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Genetic Algorithm Optimization Analysis for Temperature Control System using Cascade Control Loop Model

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Abstract: This research presented a holistic approach in determining the trade-off optimized Proportional-Integral-Derivative (PID) tunings for both servo and regulatory controls of the cascade control loop by using Genetic Algorithm (GA). Performance of GA-based PID tunings was significantly compared with the IMC-based single loop tunings and conventional cascade control tunings. GA-based PID tunings eliminated the complicated mathematic calculations in obtaining the correlation PID tuning values and also reduce the dependency on engineering knowledge, experience, and skills. The performance of transient and steady-state responses was compared through time domain specification, performance index, and process response curve. It is concluded that the GA-based PID tunings for the cascade control loop had produced the best result for both servo and regulatory control objectives, which is eventually determined.

Keywords: Cascade Loop, Stability Margin, Genetic Algorithm, Optimized PID tunings, Improved Control Performance

1. Introduction

Effective tuning of Proportional-Integral-Derivative (PID) controller is a critical task during the process operation. It has to ensure the process stability and also the prolong equipment life span of the used equipment. PID controller consists the combination of three control functions, namely Proportional gain (K_c), Integral gain (K_i), and Derivative gain (K_d). Incorporating a PID controller into the single loop feedback control system is commonly used however it creates error [1], [2].

The PID controller tunings are obtainable through Internal Model Control (IMC) that calculates the correlation PID tunings by respective developed mathematic formulas. Nevertheless, the tunings for the respective servo and regulatory control objectives involve different formulas resulting in a lot of mathematic calculations required for finding the correlation PID tuning values. The best tuning of servo control causes the higher overshoots in regulatory control whereas the best tuning of regulatory control causes the sluggish response to the servo control. Therefore, the conventional method is only sufficiently handling the basic process function to one control objective and yet to optimize the operation of the controlled process.

Applying the cascade control loop is purposely to improve the overall process performance particularly in dealing with the external disturbance [3], [4]. Block diagram of the cascade control loop is illustrated in Fig. 1.

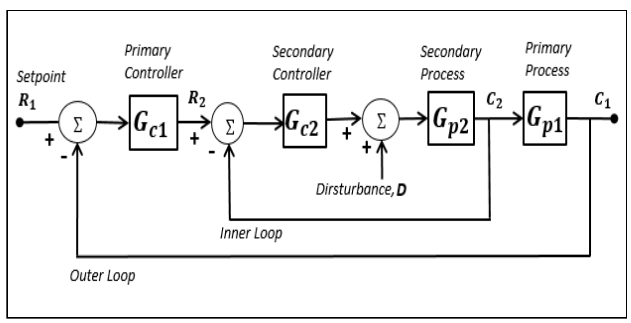

Figure 1. Block diagram of the cascade control loop

The cascade loop consists of an inner loop, which is nested to the outer loop. The outer loop compares the feedback signal with the setpoint (R_1) and produces an error signal to the outer controller (G_{c1}). The manipulation value of G_{c1} has become the setpoint to the inner controller (G_{c2}) and the inner process model (G_{p2}). When the external disturbance (D) is imposed, the inner loop instantly reacts to

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the D before it starts to affect the actual controlled process in the outer loop. Therefore, the nested G_{p2} process model must have dynamic behavior faster than G_{p1} so the inner loop is able to stabilize the imposed disturbance before the performance of the exact controlled parameter is affected by the disturbance.

The focus in evolutionary strategies has gained more attention from the research community and the industries in the Industrial Revolution 4.0. Among them, Genetic Algorithm (GA) is an outstanding algorithm that performs an exploration of the search space, which develop gradually in analogy to the nature evolution. It uses probabilistic transition rules and handles a population of potential solutions known as chromosomes for calculating and selecting the trade-off optimized PI tunings from the fitness function. Only one tuning is requested to be fixed for both servo and regulatory control objectives. The ultimate achievement of this paper is the improved dynamic performance of the process control through optimization analysis, which reduces dependency on engineering knowledge, skills, and complex mathematic calculation. The paper is organized as follows: Problem statement, literature review, and GA analysis are explained in Section 2. Research development and stability analysis of cascade control loop is presented in Section 3. Analysis and results are discussed in Section 4. Last but not least, the research conclusion is covered in Section 5.

2. Problem Statement, Literature Review and Genetic Algorithm

A. Problem Statement

The conventional PID control settings that use the conventional method is adequate to handle the basic process function but still unable to optimize the control performance of the process. PID settings for the servo and regulatory control objectives are not fixed to each other. The tuning of servo control causes higher overshoots for the regulatory control. In contrast, tunings for the regulatory control results sluggish in response to the control performance in servo control [5]. So far, the achievements of applying cascade control are focused on the contents of regulatory control but the improvement to the servo control is limited.

Besides, the initial practice of tuning by using PID tunings involves some formula calculations and state-of-art tuning that requires knowledge, engineering experience and skills. The calculation of cascade control tunings mostly involves complex mathematic calculation to solve higher-order formulas, which is time consuming and troubling to the users [6], [7] especially it easily leads to mistake in calculation.

