IOP Conference Series: Materials Science and Engineering

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To cite this article: I M Chew *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **495** 012020

IOP Conf. Series: Materials Science and Engineering **495** (2019) 012020 doi:10.1088/1757-899X/495/1/012020

Optimized Computational Analysis of Feedforward and Feedback Control Scheme using Genetic Algorithm Techniques

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Abstract. A computational analysis using Artificial Intelligence techniques has drawn its attention in Industrial Revolution 4.0. There are self-regulating and integrating processes involved. The commonly used control method involves single-loop feedback control. Embedding feedforward algorithm is aimed to improve the steady state response of the controlled process without affecting the performance of transient response. Apart of it, two optimal tunings are respectively applied to suit to the different control objectives. Correlation PID tunings are applied to respective objective somehow is very relying to the engineering experience and skills. This paper proposed using Genetic Algorithm for optimization analysis to search a trade-off optimized PI controller settings, which reduces dependency on skills as well as provide better insights to all practical engineers for commending effective PI tunings to the real control practices of plants. Initially, the respective process and disturbance models of LOOP-PRO software for both Jacketed-reactor and Pumped-tank were developed. Then, the simulation analysis of PI tunings was conducted to feedback control, feedforward and feedback and Genetic Algorithm scheme. Relative performance was compared in terms of graphs, performance index, and performance indicator. It is concluded that Genetic Algorithm has consistently provided a trade-off optimized PI controller settings for both Jacketed-reactor and Pumped-tank.

1. Introduction

In palm oil mills, water level control of a boiler system is critically important in producing consistent pressurized steam that rotates turbines for generating electricity supplied throughout the production plant. Steam is also supplied to many processes such as sterilization, cleaning process and etc. The most common type of boiler system is known as a natural-circulation boiler, while the large boiler drum will need a pump to assist water circulation thereby is known as the assisted-circulation boiler [1,2]. It is important to note that natural-circulation boiler is a self-regulating process whereas assisted-circulation boiler is known as the integrating process. Nonetheless, the water level control is still a primary control objective. Few issues will occur if the different boiler operation is not controlled properly. Overly high water level causes high moisturized pressurized steam supplied to turbines that will corrode the steel parts of equipment such as turbines, nuts, and jointing points. On the other hand, too low water level consequences overheating and damage of the welding parts connected to the boiler drum.

In a natural-circulation boiler, varies of water inflow changes the water outflow until the water level will settle out at a new operation level. It is more simple to be controlled [4]. Whereas, the assisted-circulation boiler has water outflow is constantly varying as water inflow has changes. The water level of the boiler drum is only stable in an open loop configuration at its equilibrium operating point, where the inflow and outflow are equal [3]. The changes of inflow water lead to unstable control if it is not handled properly [5]. In a closed-loop control, when a stabilized process is disturbed by any environment disturbance for either inflow or outflow, the controller output will vary with time at the certain speed so as to regulate process variable correct fix to the set value. It is important to note that control tuning methods that are proven for self-regulating process yields poor and even unstable performance when applied to the integrating process [5].

2. Background & Literature Review

2.1. Feedforward control of self-regulating and integrating process

A typical single-loop feedback control system can work well in servo but not regulatory control. Servo control involves changes of the setpoint causes vary response curves, which is analyzed by the setpoint tracking analysis. In contrast, regulatory control reflects capability of the controlled parameter rejects to the external inferences, which is determined by disturbance rejection performance. The conventional tuning method such as Internal Model Control (*IMC)* is widely utilized in many industries due to its consistency to drive process variable to the setpoint without creating overshoot, see literature [6]. However, *IMC* is less robust in dealing with regulatory control problems. Corrective action from the controller has only begun after the measured process variable has been forced away from the setpoint thereby it degrades the performance of a stable operation. To cope with it, feedforward control algorithm is embedded into the single feedback control loop for the purpose to instantly measure the disturbance and then regulating the incremental ratio of control actions as accord to changes of the load [6,7]. Figure 1 illustrates the feedforward function is embedded into a feedback control system.

