Model based PID controller for integrating process with its real time implementation

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***Abstract*— A model based PID controller is designed for purely integrating process with delay (IPD) as this model represents a wide range of industrial processes. Internal Model Control (IMC) technique is a superior method for controlling such processes. Here, we find out a set of IMC tuning rules for IPD process. Performance of the proposed controller is evaluated under both set point change and load variation through simulation study as well as from experimental verification on dc position control application. An overall improvement is observed in the performance of the proposed controller under both transient and steady state conditions in comparison with existing model based PID tuning relations.**

***Keywords*— PID controller, Model based tuning, Integrating process, Set point weighting, Position control**

I. INTRODUCTION

Processes with integrating nature and time delay are quite familiar in various industrial applications [1]. $\frac{k}{s}e^{-\theta s}$ is considered to be an adequate model to represent the dynamics for such processes [2]. This integrating plus delay (IPD) model contains only two parameters (k and θ) and hence simple enough for identification. PID control is most widely accepted in industrial applications for their simplicity and effectiveness [3]. But, their performance based on ultimate cycle based tuning relations [4, 5] is not satisfactory for IPD processes.

Internal model control (IMC) is a superior control methodology for IPD processes to provide good transient and steady state response as well as robustness simultaneously [6]. Proper selection of only one adjustable parameter (closed loop time constant) can provide the trade-off between set point tracking and disturbance rejection [7]. A significant amount of research on IMC controller design have been reported [8-10] to enhance the closed loop performance of integrating processes with time delay. IMC-PID controller proposed by Shamsuzzoha et al. [8] mainly focuses on the disturbance rejection. In [9], Panda derived analytical expressions for IMC controller parameters using Laurent series. Visioli [10] used genetic algorithm based optimization technique to find out the tuning parameters for integrating processes by minimizing integral performance criteria but he recommended two separate settings of PID controller for set point response and load disturbance rejection. Direct Synthesis (DS) based PID controller in series with a lead/lag compensator is suggested by Rao et al. [11] for this class of process.

Despite the fact that the design of PID controller based on IMC technique has been explored by a number of researchers, till now, design of a simple and robust PID controller with improved overall performance remains an open issue. Here, we propose a simple IMC design procedure for IPD process which offers improved set point response and load rejection behaviour simultaneously along with quite acceptable robustness. A simple guide line is suggested for selection of closed loop time constant λ depending on the dead time θ of the process model. To establish the effectiveness of the proposed scheme over the other reported techniques an extensive simulation study is made with two standard models of IPD process [8, 11]. Performance based comparison is made with model based PID settings given by Chidambaram et al. [1], Shamsuzzoha et al. [8], Panda [9], Visioli [10], Rao et al. [11] along with ultimate cycle based relations given by Luyben [5] and Ziegler-Nichols [4]. For having a clear comparison among the reported PID controllers, performance indices – percentage overshoot (*%OS*), rise time (t_r), settling time (t_s), integral absolute error (*IAE*), and integral time absolute error (*ITAE*) are calculated for each setting separately. Robustness of the controllers is also tested by increasing the dead time by 10% for each process from their respective nominal value. In addition to simulation study performance evaluation is also made on a laboratory scale dc position control application. Simulation as well as experimental results clearly reveals that the proposed IMC-PID controller offers an improved overall performance under both the set point change and load disturbance along with considerable robustness in comparison with the other model based as well as ultimate cycle based tuning rules.

II. PROPOSED CONTROLLER

Fig. 1(a) shows the block diagram of the IMC control technique and Fig. 1(b) represents the equivalent classical feedback control structure, where $G_p(s)$ is the process, $\tilde{G}_p(s)$ is the process model, and $G_c(s)$ is the IMC controller. The controlled variables are related as follows –

$$y=\frac{G_pG_c}{1+G_c\left(G_p-\tilde{G}_p\right)}r+\left[\frac{1-\tilde{G}_pG_c}{1+G_c\left(G_p-\tilde{G}_p\right)}\right]d\,. \qquad (1)$$

If the model is perfect $G_p(s)=\tilde{G}_p(s)$, then set point and disturbance responses are simplified as –

$$\frac{y}{r}=G_pG_c \quad \text{and} \quad \frac{y}{d}=\left[1-\tilde{G}_pG_c\right]G_p\,. \qquad (2)$$

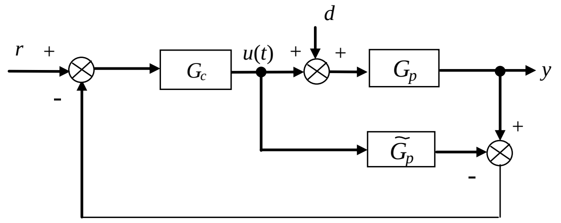

Fig. 1(a) Block diagram of IMC structure.

