# A Novel Evolutionary Tuning Method for Fractional Order PID Controller

Subhransu Padhee, Abhinav Gautam, Yaduvir Singh, and Gagandeep Kaur

**Abstract— PID controller is a well known controller which is used in most control applications. Around 90% control applications use PID controller as the controlling element. The tuning of PID controller is mostly done using Zeigler-Nichols tuning method. But there are some inherent drawbacks of Ziegler-Nichols based tuning. For the optimal tuning of controller, the tuned values have to be changed using computer simulation to meet the process needs. In PID controller the derivative and the integral order are in integer. Fractional order PID (FOPID) is a special kind of PID controller whose derivative and integral order are fractional rather than integer. The key challenge of designing FOPID controller is to determine the two key parameters λ (integral order) and μ (derivative order) apart from the usual tuning parameters of PID using different tuning methods. Both λ and μ are in fraction which increases the robustness of the system and gives an optimal control. This paper proposes a novel tuning method for tuning λ and μ of FOPID using genetic algorithms.**

***Index Terms*—Fractional order PID, genetic algorithms, PID, Ziegler-Nichols**

## I. Introduction

PID controllers have been used for several decades in industries for process control applications. The reason for their wide popularity lies in the simplicity of design and good performance including low percentage overshoot and small settling time for slow process plants [1]. The performance of the PID controllers can be improved by making use of fractional order derivatives and integrals. This flexibility helps to design more robust control system. In fractional order PID (FOPID) controller, the integral and derivative orders are usually fractional. In FOPID besides $K_p$, $K_i$, $K_d$ there are two more parameters λ and μ, the integral and derivative orders respectively. If λ =1 and μ =1, then it becomes integer PID. If λ and μ are in fractions then it becomes fractional order PID.

Many random search methods, such as genetic algorithm (GA) have recently received much interest for achieving high efficiency and searching global optimal solution in problem space [2]. Due to its high potential for global optimization, GA has received great attention in control systems such as the search of optimal PID controller parameters.

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## II. Integer and Fractional Order PID Controller

### A. Integer Order PID Controller

The mnemonic PID refers to the first letters of the names of the individual terms that make up the standard three-term controller. These are P for the proportional term, I for the integral term and D for the derivative term in the controller. Three-term or PID controllers are probably the most widely used industrial controller. Even complex industrial control systems may comprise a control network whose main control building block is a PID control module. The three-term PID controller has had a long history of use and has survived the changes of technology from the analogue era into the digital computer control system age quite satisfactorily. It was the first (only) controller to be mass produced for the high-volume market that existed in the process industries. Eq(1) shows the time domain equation of ideal PID controller.

$$u(t) = K_c\left(e(t) + \frac{1}{\tau_i}\int_0^t e(t)dt + \tau_d\frac{de(t)}{dt}\right) \quad (1)$$

e(t) is the error signal, u(t) is the controller output, $K_c$ is the controller gain, $\tau_i$ and $\tau_d$ are integral gain and derivative gain respectively. Eq(2) shows the Laplace domain equation of ideal PID controller.

$$G_{PID}(s) = \frac{u(s)}{e(s)} = K_c\left(\frac{\tau_i\tau_d s^2 + \tau_i s + 1}{\tau_i s}\right) \quad (2)$$

Eq(3) represents the Laplace domain expression of real PID controller.

$$G_{PID}(s) = \frac{u(s)}{e(s)} = K_c\left(\frac{\tau_i s + 1}{\tau_i s}\right)\left(\frac{\tau_d s + 1}{1 + \tau_f s}\right) \quad (3)$$

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### B. Fractional Calculus

The concept of fractional order controller means controllers can be described by fractional order differential equations. Of the several definitions of fractional derivatives, the Grunwald- Letnikov and Riemann-Liouville definitions are the most used. These definitions are required for the realization of discrete control algorithms.

$$D_t^{v} f(t) = \begin{cases} \dfrac{1}{\Gamma(-v)} \displaystyle\int_a^t (t-x)^{-v-1} f(\tau) d\tau & v<0 \\ \dfrac{d^n f}{dt^n} & a = n \in N \\ \dfrac{d^n}{dt^n}\left[D_t^{-(n-\alpha)} f(t)\right] & 0 \le n-1 < \alpha < n \\ \dfrac{1}{\Gamma(n-\alpha)} \dfrac{d^n}{dt^n}\left[\displaystyle\int_a^t \dfrac{f(\tau)}{(t-\tau)^{\alpha-n+1}} d\tau\right] & \end{cases} \quad (4)$$

