om Prakash) [1], in which the parameters of $PI^{\lambda}D^{\mu}$ controller has been obtained in three steps (Ziegler and Nichol's method to find proportional K_p, integral K_i parameters, Åström-Hägglundmethod to find derivative parameter K_d and the remainedparameterλandμfound by optimization toolboxof the MATLAB "fsolve").While in our optimizationmethod, the five parameters found directly by utilizing PSO algorithm.

II. FRACTIONALCALCULUS

Fractional calculus is a generalization of integration and differentiation to non-integer order fundamental operator ${}_aD_t^r$, where a and t are the limits of the operation and $r \in R$. The continuous Integra-differential operator is defined as:

$$ {}_aD_t^r = \begin{cases} \frac{d^r}{dt^r} & : r > 0, \\ 1 & : r = 0, \\ \int_a^t (d\tau)^{-r} & : r < 0. \end{cases} \quad (1)$$

The three equivalent definitions most frequently used forthegeneralfractionaldifferintegralaretheGrünwald-Letnikov(GL)definition, the Riemann-Liouville (RL) and the Caputo definition. The GL definition is given by:

$$ {}_aD_t^r f(t) = \lim_{h \to 0} h^{-r} \sum_{j=0}^{\left[\frac{t-a}{h}\right]} (-1)^j \binom{r}{j} f(t - jh) \quad (2)$$

where [.] means the integer part. The RL definition is given as:

$$ {}_aD_t^r f(t) = \frac{1}{\Gamma(n-r)} \frac{d^n}{dt^n} \quad (3)$$

for ($n - 1 < r < n$) and where $\Gamma(.)$ is the Gamma function. The Caputo definition can be written as:

$$ {}_aD_t^r f(t) = \frac{1}{\Gamma(n-r)} \int_a^t \frac{f^{(n)}(\tau)}{(t-\tau)^{r-n+1}} d\tau \quad (4)$$

for ($n-1 < r < n$). The initial conditions for the fractional order differential equations with the Caputo derivatives are in the same form as for the integer-order differential equations.

In the above definition, $\Gamma(m)$ is the factorial function, defined for positive real m, by the following expression:

$$\Gamma(m) = \int_0^\infty e^{-u} u^{m-1} du \quad (5)$$

for which, when m is an integer, it holds that:

$$\Gamma(m+1) = m! \quad (6)$$

The definition of fractional derivative easily derives by taking an n order derivative (n suitable integer) of a m order integral (m suitable non integer) to obtain an $n - m = q$ order one:

$$\frac{d^q f(t)}{dt^q} = \frac{d^{n-m} f(t)}{dt^{n-m}} = \frac{1}{\Gamma(m) dt^n} \frac{d^n}{dt^n} \int_0^t (t-y)^{m-1} f(y) dy \quad (7)$$

It must be noted that for $q = 1$($n = 2$, $m = 1$), (7) becomes the canonical first order derivative.

Laplace transform of non-integer order derivatives is necessary for an optimal study.Fortunately, not very big differences can be found with respect to the classical case, confirming the utility of this mathematical tool even for fractional systems. Inverse Laplace transformation is also useful for time domain representation of systems for which only the frequency response is known. The most general formula is the following:

$$L\left\{\frac{d^m f(t)}{dt^m}\right\} = s^m L\{f(t)\} - \sum_{k=0}^{n-1} s^k \left[\frac{d^{m-1-k} f(t)}{dt^{m-1-k}}\right] \quad (8)$$

where n is an integer such that $n - 1 < m < n$.