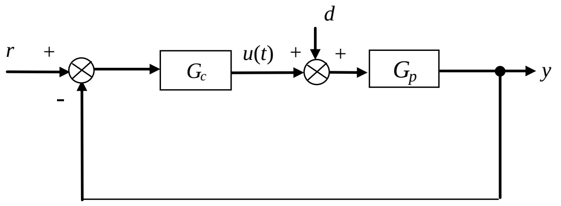

Fig. 1(b) Block diagram of feedback control system.

A. Controller design

IMC based controller design involves two steps –

Step I: Process model is factored into invertible and noninvertible parts

$$\tilde{G}_p=\tilde{G}_{p-}\times\tilde{G}_{p+} \qquad (3)$$

where $\tilde{G}_{p-}$ is the portion of the model which can be inverted to realize the controller and $\tilde{G}_{p+}$ is the noninvertible portion of the model (usually contains dead time and/or right half plane zeros).

Step II: Ideal IMC controller is the inverse of the invertible portion of the process model

$$\tilde{G}_c=\tilde{G}_{p_-}^{-1}. \qquad (4)$$

To make the IMC controller proper, a filter (*f*) is added and hence the actual IMC controller is given by

$$G_c=\tilde{G}_c\times f=\tilde{G}_{p_-}^{-1}\times f\,. \qquad (5)$$

Here, our goal is to design an IMC-PID controller for pure integrating process with delay i.e. for IPD process whose transfer function is given by

$$G_p=\frac{k}{s}e^{-\theta s}\,. \qquad (6)$$

With first-order Padé approximation for the time delay ($e^{-\theta s}=\left(1-0.5\theta s\right)\big/\left(1+0.5\theta s\right)$), IPD model is represented as

$$G_p=\frac{k\left(1-0.5\theta s\right)}{s\left(1+0.5\theta s\right)} \qquad (7)$$

$$=\frac{k}{s\left(1+0.5\theta s\right)}\left(1-0.5\theta s\right)=\tilde{G}_{p-}\times\tilde{G}_{p+}\,.$$

To cancel the unstable zero, filter f is chosen as

$$f=\frac{\beta s+1}{\left(\lambda s+1\right)^2}\,. \qquad (8)$$

From Fig. 1(b), the feedback controller which is equivalent to the IMC controller G_c is represented by

$$G_{IMC}=\frac{G_c}{1-\tilde{G}_pq}=\frac{\tilde{G}_{p_-}^{-1}f}{1-\tilde{G}_p\tilde{G}_{p_-}^{-1}f}=\frac{\tilde{G}_{p_-}^{-1}f}{1-\tilde{G}_{p_+}f}\,. \qquad (9)$$

Now substituting (7) and (8) into (9) IMC-PID controller is given by

$$G_{IMC}=\frac{s\left(1+0.5\theta s\right)\left(\beta s+1\right)/k\left(\lambda s+1\right)^2}{1-\left[\left(1-0.5\theta s\right)\left(\beta s+1\right)/\left(\lambda s+1\right)^2\right]}. \qquad (10)$$

The above relation is further simplified to obtain the tuning parameters for a non-interacting PID controller as follows -

$$G_{IMC}=K_c\left(1+\frac{1}{T_is}+T_ds\right), \qquad (11)$$

where $K_c=\dfrac{2\lambda+\theta}{k\left(\lambda+0.5\theta\right)^2}$, (12)

$$T_i=2\lambda+\theta, \qquad (13)$$

$$T_d=\frac{\lambda\theta+0.25\theta^2}{2\lambda+\theta}. \qquad (14)$$

B. Selection of λ

In the expressions of K_c, T_i, and T_d, the only unknown parameter is λ. Selection of suitable value of λ plays the significant role in determining the process response under transient and steady state conditions. λ also provides the trade-off between the performance and robustness of the controller. From an extensive simulation study here we suggest a simple relation for obtaining the value of λ for IPD process as given by

$$\lambda = 1 + \theta \tag{15}$$

where θ is the dead time and hence λ is always greater than 1. To reduce the overshoot during set point change a fixed set point weighting factor is introduced with the proportional term of PID controller relation. Here we apply 0.5 as set point weighting factor in simulation study.