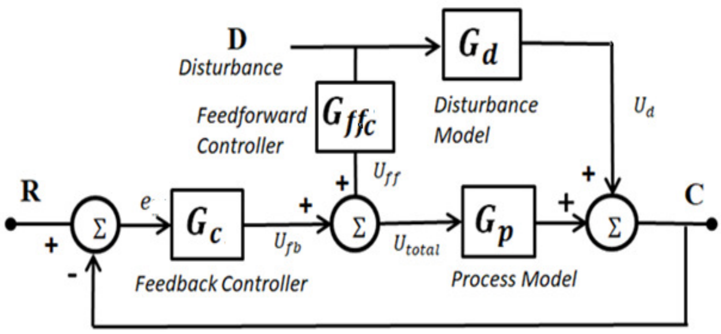

Figure 1. Block diagram of feedforward and feedback control scheme

Where,

G_c = PID Controller
G_d = Disturbance Model
G_p = Process Model
G_{ffc}=Feedforward Controller

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The applied control model is known as Proportional-Integral-Derivative (*PID)* controller which is widely used in many processes. The output of the error signal is the input to the *PID* controller whereas the output of the *PID* controller is a control action to the process. As the feedforward algorithm immediately measures the disturbance and channel it to the feedforward controller for compensating of control actions from *PID* controller, without waiting any deviation happens in the process variable. Thereby, the provided 'early warning' signals enable control scheme has the opportunity to eliminate the effect of a disturbance before the controlled variable deviates from the setpoint value [7-9]. However, the success of the performed analysis should also consider accuracy of the approximated process and disturbance model when it is compared to the real physical boiler system. The dynamic behaviour of both self-regulating and integrating process can be approximated into First Order plus Dead Time (*FOPDT)* model as tabulated in table 1.

Table 1. Dynamic behavior of process and disturbance model.

	Self-regulating Process Model		Integrating Process Model	
	Process, G_p	Disturbance, G_d	Process, G_p	Disturbance, G_d
FOPDT	$\frac{K_p e^{-\theta_p s}}{\tau_p s + 1}$	$\frac{K_d e^{-\theta_d s}}{\tau_d s + 1}$	$\frac{K_p e^{-\theta_p s}}{s}$	$\frac{K_d e^{-\theta_d s}}{s}$

Where,

K_p =Process Gain
K_d= Disturbance Gain
τ_p = Process Time Constant
τ_d = Disturbance Time Constant
θ_p = Process Deadtime
θ_d = Disturbance Deadtime

The performance of both self-regulating and integrating processes are studied through Jacketed-reactor and Pumped-tank function of LOOP-PRO software, which is widely used in process control analysis [4].

2.2. *Performance Index based on the measurement of Integral Error*

The overall performance of the respective self-regulating and integrating systems are evaluated by accumulating integral error signals of the response [17]. There are three types of measurement for minimum integral error signals include Integral Absolute Error (*IAE*), Integral Square Error (*ISE*), and Integral Time Absolute Error (*ITAE*) index as shown in figure 2.

The respective setpoint and disturbance signals are applied to the control loop then integral error values were recorded. All values were presented in indexes, which is the sum total area under the response curve. The smaller index value reflects a better performance. Performance indexes of feedback-only, feedforward and feedback, and Genetic Algorithm (*GA)* is to be compared and analyzed.