B. Literature Study

Advanced control method such as the cascade control is accepted in many controlled processes. Lee and Oh [6] presented a general structure of Enhanced-cascade control. Santosh and Chidambaram [8] proposed a simple method to design P or PI controllers for the unstable first order plus time-delay systems. Nandong and Zhang [9] proposed multi-scale control scheme for cascade processes with time-delays. Further on, Manh et al. [10] used the synthesis method to develop a robust cascade control system. Thirymarimurugan et. al. [11] compared the performance of the parallel and series type cascade control loop. Zarate-Navarro et al. [12] presented a class of continuous chemical reactors with cascade control. However, all the mentioned literature utilized deterministic approaches, which required complex mathematic calculations as accorded to newly developed algorithms in their respective research.

GA had been successfully applied to solve many different optimization problems. Kaya and Nalbantoğlu [4] used GA in a cascade control loop to tune controller terms simultaneously in the presence of disturbances. Ali et al. [13] applied GA-based Linear Quadratic Gaussian controller to reduce the frequency deviations and settling time in Load Frequency Control. Elgothamy et al. [14] enhanced GA to solve a dynamic large optimization problem. In laser welding process, Vijaya, Ranjithkumar, and Shanmugarajan [15] compared among the GA with Response Surface Methodology in parameter optimization. Hai et al. [16] used GA to improve the performance of an internal combustion engine. Besides, Juneja et al. [17] utilized GA to solve Travelling Salesman Problem. However, all the reviewed literatures were only focused either on servo or regulatory controls. In this paper, GA has been utilized further for obtaining a trade-off optimal tuning values or both servo and regulatory control problems through simultaneous tuning method. The incorporation of both inner and outer loops of Process Control Simulator (SE-201) are developed and the optimization of PID settings are analyzed by using MATLAB simulation software.

C. Genetic Algorithm and Its Applications in the Cascade Control Loop

Fig. 2 depicts how GA analysis is applied to the cascade control loop. GA will randomly choose the PI values for simulation analysis of the servo and regulatory control problems. It respectively produces error signals through the applied setpoint and disturbance signals and then accumulates the total produced integral errors, which is also known as the performance index.

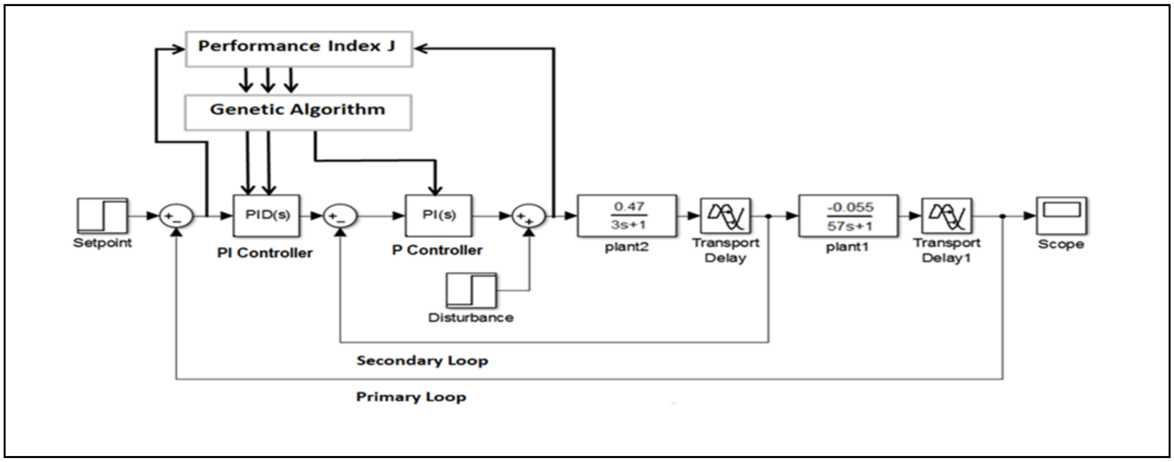

Figure 2. The applied GA analysis to the cascade control loop

Initially, the upper and lower bound limits for the optimization analysis, the objective function for producing the fitness value of solutions and the number of optimized parameters are identified. For the PID control, the first generation of chromosomes or population is produced randomly, where C_k is the gain chromosome. C_k represents a single individual population of PID parameters of $K_cK_iK_d$, where $K_c = c1, c2, \ldots cn$, $K_i = i1, i2, \ldots in$, $K_d = d1, d2, \ldots dn$. The initial population is the parents and it is randomly chosen. The fitness test of each population that produces a new generation contains information of the previous generation plus the newly produced genes, that are superior compared to the previous generation [4], [18].

