Neuro-Fuzzy Modified Smith predictor for IPDT and FOPDT Processes Control

Hao Chen*, Zoubir Zouaoui, Zheng Chen*****

Institute for Arts, Science and Technology,
Glyndwr University,
Mold Road, Wrexham,
Wales, UK. LL11 2AW
*Email: haochen84@yahoo.co.uk**
*z.zouaoui@glyndwr.ac.uk***
*z.chen@glyndwr.ac.uk****

Abstract In this paper, intelligent control approaches are introduced to overcome the problems highlighted in the standard Smith predictor. First, in order to overcome the steady state error in the Integrator Plus Dead Time (IPDT) process control due to disturbance loading, a new fuzzy logic control based SP is developed by intentionally introducing a model mismatch to improve the system performance in terms of disturbance rejection and robustness to process modelling errors. In addition, for the First Order Plus Dead Time (FOPDT) process control, a SP based neural network control scheme is proposed to deal with the process modelling errors and proved to provide a significantly improved robustness. The neural network (NN) was designed to work with different types of modelling errors. Simulation results show that this NN approach provides excellent performance in terms of robustness to modelling errors and high adaptability to the control of both IPDT and FOPDT processes.

Keywords: Dead-time, Smith predictor, Fuzzy logic, Modelling errors.

1. INTRODUCTION

In modern industrial control, time delay is a very import problem which has been paid special attention to. For a small time delay, a PID controller is commonly used. However, such a controller is not able to deal with processes with a large dead time. A standard Smith predictor (SP) is effective in dealing with a stable process with a long dead-time[1]. However, the standard SP has critical disadvantages. Firstly, if it is used for a pure integral process with a constant load disturbance, a steady-state error exists. Watanabe and Ito have developed a modified SP in the case of the IPDT process, which deliberately utilized a mismatched model instead of the known process in the minor feedback loop to overcome the problem of load disturbance rejection [2]. However, such a control scheme leads to a slow response. Another modified SP, which could provide a faster set-point response and a better load disturbance rejection proposed by Astrom et. al. [3]. The designed controller decouples the set-point response from the load response. However, in such a scheme there are too many tuning parameters, sometimes as many as six parameters, for an unpredictable gain and speed of response. Based on Astrom's SP, a new modified structure is developed to simplify the tuning rules [4]. Nonetheless, this approach is not robust enough. A new development of a modified SP for process control with integral action and long dead-time, in which a feedback to the process control response to eliminate load disturbances was proposed by Matausek et. al. [5]. Only three parameters, namely the dead-time, gain, and the desired time constant of a first order closed-loop set-point response are required to be tuned to present high performance for set-point tracking and load disturbance rejection. In order to increase the speed of response of the load disturbance rejection control system, a derivative control with a time constant Td is added into the feedback control [6]. This time constant is selected to be proportional to the model dead-time. In comparison with the previous dead-time compensation method described in [5], the approach developed in [6] provides considerably faster load disturbance rejection response. Moreover, only one parameter, that is the time constant, has to be tuned manually. Nonetheless, its efficiency is based on estimating the process gain and dead-time experimentally. Actually, in a real industrial environment, it is very difficult to provide a good accurate process model. Majhi developed a modified SP by adding an inner loop controller, which could stabilize an unstable process or an integral process. This design requires too complicated tuning rules [7].

The SP and its modifications are simple and commonly used compensators to deal with time-delayed systems [3, 5-10]. In practice, a process plant cannot be modelled accurately. Nevertheless, in practical applications, SP highly relies on the accuracy of the predicting model. It is very sensitive to process modelling errors, and even instability may be caused as soon as modelling plant mismatches become significant.

A modification to reduce the sensitivity of SP has been proposed by Wu et. al. [11]. It uses Taylor Series Expansion to represent the dead time element. Hence it copes with only the small time delay in processes, and loses efficiency and accuracy as soon as the dead time becomes significant. To reduce the sensitivity, another approach has been developed which combined the SP with a Radial Basis Function neural network acting as a main controller [12]. This development has improved the robustness to modelling errors and some other system performances. However, because the training is conducted online, the tuning approach is very complicated and time-consuming.