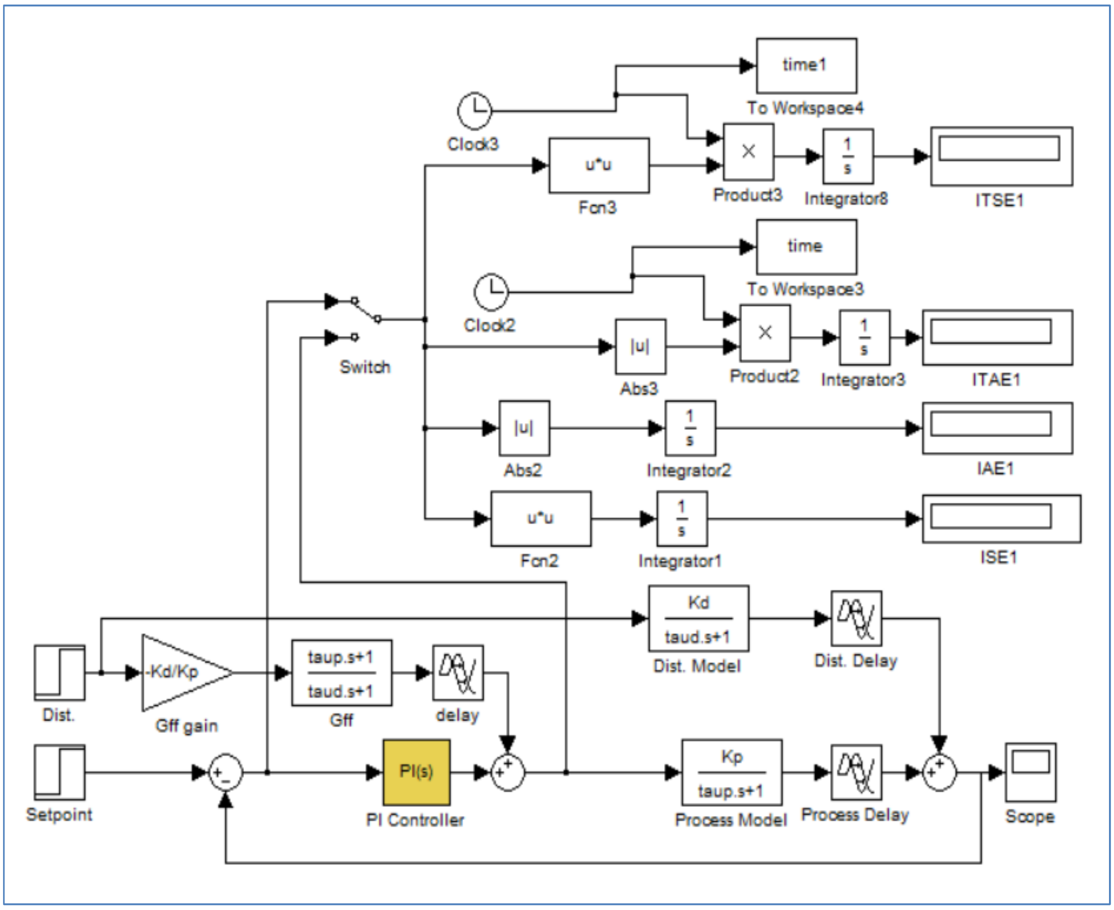


Figure 2. Performance index measurement

2.3. *Introduction to Genetic Algorithm*

This paper highlights computational optimization analysis in optimized tunings for both self-regulating and integrating processes using *GA*. *GA* was firstly proposed by Holland in 1962 [10,11]. It is the procedure of adaptive and parallel search for the solution of complex problems. *GA* has been successfully applied to many different problems, such as traveling salesman [12], graph partitioning problem, filters design, power electronics [10], etc. It has also been applied to machine learning [13], dynamic control system using learning rules and adaptive control [14]. *GA* can be interacted with other artificial intelligence techniques, like Fuzzy Sets and Artificial Neural Network, and Multi-Objective Genetic Algorithm and Superheater Steam Temperature Control [15]. In this paper, *GA* has been utilized for finding optimal tuning values of both servo and regulatory control problems in a feedforward and feedback control loop. The *GA* iteratively modifies a population of individual solutions. At each step, the *GA* selects individuals at random from the current population to be parents and uses them to produce the children for the next generation [16].

The new population contains a large amount of information about the previous generation and carries the new individuals which are superior to the previous generation. This will have repeated for many times and the fitness function of all the individuals in the population always increases until certain limit

conditions are met. At the end of optimization process, the individuals, which has the highest degree of fitness are chosen as the optimal solutions of the control terms to be optimized.
A simple *GA* flowchart is shown in figure 3. First, limits for the searching space, the fitness function for deciding the suitability of members to the solution and the parameters to be optimized are defined. Then, the first generation is produced randomly. After the fitness test of each member in the generation, the algorithm produces a new generation or is terminated according to the convergence test.