The above expression becomes very simple if all the derivatives are zero [10]:

$$L\left\{\frac{d^m f(t)}{dt^m}\right\} = s^m L\{f(t)\} \quad (9)$$

A fractional order system is that system described by the following fractional order differential equation:

$$ {}_{an}D^{\alpha n} f(x) + {}_{an-1}D^{\alpha n-1} f(x) + {}_{an-2}D^{\alpha n-2} f(x) + \cdots = {}_{bn}D^{\beta n} f(x) + {}_{bn-1}D^{\beta n-1} f(x) + {}_{bn-2}D^{\beta n-2} f(x) + \cdots \quad (10)$$

where$D^{\alpha n} = {}_0D_t^{\alpha n}$, is called the fractional derivative of order αn with respect to variable t and with the starting point $t = 0$, [11].

III. FRACTIONAL ORDER PID (FOPID) CONTROLLER

The integro-differential equation defining the control action of a fractional order PID controller is given by:

$$u(t) = K_p e(t) + K_i D^{-\lambda} e(t) + K_d D^{\mu} e(t) \quad (11)$$

where $e(t)$ is the error signal of a tracking system, $u(t)$ is the control signal, Applying Laplace transform to this equation with null initial conditions, the transfer function of the controller can be expressed by:

$$C_f(s) = K_p + K_i s^{-\lambda} + K_d s^{\mu} = K \frac{\left(\frac{s}{w_f}\right)^{\lambda+\mu} + \frac{s\delta_f s^{\lambda}}{w_f} + 1}{s^{\lambda}} \quad (12)$$

In a graphical way,the control possibilities using a fractional-order PID controller are shown in Fig. 1, extending the four control points of the classical PID to the range of control points of the quarter-plane defined by selecting the values of λ and μ [12].

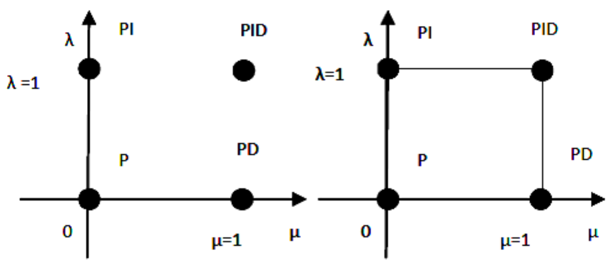


Fig 1. Fractional-order PID vs classical PID

IV. PARTICLE SWARM OPTIMIZATION (PSO)

Aspecial approach of swarm intelligence based on simplified simulations of animals' social behaviors, such as fish schooling and bird flocking, is the particle swarm optimization (PSO) algorithm. PSO is a self-adaptive search optimization. The goal of particle swarm optimization is to solve the computationally hard Optimization problems, where it is a robust optimization technique based on the movement and intelligence of swarms and applied successfully to a wide variety of search and optimization problems. It was inspired from the swarms in nature such as swarms of birds, fish, etc. The PSO developed in 1995 by James Kennedy and Russ Eberhart. The algorithm adopted uses a set of particles flying over a search space to locate a global optimum, where a swarm of n particles communicate either directly or indirectly with one another using search directions, in each iteration of PSO, each particle updates its position based on three components, by determines its velocity using, previous velocity, best previous position, and the best previous position of its neighborhood. Fig. 2, illustrate the flow chart of PSO algorithm. The basic concept of PSO lies in accelerating each particle toward the best position found by it so far (*pbest*) and the global best position (*gbest*) obtained so far by any particle, with a random weighted acceleration at each time step, this is done by (13) and (14):

$$v_{t+1} = w * v_t + c_1 * rand(0,1) * (pbest - x_t) + c_2 * rand(0,1) * (gbest - x_t) \quad (13)$$

$$x_{t+1} = x_t + v_{t+1} \quad (14)$$

where: *gbest* = Global Best Position.
pbest = Self Best Position.
C_1 and C_2 = Acceleration Coefficients.
w = Inertial Weight.

Once the particle computes the new x_t it then evaluates its new location. If fitness (x_t) is better than fitness (*pbest*), then *pbest* = x_t and fitness (*pbest*) = fitness (x_t), in the end of iteration the fitness (*gbest*) = the better fitness (*pbest*), and *gbest* = *pbest* [13].

