An auto-tuning modified Smith predictor for delay dominated integrating processes

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Abstract-Industrial chemical reactors are usually found to be integrating in nature with significant amount of time delay. To achieve and maintain the desired output from such delay dominated integrating processes is truly a challenging task for process engineers. Here, we propose an auto-tuning scheme for modified Smith predictor based PID controller so that an overall improved process response can be ensured during their close-loop operation. Initial PID tuning parameters are realized using well accepted Ziegler-Nichols ultimate cycle relation. Intricacies due to large dead time is taken care by the well-known modified Smith predictor while the proposed auto-tuning feature will provide improved responses during set point tracking as well as load recovery phases. Performance enhancement of the proposed auto-tuning modified Smith predictor is verified with well-known integrating process models with large dead time representing the behavior of chemical reactors. Considerable improvement is found during simulation study with substantial robustness.

Keywords-Dead time compensator; modified Smith predictor; auto- tuning PID controller; integrating process

1. Introduction

A wide class of chemical processes are delay-dominating in nature [1]. During close-loop operation, controlling such processes to get the desired output is truly a difficult task [2]. Especially, for processes with integrating nature such as industrial chemical reactors [3], maintaining their product quality at the desired value during set point change and in presence of undesired disturbances is an open challenge. To cope up with large dead time present in process model, Smith predictor technique [4] is an effective and widely accepted tool. For the last two decades researchers proposed several extensions and modifications [5-10] of the Smith predictor based control technique to ascertain improved process response. Among these techniques, the scheme proposed by Kaya and Atherton 1999 [8] is quite popular and this methodology is nothing but an extension of the work reported by Mataušek and Micić 1996 [11]. However, during close-loop control of chemical reactors maintaining the product quality at the desired value in presence of process uncertainties as well as undesired disturbances is beyond the scope of a conventional controller with only dead time compensating element. An auto-tuning feature is required to be incorporated along with modified Smith predictor so that an improved close-loop response may be achieved.

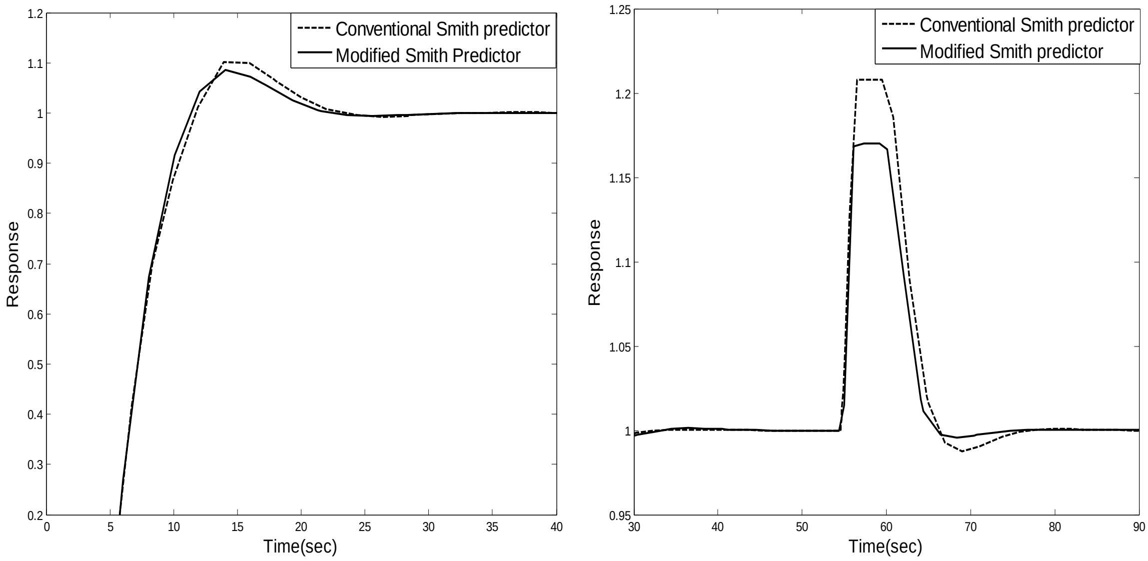


Fig. 1 Set point and load responses of the conventional [4] and modified Smith predictor [8] for delay dominated integrating process.

The responses (Fig. 1) obtained from conventional [4] and modified Smith predictor [8] during set point change and load variation for integrating process is found to be close i.e. a little improvement is found for modified Smith predictor.