The produced generation is called children. The greater the fitness function, the lower the value of the performance index, which reflects better-produced children in the new generation and the best performance index is known as the local minima. GA performs three main stages to develop global minima of children from their parents. At first, the Selection chooses chromosomes for the formation of the mating pool. Secondly, the Crossover operation exchanges the information in the mating pool to form new offspring as the children. Thirdly, the Mutation enables the newly produced chromosomes directly by flipping randomly selected bits in certain strings so as to improve the fitness of strings through minor local searches when the optimum values are nearby. Finally, the new children chromosome as the successor population is declared and will be used further to run the next iteration. Otherwise, termination of the optimization analysis is triggered by obtaining the set maximum iteration numbers or the fitness value. The flowchart of GA analysis for the cascade control loop is illustrated in Fig. 3.

Even there are concerns in selecting GA parameters, a basic guideline introduced by De Jong and Spears [19] has been referred for the PID settings of this research. The selected population size is 100-200 and crossover rate of 0.8 results in good PID settings for the robust control performance of the cascade control loop.

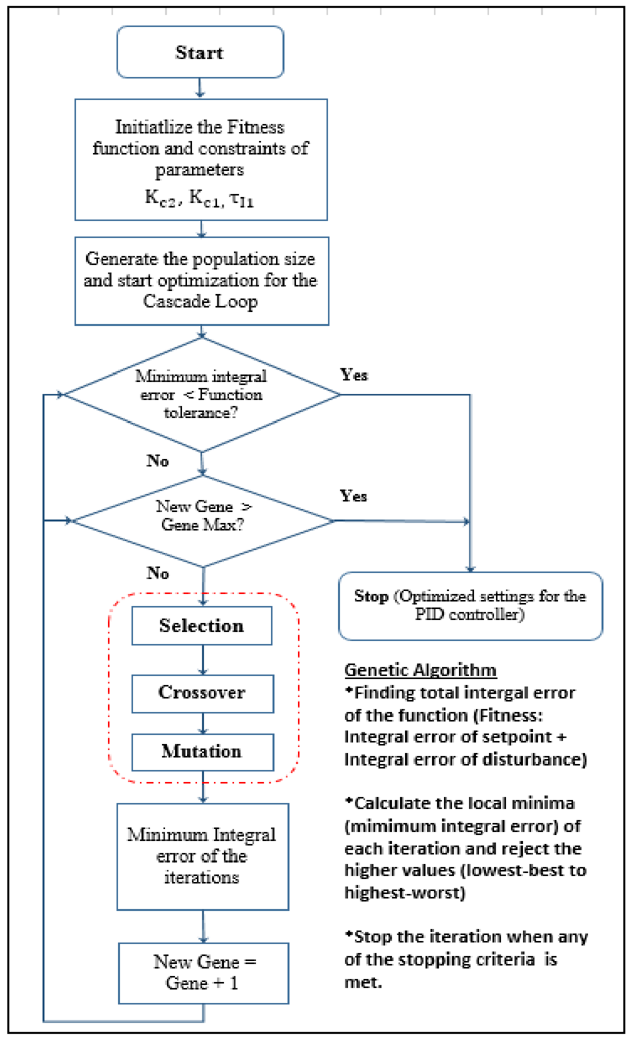

Figure 3. GA flow chart

3. Research Development and Stability Analysis of Cascade Control Loop

A. PID Tunings for the Process Control Simulator and MATLAB Graphical User Interface

Process Control Simulator (SE-201) consists of a flow control as the inner loop is fit inside in the temperature control as the outer loop. The load change of the air flow is instantly regulated by the inner loop and thus, it reduces or eliminates the impact on the temperature control as the outer loop. Servo control is obtained by adjusting the set value displayed by the computer screen whereas the regulatory control is triggered by adjusting the shutter's position. The lab-scale SE-201 is depicted in Fig. 4 and Fig 5.

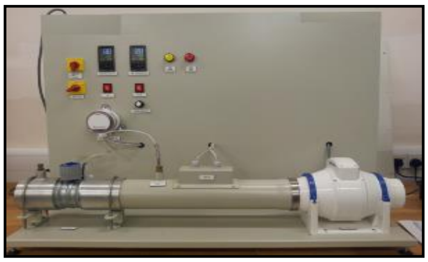

Figure 4. Physical equipment of Process Control Simulator SE-201

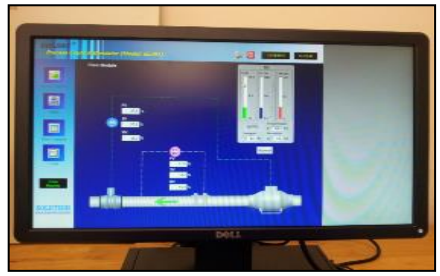

Figure 5. Computer software of Process Control Simulator SE-201

Graphical User Interface (GUI) is developed to enable the repetitive test and verification of simulation results prior to do the real testing to the SE-201. Initially, the parameters of FOPDT and controllers' settings are provided to the GUI. The simulation is started by selecting the 'Execute' button. Eventually, the simulation produces the transient and steady-state response curve, output response performance and performance indexes. Output response performance can be compared through graphs, integral error values and time-based characteristic in the Toolbox. The developed toolbox of cascade control loop is depicted in Fig. 6.