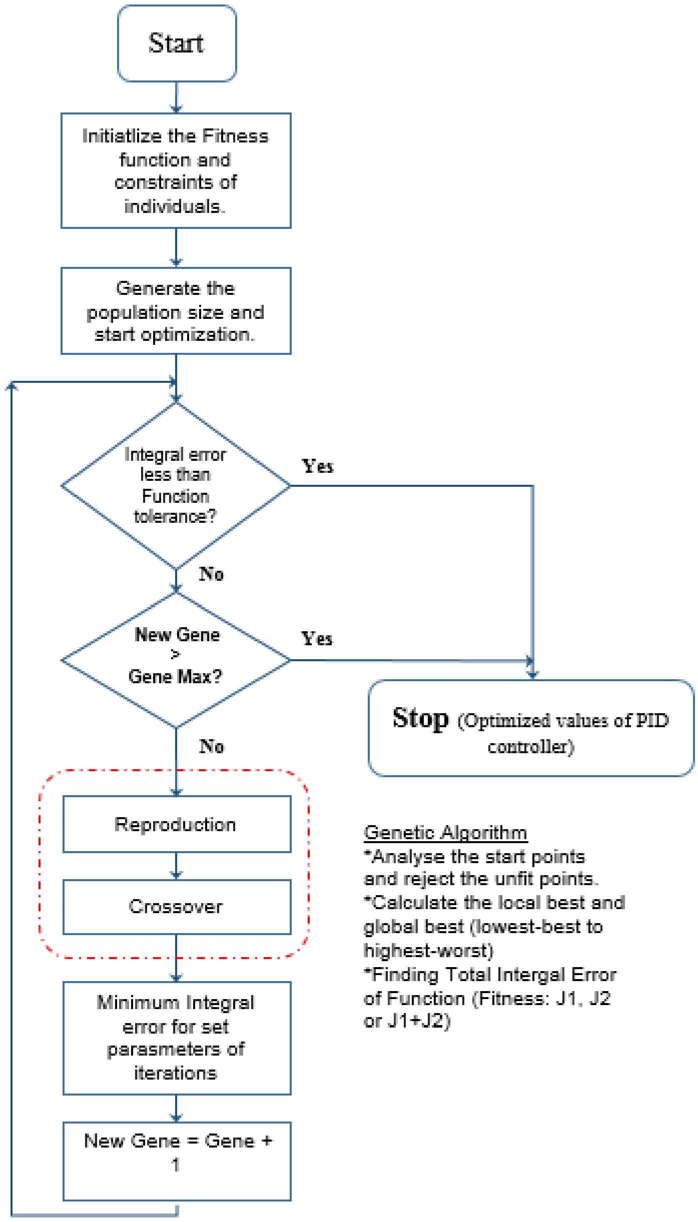


Figure 3. Flowchart of *GA* for feedforward and feedback control scheme.

2.4. Genetic Algorithm for measuring integral errors of feedforward and feedback control loop

Figure 4 illustrates the accumulated error signals from both servo and regulatory control problems that have been compared with computational optimization analysis using *GA*. The repetitive generated iterations converge the value of received integral error signals in successive iterations and eventually provide a trade-off *PID* tunings and feedforward ratio, *Γ* for the minimum integral error signal, which reflects the better controllability and robustness for both transient and steady-state responses.

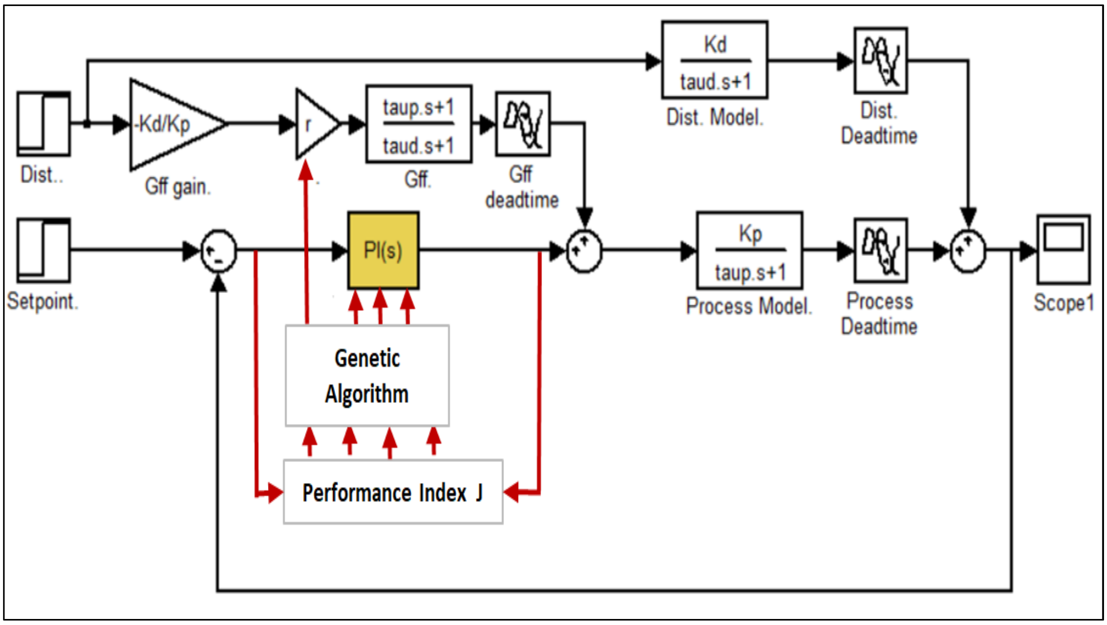


Figure 4. Block diagram of computational optimization analysis using *GA*.

