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OPTIMAL TUNING PARAMETERS OF PROPORTIONAL INTEGRAL CONTROLLER IN FEEDBACK CONTROL SYSTEMS.

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Abstract— **Most of the chemical processes with significant noise in the measured variables can be controlled using proportional-integral controllers. It is always important to determine the optimum control parameters of these proportional integral controllers depending on the different objectives. In this article, correlations which relate the optimum proportional integral controller parameters to process parameters for different types of process models are developed.**

Both servo and regulatory control correlations for proportional integral controllers are obtained for the process model types such as first order plus time delay (FOPTD) and second order plus time delay (SOPTD) with the objective of minimizing different performance criteria such as integral of absolute value of the error (IAE), integral of the time-weighted absolute value of the error (ITAE), integral of the squared value of the error (ISE) and integral of the time - weighted squared value of the error (ITSE). The corresponding performance of these proposed correlations are compared with that of the well-known tuning methods: Ziegler-Nichols continuous cycling method, Ziegler-Nichols reaction curve method, Cohen-Coon method and other proposed tuning methods in the literature in terms of values of overshoot, rise time, settling time and integral performance criteria and the advantages and disadvantages of the proposed correlations are discussed.

It is found that using correlations obtained for first order plus time delay and second order plus time delay processes, several performance characteristics such as overshoot and settling time are reduced compared to those obtained using other tuning methods. Further, the regulatory control correlations proposed for first order plus time delay processes leads to minimum values of integral performance criteria than some of the other existing methods.

Index terms-- **Process control; Design of feedback controllers; PI controller; Tuning correlations; Integral performance criteri, optimization..**

I. INTRODUCTION

Most processes in the chemical industry can be satisfactorily controlled by using proportional – integral and derivative (PID) feedback controller configuration [1-4]. Furthermore, processes with significant noise are controlled using proportion-integral control with the derivative action turned off [5-6]. For this reason, many control tuning techniques, correlations and formula have been improved and presented in the literature [7-8]. Every new approach has important contributions to controller tuning theory, which can lead to many crucial improvements with respect to minimizing the waste generated in process industries.

Madhuranthakam et al. [9] proposed a new approach to PID controller tuning. They used Matlab optimization toolbox and Simulink software simultaneously to obtain PID controller tuning correlations which relate PID controller parameters to process parameters considering the minimization of integral of absolute value of the error (IAE) for three different types of process models: first order plus time delay (FOPTD), second order plus time delay (SOPTD) and second order plus time delay with lead (SOPTDLD), separately. In this article, new correlations for the optimal tuning of proportional – integral (PI) feedback controllers are obtained by using dynamic optimization [9]. These correlations involve the optimization of the PI controller parameters with the objective of minimizating the integral of absolute value of the error (IAE), integral of the time-weighted absolute value of the error (ITAE), integral of the squared value of the error (ISE) and integral of the time - weighted squared value of the error (ITSE), separately. The correlations are obtained for two different, most common process types: first order plus time delay (FOPTD) and second order plus time delay (SOPTD). Since error, e(t) is different for set point change and load change, different correlations are obtained for servo and regulatory mechanisms. Further, the performance of the proposed correlations is compared with that of other conventional tuning techniques.

- Optimal Control Parameters

The block diagram of a conventional feedback control system in the Laplace domain is shown in Fig. 1. The output y(s), which is also called a controlled variable, is measured with an appropriate measuring device and measured value of the output, $y_m(s)$ is obtained. Then, a controller mechanism compares this measured value $y_m(s)$ to the set point, r(s) and calculates the error e(s) as shown in equation (1).

$$e(s) = r(s) - y_m(s) \quad (1)$$

The controller's aim is to eliminate this error, e(s) in order to get output, y(s) equal to set point, r(s) through the final control element (e.g. a control valve). For this purpose, the controller produces the actuating signal, u(s) which is the input to the final control element. The transfer function of the controller, $G_c(s)$ which relates the error, e(s) to actuating signal, u(s) is given in equation (2) for a PI controller.

$$G_c = K_c\left(1 + \frac{1}{\tau_I s}\right) \quad (2)$$

In equation (2), K_c is the proportional gain and τ_I is the integral time constant (also called reset time, in minutes). Optimal values for K_c and τ_I for minimizing the time-integral performance criteria are achieved by conducting simulations in MATLAB and SIMULINK.

