A Novel Method for Tuning PID Controller

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***Abstract*—This research proposed a new tuning technique to search efficiently Proportional Integral Derivative (PID) parameters, by locating near-optimal tuning solutions, which compensate for delay time. The purpose is that to minimize response time by optimized PID gains *Kp, Ki, Kd* within a deferent order model. Related to survey, numerous existing papers propose to optimize proportional gains by introducing various methods. Most of these works cannot achieve to find the best solution for optimization of different orders system. By using both proposed tuning with improved selective switching, it is possible to obtain a maximum optimization for any order system. Proposed tuning was applied by using 17 steps with less than 39 generation loops; each generation includes four loops calculation. Response time is measured and compared with previous times until reached to optimal gains, then fixed *Kp*,*K*i,*Kd*. The results show decreasing rise time to 0.0165s in the second order, and 0.119s in the third order with zero overshoot. Results prove that this method leads to more precise, effective, robust, optimization with less iteration and applicable to various plants. Furthermore, it is a quick, simple, powerful and more practical methodology, compared with PID toolbox tune.**

***Index Terms*—Iiteration; PID Controller; Response Time; Tuning.**

I. INTRODUCTION

Due to the extensive use of PID's in industry, tuning methods for PID controllers are always a topic of interest for process industries, as they provide an easy way to control any kind of process [1-3]. Tuning PID implies adjusting the controller's gains: proportional *Kp*; integral *Ki*; Derivative *K*d, whereas tuning controller refers to adjusting controller gains, in order to fulfil the performance specifications like margin of stability, transient response and bandwidth. Despite having only three parameters, it is difficult to tune these gains to get optimization without a systematic procedure. In fact, a visit to a process plant will usually show that a large number of the PID controllers are poorly tuned. The issue is that the controller obtains designed on the base of a plant display [4], [5-8] In the last five decades, many authors have proposed many tuning methods to obtain better performance. The early published literature surveyed basically focuses on classical methods such as the Ziegler–Nichols oscillation method, the Ziegler Nichols reaction curve method, the Cohen Coon curve method, and the Chien-Hrones-Reswich method. These classical methods are easy to use and are widely used in case of requiring a better disturbance response. However, they are deficient for performance processes and often unable to obtain optimal system responses and require additional adjustments. These methods have a limited precision in dynamic systems, beside cannot perform fully for multiple specification design issues [6, 7, 9-11]. Obviously, traditional tuning methods are not ideal for improving response time with overshoot. The common problem in dynamic systems, that is impossible to describe the real plant exactly, in case of unbalancing behavioural between controller and plant system. It is necessary to expand the abilities of PID controllers to include new features. As some techniques are better than others for any given application, each method has its advantages and disadvantages [7, 8, 12-14]. Several researchers focused on these drawbacks by developing tuning algorithms. Current trends show that there has been a drastic improvement in tuning using evolutionary algorithms or intelligent techniques, which gives a better result after every iteration [9,13,15,16]. Few computational algorithms frequently used these days, for instance Internal Model Control (IMC), which uses to reduce the error by predicting the output, besides adjusting the controller gain to achieved the desired closed loop response with sophisticated overshoot [10,17]. There is another high-performance tuning, such as Particle Swarm Optimization (PSO) which uses to minimize Overshoot [7, 18-20], and Genetic Algorithm (GA) which has a capability to optimize proportional gains and to overcome the limitations of the nonlinear PID controller [2-4, 21-24]. A considerable amount of research work has also been carried out to develop better tuning techniques, such as artificial neural networks which adapt based on the behavior of a system's input and output [2,15]. Fuzzy logic techniques usually implement a control strategy derived from linguistic rules [11,25,26]. These controllers can conquer drawbacks with minor changes in parameters despite variable loading. Adaptive controller is another intelligent technique, but there is no guarantee to remain globally stable with large changes in system's parameters [12,27]. Several researchers have tried to use two sets of evolutionary techniques (heuristic algorithms), for example, Differential Evolution (DE) and Genetic Algorithm (GA) to optimize high order system [28]. Others used GA with PSO to raise the possibility of optimization in search space. Although, this method is an effective solution, but it suffers from a major disadvantage of being trapped in local minima [26]. In summary, most of these methods cannot get excellent results in real control systems, since most systems are not linear. Ultimately, there are many PID tuning methods introduced in this section, classical and evolutionary methods, despite their advantages, there are process drawbacks too. For this reason, finding new tuning methods is considered to obtain a better controller optimization. In view of the investigation in [29], a new iterative tuning algorithm was proposed. This paper outlines specific methods, which have provided satisfactory solutions in terms of Overshoot (*P*), Rise time (*tr*), Settling time (*ts*), Dead time (*td*), and Steady state error (*e*) with a different order model.