III. Results

In this section we will demonstrate the simulation as well as experimental results. Performance based comparison is made for our proposed controller with the other reported model based and ultimate cycle based tuning rules for two well known IPD process models [8, 11].

A. Simulation study

$$\text{IPD-I: } G_p = \frac{0.0506}{s} e^{-6s} , \tag{16}$$

$$\text{IPD-II: } G_p = \frac{1}{s} e^{-5s} . \tag{17}$$

IPD-I (16) is a well known model recommended by Chidambaram [1], Chien [2], and Shamsuzzoha [8] whereas IPD-II (17) is suggested by Rao [11]. Here, a comparative study is made among the proposed IMC-PID controller with the other model based PID tuning techniques by Chidambaram [1], Shamsuzzoha [8], Panda [9], Visioli [10], and Rao [11]. Performance based comparison is also made with two widely accepted ultimate cycle based tuning (model independent technique) by Ziegler-Nichols [4] and Luyben [5]. Responses are observed and the corresponding performance indices are recorded (Table I) for the nominal as well as with 10% increased value of process dead time to ensure the robustness of the individual controller for both the IPD processes. Figs. 2(a)-2(g) show the responses of IPD-I for nominal value of dead time. Responses for IPD-II are shown in Figs. 3(a)-3(g) and the performance indices are listed in Table II for both the nominal and 10% higher value of dead time. Process responses and the performance indices for both IPD-I and IPD-II under proposed PID controller clearly exhibit an overall improvement in transient and steady state performance in comparison with model based as well as model independent tuning methods. Proposed controller also demonstrates enhanced robust feature in comparison with others tuning relations even with 10% higher value of dead time.

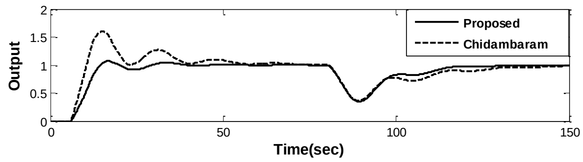

Fig. 2(a) Proposed and Chidambaram responses of (16) for nominal θ.

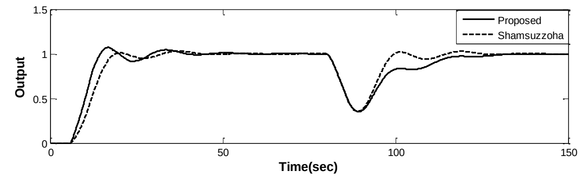

Fig. 2(b) Proposed and Shamsuzzoha responses of (16) for nominal θ.

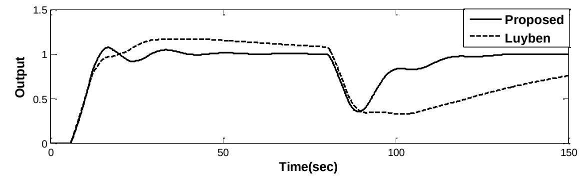

Fig. 2(c) Proposed and Lubyen responses of (16 for nominal θ.

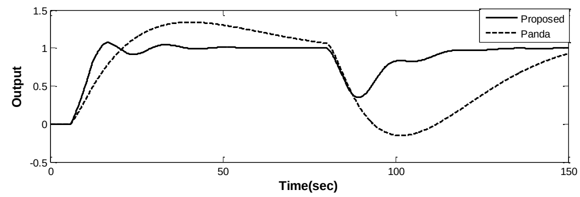

Fig. 2 (d) Proposed and Panda responses of (16) for nominal θ.

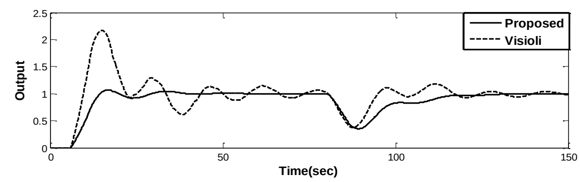

Fig. 2(e) Proposed and Visioli responses of (16) for nominal θ.