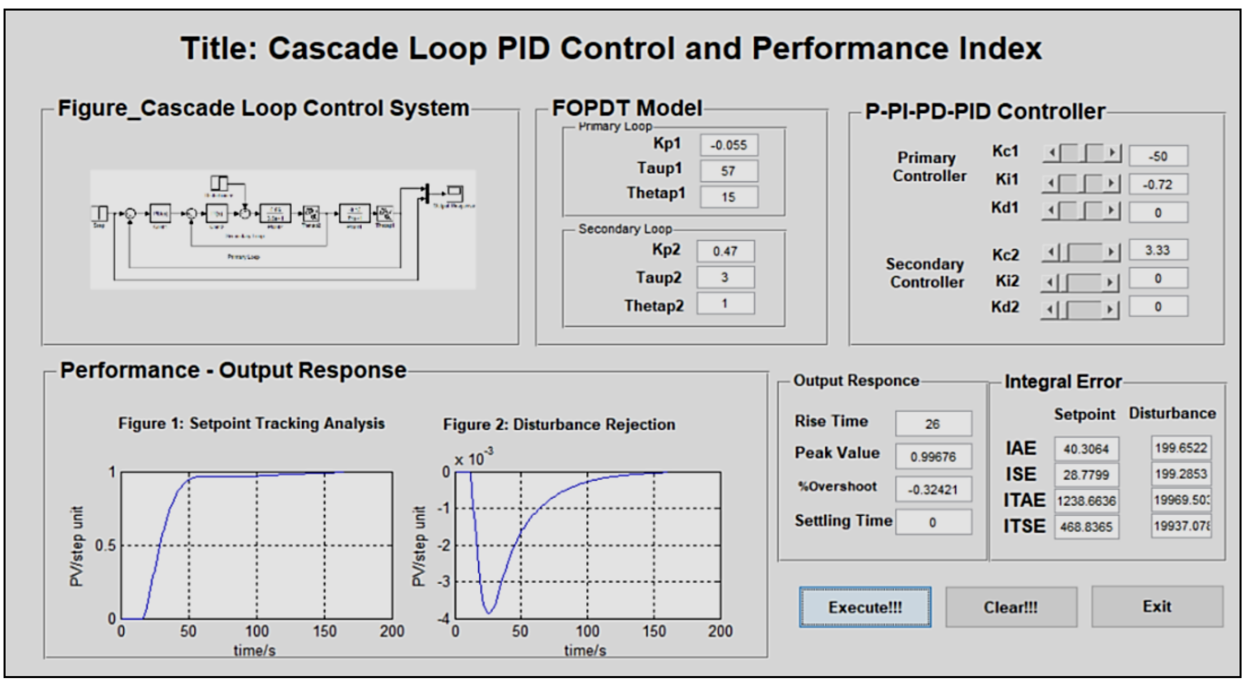

Figure 6. GUI for cascade control loop

B. Objective Function of GA-based Optimization Analysis

```
%%%Title: Objective function for GA-based Optimization Analysis ...
        .... for the Cascade Control Loop.
%%%Date: Dec 2018.

function [J]=pid_optimtest4Jobrun(x)

s=tf('s');
%Inner Loop Process (Secondary)
plant2=0.47*exp(-1*s)/(3*s+1);

Kc2 = x(1)
cont2 = Kc2; %Inner Loop Controller

%Outer Loop Process (Primary)
plant1= -0.055*exp(-15*s)/(57*s+1);
Kc1 = x(2)
Ki1 = x(3)

cont1 = Kc1 + Ki1/s;  %Outer Loop Controller

dt=0.01;
t=0:dt:500; %time Frame - can set from 100s to 5000s

%Error of setpoint tracking
e1= 1-step((plant1*plant2*cont1*cont2)/(1+plant2*cont2+plant1*plant2*cont1*cont2),t);
J1 = sum(t'.*abs(e1)*dt) %ITAE of Servo Control

%Error of disturbance rejection
e2= 1+step(plant1/(1+plant2*cont2+plant1*plant2*cont1*cont2),t);
J2 = sum(t'.*abs(e2)*dt) %ITAE of Regulatory Control

%Total errors for both Servo and Regulatory Control
J=J1+J2
```

Figure 7. Objective function of GA-based optimization analysis

The objective function of the cascade control system is illustrated in Fig. 7. Objective function describes how all the involved mathematical formulas can be interacted in determining the error values. This is the developed source code file to communicate with GA toolbox in MATLAB. In this research, the developed objective function consists three main types of mathematical formulas include process models, controller algorithms and integral error measurements.

In the objective function, the inner and outer loop processes reflect the open loop dynamic behaviour. The parameters x(1), x(2) and x(3) are analysed in the optimization analysis. In this stochastic approach, random control values will be selected for iteration and the step test will be applied to the servo and regulatory controls. Then, the error values for both servo and regulatory controls are simulated and measured by using ITAE. Error values of respective J1 and J2 are added to produce total error value, J in which the smaller values reflected the better PID settings. The produced error value is compared with the following iteration to determine the better PID settings and this will continue until the operation is eventually terminated.