The content of this paper is composed as follow: the theory of PID controller was presented in Section II, proposed methodology was demonstrated in Section III and experimental results with discussion were shown in section

IV. Finally, conclusions follow in Section V.

II. PID CONTROLLER

PID algorithm is a combination of a proportional, an integral, and a derivative controller. The proportional parameter is used to decrease error responses to disturbances. The integral parameter is used to reduce steady-state error by the addition of a pole at the origin and raising system type by one. The derivative parameter dampens the dynamic response by the addition of a finite zero to the open loop plant Transfer Function (TF) to evolve the transient response or stability of the system. Table 1 shows the influence of PID parameters to plant system in term of Overshoot and Response time [3,13]. Basically, PID controller comprises of three blocks of control proportional (P), integral (I) and derivative (D). A simplified block diagram of its structure with closed loop unity feedback system shown in Figure 1. *r (t)* is the reference input signal, where error signal e(t) is defined as $e(t)=r(t)-y(t)$. Whereby *u (t)* is the input signal to the plant equal to the proportional gain Kp times the magnitude of the error as derived from Equation (1), plus the integral gain Ki times the integral of the error as derived from Equation (2), plus the derivative gain Kd times the derivative error as derived from Equation (3) [3].

Table 1
Effects of PID Gains Separately [13]

Gains	*tr*	*P*	*ts*	*e*	Stability
Kp	Reduce	Raise	Minor	Reduce	Downgrade
Ki	Reduce	Raise	Raise	Remove	Downgrade
Kd	Minor	Reduce	Reduce	No effect	Get better when *Kd* small

These parameters are distributed and influenced by the past, present and future times. The Proportional controller (P) depends on the present error to control the system, the Integral controller acts on the collection of past errors to removes the offset which introduced by the proportional control that brings a phase lag into the system, where Derivative controller uses to predict of future errors to reduce Overshoot by inserting a phase lead action, to remove the effect of phase lag that was introduced by an integral part [16]. The distinction between the coveted (t) and actual output (t), (t) is the PID control law. The basic equation for a PID algorithm is outlined in Equation (4) [4]. PID algorithm relies on summing these three proportional actions as derived from Equation (5), provides a capability to adjust processing system efficiently. This algorithm attempts to correct the error between a measured process and a variable desired set point output that can adjust the process accordingly [3,30]. With the approximation of the time delay the transfer function become as derived from Equation (9). On the other side, the mathematical model of a second-order plant system as derived from Equation (6). Whereby, the TF of a time delay is outlined in Equation (7). For the design of the controller parameters, it is necessary to substitute Equation (8) with an approximation, in the form of a rational TF as derived from Equation (8).