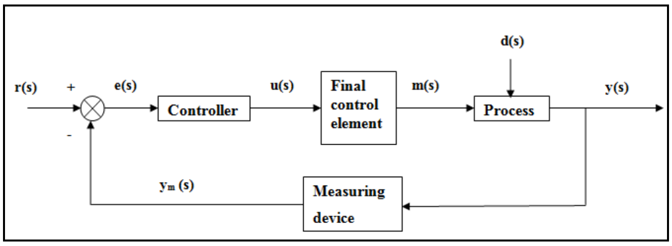

Fig. 1. Block diagram for conventional feedback control loop

The different integral performance criteria used in the optimization constitutes of: integral of the absolute value of the error (IAE), integral of the time-weighted absolute value of the error (ITAE), integral of the squared value of the error (ISE), and integral of the time - weighted squared value of the error (ITSE) and the corresponding formula are shown in equations (3) through (6).

$$IAE = \int_0^\infty |e(t)|dt \quad (3)$$

$$ITAE = \int_0^\infty t \cdot |e(t)|dt \quad (4)$$

$$ISE = \int_0^\infty e^2(t)dt \quad (5)$$

$$ITSE = \int_0^\infty te^2(t)dt \quad (6)$$

The process used in the simulations includes first order plus time delay (FOPTD) and second order plus time delay for which the transfer functions (K_pG_p) are given by equations (7) and (8) respectively. In these equations, τ_1 and τ_2 are process time constants and θ is the dead time.

$$K_pG_p = \frac{K_p \exp(-\theta s)}{\tau_1 s + 1} \quad (7)$$

$$K_pG_p = \frac{K_p \exp(-\theta s)}{(\tau_1 s + 1)(\tau_2 s + 1)} \quad (8)$$

The procedure used for obtaining optimal K_C and τ_I are shown below:

1) For each process model type (FOPTD and SOPTD); sets of process models which have different values of parameters τ_1 and τ_2 (process time constants) and θ (dead time) are defined.
2) For each process defined in step 1, Ziegler-Nichols continuous cycling method was applied and the optimal proportional-integral control parameters (proportional gain, K_c and integral time constant,τ_i) according to this method are calucalted. These control parameters are used as the initial guesses in the optimization process which is executed in Matlab software.
3) The feedback control system which involves the process model and the PI controller is simulated in Simulink software. For unit step change in set point and load, all minimization performance criteria (IAE,ITAE,ISE and ITSE) are calculated with the addition of required simulink blocks in this Simulink models.
4) The optimization process is executed using 'lsqnonlin' function MATLAB. This function uses the outputs (the values of IAE, ITAE, ISE and ITSE) of the Simulink models which is created in step 3 to calculate the objective function. At the end, this matlab program gives the optimum PI control parameters as the output of the optimization process.
5) The simulink model and the matlab codes are executed simultaneously to find out the optimum process control parameters at which each minimization performance criteria is minimum for each processes defined in step 1 separately. As a result, optimum control parameters are obtained corresponding to each set of process parameters.
6) These PI controller parameters and process parameters are made dimensionless by multiplying/dividing by the appropriate scale factors such as $\theta/(\theta+\tau_1)$ and $\theta/(\theta+\tau_1+\tau_2)$ for FOPTD and SOPTD processes respectively.
7) By using regression techniques, simple correlations are obtained for the controller parameters as fuctions

of process parameters for the corresponding two process models and four minimization criteria. Several sets of dimensionless groups are tried and the ones with highest correlation coefficient, R^2, are obtained.

8) Finally, the proposed PI controller tuning correlations (for K_c and τ_I) as functions of the process parameters (K_p, τ_1, τ_2 and θ) are obtained for each process type, for each minimization criteria and for servo and regulatory control, separately.