$\Gamma(.)$ is called the Euler's gamma function

$$\Gamma(x) = \int_0^{\infty} e^{-t} t^{x-1} dt, x > 0 \quad (5)$$

With special case when x = n

$$\Gamma(n) = (n-1)! \quad (6)$$

The Laplace transformation of Riemann-Liouville definition is discussed below.

$$L\left\{D^{-\alpha} f(t)\right\} = s^{-\alpha} F(s) \quad (7)$$

$$L\left\{D^{\alpha} f(t)\right\} = s^{\alpha} F(s) - \sum_{k=0}^{n-1} s^k \left[D^{\alpha-k-1} f(t)\right]_{t=0} \quad (8)$$

$$(n-1 \le \alpha \le n)$$

Eq(7) and Eq(8) represents the Laplace transformation of fractional order system.

### C. *Fractional Order PID Controller*

The fractional-order controller will be represented by fractional-order $PI^{\lambda} D^{\mu}$ controller with transfer function given by the following expression:

$$G_{FOPID}(s) = \frac{u(s)}{e(s)} = K_c\left(1 + \frac{1}{\tau_i s^{\lambda}} + \tau_d s^{\mu}\right) \quad (9)$$

Where λ and μ are an arbitrary real numbers, $K_p$ is amplification (gain), $T_i$ is integration constant and $T_d$ is differentiation constant. Taking λ=1 and μ=1, a classical PID controller is obtained. For further practical digital realization, the derivative part has to be complemented by first order filter. The filter is used to remove high frequency noise.

$$G_{FOPID}(s) = K_c\left(1 + \frac{1}{\tau_i s^{\lambda}} + \frac{\tau_d s^{\mu}}{\frac{\tau_d}{N} s + 1}\right) \quad (10)$$

The $PI^{\lambda} D^{\mu}$ controller is more flexible and gives an opportunity to better adjust the dynamics of control system. Its compact and simple but the analog realization of fractional order system is very difficult.

## III. PROBLEM FORMULATION

The transfer function considered for the implementation of PID and FOPID controller is given as

$$G(s) = \frac{40}{2s^3 + 10s^2 + 82s + 10} \quad (11)$$

To tune the PID controller, Zeigler-Nichols closed loop oscillation based tuning is used. After tuning the PID controller, the values of $K_c$, $T_i$ and $T_d$ comes out to be 6, 0.49 and 0.1225 respectively.

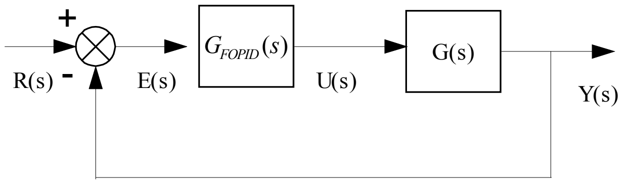


Fig. 1 Block diagram representation of system with fractional order PID controller

Figure 1 represents the integer order process with fractional order controller. In fractional order PID controller, apart from the three tuning parameters ($K_p$, $K_i$ and $K_d$) there are two additional tuning parameters that is λ and μ. λ is integral order and μ is derivative order. The range of λ and μ can be anything except 1, but these are in fraction. The three controller parameters ($K_p$, $K_i$ and $K_d$) of FOPID are tuned using Zeigler-Nichols method and to find the optimal values of λ and μ, genetic algorithm is used.

## IV. GENETIC ALGORITHM BASED TUNING OF FRACTIONAL ORDER PID CONTROLLER

### A. *Overview of genetic algorithm*

Genetic algorithm introduced by Holland in 1975 is used for optimization of existing rule base of fuzzy inference system. Genetic algorithm belongs to the group of optimization methods called as non traditional optimization methods. GA tries to imitate natural genetics and natural selection. The main philosophy behind GA is survival of the fittest. As a result GA is used primarily for maximization problems in optimization. GA don't suffer from the basic setback of traditional optimization methods such as getting stuck in local minima. This is because GA works on the principle of natural genetics, which incorporates large number of randomness.