C. Stability Analysis of the Cascade Control Loop (P-PI controller)

Stability Analysis is purposely to justify the upper and lower bounds settings of the GA analysis and enabling more precise or effective analysis to be conducted in this research work. The block diagram of inner loop is depicted in Fig. 8.

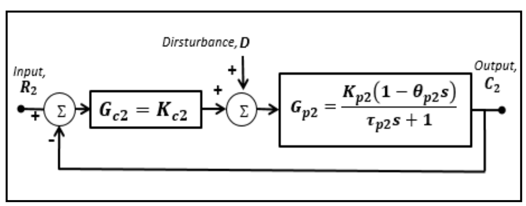

Figure 8. Block diagram of the inner loop

where, K_{c2} = Inner loop proportional gain;
K_{p2} = Inner loop process gain;
θ_{p2} = Inner loop deadtime;
τ_{p2} = Inner loop time constant.

The formulated closed-loop transfer function gives (1)

$$\frac{C_2}{R_2} = \frac{\frac{K_2'}{1+K_2'}(1-\theta_{p2}S)}{\left(\frac{\tau_{p2}-K_2'\theta_{p2}}{1+K_2'}\right)s+1} \quad (1)$$

where, Inner loop total gain, $K_2' = K_{c2}K_{p2}$.

According to necessity criterion of the Routh Stability, all the coefficients of polynomial in the denominator must be > 0. Solving the characteristic equation or the denominator of (1) to produce

$$(\tau_p - K_2'\theta_p)s + (K_2' + 1) = 0 \quad (2)$$

Replace $K_2' = K_{c2}K_{p2}$ into $(\tau_p - K_2'\theta_p) > 0$ and $K_2' > 0$. Then, simplify it gives (3)

$$0 < K_{c2} < \frac{\tau_{p2}}{K_{p2}\theta_{p2}} \quad (3)$$

Applying Taylor series approximation to produce exponential function and simplify the inner loop transfer function, H_{sec} in (4)

$$H_{sec} = \frac{C_2}{R_2} = \frac{K_{sec}e^{-\theta_{p2}s}}{\tau_{sec}s+1} = 0 \quad (4)$$

where, Secondary loop gain, $K_{sec} = \frac{K_2'}{1+K_2'}$ and Secondary loop time constant, $\tau_{sec} = \left(\frac{\tau_{p2}-K_2'\theta_{p2}}{1+K_2'}\right)$

The transfer function H_{sec} is arranged with the augmented outer loop is shown in Fig. 9.

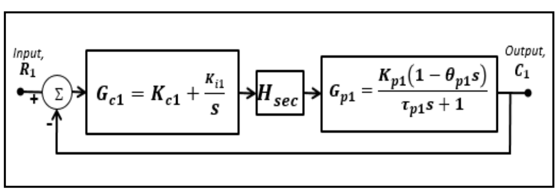

Figure 9. The simplified block diagram of the cascade control loop

where, G_{p1} = Outer loop process model;
G_{c1} = Outer loop controller;
K_{p1} = Outer loop process gain;
τ_{p1} = Outer loop time constant;
θ_{p1} = Outer loop deadtime;
K_{c1} = Outer loop Proportional gain;
K_{i1} = Outer loop Integral gain.

Incorporating of H_{sec} and G_{p1} and the simplification by using Skogestad's Half Rule [20], the dynamic model of primary loop, G_{pri} is as illustrated in (5)

$$G_{pri} = \frac{K_{sec}K_{p1}e^{-(\theta_{p1}+\theta_{p2})s}}{(\tau_{sec}s+1)(\tau_{p1}s+1)} = \frac{K_{pri}e^{-\theta_{pri}s}}{(\tau_{pri}s+1)} \quad (5)$$

where, Primary gain, $K_{pri} = K_{sec}K_{p1}$ (6)
Primary time constant, $\tau_{pri} = \tau_{p1} + 0.5\tau_{sec}$ (7)
Primary dead time, $\theta_{pri} = \theta_{p1} + \theta_{p2} + 0.5\tau_{sec}$ (8)

The developed primary closed-loop transfer function is illustrated in (9)

$$\frac{C_1}{R_1} = \frac{G_{c1}H_{sec}G_{p1}}{1+G_{c1}H_{sec}G_{p1}}$$

$$= \frac{(K_{c1}\tau_{i1}s + K_{c1})\left(K_{pri}e^{-\theta_{pri}s}\right)}{(\tau_{i1}s)(\tau_{pri}s+1) + (K_{c1}\tau_{i1}s + K_{c1})\left(K_{pri}e^{-\theta_{pri}s}\right)} \quad (9)$$

Stability of the cascade control loop is determined by the denominator of the closed-loop transfer function with Taylor's approximation and is arranged as depicted in (10)

$$(\tau_{i1}\tau_{pri} - K_{c1}\tau_{i1}K_{pri}\theta_{pri})s^2 + \cdots$$
$$\ldots(\tau_{i1} + K_{c1}\tau_{i1}K_{pri} - K_{c1}K_{pri}\theta_{pri})s + K_{c1}K_{pri} = 0 \quad (10)$$

According to the necessity criterion of Routh-Hurwitz criterion, the second-order system $as^2 + bs + c = 0$ should have value $a > 0$, $b > 0$, and $c > 0$ for a stable control. So, all the terms in (10) should be greater than zero. Simplify the parameters in the term to produce (11) and (12).