3. Formulation Of Feedforward Plus Feedback Algorithm And Stability Margin

3.1. Formulation of feedforward and feedback control scheme

Refer to figure 1, the developed transfer function of feedforward and feedback control scheme is shown in equation (1).

$$C = \frac{G_d + G_p G_{ffc}}{1 + G_c G_p} D + \frac{G_c G_p}{1 + G_c G_p} R \tag{1}$$

The closed-loop transfer function for a load change is depicted in equation (2).

$$\frac{C(s)}{D(s)} = \frac{G_d + G_p G_{ffc}}{1 + G_c G_p} \tag{2}$$

We do expect "perfect" control where the controlled variable remains exactly at the setpoint despite arbitrary changes in the disturbance, D. Thus, the setpoint is constant (R(s) = 0), we want C(s) = 0 even though D ≠ 0, equation above is satisfied as $G_d + G_p G_{ffc} = 0$.
Solving for G_{ffc} gives the ideal feedforward controller is as shown in equation (3).

$$G_{ffc} = -\frac{G_d}{G_p} \tag{3}$$

As shown in the table 1, the respective G_p and G_d are applied to (3) to produce a feedforward expression for both self-regulating and integrating processes. The self-regulating transfer function has lead and lag compensation whereas the integrating transfer function is not.

In self-regulating control, Ogata explained the lead and lag compensation and impact towards disturbance rejection performance [18]**.** Jobrun recommended to apply a feedforward filter that improves rejection to disturbance [8]. In this paper, the author suggests a feedforward ratio, $\boldsymbol{\Gamma}$ for adjusting feedforward gain and thus to change the capability in rejecting disturbances. Therefore, the re-defined G_{ffc} is depicted in table 2.

$\boldsymbol{\Gamma}$, which is the tuning operator for feedforward ratio and $\Gamma \in (0, 1)$ a positive scalar parameter which can be used to tune G_{ff}.

Table 2. Feedforward controller expression for both self-regulating and integrating process.

	Self-regulating Process Model	Integrating Process Model
Feedforward Controller	$-\Gamma \frac{K_d\left(\tau_p s+1\right)}{K_p\left(\tau_d s+1\right)} e^{-(\theta_d-\theta_p)s}$	$-\Gamma \frac{K_d}{K_p} e^{-(\theta_d-\theta_p)s}$

The feedforward model consists of three main parts includes gain, lead/lag, and deadtime. These three blocks are combined to implement a dynamic G_{ffc} [4]. When designing a G_{ffc}, the reliability of the resulting controller becomes an issue. In enabling feedforward controller to be realizable, the total deadtime must be nonnegative, where $\theta_d - \theta_p \geq 0$ or $\theta_d \geq \theta_p$. Otherwise, Erikson [6] suggested choosing θ_d to be similar value with θ_p so to make total deadtime equal to 0.

3.2. Formulation of stability margin

The stability of the closed-loop control is reflected by the denominator of the transfer function. Stability is determined by the terms in the characteristic equation, which is mainly referring to the denominator of the transfer function [1,5]. However, the disturbance process and feedforward controller appear only in the numerator of the transfer function. Therefore, a feedforward controller does not destabilize control, although it potentially leads to poor control due to inability to reduce the steady-state offset to zero. The formulation of the stability margin for both self-regulating and integrating processes are explained in the following section.

3.2.1. Stability margin for the self-regulating process. From characteristic equation, $1 + G_{c2}G_{p2} = 0$.

Applying Taylor approximation, $e^{-\theta_p s} \approx (1-\theta_{p2}S)$ to produce equation (4).

$$1 + \left(K_c + \frac{K_i}{s}\right)\left(\frac{K_p}{(\tau_p s+1)}\left(1-\theta_p s\right)\right) = 0 \tag{4}$$

Solve equation (4) to obtain equation (5)

IOP Conf. Series: Materials Science and Engineering **495** (2019) 012020 doi:10.1088/1757-899X/495/1/012020

$$s^2(\tau_p - K_c\theta_p K_p) + (1 + K_cK_p - K_i\theta_pK_p)s + K_iK_p = 0 \tag{5}$$

From term s^2, $\tau_p - K_c\theta_pK_p > 0$, solve it to obtain equation (6)

$$K_c < \frac{\tau_p}{\theta_pK_p} \tag{6}$$

From term s, $1 + K_cK_p - K_i\theta_pK_p > 0$, solve it to obtain equation (7)

$$K_i = \frac{K_c}{\tau_i} < \frac{1+K_cK_p}{\theta_pK_p} \tag{7}$$

3.2.2. Stability margin for integrating process. From characteristic equation, $1 + G_{c2}G_{p2} = 0$. Applying Taylor approximation, $e^{-\theta_p s} \approx (1-\theta_{p2}S)$ to produce equation (8)

$$1 + \left(K_c + \frac{K_i}{s}\right)\left(\frac{K_p}{s}(1 - \theta_ps)\right) = 0 \tag{8}$$