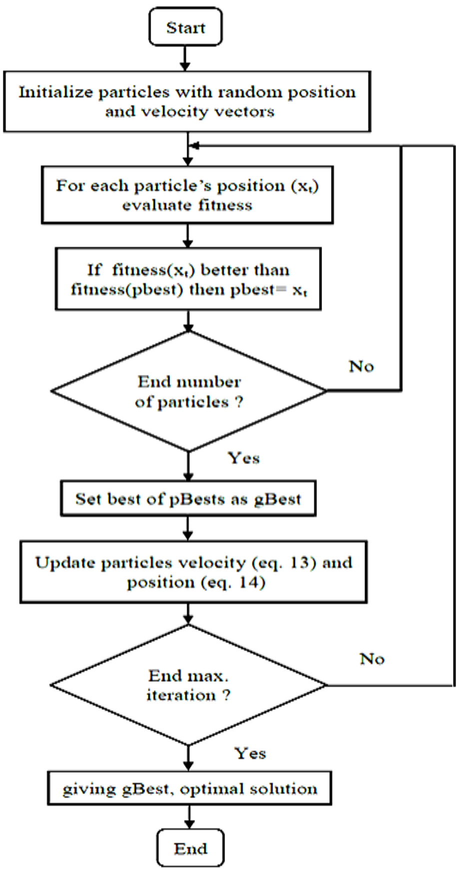


Fig 2. Flow chart of PSO algorithm

V. DESIGN OF PI$^{\lambda}$D$^{\mu}$ CONTROLLER USING OPTIMAL PSO ALGORITHM

Theclosed loop system with negative unity feedback control system simulation shown in Fig. 3 with MATLAB, where the fractional order PID (FOPID) controller *Gc*(*s*) implemented by using fractional control toolbox [14], the integral of time weighted absolute error (ITAE) as objective function and the plant *G*(*s*) were implemented by MATLAB toolbox.

$$G_c(s) = K_p + \frac{K_i}{s^{\lambda}} + K_d s^{\mu} \quad (15)$$

$$G(s) = \frac{1}{(s^3 + 3s^2 + 2s)} \quad (16)$$

$$ITAE = \int_0^{\infty} t|e(t)|dt \quad (17)$$

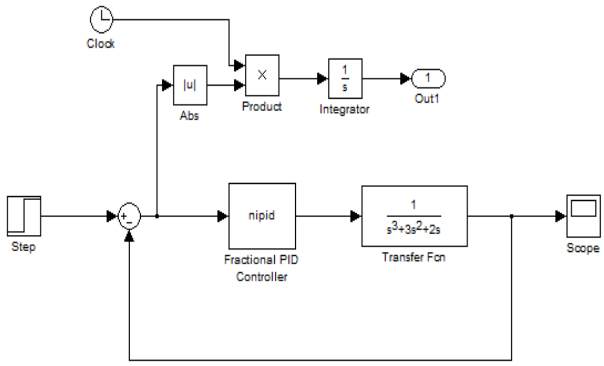


Fig 3. Negative unity feedback FOPID control system

The PSO algorithm method has been implemented as M file which interconnected to simulink model, where the FOPID controller parameters are computed and feed to the GUI of the controller. The optimization performed with this initial parameter, number of particles 30, number of dimensions 5, maximum iteration 50, C_1=1, C_2=3, with the objective functionITAE. The initial values of five parametersK_p, K_i, K_d, λ,and μ of the fractional order PID controller will be generate in PSO program and submit in simulation diagram in Fig. 3, and running the simulation automatically then compute the objective function ITAE and go back with value of ITAE to PSO program to improve the value of K_p, K_i, K_d, λ, and μ, and go on. In the end of iteration the five parameters of the fractional order PID controller K_p, K_i, K_d, λ, and μ has been obtained directly according to the minimum value of objective function ITAE. The obtained results shown in the Table I.