Here, we propose an auto-tuning scheme [12-14] for modified Smith predictor based PID controller. Initial settings of the PID controllers are accomplished based on well accepted Ziegler-Nichols (ZN) [15] ultimate cycle tuning. The modified Smith predictor technique [8] is quite useful for compensating the consequences of large dead time present in process characteristics. Here, the suggested auto-tuning scheme will provide the required variation in control action during close-loop operation. As a result, an improved process response may be achieved during set point tracking as well as load rejection phases compared to modified Smith predictor [8] based control strategy. Usefulness of the proposed scheme is verified on reputed integrating process models with significant time delay and these models basically resemble the behaviour of chemical reactors [16]. Superiority of the proposed method is observed through graphical responses along with quantitative performance indices – integral error (IAE, ISE) and integral time multiplied error (ITAE, ITSE) criterion [17] during transient operating phases. In addition to performance enhancement, substantial robustness is also found for our proposed scheme in presence of considerable uncertainty in process model parameters.

2. Modified Smith predictor

The well-known modified Smith predictor [8] control technique is nothing but an augmentation of the actual Smith predictor methodology so that process responses can be enhanced up to certain extent. This structure as shown in Fig. 2 contains three controllers. Out of these three controllers, $G_{C1}(s)$ is present in the forward path but $G_{C2}(s)$ and $G_{C3}(s)$are present in the feedback path. Plant dynamics is realized by the model $G_m(s)e^{-\theta_m s}$ where $e^{-\theta_m s}$represents estimated dead time of the process. The actual plant $G(s)e^{-\theta s}$ is present in the forward path of the control loop of Fig. 2.

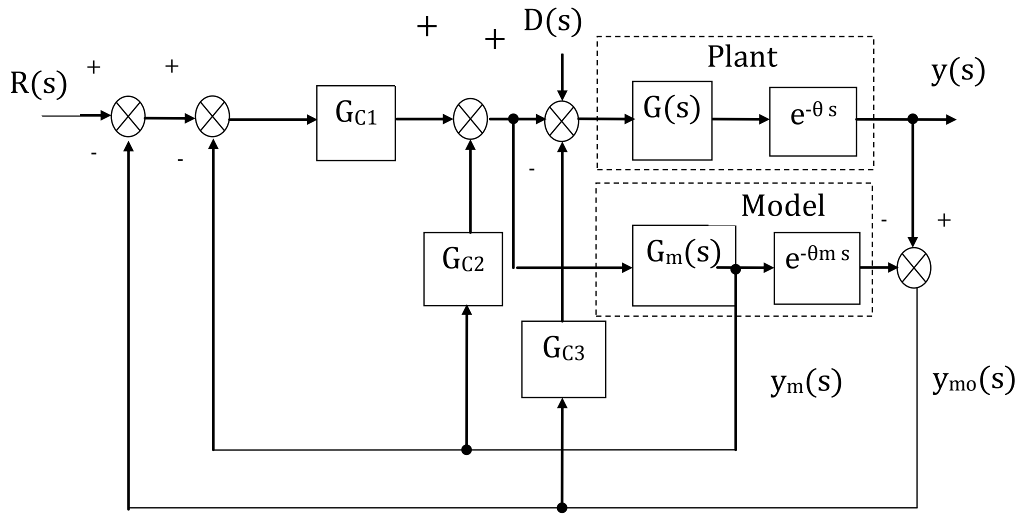


Fig.2. Modified Smith predictor structure [8].

The modified Smith predictor presented in [8] by Kaya and Atherton utilizes the structure as shown in Fig. 2 where $G(s)e^{-\theta s}$ is the transfer function of the plant with delay, $G_m(s)e^{-\theta_m s}$ is the dynamic model of the plant with delay present in the parallel path. $D(s)$is the disturbance signal considered to be incorporated in the process. Here, in the control loop structure as shown in Fig. 2 $G_{C1}(s)$is a conventional PI controller targeted towards satisfactory set point response, $G_{C2}(s)$ is a P controller to restrict the overshoot in process, and $G_{C3}(s)$ is a PD controller to minimize the effect of undesired disturbances.