Solve equation (8) to obtain equation (9)

$$s^2(1 - K_c\theta_pK_p) + (K_cK_p - K_i\theta_pK_p)s + K_iK_p = 0 \tag{9}$$

From term s^2, $1 - K_c\theta_pK_p > 0$, solve it to obtain equation (10)

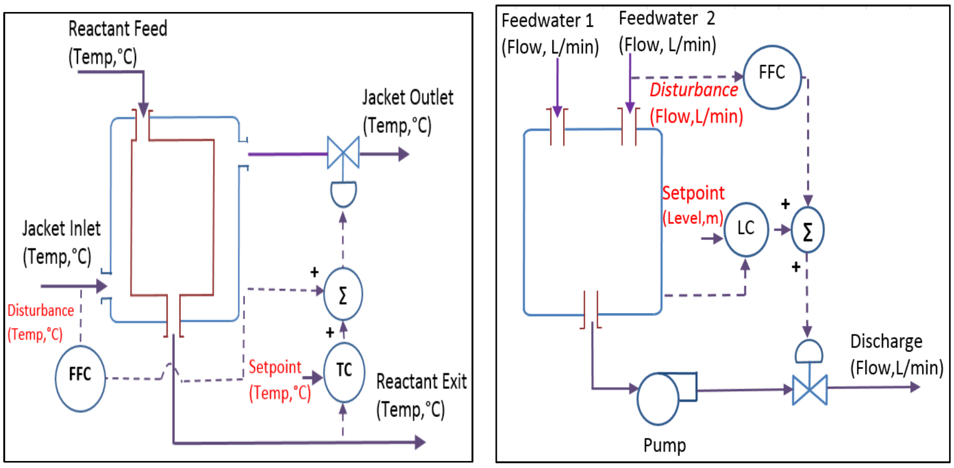
$$K_c < \frac{1}{\theta_pK_p} \tag{10}$$

From term s , $K_cK_p - K_i\theta_pK_p > 0$, solve it to obtain equation (11)

$$K_i = \frac{K_c}{\tau_i} < \frac{K_c}{\theta_p} \tag{11}$$

3.3. Case studies for Self-regulating and integrating process

In visualizing the principle of computational optimization analysis to the feedforward and feedback control scheme, the case studies were conducted with Jacketed-reactor and Pumped-tank in LOOP-PRO software [4]. LOOP-PRO provides very compatible functions for the case studies. As noted, Jacketed-reactor is used for self-regulating process whereas Pumped-tank is used for integrating process. The figures for both functions are illustrated in figure 5 (a) and (b).



(a) Jacketed-reactor (b) Pumped-tank

Figure 5. Case studies of self-regulating and integrating process

At first, the manual mode of respective function was set for open loop test where the changes of water level were accumulated by imposing different manipulation value and then disturbances. Those are critical move to develop process and disturbance models.

In auto mode, the setpoint value of Jacketed-reactor is set in between 90 - 95 ^{0}C whereas the disturbance test is set in between 45 - 55 ^{0}C. On the other hand, the setpoint value of Pumped-tank is set in between 5 - 6 m whereas disturbance value is set in between 1.5 - 2.5 L/min for the disturbance test. The responses from testing were recorded and compared.

4. Analysis and Result

4.1. Developing of FOPDT models and correlation tunings of PI controller and Γ.

The process and disturbance model are developed through open loop test method as detailed in the literature [19] and [20]. The generated *FOPDT* for both process and disturbance models for both self-regulating and integrating processes are depicted in table 3.

Table 3. Process model and disturbance model of jacketed-reactor and pumped tank from the Loop-Pro Software

Model	Jacketed-reactor (self-regulating)	Pumped-tank (Integrating)
Process Model	$\frac{-0.329e^{-0.721s}}{1.84s+1}$	$\frac{-0.0238e^{-0.9721s}}{s}$
Disturbance Model	$\frac{0.8105e^{-1.029s}}{2.268s+1}$	$\frac{-0.0971e^{-0.9721s}}{s}$

PI controller settings were respectively applied to Jacketed-reactor and Pumped-tank function in LOOP-PRO software. The correlation tuning values of PI controller and tuning operator, Γ to feedforward and feedback control scheme are tabulated in table 4. Moreover, PI controller settings are compared through feedback-only, feedforward and feedback, and *GA* optimization control scheme.