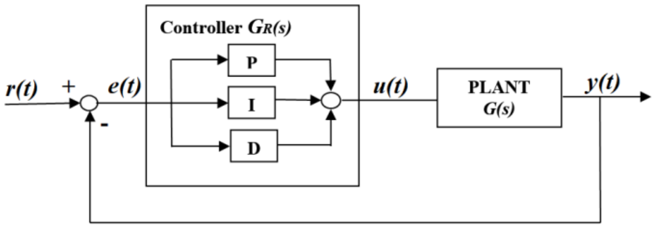

Figure 1: Block Diagram of Unity Closed Loop Control System [16].

$$Pterm = Kp \times Error \quad (1)$$

$$Iterm = Ki \times \int Error\, dt \quad (2)$$

$$D\, term = Kd \times \frac{d(Error)}{dt} \quad (3)$$

$$u(t) = KPe(t) + Ki \int e(t)d(t) + \frac{K\, d\, de(t)}{dt} \quad (4)$$

$$GR = \frac{U(s)}{E(s)} = P + \frac{I}{S} + Ds \quad (5)$$

$$G(s) = \frac{bo}{a_2 s^2 + a_1 s + a_0} e^{-Ds} = \frac{bo}{a_2 s^2 +_{1.1} s + 0.2} e^{-0.15s} \quad (6)$$

$$H(s) = e^{-Ds} = e^{-1.5s} \quad (7)$$

$$e^{-Ds} \approx \frac{1 - \frac{D}{2} S}{1 + \frac{D}{2} S} = \frac{1 - 0.75s}{1 + 0.75s} \quad (8)$$

$$G(s) = \frac{-0.75bo\, s + b0}{0.75a2\, s^3 + (a2 + 0.75a1)s^2 + (a1 + 0.75ao)s + ao} \quad (9)$$

III. THE PROPOSED METHODOLOGY

In order to verify the robustness of the proposed tuning method, three plants were considered with different TF as shown in Figure 2. The first one (Polynomial Second-Order Model) as in case 1 is ideally used to approximate a massive variety of plants [21]. The second TF (Pols Zeros Model) as in case 2, which is used to process first order dynamics with a time delay. The third TF (Third Order Model) as in case (3), which uses to improve the methodology of tuning parameters through intelligent techniques. All these systems obtained by using System Identification toolbox that provides an application in both time-domain and frequency-domain to extract mathematical models of any dynamic system by measuring input-output plant. [13,21,31]. Significantly, all these models are very poor and cannot provide a sophisticated minimization response without using controller as shown in Table 2. It is very beneficial to use PID controller to minimize response time of these studied systems. However, it needs an improved algorithm to tune proportional gains. Practically, there are many models, many tuning methods and many possible performance criteria, so the comparison to other tuning methods for a specific plant is virtually impossible [5]. For these reasons, the best comparison for all cases to estimate the performance of proposed tuning with another approach by using PID toolbox tune. Matlab PID toolbox tune was considered the best application to tune PID gains with minimizing response time. The aim is to find optimal PID parameters that will provide better minimization of response time in cases 1, 2, 3. Initially, we used toolbox to tune these systems and to minimize response time. Table 3 shows the simulation results of tuning controller based toolbox tune. These results which represented in response time parameters cannot produce optimal minimization for all cases especially in case 3, in case of poor settling time 104 sec. By contrast, PID based these systems need to fine adjustment by improving tuning algorithm to achieve both optimal gain with minimization responses.

Table 2
Step Responses of Uncontrolled Systems

Step Responses	Case 1	Case 2	Case 3
tr sec.	0.918	4.92	1.83
ts sec.	1.67	8.29	3.37
td sec	0.125	0.8	0.4
error	0.9583	0.5	0.01
Peak Amplitude	0.0417	0.5	0.993
Final value	0.0417	0.5	0.933

Table 3
Step Responses Based Matab PID toolbox

Step Responses	Case 1	Case 2	Case 3
tr sec.	0. 326	0.415	15.5
ts sec.	1.22	0.865	104
td sec.	0.0451	0.0212	0.24
Overshoot	7.22	0	8.78
Error	0.02	0.02	0.02
Peak Amplitude	1.028	0.995	1.09
Final Value	1	1	0.994
Kp	24.35	20.40	0.1017
Ki	79.62	3.3169	0.0286
Kd	1.3653	27.034	2.9139

A. Tuning Procedure

In this research, we proposed improved iteration tuning to overcome previous drawbacks of Matlab PID toolbox tune. A new tuning iteration strategy is used to evaluate optimum PID gains, experimented with three different nonlinear models, cases 1, 2,3. In order to improve iteration tuning, we proposed an algorithm based on finite loop tuning gains to minimize response time in PID controller with second and third order system as explained in Figure 2.

