Proceeding of the 2004 American Control Conference
Boston, Massachusetts June 30 - July 2, 2004



# Control of Integrating Dead Time Processes with Long Time Delay

Hossam A. Abdel Fattah, Ahmed M. Gesraha and Adel A. Hanafy
Electrical Power and Machines Department
Faculty of Engineering, Cairo University, Giza, Egypt

*Abstract* – **A controller that is characterized by its robustness against modeling errors and its high disturbance rejection capability is developed for integrating processes with time delay. The proposed controller structure, similarly to several controllers proposed in the literature, includes two loops, one for set-point tracking and the second for disturbance rejection. Simulation results illustrate the good response of the proposed scheme with respect to existing results.**

## I. INTRODUCTION

In process control, two typical kinds of processes exist. One can be described by a time constant plus time delay model, and the other, by an integrator plus time delay model. For a process consisting of a time constant and a time delay, many controllers have been developed. For example, for relatively small time delay, the conventional controller (PID) is better, if large time delays are present, the (SP) is an effective compensator [1]. However, neither the PID controller nor the Smith Predictor (SP) can be used directly for the integrator process with time delay in the presence of load disturbance, which cannot be rejected by both control techniques. Independently of the PID parameters used in the SP, a load disturbance will always result in a steady state error.

To solve the problem of the SP, [2] has proposed a modification of the SP, which yields zero steady state error for integrating plants. The main disadvantage of this control system design technique is that the set point and load disturbance responses are very oscillatory and the response of the system tends to be slow [3].

To overcome the problems associated with [2], [3] proposed a new SP. A convenient property of this controller is that it decouples the set point response from the load response and hence faster set point response and better load disturbance rejection can be obtained. Nevertheless, the controller has large number of adjustable parameters and there are no effective rules to direct the user to tune them [4], [5].

[4] investigated this problem, and improved the results of [3], by reducing the parameters to only two adjustable parameters. Moreover, the proposed method provides a systematic method for tuning these parameters. However, the scheme of [4] includes a positive feedback loop that is a potential instability source [6], resulting in limited robustness.

[5] proposed a controller based on a simple and straightforward modification of the SP, which produces similar results as [3]; but is much easier to tune. However, the set point and load responses are no longer separated from each other and consequently they cannot be independently optimized, resulting in limited robustness [6]. The authors of [5] introduced another modification of their scheme in [13] that further improved their controller.

[7] also proposed another modification of [2] to overcome the controller problem proposed by [3]. The controller offers similar robustness and better performance than the others. The disadvantage of this control system design technique is that the parameters of the controller need to be retuned if a mismatch between the model and the actual plant exists.

The authors of [6] proposed another scheme, which is a further development of the Smith Predictor of [3]. This method has fast set-point tracking, efficient load disturbance rejection, and better robustness than previous methods.

In [10], the internal model principle and control structure of the Smith Predictor (IMPACT) is proposed. The concept of internal model consists of incorporating the disturbance or/and plant models into the control portion of the system. [10] succeeds in minimizing the effects of immeasurable external disturbances on the steady-state value of controlled variable, and increasing the system robustness with respect to changes or uncertainties in the plant parameters.

In our work [11], we carried out a comparative simulation study of the previously published papers described above. The major concern was to compare between the methods according to the following criteria:

1. Their sensitivity to the relative value of the time delay to the system time constant
2. Their sensitivity to modeling errors in the time delay, whether it is over-estimated or under-estimated

The simulations of [11] showed that the best responses according to the above criteria are the work of [5], [6] and [10]. However, even for these methods, the robustness and speed of response, especially due to a load disturbance, seems to still require further improvement.

## II. PROPOSED METHOD

In this section, a new dead time compensation technique for integrating plants with long time delay (IPTD) is presented to improve existing schemes robustness and speed of response. The proposed method, as will soon be clear is characterized by:

1. A double compensator structure as in [3] and [4], for set point tracking and for disturbance rejection.
2. The disturbance controller can be interpreted as a disturbance estimator, which in steady-state gives the required control action to cancel load disturbances and to overcome the main drawback of the Smith Predictor.
3. A disturbance cancellation component: This is the major improvement proposed in this work. This cancellation is inspired by a simple plant inversion idea.
4. A clear quantification of the compromise between system robustness and performance quality pointed out

in [10] and [12]. System robustness can be improved by tuning a single parameter, but the price paid is in system response speed.