Table 4. PI controller and Γ setting of different tuning methods

Tuning Method	Self-regulating Process Control			Integrating Process Control		
	Kc	Tau i	$\boldsymbol{\Gamma}$	Kc	Tau i	$\boldsymbol{\Gamma}$
Feedback-only	-0.861	1.84	0	-17.3	7.5	0
Feedforward plus feedback	-0.861	1.84	1	-17.3	7.5	1
Optimization-*GA*	-1.564	1.6	0.9	-33.79	6.62	1

Correlation PI tunings of feedforward and feedback control scheme is similar to feedback-only control scheme because both tuning methods are accomplished by *IMC* tunings. However, feedforward and feedback control scheme had been applied thereby $\boldsymbol{\Gamma} = 1$.

Computational optimization analysis was conducted by using *GA* has recommended $\boldsymbol{\Gamma} = 1$ for integrating process because integrating process does not have lead and lag component. Thus, *GA* did not rely on the ratio, $\boldsymbol{\Gamma}$ to produce optimal *PI* control values.

4.2. Stability Margin

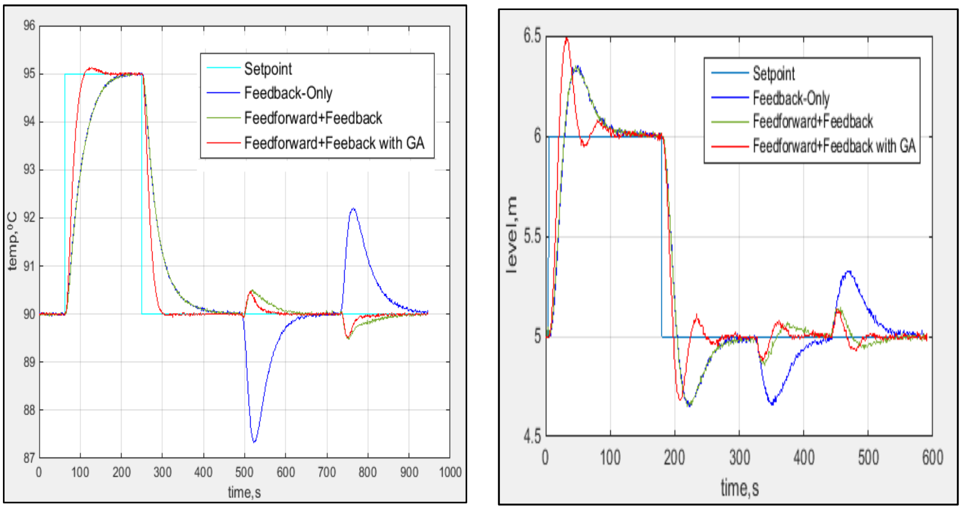
The calculation of respective stability margin for self-regulating and integrating process are obtained through equations (4), (5), (6), and (7) are illustrated in table 5. It is interesting to note that the range can be used as the upper and bottom limit settings for *GA* optimization analysis.

Table 5. Stability Margin for both self-regulating and integrating process.

Process Model	Jacketed-reactor (self-regulating)	Pumped-tank (Integrating)
Proportional gain, Kc	$0 < K_c < 7.76$	$0 < K_c < 41.02$
Integral time constant, $\boldsymbol{\tau_i}$	$\tau_i > 4.66$	$\tau_i > 1$

4.3. Improvements on feedforward plus feedback control and computational optimization analysis.

Figure 6 (a) and (b) depicts that the steady-state response of both self-regulating and integrating processes had been greatly improved when feedforward algorithm was applied as compared to feedback-only control scheme. Graphical data showed that overshoots and settling time of feedforward and feedback control scheme are reduced as compared to feedback-only control scheme. It reflected the better controllability and performance in regulatory control. However, feedforward control algorithm inherently did not improve transient response. Impressively, *GA* enhanced both transient and steady-state responses by providing more robust and smoothen responses with minimum settling time.



(a) Self-regulating (b) Integrating

Figure 6. Responses of feedback-only, feedforward and feedback and GA optimization control scheme for both self-regulating and integrating process.

4.4. Relative performance index

One of the typical approach to compare overall performance of controlled system is by measuring integral error signals from the transient and steady-state responses. It is obtainable by developing both feedforward and feedback control function of both self-regulating and integrating processes in Matlab environment for measurement of *IAE, ISE,* and *ITAE* as depicted in figure 2. The respective servo and regulatory control were applied to the control loop and the generated integral error values were recorded. All values were presented in indexes, whereby the smaller index value reflects the better performance. Performance indexes of feedback-only, feedforward plus feedback and *GA* optimization control scheme of Jacketed-reactor are tabulated in table 6.