- Results and Discussion

The tuning correlations obtained using the proposed method for FOPTD and SOPTD processes are summerized and shown in Table 1 and Table 2 respectively.

Table. 1 Proposed tuning relations for FOPTD model and IAE, ITAE, ISE and ITSE minimization criteria

FOPTD Model - IAE Minimization Correlations		
Tuning Parameter	**Set point change**	**Load change**
K_c	$\frac{0.4591}{K_p}\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.126}$	$\frac{0.4755}{K_p}\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.269}$
τ_I	$0.81978\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.068}$	$\theta\left[3.5423\left(\frac{\theta}{\theta+\tau_1}\right)^2 - 6.7028\left(\frac{\theta}{\theta+\tau_1}\right)+4.1042\right]$
FOPTD Model - ITAE Minimization Correlations		
Tuning Parameter	**Set point change**	**Load change**
K_c	$\frac{0.417}{K_p}\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.174}$	$\frac{0.4834}{K_p}\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.21}$
τ_I	$0.73728\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.1}$	$\theta\left[2.1202\left(\frac{\theta}{\theta+\tau_1}\right)^2 - 5.0508\left(\frac{\theta}{\theta+\tau_1}\right)+3.666\right]$
FOPTD Model - ISE Minimization Correlations		
Tuning Parameter	**Set point change**	**Load change**
K_c	$\frac{0.478}{K_p}\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.183}$	$\frac{0.5387}{K_p}\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.315}$
τ_I	$0.73268\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.331}$	$\tau_1\left[3.0447\left(\frac{\theta}{\theta+\tau_1}\right)^2 + 1.5048\left(\frac{\theta}{\theta+\tau_1}\right)+0.3332\right]$
FOPTD Model - ITSE Minimization Correlations		
Tuning Parameter	**Set point change**	**Load change**
K_c	$\frac{0.4342}{K_p}\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.177}$	$\frac{0.5036}{K_p}\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.288}$
τ_I	$0.67218\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.253}$	$\tau_1\left[1.8377\left(\frac{\theta}{\theta+\tau_1}\right)^2 + 2.1668\left(\frac{\theta}{\theta+\tau_1}\right)+0.1714\right]$

Table 2. Proposed tuning relations for SOPTD model and IAE, ITAE, ISE and ITSE minimization criteria

SOPTD Model - IAE Minimization Correlations		
Tuning Parameter	**Set point change**	**Load change**
K_c	$\frac{0.4082}{K_p}\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.016}$	$\frac{0.4196}{K_p}\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.184}$
τ_I	$0.7471\,\theta\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.326}$	$0.2946\left(\frac{\theta}{\tau_1}\right)(\theta+\tau_2)\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.906}$
SOPTD Model - ITAE Minimization Correlations		
Tuning Parameter	**Set point change**	**Load change**
K_c	$\frac{0.4311}{K_p}\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-0.978}$	$\frac{0.4269}{K_p}\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.129}$
τ_I	$0.858\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.172}$	$0.3128\left(\frac{\theta}{\tau_1}\right)(\theta+\tau_2)\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.82}$
SOPTD Model - ISE Minimization Correlations		
Tuning Parameter	**Set point change**	**Load change**
K_c	$\frac{0.4422}{K_p}\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.028}$	$\frac{0.5}{K_p}\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.168}$
τ_I	$0.598\,\theta\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.592}$	$0.3351\left(\frac{\theta}{\tau_1}\right)(\theta+\tau_2)\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.848}$
SOPTD Model - ITSE Minimization Correlations		
Tuning Parameter	**Set point change**	**Load change**
K_c	$\frac{0.4502}{K_p}\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-0.963}$	$\frac{0.5206}{K_p}\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.099}$
τ_I	$0.7106\,\theta\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.354}$	$0.3597\left(\frac{\theta}{\tau_1}\right)(\theta+\tau_2)\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.765}$

- *Case Study for FOPTD Process-Servo Mechanism*

The performance of FOPTD system using the tuning correlations obtained from the above procedure is compared with those obtained using other conventional tuning rules such as Ziegler-Nichols (Z-N) and Cohen-Coon (C-C) methods. For three different FOPTD processes (described by equations (9) through (11)), the responses are obtained for set point changes.

$$G_{p1}(s) = \frac{e^{-s}}{5s+1} \qquad (9)$$

$$G_2(s) = \frac{e^{-5s}}{5s+1} \qquad (10)$$

$$G_{p3}(s) = \frac{e^{-10s}}{5s+1} \qquad (11)$$

Figs. 2-4 show the comparison of the responses using the tuning rules obtained from the proposed method for different objectives considered (IAE, ITAE, ISE and ITSE) with the responses using Z-N and C-C methods.