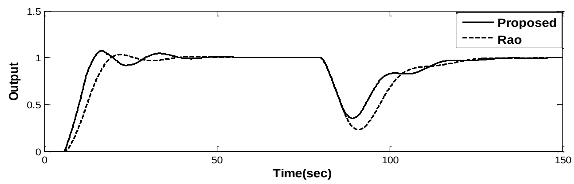

Fig. 2(f) Proposed and Rao responses of (16) for nominal θ.

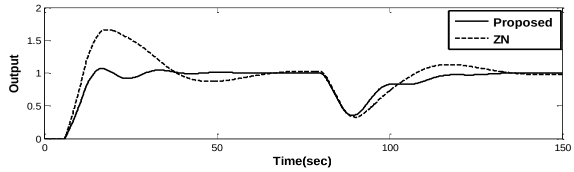

Fig. 2(g) Proposed and Ziegler-Nichols responses of (16) for nominal θ.

TABLE I
PERFORMANCE ANALYSIS FOR THE PROCESS IN (16)

θ=6s	%OS	$t_r(s)$	$t_s(s)$	IAE	ITAE
Proposed	7.2	14.6	48	21.41	1048
Chidambaram	60.2	10.5	71.4	29.18	1527
Luyben	16.7	20.4	*	51.02	4136
Shamsuzzoha	1.1	19.1	52.3	13.81	792.9
Panda	34.2	21.1	99.9	71.57	5702
Visioli	117	9.8	*	31.12	1238
Rao	3.1	19.6	48.9	25.71	1299
Ziegler-Nichols	65.6	11.4	71.6	34.16	1599
θ=6.6s (i.e., 10% increased)					
Proposed	19.7	14.4	63.1	23.68	1115
Chidambaram	76.7	11.1	*	32.13	1603
Luyben	18.2	16.1	*	51.92	4158
Shamsuzzoha	13.5	17.3	67.4	18.08	1142
Panda	36.5	20.9	88.3	72.84	5733
Visioli	144.4	10.3	*	39.86	1614
Rao	11.28	18.5	62.4	27.57	1356
Ziegler-Nichols	83.5	12	81.6	37.43	1762

* Not settled within simulation period

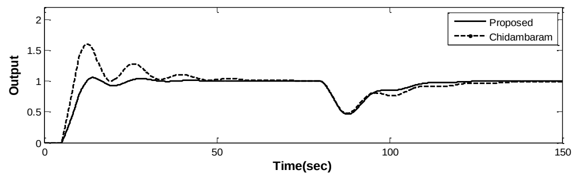

Fig. 3(a) Proposed and Chidambaram responses of (17) for nominal θ.

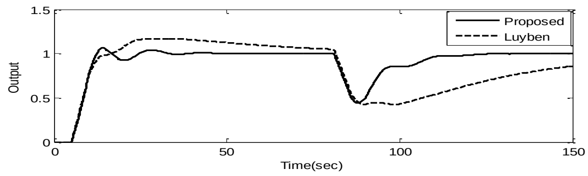

Fig. 3(b) Proposed and Lubyen responses of (17) for nominal θ.

TABLE II
PERFORMANCE ANALYSIS FOR THE PROCESS IN (17)

θ=5s	%OS	$t_r(s)$	$t_s(s)$	IAE	ITAE
Proposed	5.8	12.50	48.6	16.64	732.1
Chidambaram	59.8	8.80	63	22.89	1062
Luyben	16.9	17	*	41.16	3136
Shamsuzzoha	0	41.1	41.1	17.16	1161
Panda	30.7	21.5	*	69.32	5639
Visioli	117.1	8.1	*	25.39	886.6
Rao	3.1	16.30	44.6	19.73	884.4
Ziegler-Nichols	67.7	9.5	75.20	27.53	1143
θ=5.5s (i.e., 10% increased)					
Proposed	18.1	12.02	55.20	18.33	769.6
Chidambaram	76.4	9.20	83.70	25.45	1123
Luyben	18.4	13.40	*	41.84	3144
Shamsuzzoha	0	65.7	65.7	17.67	1705
Panda	32.3	21.3	108.10	70.37	5669
Visioli	146.7	8.6	*	33.69	1242
Rao	12.8	15.50	55.40	21.28	927.3
Ziegler-Nichols	70.9	10	72.2	29.08	1216

*Not settled within simulation period

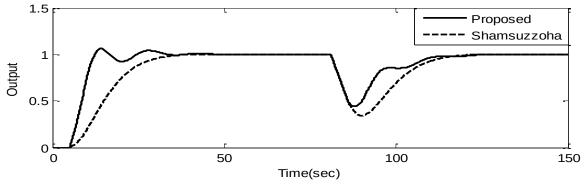

Fig. 3(c) Proposed and Shamsuzzoha responses of (17) for nominal θ.