Here,

$$G_{C1}(s) = k_{p1}e(k) + k_{i1}\sum_{i=0}^{k} e(i), \quad (1)$$

$$G_{C2}(s) = k_{p2}.y_m(s), \quad (2)$$

$$G_{C3}(s) = k_{p3}y_{mo}(s) + k_{d3}\,\Delta y_{mo}(s). \quad (3)$$

Here k_{p1}, k_{i1}, k_{p2}, $k_{p3}$and $k_{d3}$the proportional, integral and derivative gains for conventional PI, P and PD controllers. All the three controllers are tuned based on ZN ultimate cycle tuning guidelines. Due to presence of more than one controller, this control technique is not capable enough for integrating processes where one pole is located at the origin. Hence, instead of fixed tuning, some auto-tuning mechanism may be utilized to ascertain improved process responses.

3. Auto–tuning controllers

PI controllers are mostly utilized in close-loop control of industrial chemical reactors for their simple design and hassle free tuning [3]. Due to the presence of measurement noise PI controllers are more preferable than the PID controllers in practical use. For this reason 90% of the PID controllers have their derivate action turned off. To achieve an overall improved process response, the auto-tuning mechanism [12] of PI controller using the Ziegler–Nichols ultimate cycle method is more effective than the conventional fixed tuning. The auto-tuning PI, P and PD controller is designed incorporating the gain updating factor α, β and γ a function of error e(k) and the feedback parameter$y_m(s)$, $y_{mo}(s)$ and change of error Δe(k) of the controlled variable.Hence, the tuning parameters of ZN tuned PI controller get adjusted continuously depending on the process operating conditions. The modification schemes for the proportional and integral gains using the gain updating factor α are depicted by the following empirical relations –

$$k_{p1}^t = k_{p1}(1 + k_1|\alpha(k)|) \quad (4)$$

$$k_{i1}^t = k_{i1}(0.5 + k_2|\alpha(k)|) \quad (5)$$

In relations (4) and (5), k_{p1}^t and k_{i1}^t are the modified proportional and integral gains respectively at k^{th} instant. $k_1$and k_2 are two positive constants, suitably chosen to provide the required variations of k_{p1}^t and k_{i1}^t from their initial values to achieve the desired response. The gain updating factor α is defined as

$$\alpha(k) = e_N(k) \times \Delta e_N(k) \quad (6)$$

Where

$$\Delta e_N(k) = e_N(k) \times e_N(k-1) \quad (7)$$

Here, $e_N(k)$and $\Delta e_N(k)$ are normalized values of error and change of error. Hence, the expression of the auto-tuning PI controller is given by,

$$u_1^t(k) = k_{p1}^t e(k) + k_{i1}^t \sum_{i=0}^{k} e(i) \quad (8)$$

Here $u_1^t(k)$ is modified control action offered by $G_{C1}(s)$. Similar to $G_{C1}(s)$, proportional gain of the controller $G_{C2}(s)$is also modified by the nonlinear parameter β using the following relation (12) where $k_4$is a positive constant to ensure desired variation in control action is.

$$k_{p2}^t(k) = k_{p2}(1 + k_4|\beta(k)|) \quad (9)$$

Hence, the auto-tuning P controller can be expressed as

$$u_2^t(k) = k_{p2}^t(k) y_m(s) \quad (10)$$

Similar to $G_{C1}(s)$ and$G_{C2}(s)$, proportional and derivative gains of the PD controller i.e. $G_{C3}(s)$ are also modified by the dynamic factorγas in [13]. The online gain modification mechanism for the PD controller is given by the following relations

$$k_{p3}^t(k) = k_{p3}(1 + k_1\gamma(k)) \quad (11)$$

$$k_{d3}^t(k) = k_{d3}(1 + k_3|\gamma(k)|) \quad (12)$$

Here, $K_{p3}^t(k)$ and $K_{d3}^t(k)$ are the modified proportional and derivative gains varying continuously depending on γ. $k_3$is a positive constant for providing an appropriate variation of damping to get the desired closed-loop response. Hence, the auto tuning PD controller can be expressed as

$$u_3^t(k) = k_{p3}^t(k) y_{mo}(s) + k_{d3}^t \Delta y_{mo}(s) \quad (13)$$

As a result, due to incorporation of the auto tuning schemes in all three controllers instead of their fixed tuning we can expect an improved process responses compared to their conventional control strategy i.e. in presence of modified Smith predictor compensator.
The structure of the proposed auto-tuning modified Smith predictor is shown in Fig. 3.