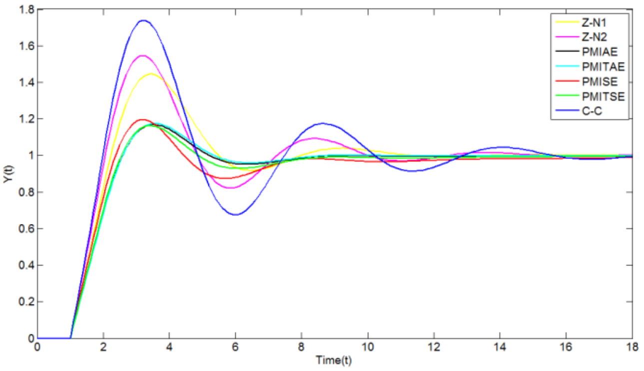

Fig. 2.The comparison of tuning methods for the case study 1 with $\tau_1 = 5$ and $\theta = 1$

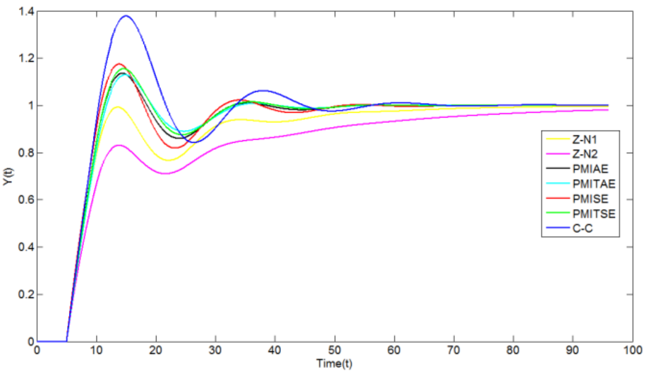

Fig.3.The comparison of tuning methods for the case study 2 with $\tau_1 = 5$ and $\theta = 5$

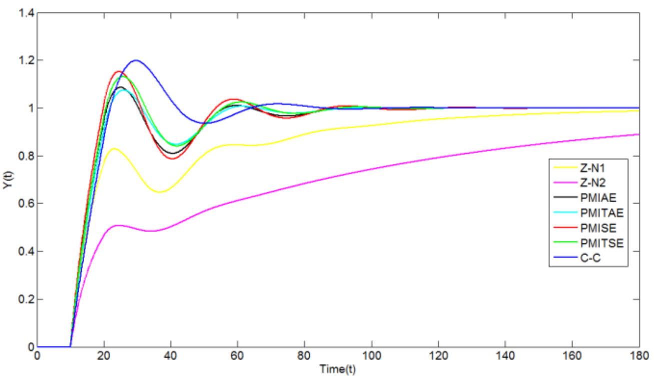

Fig. 4. The comparison of tuning methods for the case study 3 with $\tau_1 = 5$ and $\theta = 10$