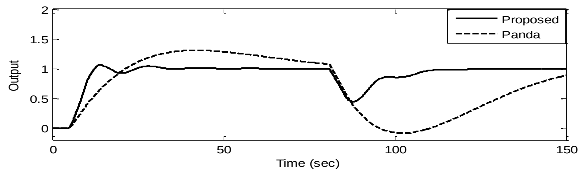

Fig. 3(d) Proposed and Panda responses of (17) for nominal θ.

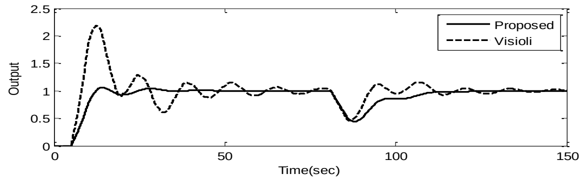

Fig. 3(e) Proposed and Visioli responses of (17) for nominal θ.

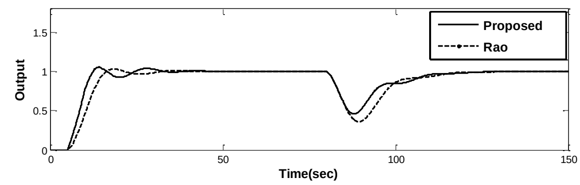

Fig. 3(f) Proposed and Rao responses of (17) for nominal θ.

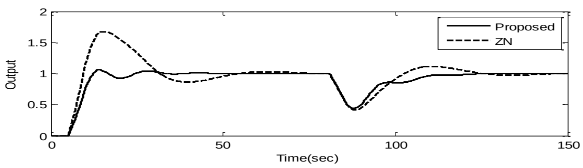

Fig. 3(g) Proposed and Ziegler-Nichols responses of (17) for nominal θ.

B. Real time implementation

Servo position control mechanism is a typical example of integrating system and it mostly used where robot and manipulator arm movements are involved. Performance of the proposed controller is tested along with other model based controllers by Chidambaram [1], Shamsuzzoha [8], Panda [9], Visioli [10], and Rao [11] on a laboratory scale PC based DC servo motor (Digital Servo Workshop with MATLAB, Model: 33-004, Manufacturer: Feedback [12]) to demonstrate the effectiveness of our proposed controller. Responses for ultimate cycle based tuning rules by Ziegler-Nichols [4] and Luyben [5] are also tested. Digital servo rig has two parts, namely hardware and software. The hardware units are mechanical unit (Model: 33-100) and digital unit (Model: 33-120). We implement the proposed controller along with other controllers using SIMULINK programming under MATLAB 6.5. To introduce delay in the process, SIMULINK 'delay' block of 2 sec is introduced in the forward path of the control loop. The reference signal and load disturbances are applied using SIMULINK library functions. The experimental setup is shown in Fig. 4.

Fig. 4 Experimental set up.

For model identification, we assumed the position control system to be a purely integrating process with delay (2 sec forward path delay), i.e., $G_p(s) = K e^{-\theta s}/s$. Parameters of the model, i.e., K and θ are obtained through *relay-feedback* experiment [13, 14]. The identified model is found to be

$$G_p(s) = \frac{1.78 e^{-1.28s}}{s} \quad . \tag{18}$$

Responses under both set point change and load variation for the proposed PID controller and the other reported PID tuning rules are shown in Figs. 5(a)-5(g).

From the simulation study as well as real time experimental results, it is evident that in each case, the proposed controller exhibits consistently improved overall performance under both set point change and load variation with acceptable robustness. The smoothness in variation of control action also verifies that in real life application it would not put any constraint on actuator movement.