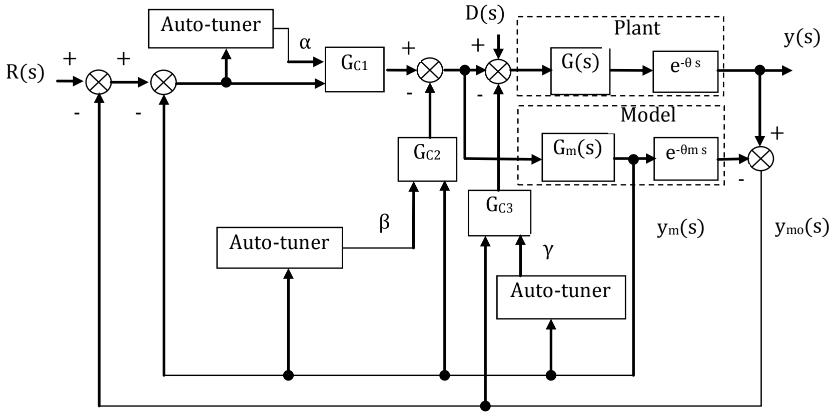


Fig. 3 Auto-tuning scheme with modified Smith predictor control technique

Instead of the auto-tuner block, the structure of the proposed auto-tuning modified Smith predictor is similar to Fig. 2. Here, all the controllers $G_{c1}(s)$, $G_{c2}(s)$ and $G_{c3}(s)$are considered to be auto-tuning in nature instead of their fixed tuning as shown in Fig. 3. Here, the choice of constants i.e.,k_1, k_2, k_3 and k_4 present in the expressions of the auto-tuning relations are very crucial. Based on the expertise of the operator, suitable values of theses tuning parameters are to be chosen so that we can ascertain the desired variation of control action to achieve enhanced process responses compared to the conventional Smith predictor structure.

4. Results

In this section, performance of the proposed auto-tuning modified Smith predictor is compared with fixed tuned modified Smith predictor [8] during set point tracking and load rejection phases. A unit step input is introduced at time $t = 0$ and as the process reaches steady state condition, a pulse like load disturbances $D(s)$are incorporated in the process at $t = 30$ sec.

A. Integrating process with dead time

We consider a very popular model of integrating process with long dead time as described by the transfer function

$$G(s) = \frac{1}{s} e^{-5s} \tag{14}$$

This model with time delay 5 sec is a well-accepted example of a chemical reactor process. As mentioned previously all the controllers $G_{C1}(s)$, $G_{C2}(s)$and $G_{C3}(s)$of the conventional and proposed auto-tuning modified Smith predictors are tuned according to ZN [15] tuning relations. The additional tuning constants k_1, k_2, k_3 and k_4 are required to be chosen based on the desired response. Here, we choose $k_1 = k_3 = 10\ and\ k_2 = k_4 = 1$. Responses during set point tracking and load rejection phases are shown in Fig. 4 where the solid line represents the response of the proposed auto-tuning modified Smith predictor and dashed line for the conventional Smith predictor [4].