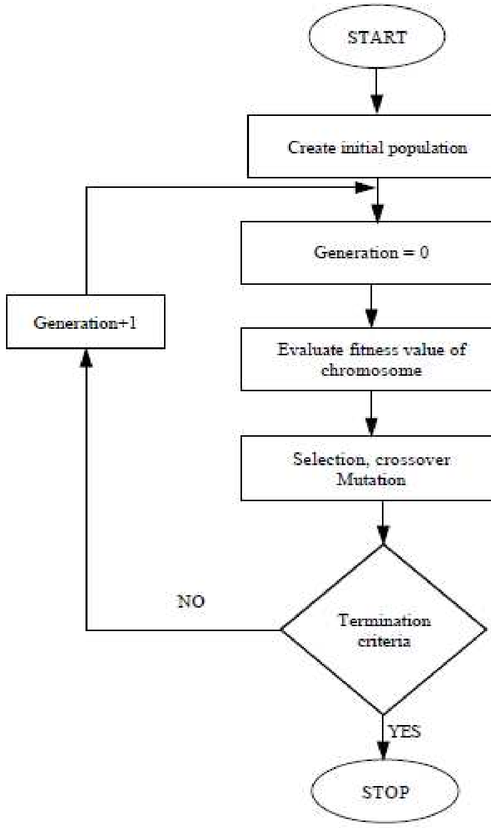


Fig. 2 Flow chart of genetic algorithms

Figure 3 shows the operational flow chart of a genetic algorithm. There are basically three operators of genetic algorithm, namely reproduction, crossover and mutation. This operators are used till, the genetic algorithm finds the optimal values.

*B. Optimal values of λ and μ using genetic algorithm*

Unlike optimization of PID controller, where the main objective was to find out the optimal set of values of $K_p$, $K_i$ and $K_d$, in fractional order PID controller the objective is to find out the optimal values of λ and μ. If λ and μ are changed, it affects the unit step response of the system because λ and μ represents the integral and derivative term. To find out the optimal values of λ and μ, genetic algorithm is used. Figure 5 represents the GA based finding of optimal values of λ and μ.

First of all a good set of values of λ and μ are considered as parents and to get the new set of values of λ and μ, crossover operation is performed between two good values of λ and μ. So the first generation of offspring's is produced. The total population increases and selection operation is performed on the population. The good chromosomes are kept where as the worst chromosomes are left out. Then the ISE value of the good chromosomes are checked to find out if these are the best chromosomes or optimal chromosomes, if the ISE value is not satisfied, then again crossover between the best chromosomes are performed, till the ISE value comes within limit. To get more optimal results, mutation operation is performed. By the above steps the optimal values of λ and μ are achieved.

*C. Parameters of genetic algorithm*

| Parameter | Values |
|---|---|
| Lower Bound [λ μ] | [0 0] |
| Upper Bound [λ μ] | [100 100] |
| Population Size | 40 |
| Crossover fraction | 0.8 |
| Mutation fraction | 0.01 |
| Stopping Criteria (iterations) | 100 |
| Stopping Criteria | ISE (integral square error) |