### *A. Proposed Method Development*

Firstly, a simple idea for disturbance cancellation based on a system inversion approach is presented for the case of a plant with no time delay. Secondly, the scheme of [3] is modified to be able to treat plant inversion but with no time delays. Finally the scheme is adapted to remove the requirement of implicit plant inversion, which in the case of integrating plants with time delay inevitably leads to a non-causal system with time advance.

Consider the problem of controlling a plant with transfer function $G_p(s)$ by a feedback controller $C(s)$. The plant is subjected to a load disturbance $D(s)$ and a set point $R(s)$. Assume that the plant is invertible, the output $Y(s)$ is given in terms of $R(s)$ and $D(s)$ as:

$$Y(s)=\frac{C(s)G_p(s)}{1+C(s)G_p(s)}R(s)+\frac{G_p(s)}{1+C(s)G_p(s)}D(s) \qquad (1)$$

To obtain perfect disturbance rejection, the term $\gamma(s)$ shown in Fig. 1 can be added in the minor loop such that $\gamma(s){G_p}^{-1}(s)$ is causal. In order to keep the transfer function from $R(s)$ to $Y(s)$ unaffected, an additional block $G_0(s)$ is introduced as shown in Fig. 1.

In the case depicted in Fig. 1, the output Y(s) is given in terms of R(s) and D(s) as:

$$Y(s)=\frac{G_p(s)C(s)}{1+G_p(s)C(s)}R(s)+\frac{C(s)(1-\gamma)}{1+G_pC(s)}D(s) \qquad (2)$$

It is clear that if ${G_p}^{-1}(s)$ is causal then setting ($\gamma=1$) will immediately give perfect disturbance cancellation. In the general case, it is quite easy to choose $\gamma(s)$ such that $\gamma(s){G_p}^{-1}(s)$ is causal, and such that the DC gain from $D(s)$ to $Y(s)$ is zero to ensure asymptotic disturbance rejection.

The same development can be applied to the two controller scheme DTC proposed by [3] and for simplicity, the plant was supposed to be invertible with no time delay as shown in Fig. 2. In this figure $F_1(s)$ and $F_2(s)$ are two transfer functions selected such as to obtain a relation between $Y(s)$, $R(s)$ and $D(s)$ similar to (2), namely such that:

$$Y(s)=\frac{C(s)G_p(s)}{1+C(s)G_p(s)}R(s)+\frac{G_p(s)(1-\gamma(s))}{1+M(s)G_p(s)}D(s) \qquad (3)$$

The output $Y(s)$ is given in terms of $R(s)$ and $D(s)$ as:

$$Y(s)=\frac{CG_p}{(1+F_1F_2+CG_p)-F_2}R(s)+\frac{G_p(1+F_1F_2+CG_p)}{(1+CG_p)(1+MG_p)+F_1F_2(1+MG_p)-F_2(1+MG_p)}D(s) \qquad (4)$$

To get the values of $F_1$ and $F_2$, in order to obtain Equation (3), the following conditions must be met:

$$F_1F_2(1+MG_p)-F_2(1+MG_p)=0 \qquad (5)$$

$$1+F_1F_2+CG_p=(1-\gamma)(1+CG_p) \qquad (6)$$

From (5), dividing by $F_2$, chosen non zero in the sequel:

$$F_1(1+MG_p)=(1+MG_p) \qquad (7)$$

This immediately implies that: $F_1=1$

By substituting in (6) and rearranging, we obtain:

$$F_2=-\gamma(1+CG_p) \qquad (8)$$

Clearly the values of $F_1$ and $F_2$, given above, lead to the desired transfer function given in (3). In this case, setting $\gamma=1$ will give perfect disturbance cancellation.

Finally, in the case of integrating plant with time delay, the scheme shown in Fig. 2 is not suitable, because $G_p^{-1}(s)$ is a non-causal plant with time advance. By a simple modification of Fig. 2, we obtain $F_2G_p^{-1}(s)$, which can be a causal system, as shown in Fig. 3, the proposed method.