Table I. Parameters of FOPID controller obtained byPSOalgorithm

Tuning method and controller	**Parameters**				
	K_p	K_i	K_d	λ	μ
PSO algorithm, (FOPID)	98.1959	0	70.9573	0	1.4497

Step response of the system in Fig. 3 for the FOPID controller tuned by PSO algorithm in Table I, illustrated in Fig. 4.

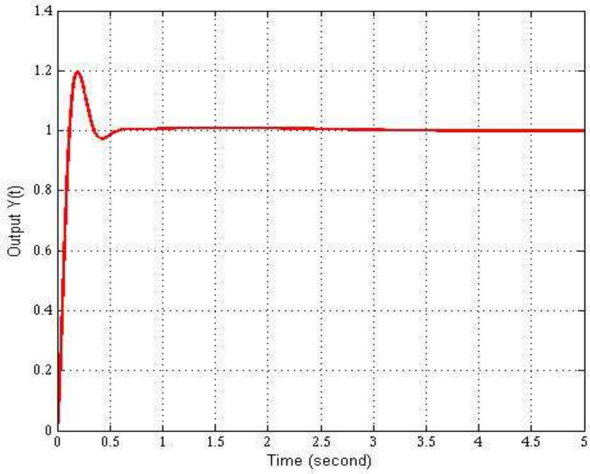


Fig 4.

Whereas the results that obtained in the proposed method by authors in [1] forλand μ and other parameters of the controller for different methods like Ziegler-Nichol's, Åström-Hägglund and the refsolver optimization method, shown in the Table II.

Table II. Parameters of PID & FOPID controllers obtained by different methods

Tuning method and controller	Parameters				
	K_p	K_i	K_d	λ	μ
Ziegler-Nichol's, (PID)	3.6	1.63	1.98	1	1
Åström-Hägglund, (PID)	4.59	1.51	3.48	1	1
Proposed method in [1], (FOPID)	3.6	1.63	3.75	1.39	0.79

Step response of the system in Fig. 3, for each controller in Table II, illustrated in Fig.5.