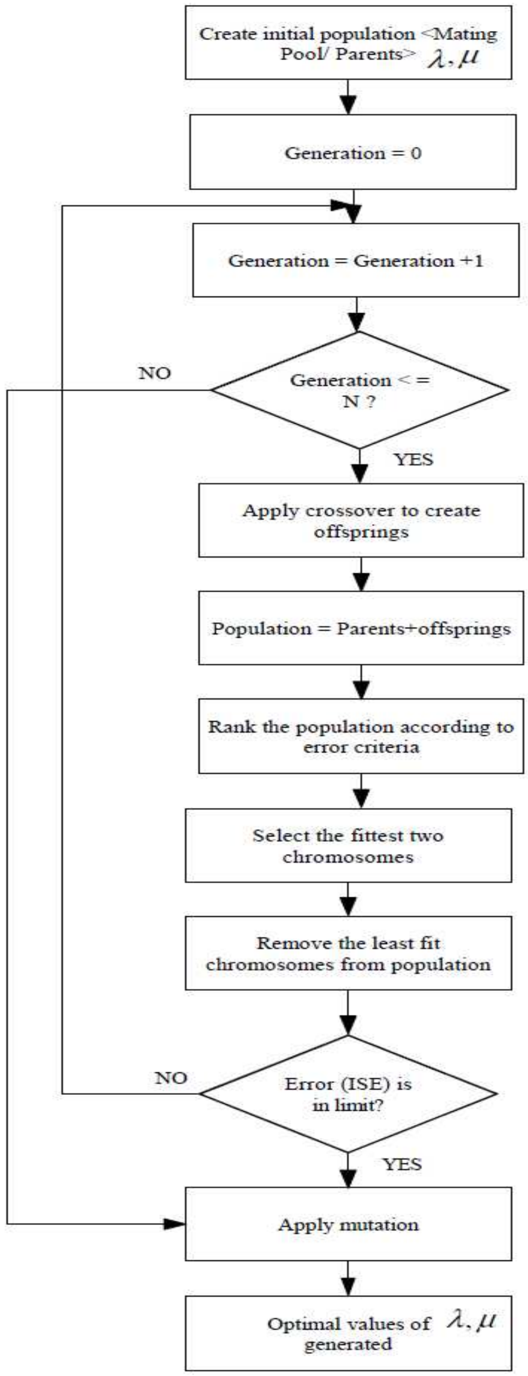


Fig. 3 Detailed flow chart of finding out optimal values of λ and μ of fractional order PID controller using genetic algorithm

Unlike other optimization problem, GA can get stuck in global optimum. To get rid of this problem, a condition checking of generation is performed.

## V. Simulations And testing

Figure 6 shows the unit step response of system using integer PID controller. In integer PID controller, the values of λ and μ are unity.

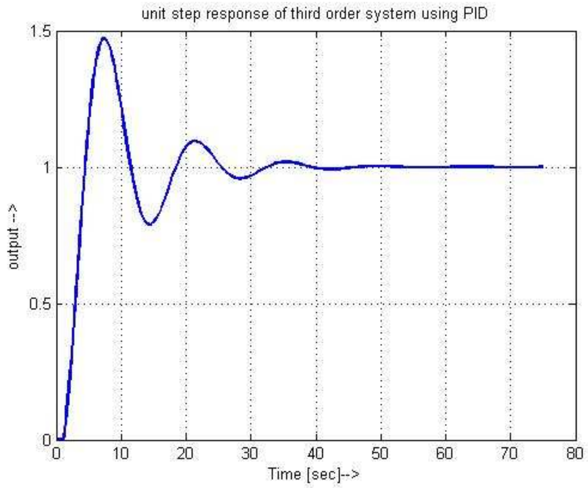


Fig. 4 Unit step response of system using integer PID controller

The step response shown above is unit step response of PID controller with the PID parameters tuned using Zeigler-Nichols closed loop oscillation based tuning method. The peak overshoot of PID controller is 47% and settling time is 23 sec.

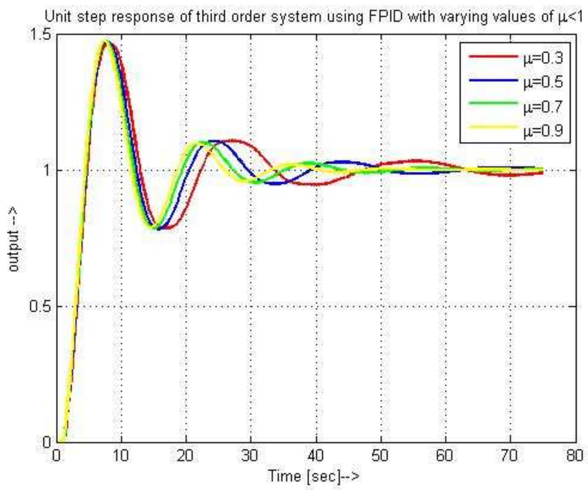


Fig. 5 Unit step response of system using fractional PID controller with varying variable μ (derivative order μ < 1)

Figure 5 shows the unit step response of system with fractional PID controller, where the derivative order μ and integral order λ of the fractional PID system are in fractions. The fractions can be less than or greater than 1. In figure 7 the integral order λ is kept constant where as derivative order μ is changed. Here derivative order μ <1.

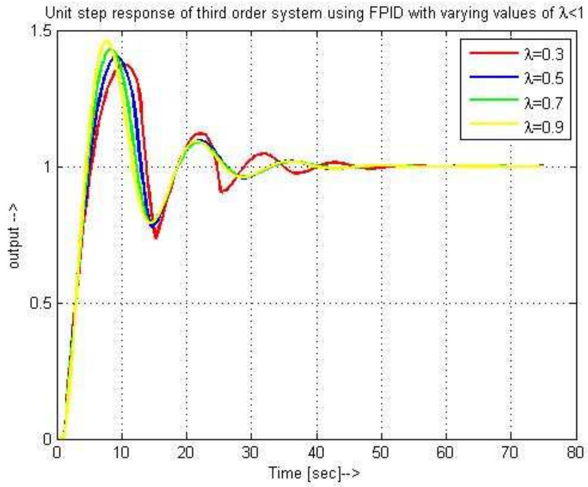


Fig. 6 Unit step response of system using fractional PID controller with varying variable λ (integral order λ < 1)

Figure 6 shows the unit step response of system using fractional PID controller where the integral order λ <1 and is variable and derivative order μ is kept fixed.