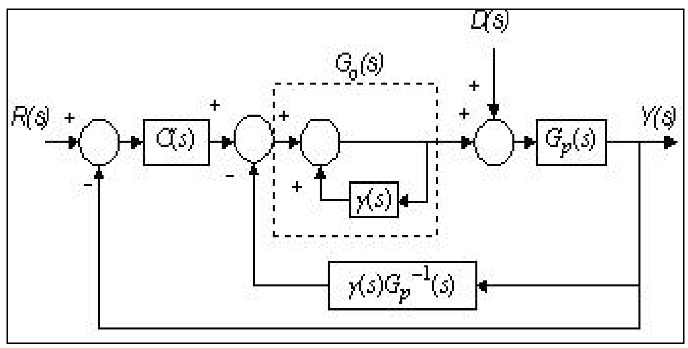


Figure 1: A Simple Control Scheme Idea

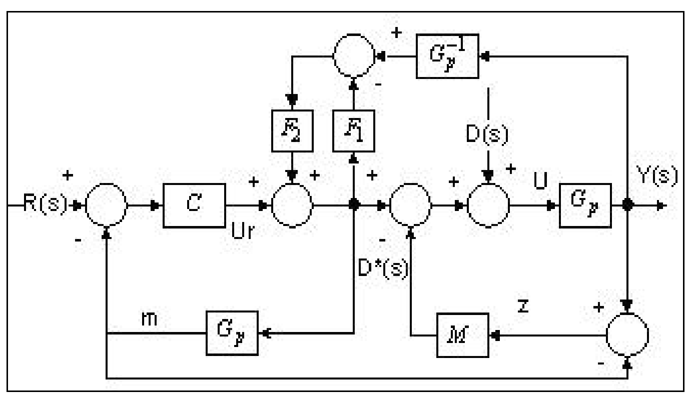


Figure 2: A Modification to the Scheme of [3]

### *B. Proposed Method Presentation*

The proposed scheme for controlling the integral plant with long time delay is graphically illustrated in Fig. 3. The proposed method is a modification of [3] consisting of the additional feedback path $F_2G^{*-1}$ from the plant output $Y(s)$ to the output of the set point controller $C(s)$. In order to keep the transfer function from *R(s)* to *Y(s)* unaffected the block $G_o(s)$ is introduced, where

$$G_o(s) = \frac{1}{1 + F_1 F_2} \tag{9}$$

The two controllers *C(s)* and *M(s)* are configured to track the set point changes and reject the load disturbance, respectively. The set-point controller *C(s)* is designed to be a proportional controller in order to obtain a first order response for set-point inputs and the load disturbance controller $M(s)$ is designed to be a low-pass filter as will be shown later.

The symbols used in Fig. 3 are compatible with those used so far and are detailed as explained next. The process is characterized by the transfer function:

$$G_p(s) = G(s)e^{-sL} = \frac{K_p}{s} e^{-sL} \tag{10}$$

The process model is composed of two parts, $G^*(s)$ and $L^*$, which are the estimates of *G(s)* and *L*, respectively.

After some lengthy, but straight forward calculations, the expression of the output *Y(s)* in terms of the reference *R(s)* and the disturbance *D(s)* can be found to be as follows:

$$H_r(s) = \frac{Y(s)}{R(s)} = \frac{Num_1}{Den_1 - Den_2} \tag{11}$$

$$Num_1 = CG(1 + MG^* e^{-sL^*})e^{-sL} \tag{12}$$

$$Den_1 = (1 + F_1 F_2 + CG^*)(1 + MGe^{-sL}) \tag{13}$$

$$Den_2 = F_2 GG^{*-1}(1 + MG^* e^{-sL^*})e^{-sL} \tag{14}$$

The transfer function of the load disturbance response is:

$$H_d(s) = \frac{Y(s)}{D(s)} = \frac{Num_2}{Den_3 - Den_4} \tag{15}$$

$$Num_2 = Ge^{-sL}(1 + F_1 F_2 + CG^*) \tag{16}$$

$$Den_3 = (1 + CG^* + F_1 F_2)(1 + MGe^{-sL}) \tag{17}$$

$$Den_4 = F_2 Ge^{-sL}\left(G^{*-1} + Me^{-sL^*}\right) \tag{18}$$

Again, in order to obtain a transfer function equal to that of (3), the transfer functions $F_1(s)$ and $F_2(s)$ have to be chosen in a way to meet the following conditions:

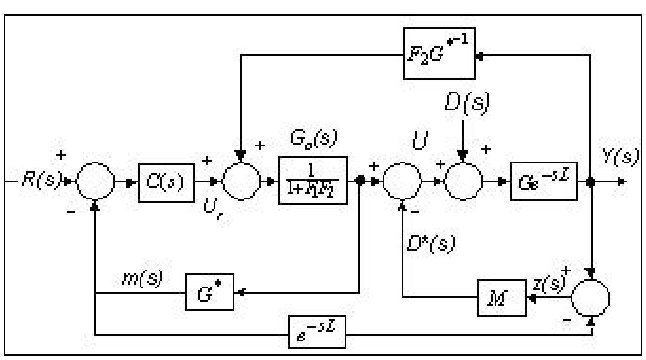

Figure 3: Proposed Scheme

$$F_1 F_2 \left(1 + MGe^{-sL}\right) - F_2 Ge^{-sL}\left(G^{*-1} - Me^{-sL*}\right) = 0 \tag{19}$$

$$1 + F_1 F_2 + CG^* = (1 - \gamma)(1 + CG^*) \tag{20}$$

Rearranging (19), and dividing by $F_2$ which will be chosen non zero gives:

$$F_1(1 + MGe^{-sL}) = GG^{*-1}e^{-sL} + MGe^{-sL}e^{-sL^*} \tag{21}$$

Or in other words that:

$$F_1 = \frac{e^{-sL}(GG^{*-1} + MGe^{-sL^*})}{(1 + MGe^{-sL})} \tag{22}$$

Solving (20) for $F_2$ gives that:

$$F_2 = \frac{-\gamma(1 + CG^*)(1 + MGe^{-sL})}{e^{-sL}(GG^{*-1} + MGe^{-sL^*})} \tag{23}$$

However, if perfect modeling is assumed, we obtain, i.e. if it is assumed that $G = G^* = \frac{K_p^*}{s}$ and $L = L^*$ then

$$F_1 = e^{-sL^*} \tag{24}$$

$$F_2 = \frac{-\gamma(1 + CG^*)}{e^{-sL^*}} \tag{25}$$

This means that:

$$F_2 G^{*-1} = \frac{-\gamma(1 + CG^*)G^{*-1}}{e^{-sL^*}} \tag{26}$$

To guarantee the causality of $F_2 G^{*-1}$, $\gamma(s)$ is chosen as:

$$\gamma = \frac{e^{-sL^*}}{\alpha s + 1} \tag{27}$$

Hence the following relationships hold:

$$F_2 G^{-1} = \frac{-(s + C)}{\alpha s + 1} \tag{28}$$

$$F_1 F_2 = \frac{-(s + C)}{\alpha s^2 + s} e^{-sL^*} \tag{29}$$

$$F_2 = \frac{-(s + C)}{\alpha s^2 + s} \tag{30}$$

Then, the output *Y(s)* in terms of the reference *R(s)* and the disturbance *D(s)* is given by:

$$Y(s) = \frac{CG^* e^{-sL^*}}{1 + CG^*} R(s) + \frac{G^*(1 - \gamma)e^{-sL^*}}{1 + MG^* e^{-sL^*}} D(s) \tag{31}$$

The previous transfer function resembles the transfer function of (3) except the existence of the time delay. Substituting from (27), and assuming that the model is given by the integrating plant $G^*$ the following transfer function is obtained:

$$Y(s) = \frac{K_p^* Ce^{-sL^*}}{(s + K_p^* C)} R(s) + \frac{K_p^*(\alpha s + 1 - e^{-sL^*})e^{-sL^*}}{(\alpha s + 1)(s + K_p^* Me^{-sL^*})} D(s) \tag{32}$$

Although the disturbance cannot be completely rejected, its effect is asymptotically rejected. The above expression of *Y(s)* shows that, the set-point response and the load response are been decoupled from each other. The performance of both set-point tracking and load rejections can be improved by separately tuning of the two controllers.