Figs. 2-4 and Table 3 clearly show that the proposed method presents a better control than the conventional techniques (Ziegler-Nichols Continuous Cycling method, Ziegler-Nichols Process Reaction Curve method and Cohen-Coon method), especially with respect to settling time (T_s), overshoot (O_s) and the corresponding values of IAE, ITAE, ISE and ITSE. For the first case study, a system which is representative of time constant dominant system (or lag dominant system) is examined and the response of each controller method is analyzed. It is seen from Fig.2, that all responses have overshoot and oscillate around the set point. All the three conventional techniques reach a set point earlier than the proposed method for the first time, which means the conventional techniques have shorter rise times (T_r) than the proposed method. However, these differences in the rise time are not quite significant which can be seen from Table 3. The important advantage of the proposed method can be seen when the settling time (T_s) values are compared. The proposed method provides shorter settling times than the conventional methods which indirectly minimizes the off-spec product in the process plant. Further, the settling time values obtained from the proposed method (the ones proposed for IAE and ITAE minimization) are nearly half the ones obtained from the conventional methods. Another benefit of the proposed tuning correlations is that they give shorter overshoot (O_S) values than the conventional techniques. The proposed correlations lead to lower values of IAE, ITAE, ISE and ITSE than the conventional techniques. For the case study 2, a system which has equal time constant (τ_1) and dead time (θ) is selected. From Fig.3, it is observed that the same comments can be made as in case study 1. The proposed method gives shorter settling time, less overshoot value and less minimization criteria values than the conventional techniques. What is really needed to be pointed out in this case study is the response got from the two Ziegler-Nichols methods. The Ziegler-Nichols methods' responses do not go beyond the value of set point, and stay below the set point and they are able to only reach the set point in their settling times. Especially, Ziegler-Nichols process reaction curve method's response is very slow. When the proposed method and Cohen-Coon method are compared in this section, the proposed method gives a shorter settling time, smaller overshoot and less minimization criteria values as mentioned before. The only advantage of Cohen-Coon method is that it gives shorter rise time but, again there are no significant differences in rise time values as seen in Table 3. In both, case studies 1 and 2, it is seen that Cohen-Coon method gives more oscillatory response than that of the proposed correlations. This is absolutely not surprising that Cohen-Coon formula produces very oscillatory set-point responses since it was derived to give quarter damping (one quarter decay ratio) [10].

Case study 3, a system which is representative of a dead time dominant system, is examined and the responses of each controller method are analyzed. Again, Ziegler-Nichols methods' responses are below the set point and reach the set point at settling times. Additionally, their responses get even worse since dead time is greater than that in case study 2. It is already known that Ziegler-Nichols continuous cycling method tuned PI controller produces sluggish set point and load-disturbance responses for large dead-time systems and that is the reason why it is thought to increase the integral action to overcome this problem while refining Ziegler-Nichols closed-loop tuning formulas [29]. In this case study, the proposed method provides a better response than Cohen-Coon method in every respect. The proposed method gives shorter rise time, smaller settling time, less overshoot and less minimization criteria values than Cohen-Coon method. Hence, the proposed method gives good responses even in dead time dominant systems.

- *Case Study for FOPTD Process-Regulatory Mechanism*

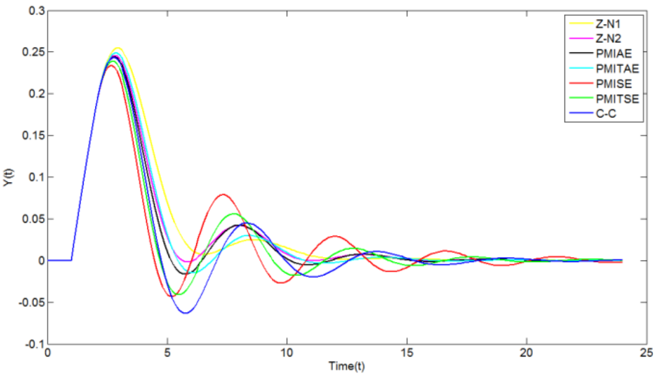

Fig. 5. The comparison of tuning methods for the case study 1 ($\tau_1 = 5$, $\theta = 1$)

Figs. 5-7 show the corresponding responses for a unit step change in the load for the processes given in equations (9) through (11). For case study 1, Fig.5, shows the comparisons of the responses of the tuning methods for regulatory control system. Two Ziegler-Nichols methods give oscillations over the set point (set point is 0 in this case). On the other hand, Cohen-Coon method gives more oscillations than Ziegler-Nichols method. With the proposed method of tuning, it is clearly seen that it gives a better response than the conventional methods in many aspects. When the objectives