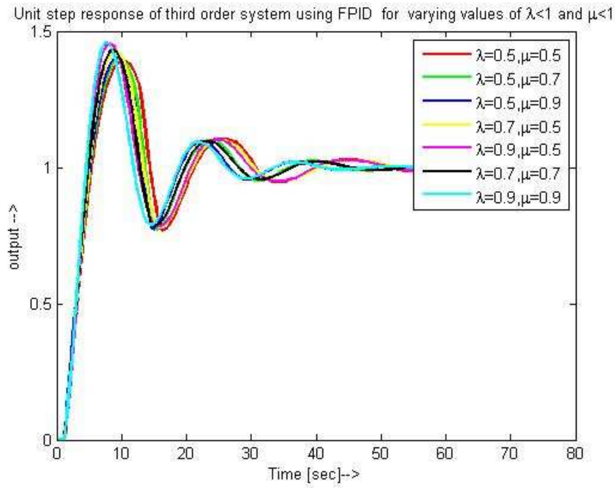


Fig. 7 Unit step response of system using fractional PID controller with varying variable μ and λ (derivative order μ < 1, integral order λ <1)

Figure 7 shows the unit step response of system using fractional PID controller where the integral order λ <1 and derivative order μ < 1.

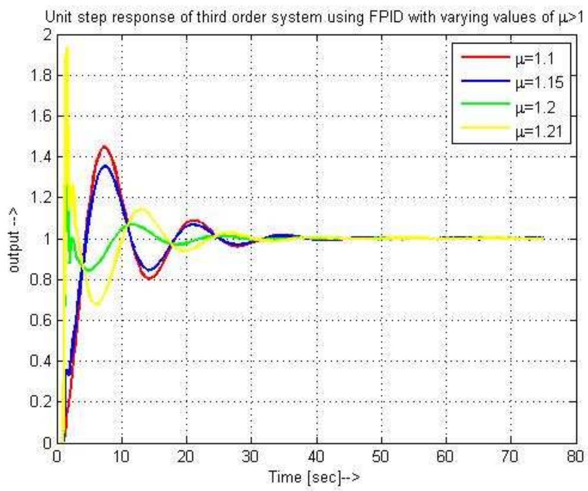


Fig. 8 Unit step response of system using fractional PID controller with varying variable μ (derivative order μ > 1)

Figure 8 shows the unit step response of system using fractional PID controller where derivative order μ > 1.

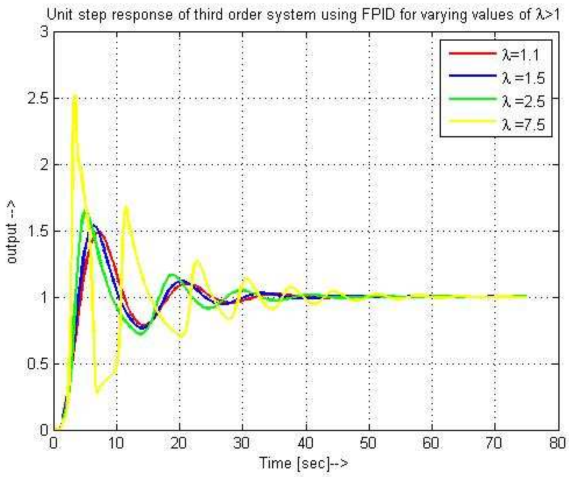


Fig. 9 Unit step response of system using fractional PID controller with varying variable λ (integral order λ > 1)

Figure 9 shows the unit step response of system using fractional PID controller where the integral order λ > 1

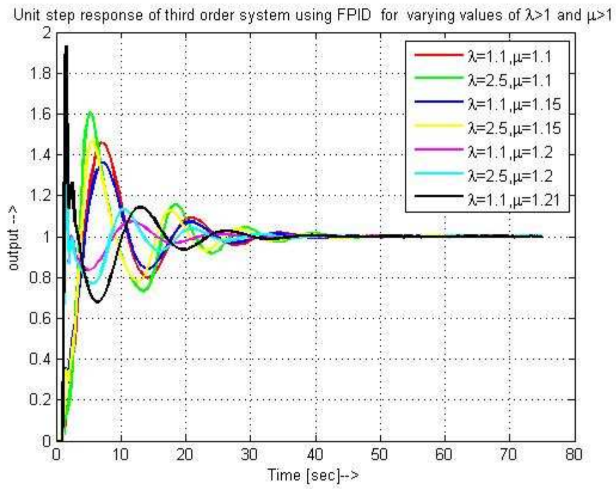


Fig. 10 Unit step response of system using fractional PID controller with varying variable μ and λ (derivative order μ > 1, integral order λ > 1)

Figure 10 shows the unit step response of system using fractional PID controller where the integral order λ > 1 and derivative order μ > 1.