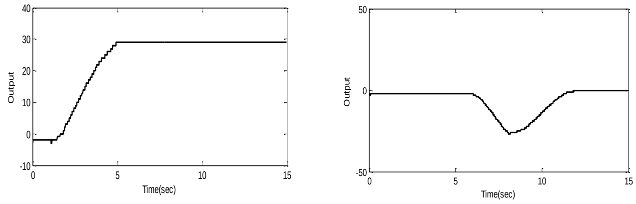

Fig. 5(a) Set point and load responses for proposed tuning.

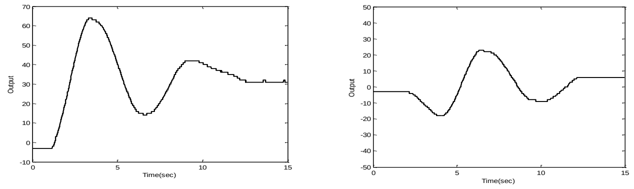

Fig. 5(b) Set point and load responses for Chidambaram tuning.

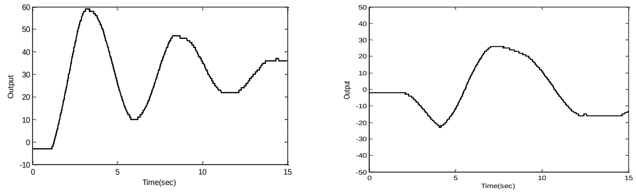

Fig. 5(c) Set point and load responses for Ziegler-Nichols tuning.

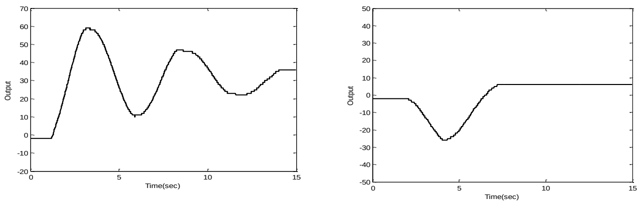

Fig. 5(d) Set point and load responses for Luyben tuning.

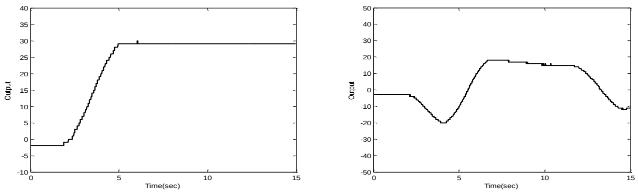

Fig. 5(e) Set point and load responses for Shamsuzzoha tuning.

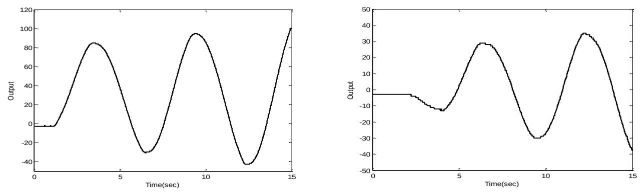

Fig. 5(f) Set point and load responses for Visioli tuning.

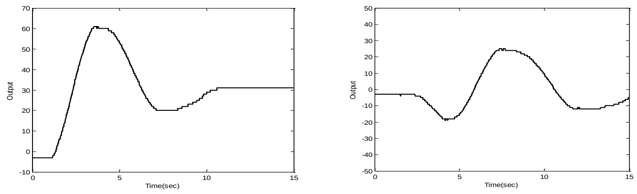

Fig. 5(g) Set point and load responses for Rao tuning.

IV. CONCLUSIONS

Here, we propose a model based IMC technique for designing PID controller with purely integrating plus time delay process model. This distinctive model is quite popular due to its simplicity in modeling various industrial integrating processes. In designing this model based tuning relation our main goal is to develop a simple and straight forward PID setting with clear guide lines which can offer an improved overall performance under both set point change and load disturbance. Another important feature is the robustness of the controller. A detailed comparative study is made for the proposed PID controller along with recently reported model based tuning methods as well as well known model free tuning techniques. From the simulation and experimental results it is found that our proposed IMC-PID controller offers an overall improved performance along with adequate robustness in its behaviour. A simple relation is suggested here for selection of the only tuning parameter λ in terms process dead time (θ). So, there is scope of finding out more suitable expression for λ which can offer better performance. In addition, other standard forms of integrating process models may also be considered to find out their improved model based IMC tuning relations.

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