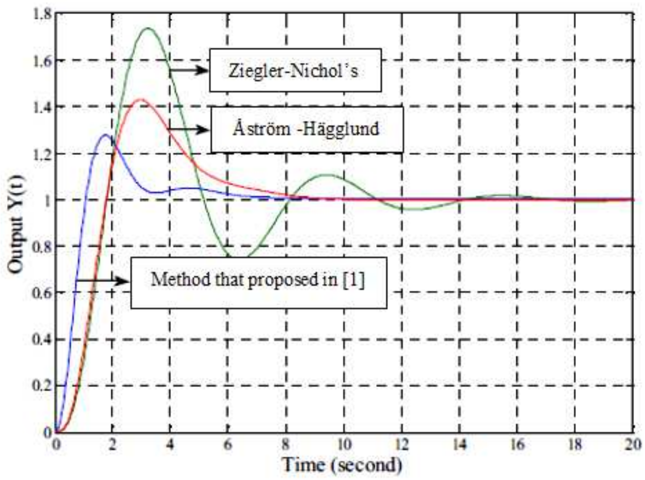


Fig 5. Step response of PID & FOPID control systems tuned by differentmethods

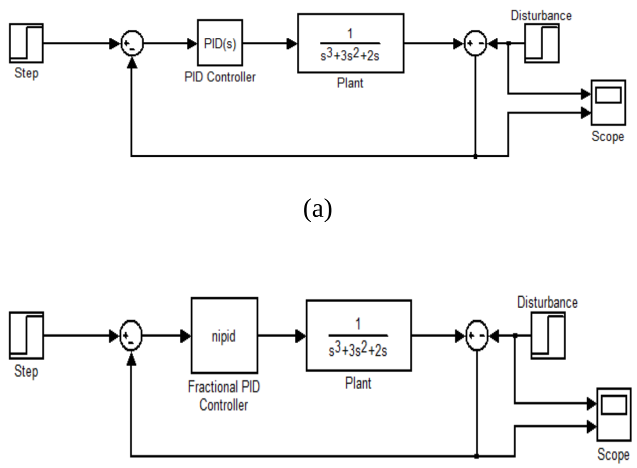
Step response of the system gives valuable information such as maximum overshoot (Mo.s %), rise time (Tr), peak time (Tp) and settling time (Ts). It can be observed from the Table III, that the PSO algorithm method gives much better time domain performance with respect to the proposed methods in [1],specially for maximum overshoot(Mo.s%), rise time(Tr), peak time(Tp) and settling time(Ts).

Table III. Step response specification of PID & FOPID controllers

Tuning method and controller	Step response specification			
	Maximum overshoot (Mo.s %)	***Peak time (Tp)***	***Rise time (Tr)***	***Settling time (Ts)***
Ziegler-Nichol's,(PID)	73.5	1.67	3.25	12.5
Åström-Hägglund,(PID)	43	1.66	2.95	6.67
Proposed method in [1], (FOPID)	27.9	0.96	1.74	4.65
PSO algorithm, (FOPID)	19.7	0.195	0.084	0.476

VI. ROBUSTNESS TEST OF THE SYSTEM

The main advantages of the fractional order controller are the robustness of the system whenever a disturbance occurred and in case of the uncertainty in the parameters. The system which has been designed tested by two type of disturbance one is when a load or perturbation was applied on the system.The second when selected parameters are deviated from its original value by 20%.Fig. 6 shown the simulation system for PID and FOPID controller with disturbance putting after the plant, because if the disturbance put between the controller and the plant the system never affect (i.e. the system is very robust).

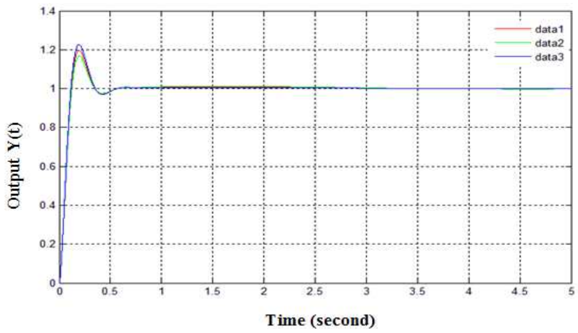


(a)

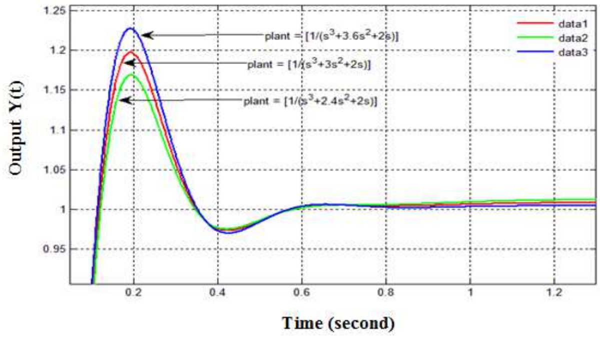
(b)

Fig 6. (a) System for PID controller with disturbance, (b) System for FOPID controller with disturbance

Fig. 7 shown that the system for FOPID controller remains stable and very little effect on the time domain performance which means the sensitivity is very much low considering the deviated parameter from is original value.