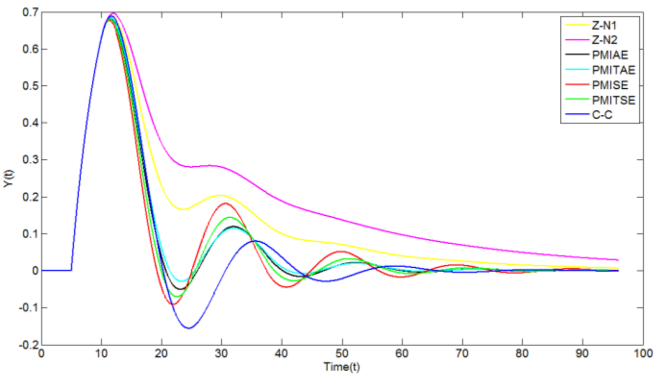

Fig.6. The comparison of tuning methods for the case study 2 ($\tau_1 = 5$, $\theta = 5$)

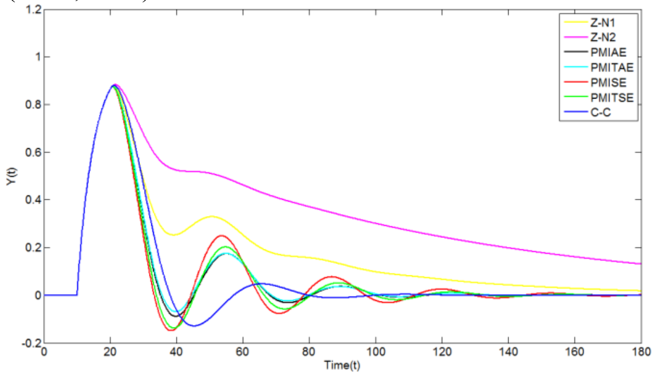

Fig.7. The comparison of tuning methods for the case study 3 ($\tau_1 = 5$, $\theta = 10$)

for IAE and ITAE minimization are used, the proposed method provides a response with fewer oscillations than other methods. When the dead time to process time constant ratio gets bigger which is the case in case studies 2 and 3 (dead time values are 5 and 10 for the case studies 2 and 3, respectively), it can be obviously seen that the response of two Ziegler-Nichols methods are unacceptable. The same consequence was mentioned in the servo control section. It should be noted that Ziegler-Nichols continuous cycling method-tuned PI controller produces sluggish set point and load-disturbance responses for large dead-time systems and that is the reason why it is thought to increase the integral action to overcome this problem while refining Ziegler-Nichols closed-loop tuning formulas [10]. It can be concluded that Ziegler-Nichols methods (process reaction curve and continuous cycling method) do not provide good PI control when the system has large dead time. From Table 4, the proposed method provides less minimization criteria values than the conventional methods except for the ITAE minimization in case study 3. In this latter case, the proposed method for the ITAE minimization gives less ITAE value than Ziegler – Nichols methods but more ITAE value than Cohen-Coon method. This procedure of obtaining the tuning parameters as a function of process parameters is extended to the second order plus time delay systems. It is observed that the performance of the control for SOPTD systems with the proposed tuning parameters performed better than the other conventional methods with respect to all process response characteristics.

Table 3. Tuning parameters and performance characteristics for FOPTD process type and servo control