The proposed strategy relies on four loops to generate minimization Responses with Overshoot, by increment PID gains values separately. Each new generation compared with previous one until reached to optimal gains *Kp*, *Ki*, *Kd*. However, the forth loop used to decrement them jointly to obtain optimal minimization of response time. The proposed basic process that being used in MATLAB outlined into 17 basic steps. Initially, initialize *Kp*=1, *Ki*=0, *Kd*=0, Then apply this algorithm to three experimental plants. Each loop employed separately to find initial values gains then calculate responses for each loop to get initial minimal responses. Then, repeated these loops separately to achieve optimal gains and to minimize both response time and overshoot. This strategy succeeded to optimize PID parameters and achieved the benefits outlined in the introduction. It follows that the robustness of control system with all cases tuning based proposed method is higher than the robustness of tuning by Matlab toolbox. It was developed by the simulation of a simplified system and is robust in solving a continuous nonlinear system. Furthermore, gives an improvement strategy and a promising methodology for tackling the optimal PID gains issue.

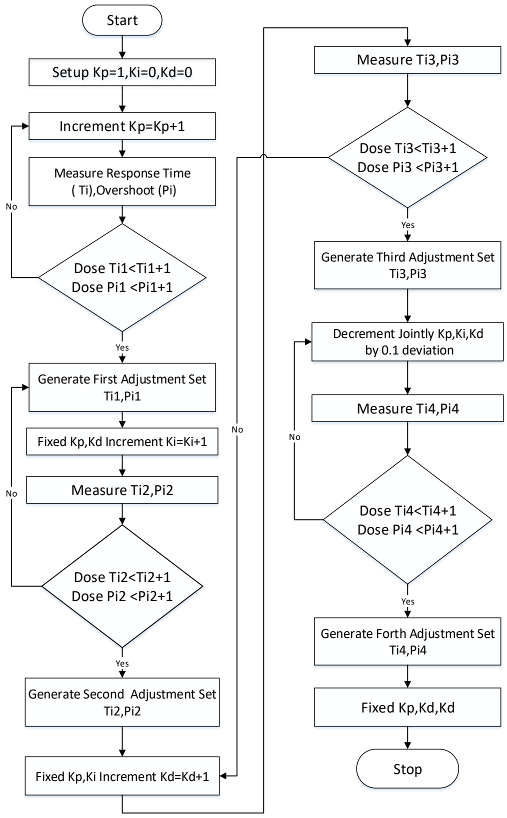

Figure 2: Research Methodology.

B. Novel Controller Circuitry

The limitation of using PID controller with multiple order system considered another problem issue, in case of lowest performance tracking when the plant system was changed. The second aim is to increase tracking performance in a single PID controller to be used with multiple systems. By contrast, proposed methodology relies on both novel switching circuitry with improved algorithm. Novel circuitry gives a capability to use single PID controller with different order system leads to decrease area size of controller design, where proposed algorithm gives the ability to minimize response time of models with fixed number of iteration that overcomes toolbox tune. Considerably, there is a closed relationship between controller design and tuning gains. Therefore, proposed controller can be effectively executed and has an amazing edge for development. To implement the proposed tuning method, an improvement selective plant switching was designed to select multiple models logically to obtain results for each case as shown in Figure 3.

This design gives a capability for the controller to be used with both second and third order systems. It is combined PID controller with second and third order models. Proposed design is simulated using SIMULINK in MATLAB. Proposed controller has five logical switches to selects one desired plant between three different models as described in Table 4.

Table 4
Status of Logical Switches to Select Desired Model.