Elarafi et al. developed an artificial neural network predictive controller for pH neutralization processes control which outperformed the conventional PI/PD controllers [13]. It achieves a relatively fast settling time and small controller variable deviation. However, the disadvantage of this proposed controller is that it is very complex and difficult to tune. Fuzzy logic attracted also special attention in recent research works [14-19] . Most of these applications have concentrated on achieving the desired system performance from the human operators' experience. However, if a fuzzy-logic-based controller is used as the main controller for nonlinear processes control, it must be difficult to determine optimally the membership functions and linguistic rules [20].

In this paper, two intelligent system approaches have been developed as new modified predictors to overcome the problems of the original SP control scheme. First, an intentionally predicted model mismatch is introduced by applying a fuzzy logic method to cope with the steady state error problem for the control of IPDT processes with a disturbance load. Simulation results are conducted to evaluate the effectiveness and robustness of this fuzzy logic based predictive control. Secondly, a back-propagation neural network approach is used as the main controller instead of the original control action in a SP. This neural network control method gives good robustness to modelling error. From simulation evaluations, this neural controller also shows good adaptability in dealing with the rejection of disturbance load in the case of IPDT process control.

2. Smith Predictor

A standard SP is shown in Fig 1 below.

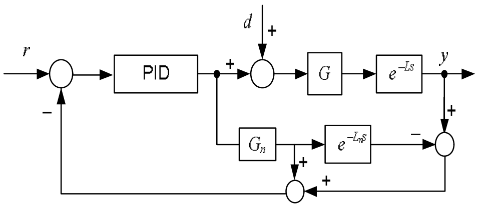

Fig. 1. Smith Predictor

The closed loop relation can easily be derived as

$$Y(s) = \frac{C(s)G(s)e^{-Ls}}{1+C(s)[G_n(s)-G_n(s)e^{-L_n s}]+C(s)G(s)e^{-Ls}} R(s) + \frac{G(s)e^{-Ls}\langle 1+C(s)[G_n(s)-G_n(s)e^{-L_n s}]\rangle}{1+C(s)[G_n(s)-G_n(s)e^{-L_n s}]+C(s)G(s)e^{-Ls}} D(s) \qquad (1)$$

Where $C(s)$ is the controller, $G(s)$ and L are the process plant and dead time, $G_n(s)$ and L_n are the predicted model and time delay. With an accurate process predicted model, this closed loop transfer function can be simplified to:

$$Y(s) = \frac{C(s)G(s)e^{-Ls}}{1+C(s)G(s)} R(s) + \frac{G(s)e^{-Ls}\langle 1+C(s)[G(s)-G(s)e^{-Ls}]\rangle}{1+C(s)G(s)} D(s) \qquad (2)$$

Consequently, the dead time is completely moved out of the closed loop, and the effect of dead time is reduced.

3. MODIFICATION OF SP FOR IPDT PROCESS CONTROL

Consider a PID controller $C(s) = K_P + K_I/s + K_D s$, and assume the process plant and predicted model have both an IPDT transfer function (i.e., $G(s)e^{-Ls} = \frac{K}{s}e^{-Ls}$ & $G_n(s)e^{-L_n s} = \frac{K_n}{s}e^{-L_n s}$,). Then, from Eq. (1) at the steady state the response to a disturbance load $D(s) = 1/s$ is derived as:

$$\lim_{s\to 0}(s \cdot Y(s)) = K_n \cdot L_n \qquad (3)$$

K_n is the model gain, and L_n is the model dead time. As shown in Eq. (3), a disturbance load to the process yields a steady-state error which equals to the product of the integrator gain and dead time of the process.