It is worth pointing out that, if there is a mismatch between the model and the process and if the plant is stable despite the mismatch, the final value of the output due to a step disturbance can be easily found out from the set of equations previously presented. For the values of $F_1$ and $F_2$ above, the output will be given by:

$$Y(\infty) = \lim_{s\to 0} sY(s) = \frac{e^{-sL^*}(\alpha s + 1 - e^{-sL^*})}{(\alpha s+1)(s + MGe^{-sL^*})}\frac{d}{s} = 0 \quad (33)$$

This grantees zero steady state error even in the presence of uncertainty provided that the system is stable. This can be considered as one of the robustness aspects of the proposed method. However we do not prove in this work the stability of the system when there is a mismatch, we only illustrate it with simulations later on.

### *C. Proposed Method Tuning*

The set-point controller *C(s)* is chosen to be a gain controller $C(s) = K_r$ , this guarantees a first order set-point response. Let $K_p^*$ be the best available estimate of $K_p$. The direct synthesis method is employed. Let $H_{rd}(s)$ denote the desired form of $H_r$ where:

$$H_{rd} = \frac{1}{T_r s + 1} e^{-sL^*} \quad (34)$$

where $T_r$ is the desired closed loop time constant. Letting $H_{rd}(s) = H_r(s)$, then:

$$K_r = \frac{1}{K_p^* T_r} \quad (35)$$

The tuning formula of the load disturbance estimator *M(s)* is quite similar [13], which is as follows:

$$M(s) = \frac{K_d(T_d s + 1)}{(T_f s + 1)} \quad (36)$$

$$T_f = \frac{T_d}{10} \quad (37)$$

$K_d$ and $T_d$, are the gain and derivative term, respectively. To get $K_d$ and $T_d$, assuming $L=L^*$, then, the stability of the proposed method depends on the roots of the equation:

$$s + \frac{K_p^* K_d (T_d s + 1)}{(T_f s + 1)} e^{-sL^*} = 0 \quad (38)$$

(38) can be rewritten as:

$$1 + W(s) = 0 \quad (39)$$

$$W(s) = \frac{K_p^* K_d (T_d s + 1)}{s(T_f s + 1)} e^{-sL^*} \quad (40)$$

System stability is guaranteed if we can guarantee that all the roots of (38) or equivalently (39) are in the left hand side. One way to achieve this requirement is to apply the Nyqiust criterion on *W(s)*, since (39) looks like a characteristic equation. We will denote by $\phi_{pm}$ the phase margin of *W(s),* which is not in any way the phase margin of the proposed system.

In order to achieve the above mentioned requirement, $\phi_{pm}$ must be greater than zero.

$$\phi_{pm} = \pi + \arg\{W(j\omega_p)\} \quad (41)$$

$$|W(j\omega_p)| = \frac{K_d K_p^* \sqrt{1 + T_d^2 \omega_p^2}}{\omega_p \sqrt{1 + T_f^2 \omega_p^2}} = 1 \quad (42)$$

Let the derivative time constant $T_d$ be chosen proportional to the time delay ($L^*$), with ($0 \le \beta < 1$) the proportionality constant, a tuning parameter

$$T_d = \beta L^* \quad (43)$$

By ignoring the influence of the low pass filter time constant $T_f$ (since $T_f = T_d/10$ ), (42) is given by:

$$|W(j\omega_p)| = \frac{K_d K_p^* \sqrt{1 + T_d^2 \omega_p^2}}{\omega_p} = 1 \quad (44)$$

Using the approximation $\tan^{-1}(T_d \omega_p) \approx T_d \omega_p$ , then $\phi_{pm}$ can be written as:

$$\phi_{pm} = \pi - \frac{\pi}{2} + \tan^{-1}(T_d \omega_p) - L^* \omega_p = \frac{\pi}{2} + L^* \omega_p (\beta - 1) \quad (45)$$

Using (43) and (44), one can deduce that:

$$\omega_p = K_d K_p^* \sqrt{1 + \beta^2 L^{*2} \omega_p^2} \quad (46)$$

From which it can be seen that:

$$K_d = \frac{\omega_p}{K_p^* \sqrt{1 + \beta^2 L^{*2} \omega_p^2}} \quad (47)$$

However, using the fact that:

$$\omega_p = \frac{\frac{\pi}{2} - \phi_{pm}}{(1-\beta)L^*} \quad (48)$$

it can be deduced that:

$$K_d = \frac{\frac{\pi}{2} - \phi_{pm}}{K_p^* L^* \sqrt{(1-\beta)^2 + \beta^2 (\frac{\pi}{2} - \phi_{pm})^2}} \quad (49)$$