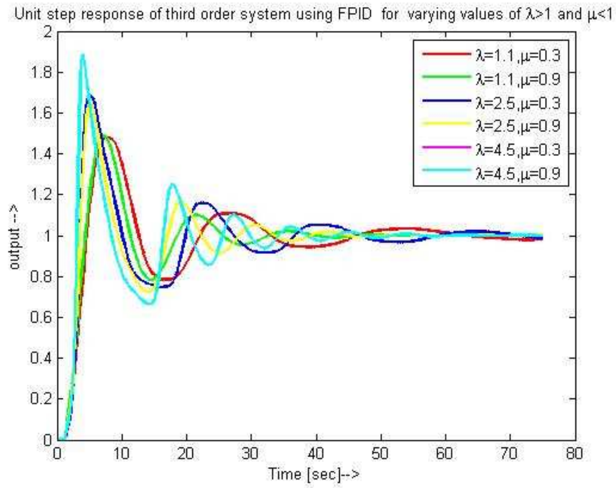


Fig. 11 Unit step response of system using fractional PID controller with varying variable μ and λ (derivative order μ < 1, integral order λ > 1)

Figure 11 shows the unit step response of system using fractional PID controller where the derivative order μ < 1, integral order λ > 1.

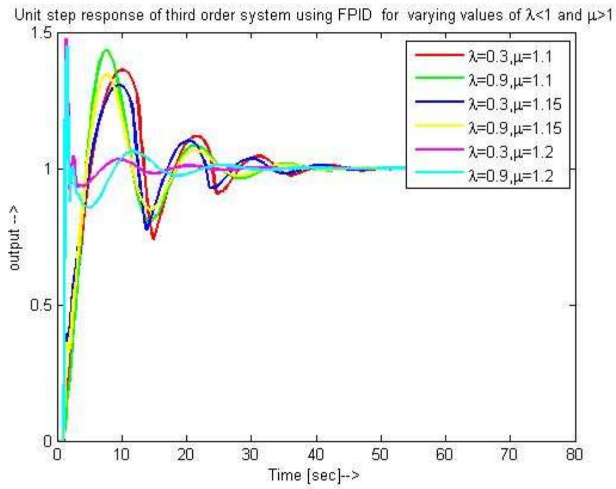


Fig. 12 Unit step response of system using fractional PID controller with varying variable μ and λ (derivative order μ > 1, integral order λ <1)

Figure 12 shows the unit step response of system using fractional PID controller where derivative order μ > 1, integral order λ < 1.

To find out the optimal value of derivative order μ and integral order λ, this paper proposes a novel method using genetic algorithm. The detailed flow chart of implementation of genetic algorithm to find out the optimal values of derivative order μ and integral order λ is shown in figure 5.

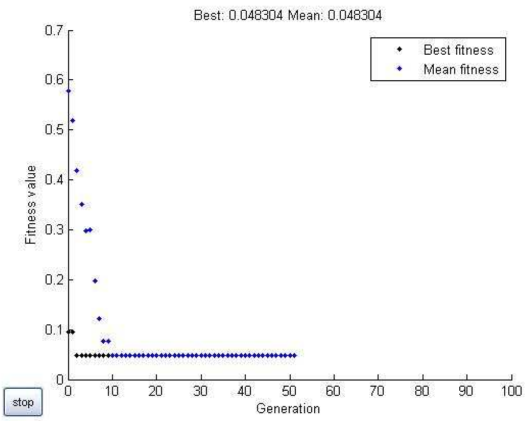


Fig. 13 Generation and fitness value graph of genetic algorithm

Figure 13 shows the graph between generation and fitness values.