Process	**Method**	**Servo Control**								
		K_c	τ_i	T_r	T_s	O_s	**IAE**	**ITAE**	**ISE**	**ITSE**
$G_{P1}(s)$	Z-N1	3.86	3.08	2.20	7.25	1.44	2.71	6.24	1.72	2.10
	Z-N2	4.50	3.30	2.10	9.15	1.55	2.99	8.31	1.81	2.51
	C-C	4.58	2.35	2.00	12.25	1.74	3.97	15.48	2.30	4.68
	PMIAE	3.45	5.56	2.50	4.55	1.17	2.15	-	-	-
	PMITAE	3.42	5.29	2.50	4.65	1.18	-	3.44	-	-
	PMISE	3.98	7.95	2.30	7.15	1.20	-	-	1.50	-
	PMITSE	3.58	6.34	2.50	7.05	1.16	-	-	-	1.24
$G_{P2}(s)$	Z-N1	1.03	12.9	11.9	46.4	-	12.57	194	7.45	38.6
	Z-N2	0.90	16.5	68.5	68.9	-	18.33	454	8.83	72.4
	C-C	0.98	5.69	10.1	40.2	1.38	12.18	136	7.69	40.0
	PMIAE	1.00	8.59	10.9	29.6	1.14	9.91	-	-	-
	PMITAE	0.94	7.90	11.2	29.8	1.13	-	74.3	-	-
	PMISE	1.09	9.22	10.3	28.9	1.17	-	-	7.02	-
	PMITSE	0.98	8.01	10.8	29.6	1.16	-	-	-	28.1
$G_{P3}(s)$	Z-N1	0.69	22.9	117	117	-	33.10	1350	16.63	247.8
	Z-N2	0.45	33.0	256	256	-	71.72	5957	31.52	1245
	C-C	0.53	7.35	21.1	55.2	1.20	19.12	269.4	13.97	108.54
	PMIAE	0.72	12.6	20.1	51.4	1.09	18.75	-	-	-
	PMITAE	0.67	11.5	20.7	52.0	1.07	-	265.0	-	-
	PMISE	0.77	12.6	19.2	50.6	1.15	-	-	13.31	-
	PMITSE	0.70	11.2	19.9	51.6	1.13	-	-	-	100.5

Table 4. Tuning parameters and performance characteristics for FOPTD process type and regulatory control

Process	**Method**	**Regulatory Control**					
		K_c	**τ_i**	**IAE**	**ITAE**	**ISE**	**ITSE**
$G_{P1}(s)$	Z-N1	3.86	3.08	0.802	3.09	0.136	0.419
	Z-N2	4.50	3.30	0.735	2.93	0.116	0.348
	C-C	4.58	2.35	0.790	3.69	0.110	0.340
	PMIAE	4.62	3.09	0.712	-	-	-
	PMITAE	4.23	2.88	-	2.70	-	-
	PMISE	5.68	3.34	-	-	0.099	-
	PMITSE	5.06	2.92	-	-	-	0.310
$G_{P2}(s)$	Z-N1	1.03	12.9	12.56	319.5	4.43	68.96
	Z-N2	0.90	16.5	18.33	637.7	6.10	122.6
	C-C	0.98	5.69	8.309	142.4	3.52	44.49
	PMIAE	1.15	8.19	7.70	-	-	-
	PMITAE	1.12	8.35	-	125.4	-	-
	PMISE	1.34	9.23	-	-	3.20	-
	PMITSE	1.23	8.57	-	-	-	40.72
$G_{P3}(s)$	Z-N1	0.69	22.9	33.09	1844	13.44	428.3
	Z-N2	0.45	33.0	71.44	6930	28.80	1662
	C-C	0.53	7.34	17.16	462.6	10.12	224.1
	PMIAE	0.80	12.1	17.11	-	-	-
	PMITAE	0.79	12.4	-	519.0	-	-
	PMISE	0.92	13.4	-	-	9.17	-
	PMITSE	0.85	12.2	-	-	-	207.3

II. CONCLUSIONS

This article presented new PI controller tuning correlations by using a dynamic optimization approach proposed by Madhuranthakam et al. [9]. PI controller tuning correlations were obtained as functions of the process parameters and were presented in the form of correlations for two different process model types: first order plus time delay (FOPTD) and second order plus time delay (SOPTD), for different minimization criteria (IAE, ITAE, ISE and ITSE), and for set point (servo control) and load change (regulatory control), separately. These correlations were used in different case studies and the performance of the proposed correlations were compared with that of Ziegler-Nichols continuous cycling method, Ziegler-Nichols process reaction curve method and Cohen-Coon method. It was observed for both FOPTD and SOPTD process models that using the proposed method lead to lower values of settling time (T_s), overshoot (O_s) and IAE, ITAE, ISE and ITSE than using the conventional tuning techniques. Furthermore, the proposed method gave better control system responses even in the case of systems with large dead time while the other methods gave poor and sluggish responses.

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