Numerous simulations reported in [11] suggest that the following: adequate values for $\beta$ and $\phi_{pm}$ are:

$$\beta = 0.4 \quad (50)$$

$$\phi_{pm} = 64^0 \quad (51)$$

or

$$K_d = \frac{1}{1.4 K_p^* L^*} \quad (52)$$

From (32), the disturbance transfer function characteristic equation is:

$$(\alpha s+1)(s+Me^{-sL^*}) \qquad (53)$$

Thus, properly choosing $\alpha$, the speed of disturbance rejection can be set. A lower value of $\alpha$ will correspond to a faster rejection of disturbance and a lower degree of system robustness, and vice versa, as shown later in the simulations. Consequently, to improve the system robustness, the speed of disturbance response must be slowed down through a higher value of time constant α. Numerous simulations, reported in [11] show that, the value of the parameter ($\alpha$) is given by:

$$\alpha = 3 * \left| L - L^* \right| \qquad (54)$$

As a summary the design steps of the controller are as follows: First a model of the plant, as good as possible should be available to provide $K_p^*$ and $L^*$. The designer then chooses the desired closed loop reference tracking time constant $T_r$, and the constant α which can be considered as the disturbance rejection time constant. The more confident the designer is in the model the smaller the value of α he can allow, as expressed by (54). However, the tuning of α might be difficult to achieve, since beforehand $L$ is unknown. An online estimation of α is currently being investigated. The set-point controller is given by (35), while the disturbance rejection controller is given by (36)(37)(43), (50) and (52).

## III. SIMULATION RESULTS

All the simulations considered are based on the following test problem: starting a zero initial conditions a unit step set-point change at time t=0 and a step load change d=-0.1 at t=100 sec are introduced. Two plants are considered: $G_{p_1} = \frac{1}{s}e^{-20s}$ and $G_{p_2} = \frac{1}{s(s+1)(0.5s+1)(0.2s+1)(0.1s+1)}e^{-20s}$

As in [5], the higher-order process $G_{p_2}(s)$ is modelled by a pure integrator plus time delay ($L^* = L + T_s$) where $T_s$ is the sum of time constants of $G_{p2}(s)$; i.e. here $L^*$ is 21.8 sec. The set-point closed loop time constant is selected to be $T_r = 2$.

### *A. Proposed Method Simulation Results*

The set-point controller gain is $K_r$=0.5. For the first plant other controller parameters are taken as: $K_d = 0.036$, $T_d = 8$ and $T_r = 0.8$; and the second plant: $K_d = 0.033$, $T_d = 8.72$ and $T_r = 0.87$.

Figure 4 illustrates the performance of the proposed scheme in the ideal case for plant 1 for $\alpha$ = 1, 10 and 30. It appears clearly that the larger the value of $\alpha$ the more sluggish is the system. The real advantage of the scheme appears when model uncertainty is considered. Figure 5 shows the performance of the scheme for plant 2 for $\alpha$ = 1, 10 and 30.

To further investigate the performance of the scheme for model mismatch, the process model and consequently the controller settings are kept unchanged for processes 1 and 2, while the process dynamics time delay is changed with different percentage. Two different situations can happen, $L^*- L>0$ the time delay is overestimated (positive mismatch) and $L^*- L<0$, the time delay is underestimated mismatch. Figure 6 shows the response at $\alpha$ = 15, with 20% positive and negative mismatch. It can be noticed that a good performance in set point and load rejection is obtained, indicating the effectiveness and robustness of the proposed method. It can be inferred from a close study of the simulations results provided that:

1. The value of $\alpha$ determines the robustness and speed of disturbance rejection in the scheme: the larger $\alpha$ the slower the load rejection and the more robust the system; the smaller $\alpha$, the more aggressive the controller is.
2. For the same value of $\alpha$, if there is a positive mismatch, the system is more robust and slower; on the contrary if there is a negative mismatch the system is less robust and faster. This is due to the fact that in the first case, the controller is tuned based on a larger delay and has smaller gains; while in the second case it is tuned for a smaller value of time delay and has larger gains.