Selecting Cases	Switch 1	Switch 2	Switch 3	Switch 4	**Switch 5**
Case 1	1	0	0	0	**1**
Case 2	0	1	0	1	**1**
Case 3	0	0	1	Don’t care	**0**

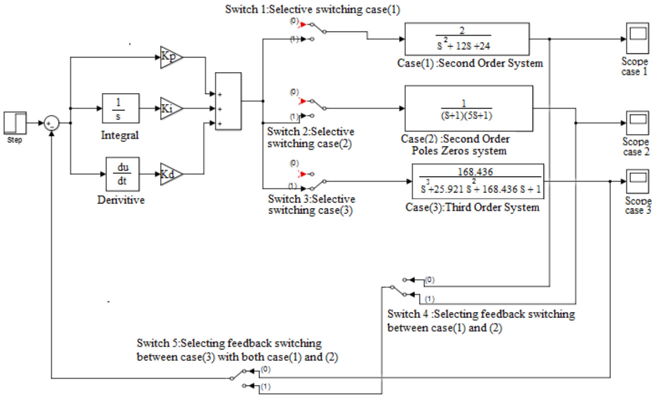

Figure 3: Proposed Overall Controller System.

IV. SIMULATION RESULTS

To obtain optimal controller gains experimentally, the initial TF Model must be specified to generate better parameters *Kp*, *Ki*, *Kd*. The performance evaluation of controller includes the estimation of responses criteria such as Rise time, Settling time, Steady state response and Overshoot. In this test, the optimization of the PID parameters based on proposed strategies which were implemented with closed loop tuning. Different gains obtained from different plant models were used, as described in Table 5. Output response time with Overshoot was captured and the PID parameters gains were calculated. A few representative results from a deferent order model were extracted in three cases to show the validation of performance comparing with Matlab PID toolbox tune. The aim is to find the optimal set of PID gains for second and third order models. The response of produced results was analysed in terms of Response criteria with Overshoot. It was found that the optimal values of the proportional gains can be obtained within 37 iterations. Figure 4 shows Case 1 simulation results comparison in response time for both proposed tuning and toolbox tune. Obviously, as it can be seen that case 1 based proposed tuning can track the given references with better minimization responses, compared with Matlab PID toolbox tune. The analysis of the performance-based proposed tuning from Figure 4 to Figure 6 shows that the enhancement was influenced by the behavioral system much better than toolbox tune. It shows that by the proposed tuning based PID controller, control accuracy throughout the process can be improved.

As shown in Table 6, it can be observed that the response time of the control system in Cases 1, 2, 3 tuning by proposed method has the reserve of responses much higher than the reserve of responses of the control system tuning by Matlab toolbox. the comparison results illustrate that a reduction in Rise time for Cases 1, 2, 3 reduced to 2.27, 25.15, 225.29 times respectively. The minimization responses are; Rise time 0.1433s, Settling time 0.4122s, Overshooting 7.8% and Steady-state error 0.01%, where the new optimal gains; *Kp* 78, *Ki* 145, *Kd* 2.5. The gains took values in a range of 0 to 150.

These results correspond to the optimized solution, which minimizes Response time criteria. Another second-order model was used type poles zeros as in Case 2. The enhancement of the response is obtained through a progress procedure of proposed strategy. Figure 5 outlines the comparison of Case 2 in response time for both proposed tuning and toolbox tune. The optimal gains were *Kp* 830, *Ki* 636 and *Kd* 644 correspond to the optimization solution that minimizes response time; Rise time 0.0165s, Settling time 0.0293s, Overshooting 0% and steady-state error 0.01%. It can be observed that the straight application of the proposed method provides the optimal gain. Ultimately, as in Case 3, a model with time-delay is used as a third model for test and analysis. Figure 6 shows the simulation results comparison of Case 3 in response time for both proposed tuning and Toolbox tune. We obtained optimal gains; *Kp* 1742, *Ki* 61, *Kd* 285 to minimize Response time; Rise time 0.0688s, Settling time 0.296s and Overshoot 1.17%.