From term s^2, $\tau_{i1}\tau_{pri} - K_{c1}\tau_{i1}K_{pri}\theta_{pri} > 0$

$$K_{c1} < \frac{\tau_{pri}}{K_{pri}\theta_{pri}} \text{ (Upper limit)} \quad (11)$$

From term s, $\tau_{i1} + K_{c1}\tau_{i1}K_{pri} - K_{c1}K_{pri}\theta_{eff} > 0$

$$\tau_{i1} > \frac{K_{c1}K_{pri}\theta_{pri}}{K_{c1}K_{pri}+1} \text{ (Lower limit)} \quad (12)$$

D. Performance Index Measurement of the Cascade Control Loop (P-PI controller)

Performance index measures the areas under the performance curve over the duration of time as compared to the set value. It comprises four different perspectives. IAE integrates the absolute error over the duration of time. ITAE multiplies the absolute error with the period of time and then integrates the total unit over the duration of time. ISE integrates the square of the absolute error over time. Besides, ITSE multiplies square of the error over the duration of time and then integrates this total unit value with duration of time [21]. Integral error measurement of the cascade control loop is illustrated in Fig. 10.

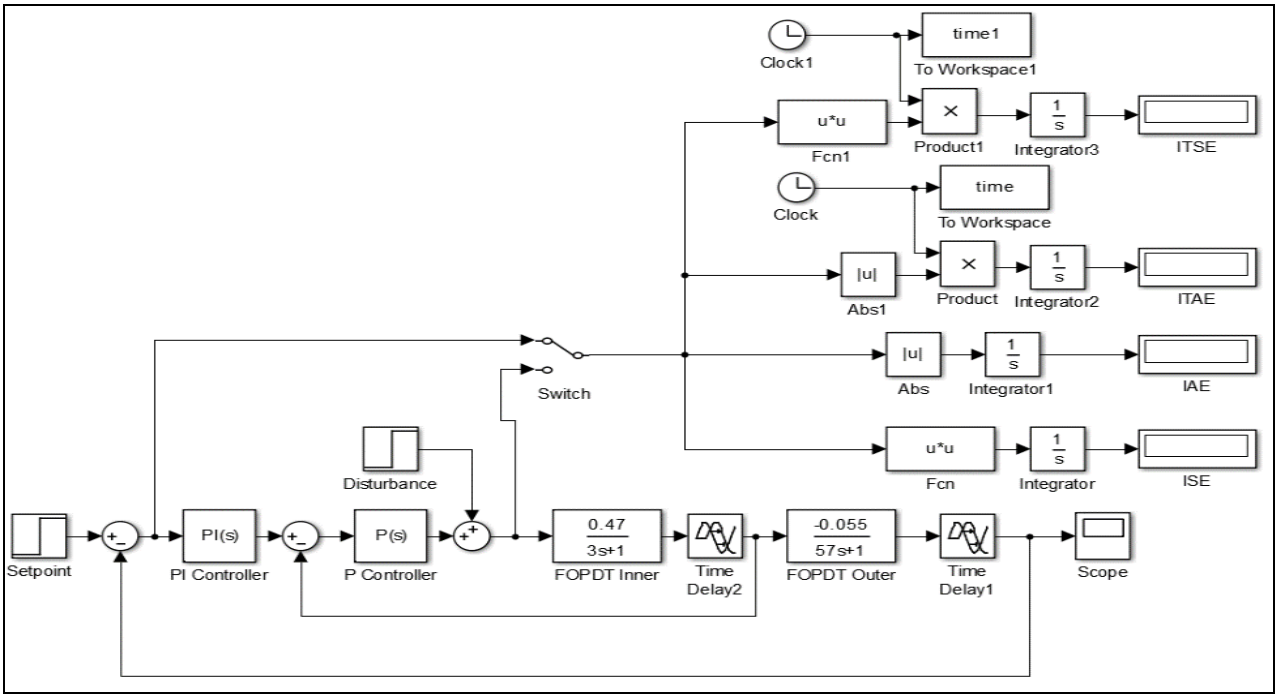

Figure 10. Integral error measurement of cascade control loop

4. ANALYSIS AND RESULT DISCUSSION

A. *FOPDT Model for the Single and Cascade Control Loops*

Dynamic behaviours of the Process Control Simulator, SE-201 is determined through an open loop bump test. The respective FOPDT models for the single and cascade control loops are illustrated in Table I.