Table 6. Performance indexes of setpoint tracking analysis and disturbance rejection performance of Jacketed- reactor

Tuning Method	Setpoint tracking analysis			Disturbance rejection performance		
	IAE	ISE	ITAE	IAE	ISE	ITAE
Feedback-only	4.30	2.13	238.7	180.8	736.7	1.137e+04
Feedforward plus feedback	4.30	2.13	238.7	179.7	728.4	1.127e+04
Optimization-*GA*	3.13	1.84	167.5	175.2	720.2	1.083e+04

Performance indexes of feedback-only, feedforward plus feedback control scheme and *GA* of Pumped-tank are tabulated in table 7.

Table 7. Performance indexes of setpoint tracking analysis and disturbance rejection performance of Pumped-tank

Tuning Method	Setpoint tracking analysis			Disturbance rejection performance		
	IAE	ISE	ITAE	IAE	ISE	ITAE
Feedback-only	6.50	3.63	102.4	261.1	633.7	2.531e+04
Feedforward plus feedback	6.50	3.63	102.4	253.2	605.6	2.492e+04
Optimization-*GA*	3.13	2.06	38.23	249.0	590.5	2.468e+04

It is noted that *GA* produced the lowest index value as compared to other control schemes. The data showed that by adding feedforward algorithm was not improving transient response. Surprisingly, *GA* further refine PI tuning values that enhanced satisfactory performance for both self-regulating and integrating processes.

4.5. Performance Indicator

The performance indicator for PI correlation tunings for feedback-only, feedforward and feedback control scheme and *GA* is illustrated in table 8. PI tuning values generated by *GA* produces the most desirable response for both servo and regulatory control problems.

Table 8. Performance indicators of setpoint tracking analysis and disturbance rejection performance of Jacketed- reactor.

Tuning Method	Setpoint tracking analysis		Disturbance rejection performance	
	Overshoot, ^{o}C	***Settling Time, s***	***Overshoot, ^{o}C***	***Settling Time, s***
Feedback-only	0	82	2.63	94
Feedforward plus feedback	0	80	0.5	35
Optimization-*GA*	0.13	34	0.4	24

Performance indicator of feedback-only, feedforward and feedback and *GA* control scheme of Pumped-tank are tabulated in table 9.

Table 9. Performance indicators of setpoint tracking analysis and disturbance rejection performance of Pumped-tank.

Tuning Method	Setpoint tracking analysis		Disturbance rejection performance	
	Overshoot, ^0C	***Settling Time, s***	***Overshoot, ^0C***	***Settling Time, s***
Feedback-only	0.35	23.39	0.35	69
Feedforward plus feedback	0.35	88	0.15	20
Optimization-*GA*	0.45	45	0.13	16

GA provides control action with the fastest settling time for both self-regulating and integrating processes and also producing smaller overshoots in regulatory control. It reflected advance of *GA* technique as compared to feedback-only and feedforward and feedback control therefore is determined as the better tuning technique for both Jacketed-reactor and Pumped-tank function in LOOP-PRO software.

5. Conclusion

As the boiler system has a significant contribution to many industries, tight control on its parameters specifically water level of boiler drum is critically needed to ensure effective function of the boiler system. In preventing issues related to water level control problems, conventional PI tunings is always recommended but sided to required control objectives somehow confuses operators in the plant. This paper suggested using *GA* for finding the trade-off optimal PI tunings for both servo and regulatory control problems. The case studies showed that computational optimization analysis using *GA* had significantly improved the transient and steady-state responses for both self-regulating and integrating processes, which were justified through Jacketed-reactor and Pumped-tank function of LOOP-PRO software. Analysis reflected optimized PI tunings of Jacketed-reactor was $\boldsymbol{K_c}$ = -1.564%/^{0}C, $\boldsymbol{\tau_i}$ = 1.6s and $\boldsymbol{\Gamma}$ = 0.9. Whereas, the optimized PI tunings of Pumped-tank was $\boldsymbol{K_c}$ = -33.79%/m, $\boldsymbol{\tau_i}$ = 6.62s and $\boldsymbol{\Gamma}$ = 1.0. It is concluded that *GA* is a stunning approach for finding a trade-off optimal PID tunings for controlling parameters in the boiler system.

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