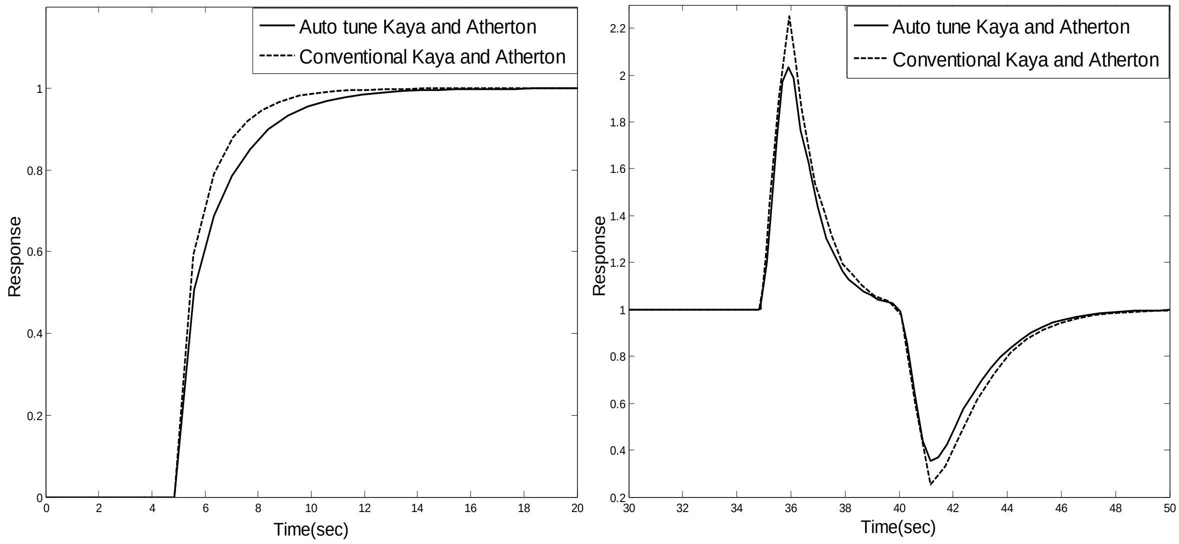


Fig. 4. Set point and load responses of the proposed auto-tuning modified Smith predictor and conventional Smith predictor are given by relation (14).

From the responses as shown in Fig. 4 it is clearly found that the proposed scheme offers an overall improved performance compared to conventional Smith predictor. For quantitative assessment, performance indices such as integral absolute error (IAE), integral-time absolute error (ITAE), integral square error (ISE), and integral time square error (ITSE) are listed in Table I.

Control technique	**IAE**	**ITAE**	**ISE**	**ITSE**
Conventional Kaya and Atherton	1.69	32.46	0.55	8.43
Auto-tuned Kaya and Atherton	1.45	24.91	0.43	4.66

To verify the robustness of the proposed scheme a considerable amount of perturbation (+20%) is introduced in process model of relation (14). Both the process parameters i.e. process gain and dead time are increased by 20% from their nominal values as shown by relation (15)

$$G(s) = \frac{1.2}{s} e^{-6s} \tag{15}$$

The response of this perturbed model during set point change and load rejection phases are depicted in Fig. 5. The related performance indices containing integral error indices are listed in Table II.

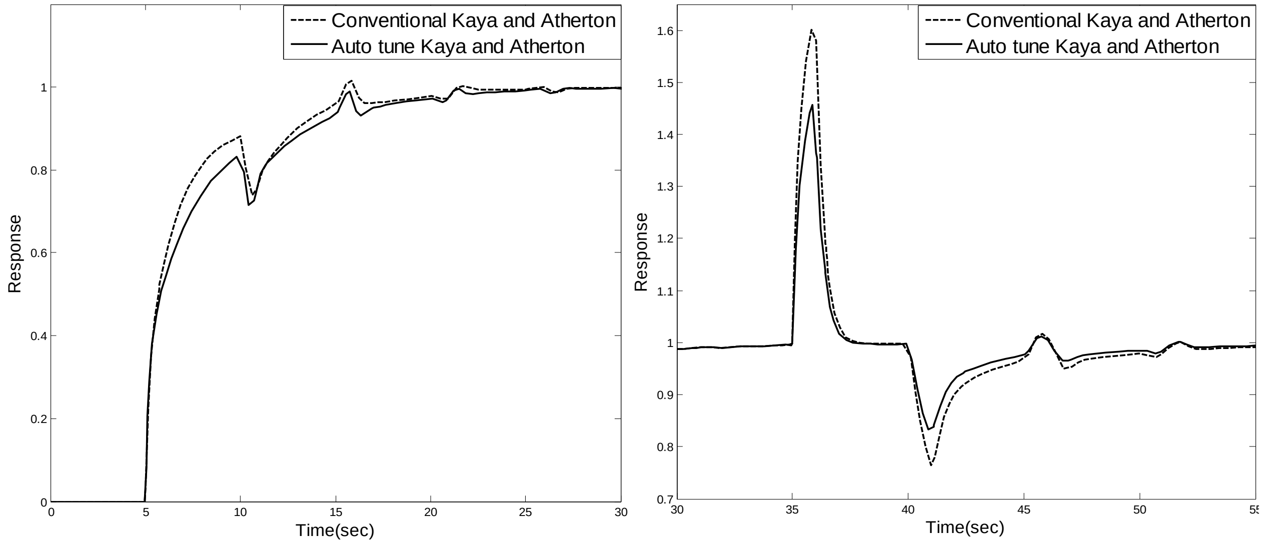


Fig. 5. Set point and load responses of the proposed auto-tuning modified Smith predictor and conventional Smith predictor with perturbed process model given by relation (15).