TABLE I. FOPDTS OF SINGLE AND CASCADE CONTROL LOOP

Control Loop	**Single Feedback Control Loop**	**Cascade Control Loop**
Inner Loop (Flow)	-	$\frac{0.47e^{-1s}}{3s+1}$
Outer Loop (Temperature)	$\frac{0.83e^{-22s}}{117s+1}$	$\frac{-0.055e^{-15s}}{57s+1}$

B. *Determining Upper and Lower Limits for the Controller Settings*

For the inner loop, the model parameters of $K_{p2} = 0.47$, $\tau_{p2} = 3$ and $\theta_{p2} = 1$ are substituted into (3) give the stability margin $K_{c2} < 6.4$. As the K_{c2} is also > 0. Thereby, $0 < K_{c2} < 6.4$.

Substitute $K_{p2} = 0.47$, $\tau_{p2} = 3$, $\theta_{p2} = 1$, $K_{p1} = 0.055$, $\tau_{p1} = 57$ and $\theta_{p1} = 15$ from Table I into (6) – (8) respectively gives $\tau_{pri} = 57.024$ and $K_{pri}\theta_{pri} = 0.651$. Substitute all these values into (11) give $K_{c1} < 57.024 / 0.651 = 87.65$. Thus, $K_{c1} < 87.65$ is the upper limit or in the form of Proportional Band, PB > 1.14% as the lower limit.

Assume that $K_{c1} = 80$ (or PB=1.2%), substitute $K_{p2} = 0.47$, $\tau_{p2} = 3$, $\theta_{p2} = 1$, $K_{p1} = 0.055$, $\tau_{p1} = 57$ and $\theta_{p1} = 15$ into (12) gives $\tau_{i1} > 12.445$ (Lower limit). Due to the K_{I1} is inversely related to τ_{i1}, the lower limit of τ_{I1} is equivalent to the upper limit of $K_{i1} < K_{c1}/\tau_{i1}$. Therefore, $K_{i1} < 6.83$ is the upper limit.

$K_{c2} \in [0, 6]$, $K_{c1} \in [-80, 0]$, $K_{i1} \in [-6, 0]$.

C. *FOPDT Model for The Single and Cascade Control Loops*

Table II depicts all PID settings for SE-201 temperature control loop. Single loop temperature control applied IMC-based moderate and aggressive mode tunings whereas the PID settings of the cascade control loop were generated by using Lee et al. [7] and Synthesis [9] tuning methods. In addition, the GA analysis was applied to calculate the optimum PID settings.

TABLE II. PI TUNINGS OF THE SINGLE AND CASCADE CONTROL LOOP OF SE-201

Tuning Methodology	**Proportional Band, PB**		**Integral Time, τ_I**	
	Inner (PB2)	***Outer***	***Inner***	***Outer***
Single - Moderate	-	75%	-	150s
Single - Aggressive	-	15%	-	150s
Cascade - Lee	22%	- 2.5%	-	63s
Cascade - Synthesis	16%	- 4%	-	58s
Cascade - GA	31%	- 2%	-	70s

D. Integral Errors of All Integral Error Measurements

In Fig. 11, the transient response of the Synthesis tunings was driven slower as compared to other tuning methods.

Lee tunings [8] reacted fast but it produced overshoots. Besides, GA-based tunings gave the best transient response as it reacted fast without producing significant overshoot.

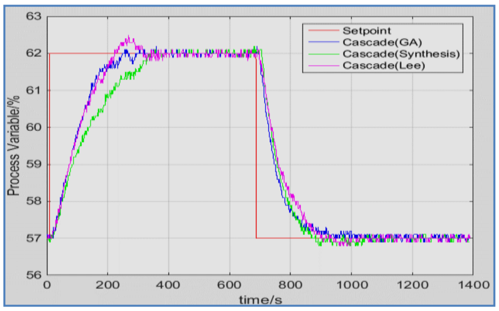

Figure 11. Transient response - comparison of the optimized cascade loop with other cascade control tuning methods

Fig. 12 compared the steady-state response, which showed that the Synthesis tunings produced the largest overshoots followed by Lee tunings. Interestingly, the GA-based tunings produced the least overshoots.

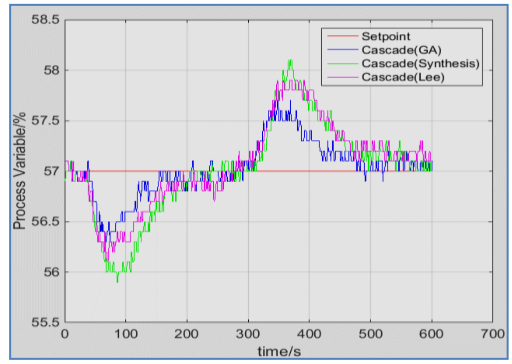

Figure 12. Steady-state response - comparison of the optimized cascade loop with other cascade control tuning methods

E. Integral Errors Measurements

Integral Error values of the temperature control system was compared among IAE, ISE, ITAE and ITSE for the respective tunings. The accumulated integral error values of GA-based tunings were the lowest for most of the measurements. The significant improvement was contributed by the servo control where the integral error values were greatly reduced as compared to other tuning methods. The performance rank was then followed by Lee, Synthesis, and IMC-based tuning as depicted in Table III.