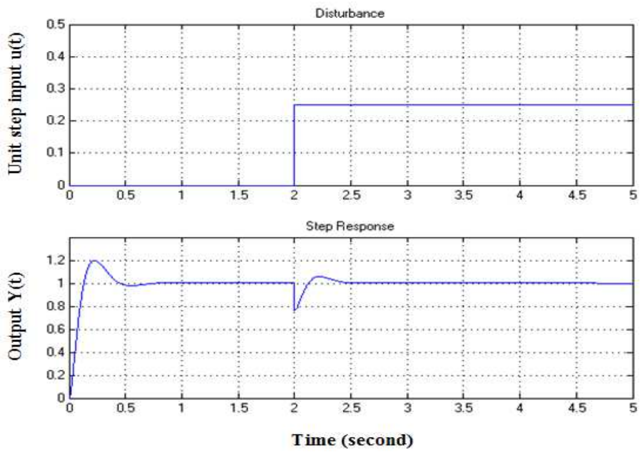
(a)



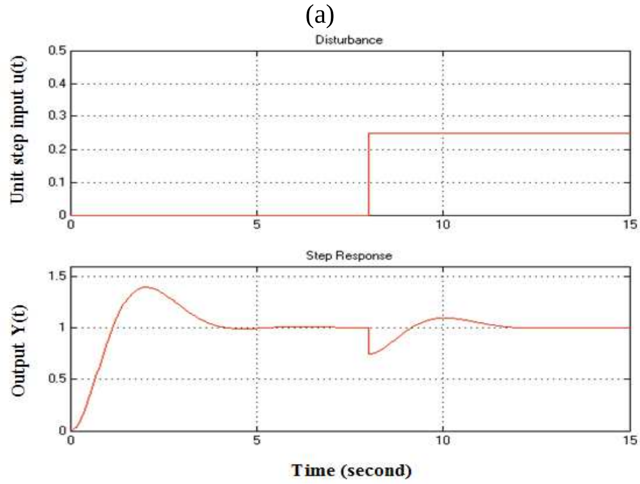
(b)

Fig 7. (a) Step response for system FOPID controller, (b) Focus (zoom) on (a)

Fig.8shown the system sensitivity for FOPID controller is very low considering the disturbance effect compared with PID controller.



(a)



(b)

Fig 8. (a) Step response for system FOPID controller with disturbance, (b) Step response for system PID controller with disturbance

Table IV shown the time domain performance for the system FOPID controller with disturbance Fig. 8(a), is better than the system PID controller with disturbance Fig. 8(b).

Table IV. Step response specification of PID & FOPID controller with disturbance

System &tuningmethod ofcontroller	**Step response specification**			
	Maximum over shoot (Mo.s %)	***Peak time (Tp)***	***Rise time (Tr)***	***Settling time (Ts)***
Åström-Hägglund (PID)	40	2	0.76	11.5
PSO algorithm,(FOPID)	19.7	0.23	0.091	2.38

VII. DISCRETIZATION OF $PI^{\lambda}D^{\mu}$ CONTROLLER

In this paper used the direct discretization method include the continued fraction expansion (CFE) of Al-Alaoui operator, that is a new mixed scheme of Euler and Tustin operators. The resulting discrete transfer function, approximating fractional-order operators, can be expressed as:

$$D^{\pm r}(z) \approx \left(\frac{8}{7T}\right)^{\pm r} \text{CFE}\left\{\left(\frac{1-z^{-1}}{1+\frac{z^{-1}}{7}}\right)^{\pm r}\right\}_{p,q}$$

$$= \left(\frac{8}{7T}\right)^{\pm r} \frac{P_p(z^{-1})}{Q_q(z^{-1})} \qquad (18)$$

Where T is the sample period, P and Q are polynomials of degrees p and q, respectively, in the variable z^{-1}[15], [16], [17].