Table 5
Enhancement Step Responses Based Proposed Method.

Specifications	Case 1	Case 2	Case 3
tr sec.	0. 1433	0.0165	0.0688
ts sec.	0.4122	0.0293	0.296
td sec.	0.001	0.001	0.0143
Overshoot	7.28	0	2.84
Error	0.01	0.01	0.01
Peak Amplitude	1.07	0.996	1.03
Final value	1	1	1
Kp	78	830	1742
Ki	145	636	61
Kd	2.5	644	2.5

Table 6
Improved Step Response Ratio Based Proposed Iteration Respect compared with PID tool box Tune.

Responses	Case 1	Case 1	Case 1
tr (times)	2.27	25.15	225.29
ts(times)	2.95	29.5	351.3
td (times)	45.1	21.2	16.7
P (times)	1	1	3.09
e (times)	2	2	2

It can be seen that the comparison results by the proposed tuning method is better than those by tuning gains based toolbox. A reduction in Settling time for Cases 1, 2, 3 decreased to 2.95, 29.5, 351.3 times respectively. Also, a reduction in Dead time for cases 1, 2, 3 decreased to 45.1, 21.2, 16.7 times respectively. Where, zero Overshoot achieved in case 2 in both methods. The results show that the novel proposed tuning method works more precisely than PID toolbox tune in all tested models. As shown in Figures 7,8,9 of three cases based proposed, it can be seen from the behavioural systems that the optimum PID gains was obtained to minimize responses time with increasing the performance models of Cases 1,2,3 (second and third Order Model). It is shown graphically that there is a substantial improvement in the time domain specification in terms of lesser Rise time, Settling time and Overshoot to generate optimal PID gains. Hence this method is a design method for determining the PID controller parameters. Obviously, the crucial points generate the optimal response time values in 37 iterations. It is noticed the performance get well optimization with best approximation PID gains. Significantly, this work presents a very simple analytic tuning procedure, which yields surprisingly superior results and is boosted with improved test bench design. Moreover, it is well suited to optimize tuning PID parameters. Specifically, it gives an invaluable insight into how a controller should be retuned in response to process changes, like changes in the time delay or gain.