TABLE III. THE MINIMUM INTEGRAL ERROR MEASUREMENT

Error	Single (Moderate Mode)		Single (Aggressive Mode)		Cascade (Synthesis)		Cascade (Lee)		Cascade (GA)	
	Servo	*Regulatory*	*Servo*	*Regulatory*	*Servo*	*Regulatory*	*Servo*	*Regulatory*	*Servo*	*Regulatory*
IAE	64.1	524.7	127.7	596.9	56.2	199.8	41.8	199.8	40.3	199.5
ISE	37.0	545.3	71.0	717.2	37.4	199.4	30.0	199.4	28.8	199.2
ITAE	4286.3	128359.9	14784.4	146384.3	2247	19970.3	1234.4	19974.1	1238.6	19969.5
ITSE	1106.3	131905.1	4000.5	172256.2	885.7	19938.5	515.2	19946.2	468.8	19937.1

F. Comparison of Improved Performance Through Optimized Cascade and Single Loop Control Tunings

The overall performance of GA-based tunings was also compared with the single loop IMC-based tunings included aggressive and moderate mode.

In Fig. 13, the transient response of GA-based tunings seemed as more promising when compared to the single loop tunings. GA-based tunings drive the process variable faster towards the new setpoint. Whereas, the IMC-based aggressive tuning drive the process variable speedily but with oscillations. Besides, the IMC-based moderate tunings drive the process variable slowly to the new setpoint.

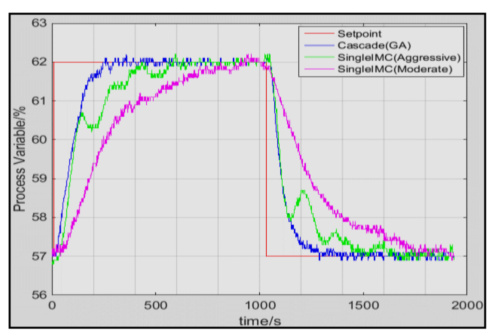

Figure 13. Transient response - comparison of the response performance for optimized cascade and single loop for PI tunings

Fig. 14 compared the steady-state response of GA-based tunings with the single loop IMC-based tunings included aggressive and moderate mode. GA-based tunings produced the most stabilized response with the least settling time and overshoots as compared to other tunings. IMC-based aggressive mode produced fast response but with more oscillations. Besides, IMC-based moderate mode produced the largest overshoots.

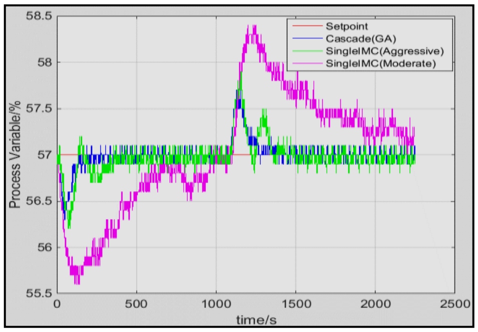

Figure 14. Steady-state response - comparison of the response performance for optimized cascade and single loop for PI tunings

Table IV showed the improvement presented by GA-based tunings as compared to single loop IMC-based tunings. The results showed that improvement of IMC-based aggressive mode has only improved 46.23% for the servo control and 23.08% for the regulatory controls. Interestingly, the GA-based tunings presented better improvements, in which the settling time was reduced to 237 seconds or 76.49% in the transient response. For the similar applied disturbance, GA-based tunings produced smaller overshoots, with an improvement of 53.85% as compared to the single loop IMC-based moderate tuning.

TABLE IV. THE IMPROVEMENT OF PERFORMANCE FOR THE TEMPERATURE CONTROL OF SE-201

Control Loop	Servo Control		Regulatory control	
	Settling Time(s)	*Improvement (%)*	*Overshoot (%)*	*Improvement (%)*
Single-Moderate	1008	-	1.3	-
Single-Aggressive	542	46.23	1	23.08
Cascade (GA)	237	76.49	0.6	53.85

5. CONCLUSION

In this paper, the optimized P-PI tunings by using GA was introduced to improve the closed-loop feedback control performance of the cascade control loop for SE-201. Studying the stability margin allows determining the upper and lower limit bounds of the controllers' parameters during the GA optimization analysis. Comparison of the curve performance for GA-based tunings with other cascade tunings as well as single loop showed that GA-based tunings produced the best performance in the closed-loop control. In conclusion, GA-based tunings improved the transient and steady-state responses of the controlled system by providing a reasonable PID tunings. The improvement of GA-based tunings includes the transient response till 76.49% and the steady-state response to 53.85% as compared to the single loop feedback control. GA-based tunings also created the least integral error values as compared to other tuning methods. The optimized setting for cascade control for the Process Control Simulator SE201 was found to be PB = 31% for the inner loop and PB = -2%, τ_i = 70s for the outer loop.

DATA ACCESSIBILITY

Data created during this research work is available at [https://drive.google.com/drive/folders/1r_U_-kgcFr6APV42NeqGgbav0LXSuaZB?usp=sharing]

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