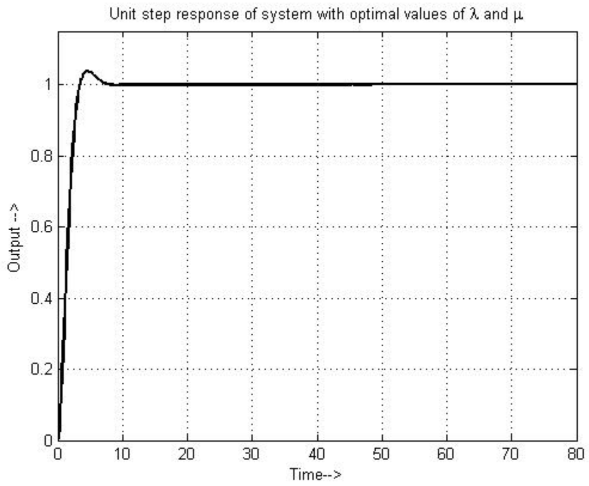


Fig. 14 Unit step response of system using fractional PID controller with optimal values of μ and λ

Figure 14 shows the unit step response of system using fractional order PID controller with optimally tuned values of μ and λ. The optimal values of μ and λ are generated using genetic algorithm. After the application of optimal tuning of μ and λ the peak overshoot and settling time of the system meets the design requirement.

## VI. RESULTS AND DISCUSSIONS

In previous section different configurations of FOPID controller is considered and the unit step response of the system with different configuration of FOPID is displayed. From the unit step response different transient parameters are calculated which are tabulated in this section. But to find out the optimal value of derivative order and integral order this paper takes help of genetic algorithm. Table 1 shows the different transient parameters of PID controller. The transient parameters considered are settling time, peak overshoot, ISE (integral square error) and ITAE (integral time absolute error).

Table 1
Time domain parameters of PID controller

| | | Ts | Mp | ISE | ITAE |
|---|---|---|---|---|---|
| 1 | λ=1, μ=1 | 23.65 | 47.15 | 2.35 | 53.7 |

Table 2 displays the transient response parameters of FOPID controller for μ < 1.

Table 2
Time domain parameters of FOPID controller with μ < 1

| | | Ts | Mp | ISE | ITAE |
|---|---|---|---|---|---|
| 1 | μ=0.3 | 41.742 | 46.0245 | 2.889 | 123.7 |
| 2 | μ=0.5 | 34.903 | 46.9016 | 2.659 | 89.85 |
| 3 | μ=0.7 | 25.293 | 47.2256 | 2.505 | 67.85 |
| 4 | μ=0.9 | 24.148 | 47.3067 | 2.405 | 56.97 |

Table 3 displays the transient response parameters of FOPID controller for derivative order μ = 1, integral order λ < 1

Table 3
Time domain parameters of FOPID controller with λ < 1

| | | Ts | Mp | ISE | ITAE |
|---|---|---|---|---|---|
| 1 | λ=0.3 | 27.228 | 37.3379 | 2.243 | 68.56 |
| 2 | λ=0.5 | 24.263 | 40.0857 | 2.253 | 56.97 |
| 3 | λ=0.7 | 24.031 | 42.9715 | 2.291 | 54.11 |
| 4 | λ=0.9 | 23.632 | 45.8391 | 2.335 | 53.58 |

Table 4 displays the transient response parameters of FOPID controller for derivative order μ < 1, integral order λ < 1

Table 4
Time domain parameters of FOPID controller with λ < 1 and μ < 1

| | | Ts | Mp | ISE | ITAE |
|---|---|---|---|---|---|
| 1 | λ=0.5, μ=0.5 | 35.404 | 38.7205 | 2.543 | 95.84 |
| 2 | λ=0.5, μ=0.7 | 26.266 | 39.7392 | 2.397 | 72.19 |
| 3 | λ=0.5, μ=0.9 | 24.703 | 40.1304 | 2.300 | 60.52 |
| 4 | λ=0.7, μ=0.5 | 28.661 | 42.1173 | 2.589 | 92.45 |
| 5 | λ=0.9, μ=0.5 | 34.542 | 45.3238 | 2.634 | 90.24 |

Table 5 displays the transient response parameters of FOPID controller for derivative order μ > 1

Table 5
Time domain parameters of FOPID controller with μ > 1

| | | Ts | Mp | ISE | ITAE |
|---|---|---|---|---|---|
| 1 | μ=1.1 | 23.268 | 44.6457 | 2.12 | 48.78 |
| 2 | μ=1.15 | 22.498 | 35.2118 | 1.42 | 38.21 |
| 3 | μ=1.2 | 13.085 | 44.9356 | 0.2717 | 12.58 |
| 4 | μ=1.21 | 20.750 | 93.3417 | 0.8473 | 29.49 |