Control technique	IAE	ITAE	ISE	ITSE
Conventional Kaya and Atherton	4.12	63.32	1.31	9.77
Auto-tuned Kaya and Atherton	4.04	62.88	1.15	9.74

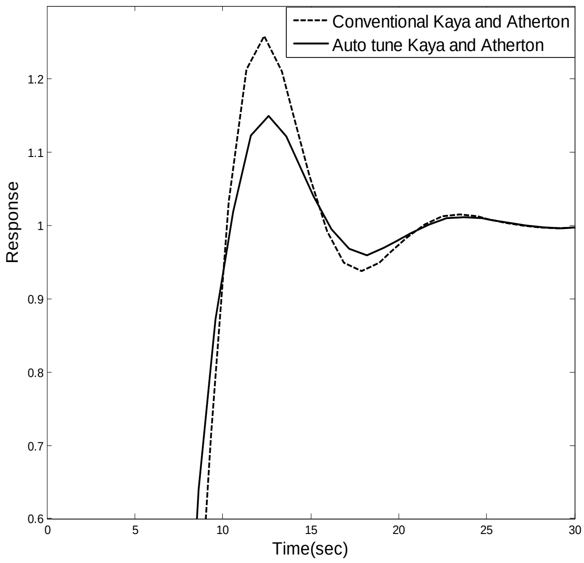
Table. II. Performance indices of the perturbed integrating process model given by relation (15).

B. Integrating process with large dead time

Here, we consider another well-known integrating process model with large dead time for performance evaluation of the proposed auto-tuning modified Smith predictor.

$$G(s) = \frac{0.2}{s} e^{-7.4s} \qquad (16)$$

Delay present in the integrating process model is 7.4 sec and this model is quite popular to represent the behavior of a chemical reactor. Here, it is to mention that the values of all the additional tuning parameters i.e., k_1, k_2, k_3 *and* k_4 are considered to be remain same as it was considered for the previous process model as given by relation (14).



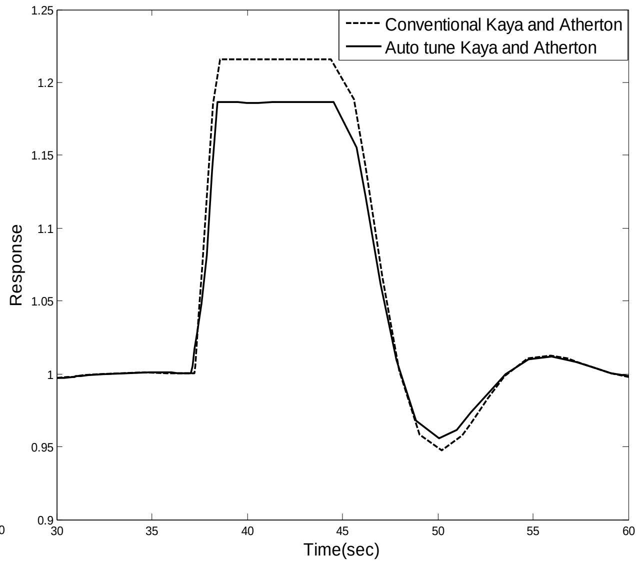


Fig. 6 Set point and load responses of the proposed auto-tuning modified Smith predictor and modified Smith predictor given by relation (16).

Control technique	IAE	ITAE	ISE	ITSE
Conventional Kaya and Atherton	3.02	24.17	1.17	2.57
Auto-tuned Kaya and Atherton	2.22	19.97	0.74	1.55

Responses during set point tracking and load rejection phases for the proposed auto-tuning modified Smith predictor and modified Smith predictor [8] with fixed tuning are shown in Fig. 6. Here, the solid line represents the responses of our proposed scheme and the dashed line for the modified Smith predictor. It is quite clear that that our proposed technique offers enhanced performance compared to static modified Smith predictor. This fact is also justified from the listed values of performance indices as depicted in Table III. All the integral error indices obtained from the reported auto-tuning modified Smith predictor are found to be smaller than the respective values calculated from the responses of conventional Smith predictor technique.

5. Conclusion

In this paper, an auto-tuning modified Smith predictor control technique is proposed for the integrating processes with long dead time. This particular family of process represents the dynamic behaviour of chemical reactors used in process industry. The proposed technique offers satisfactory result during both set point change and load varying situations than the convention technique. The most important feature of this technique is the simplicity and hence it can be realized for any practical applications like designing controller for Distributed Control System. Suitable choices of the additional tuning parameters play a crucial role in the performance of proposed scheme. Stochastic optimization schemes can be applied for optimal choice of these tuning parameters.

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