### *Comparative Simulation Results*

The proposed controller performance is compared to some the existing schemes in the literature, especially in terms of robustness to mismatch in time delay.

Figure 7 and Figure 8 show the proposed method (PM) performance as compared to the scheme of [10], denoted by (MML) for the first plant at 30% positive mismatch in time delay estimation, respectively. The scheme is tuned according to the tuning rules proposed by its authors, and in such a way that a comparison can be made with the proposed scheme. The values taken are: set point controller gain $K_r = 0.5$ for a closed loop time constant of 2 sec, order of disturbance to reject $n = 2$ and disturbance rejection time constant $T_o = 10$.

As it appears, for the same closed loop requirements, the proposed method performs much better that the method of [10], even though it appears from the investigation of [11] that it is among the most robust scheme available in the literature.

## IV. CONCLUSION

A new method for controlling integral processes with long time delay (IPTD) was proposed. The method requires a process model and two tuning parameters, a desired closed loop time constant and a robustness parameter. Robustness to dead time mismatch having the most important effect on the performance, a tuning formula can be used to choose this parameter if a bound on the mismatch can be evaluated. However, because this requirement maybe difficult to achieve, an online tuning for this parameter is currently under investigation.

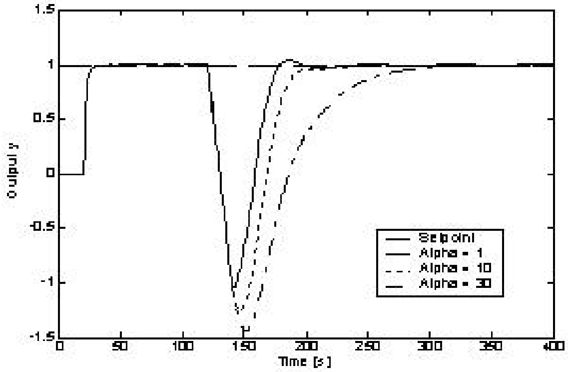


Figure 4: Proposed Method Performance at ideal case

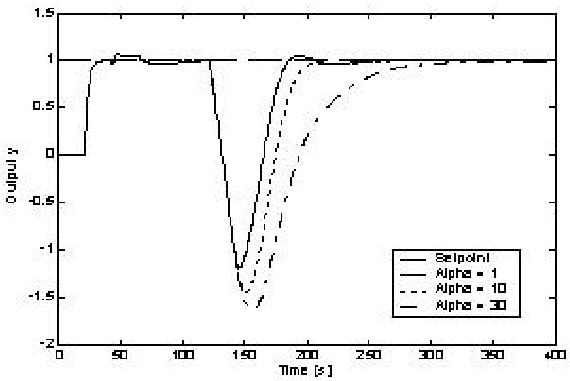


Figure 5: Proposed Method Performance with Dynamic Order Mismatch

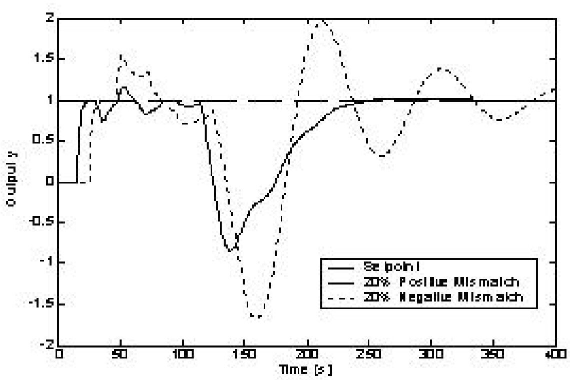


Figure 6: Proposed Method Performance with 20% Mismatch in Time Delay

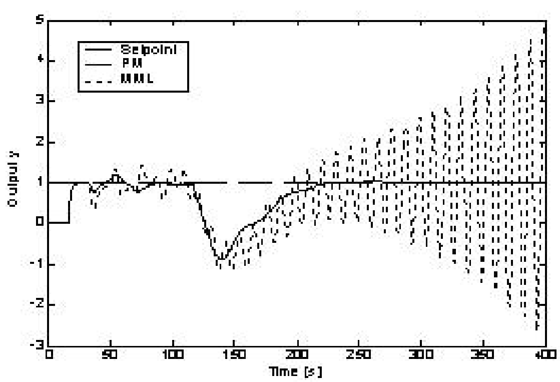


Figure 7: Comparative Simulation for +30% Mismatch in Time Delay

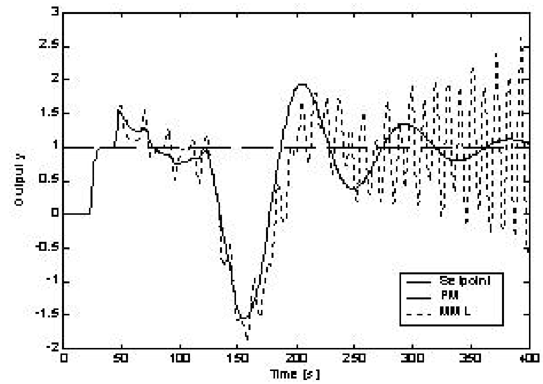


Figure 8: Comparative Simulation for -30% Mismatch in Time Delay

## REFERENCES


[1] C. Meyer, D.E. Seborg and R.K. Wood, "A Comparison of the Smith Predictor and Conventional Feedback Control," Chem. Eng. Science, Vol. 31 Jan. 1976, pp. 775-778.