By the parameters in the Table I, the continuous transfer function of $PI^{\lambda}D^{\mu}$ controller can be expressed as:

$$G_c(s) = 98.1959 + 70.9573s^{1.4497} \qquad (19)$$

The resulting transfer function of $G_c(s)$ was obtained by using (18) and for T = 0.015 second and $p = q = n = 5$, has the following form:

$$C_c(z) = \frac{4.744e07 - 1.407e08z^{-1} + 1.514e08z^{-2}}{1247 - 1639z^{-1} + 447.4z^{-2}}$$
$$\frac{-6.995e07z^{-3} + 1.221e07z^{-4} - 3.571e05z^{-5}}{+65.91z^{-3} - 13.97z^{-4} - z^{-5}} \qquad (20)$$

The transfer function (20) was rewritten to difference equation and was coded by PIC Micro C and then loaded to PIC18F45K22 memory by using the new PIC Development Board (EasyPIC v7 Development System) shown in Fig. 9 [18].

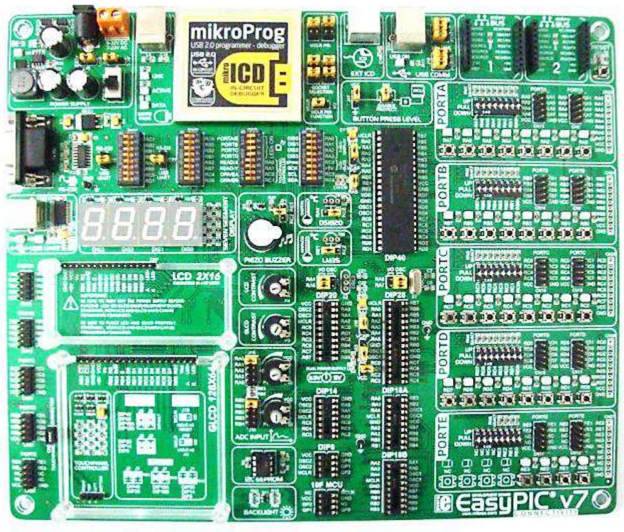


Fig 9.

The PIC Development Board for 250 Microchip PIC MCUs in DIP packaging. It features USB 2.0 programmer/debugger and over 17 essential modules necessary in development. PIC18F45K22 is the new defaultchip of EasyPIC™ v7! It has 16 MIPS operation, 64K bytes oflinear program memory, 3896 bytes of linear data memory,and support for a wide range of power supply from1.8V to5V. It's loaded with great modules: 36 General purpose I/Opins, 30 Analog Input pins (AD), Digital-To-Analog Converter(DAC), support for Capacitive Touch Sensing using Charge Time Measurement Unit (CTMU), three 8-bit timers and four16-bit timers. It also has pair of CCP,Comparators andMSSP modules (which can be either SPI or I^2C). The discrete step response of the system in Fig. 3, illustrated in Fig. 10.

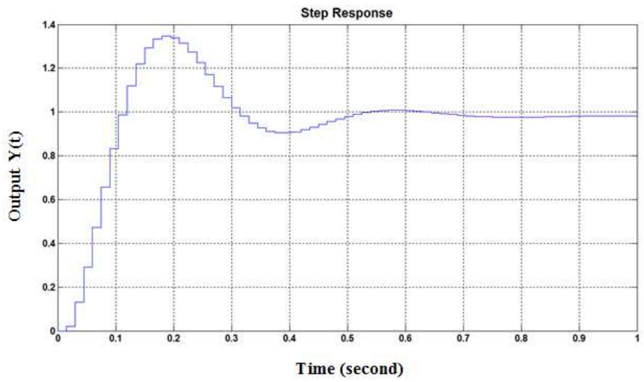


Fig 10. Discrete step response of negative unity feedback FOPID control system

VIII.CONCLUSION

In this work the PSO algorithm has been utilized to find the optimal parameters of FOPID controller which minimizing the ITAE.The major prosperities of our proposed method, the five parameters K_p, K_i, K_d, λ, and µ are found directly without spreading in steps and without need of finding the first three term of the controller. The system with FOPID controller exhibit good time domain response as compared with the integer order PIDcontroller. Besides the system becomes more robust in which a good rejection of the disturbance and less sensitive to deviation in system parameters.The time domain performance for the system exhibits a like response for both continuous and discrete time system.

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