Table 6 displays the transient response parameters of FOPID controller for integral order λ > 1

Table 6
Time domain parameters of FOPID controller with λ > 1

| | | Ts | Mp | ISE | ITAE |
|---|---|---|---|---|---|
| 1 | λ=1.1 | 23.4050 | 48.5314 | 2.381 | 54.04 |
| 2 | λ=1.5 | 27.4584 | 53.5798 | 2.475 | 56.14 |
| 3 | λ=2.5 | 26.0765 | 64.6047 | 2.713 | 63.91 |
| 4 | λ=7.5 | 37.8834 | 141.1292 | 5.643 | 121.3 |

Table 7 displays the transient response parameters of FOPID controller for derivative order μ > 1, integral order λ > 1

Table 7
Time domain parameters of FOPID controller with λ > 1 and μ > 1

| | | Ts | Mp | ISE | ITAE |
|---|---|---|---|---|---|
| 1 | λ=1.1, μ=1.1 | 22.925 | 45.8945 | 2.142 | 49.08 |
| 2 | λ=2.5, μ=1.1 | 25.475 | 60.6300 | 2.441 | 57.84 |
| 3 | λ=1.1, μ=1.15 | 22.096 | 36.1264 | 1.438 | 38.42 |
| 4 | λ=2.5, μ=1.15 | 24.189 | 46.7059 | 1.658 | 44.59 |
| 5 | λ=1.1, μ=1.2 | 13.319 | 44.7987 | 0.2839 | 13.54 |
| 6 | λ=2.5, μ=1.2 | 17.147 | 44.2505 | 0.4092 | 21.84 |
| 7 | λ=1.1, μ=1.21 | 20.628 | 93.2290 | 0.8556 | 30.17 |

Table 8 displays the transient response parameters of FOPID controller for derivative order μ < 1, integral order λ > 1

Table 8
Time domain parameters of FOPID controller with λ > 1 and μ < 1

| | | Ts | Mp | ISE | ITAE |
|---|---|---|---|---|---|
| 1 | λ=1.1, μ=0.3 | 41.357 | 47.7478 | 2.918 | 123.5 |
| 2 | λ=1.1, μ=0.9 | 23.860 | 48.6390 | 2.428 | 57.27 |
| 3 | λ=2.5, μ=0.3 | 41.870 | 68.5062 | 3.339 | 123.6 |
| 4 | λ=2.5, μ=0.9 | 30.375 | 64.9865 | 2.764 | 67.17 |
| 5 | λ=4.5, μ=0.3 | 40.946 | 102.1544 | 4.574 | 135.4 |
| 6 | λ=4.5, μ=0.9 | 32.814 | 88.3281 | 3.428 | 86.87 |

Table 9 displays the transient response parameters of FOPID controller for derivative order μ > 1, integral order λ < 1

Table 9
Time domain parameters of FOPID controller with λ < 1 and μ > 1

| | | Ts | Mp | ISE | ITAE |
|---|---|---|---|---|---|
| 1 | λ=0.3, μ=1.1 | 26.564 | 36.0403 | 2.021 | 63.14 |
| 2 | λ=0.9, μ=1.1 | 23.366 | 43.4405 | 2.098 | 48.6 |
| 3 | λ=0.3, μ=1.15 | 25.260 | 30.5292 | 1.344 | 48.47 |
| 4 | λ=0.9, μ=1.15 | 22.705 | 34.3791 | 1.403 | 38.11 |
| 5 | λ=0.3, μ=1.2 | 4.8701 | 47.5611 | 0.1939 | 5.328 |
| 6 | λ=0.9, μ=1.2 | 13.042 | 45.1063 | 0.2591 | 11.7 |

The above tables are shown for different combinations of of μ and λ. To find out the optimal value of μ and λ GA has been proposed.

## VII. CONCLUSIONS

This paper proposes a novel method of tuning the parameters of FOPID using genetic algorithm. The genetic algorithm finds the optimal value of derivative order and integral order of fractional order PID controller. With the help of fractional order PID controller, control systems responses can be designed with much more flexibility.

There are other soft computing based methods by which the optimal tuning values of FOPID can be obtained. Swarm intelligence methods like particle swarm intelligence (PSO) and ant colony optimization (ACO) can be used instead of evolutionary algorithms like GA. Fuzzy based method and adaptive neuro fuzzy based method can also be used to find the best fit values of μ and λ.

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