[2] Watanabe, K., Ito, M. "A Process Model Control for Linear Systems With Delay," IEEE Trans. Autom. Contr., Vol. 26, 1981, pp. 1261-1266.

[3] Astrom, K. J., Hang, C. C. Lim. "A New Smith Predictor for Controlling a Process with an Integrator and Long Dead Time." IEEE Trans. Autom. Contr., Vol. 39., Feb.1994, pp. 343-345

[4] Weidong Zhang and Youxian Sun. "Modified Smith Predictor for Controlling Integrator/Time Delay. Ind. Eng. Chem. Res. Vol. 35 May. 1996, pp. 2769-2772.

[5] M.R. Matausek and A.D. Micic, "A Modified Smith Predictor for Controlling a Process with an Integrator and Long Dead Time," IEEE Trans. Autom. Contr., Vol. 41, Aug. 1996. pp. 1199-1203.

[6] Yu-Chu. Tian and Furong Gao, "Control of Integrator Processes with Dominant Time Delay," Ind. Eng. Chem. Res. Vol. 38, May. 1999, pp. 2979-2983.

[7] Julio E. Normey-Tico and Eduaudo F. Camacho, "Robust Tuning of Dead-Time Compensators for Processes with an Integrator and Long Dead Time," IEEE Trans. on Autom. Contr., Vol. 44, No. 8, August 1999, pp. 1597-1603.

[8] Weidong Zhang, Youxian Sun and Xiaoming Xu, "Two Degree of Freedom Smith Predictor for Processes with Time Delay," Automica, Vol. 34, No. 10, Feb. 1998, pp. 1279-1282.

[9] Yu-Chu. Tian and Furong Gao, "Double-Controller Scheme for Control of Processes with Dominant Time Delay," IEE Proc. Control Theory Appl. Vol. 145. No. 5, September 1998, pp. 479- 484.

[10] Milic R. Stojic, Milan S. Mtijevic, and Ljubisa S. Draganovic, "A Robust Smith Predictor Modified by Internal Models for Integrating Process with Dead Time," IEEE Trans. on Autom.. Control, Vol. 46, No. 8, August 2001, pp. 1293-1298.

[11] Ahmed M Gesraha, "Robust Control of Integrating Processes with Time Delay", M.Sc. Thesis, Cairo University, July 2002.

[12] Julio E. Normey- Rico and Eduardo F. Camacho, "Unified Approach or Design Dead-Time Compenstoes for Stable and Integrative Processes with Dead Time," IEEE Trans. on Autom. Contr., Vol. 47, No. 2, Feb. 2002, pp. 299-305.

[13] M.R. Matausek and A.D. Micic, "On the Modified Smith Predictor for Controlling a Process with an Integrator and Long Dead Time," IEEE Trans. on Autom. Contr., Vol. 44, No. 8, August 1999, pp. 1603-1606.