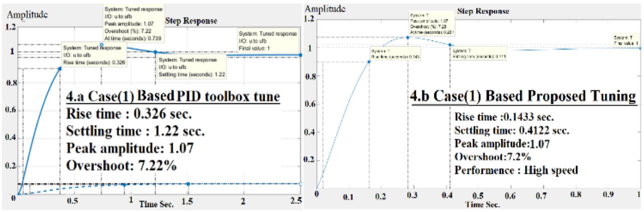

Figure 4: Case (1) Comparison Responses between Proposed Tuning and Toolbox Tune

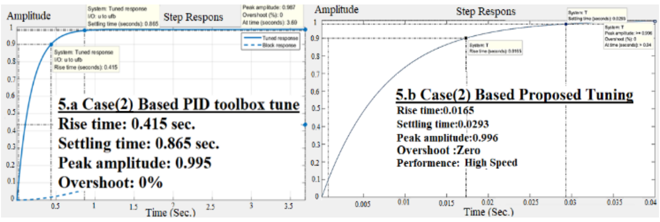

Figure 5: Case (2) Comparison Responses between Proposed Tuning and Toolbox Tune

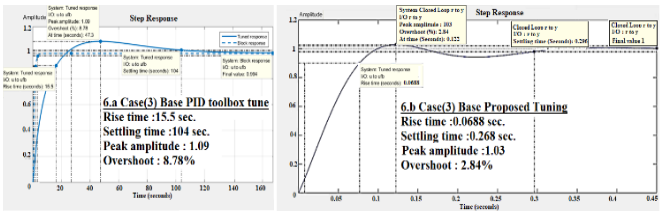

Figure 6: Case (3) Comparison Responses between Proposed Tuning and Toolbox Tune

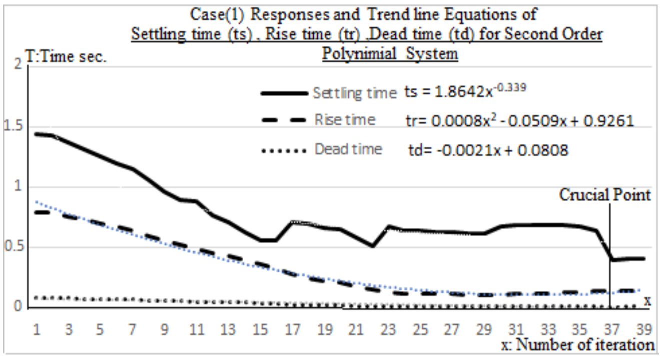

Figure 7: Responses Time of Case (1) Based Proposed Method

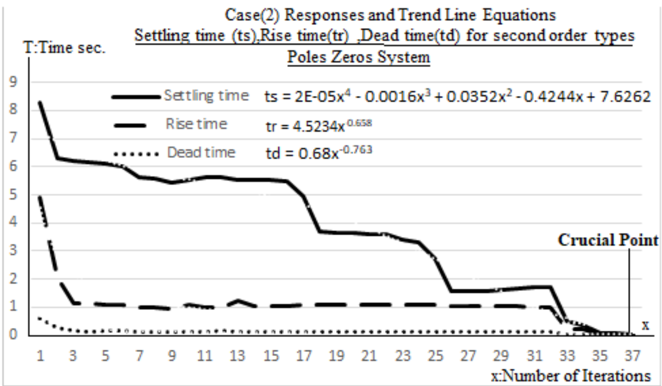

Figure 8: Response Time of Case (2) Based Proposed Method

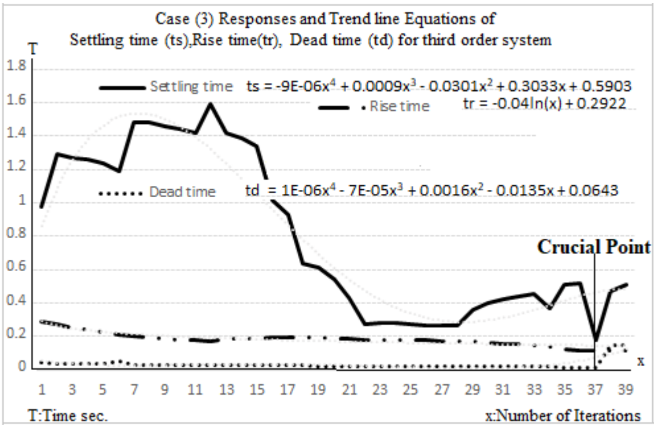

Figure 9: Response Time of Case (3) Based Proposed Method

V. Conclusion

This work proposes to implement a novel iterative-tuning method for a precision control system to obtain optimal reduction of transient response and Overshoot. An improvement test bench design proposed to select three plant models. This design has a capability to select logically the desired plant between three models in a convenient way. Experimentally, The PID gains obtained from the step response of the system were verified by three cases separately, which analyse each system independently. All models based proposed tuning showed the best-tuned result. In Case 1 based proposed tuning produce Rise time of 0.1433s with an Overshoot of 7.71%, while Case 2 (second order poles zero model) gives a Rise time 0.0165s with zero Overshoot. Case 3 (third order system) gives a Rise time of 0.0688s with an Overshoot 2.84%. All cases produce a satisfactory performance in terms of response time considering steady state error. This is typically within the required criteria for robotic applications.

The presented cases prove that superior performance in term of response time can be accomplished in various plants based proposed method. It can obtain higher quality solution with better computational efficiency. The purpose of the features outlined in this research is to consider the issue of designing control system to be used with various order models, whereas, other methods such standard methods cannot do that, considering the mathematical modelling drawbacks of the system.

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