Consider an example of an IPDT process control [3]. This plant is represented by the transfer function

$$\mathrm{G(s)e^{-Ls}} = \frac{1}{\mathrm{s}}\mathrm{e^{-5s}} \qquad (4)$$

For an accurately predicted process model, the response of the process represented by the simplified closed loop transfer function in Eq. (2) to setpoint in the presence of a constant disturbance load $\mathrm{d(t)} = -0.1$ at $\mathrm{t} = 150\mathrm{s}$ is shown in Fig 2.

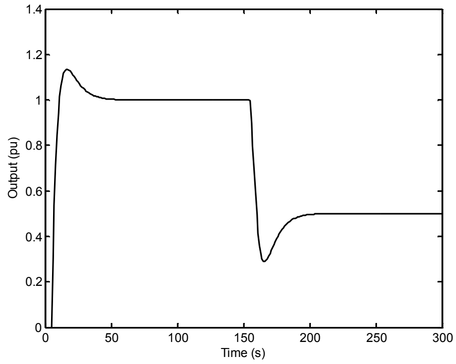

Fig. 2. Steady state error

Fig 2 shows the steady state error caused by the disturbance load in the case of the control of an Integrator Plus Dead Time control process using the original SP.

3.1Steady state error removal

In order to reduce this steady-state error, a FOPDT transfer function instead of an IPDT function, is introduced into the IPDT SP process and is used as the model for the SP.

In Fig. 1, the integrator in the predicted model is replaced by a first order expression. Therefore, the predicted model transfer function is modified to $G_n(s)e^{-L_n s} = K_n/(s +$

$a)e^{-L_n s}$, where a is a constant (a > 0). Suppose $K_n = K$ and $L_n = L$. From Eq. (3), the steady state response of the process with respect to disturbance load $D(s) = 1/s$ is given as,

$$\lim_{s\to 0}\left(s \cdot Y(s)\right) = \lim_{s\to 0}\left(\frac{G(s)e^{-Ls}\langle 1+C(s)[G_n(s)-G_n(s)e^{-L_n s}]\rangle}{1+C(s)[G_n(s)-G_n(s)e^{-L_n s}]+C(s)G(s)e^{-Ls}}\right) = 0 \qquad (5)$$

By intentionally introducing a mismatch in the predicted model, this proposed modified SP can successfully remove the steady state error in the presence of the disturbance load. Curve (1) in Fig. 5 shows the modified SP response from simulation results.

It is clear that the system set-point tracking and disturbance rejection have been achieved. However, a big overshoot exists in the transient response for the set-point tracking. In order to tackle this problem and improve the system performance, a fuzzy-logic-based method is applied for set-point weight tuning of the PID controller and is presented in the following section.

An effective way to deal with the overshoot problem is by using a weighting factor b (b<1) for the proportional action of the PID controller as shown in Eq. (6) [21].

$$u(t) = K_P[b \cdot r(t) - y(t)] + K_I \int_0^t e(\tau)d\tau + K_D \frac{de(t)}{dt} \qquad (6)$$

Where $e(t)$ is the system's error and $u(t)$ is the PID controller output

However, this method may reduce the efficiency of the proportional control action, and then causes an increase in the system rise time. An improvement was provided by using the fuzzy inference system [22]. A Fuzzy logic Method could determine the value of the weighting coefficient b(t) corresponding to the current value of system's error e(t) and its rate of change ė(t) [18]. The application of a Fuzzy-Logic-Based Set-point Weight Tuning of PID Controller in the modified SP is presented below:

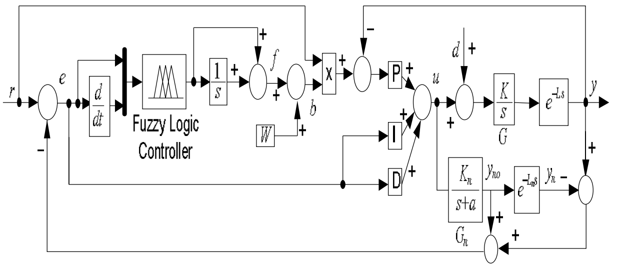

Fig. 3. Fuzzy-logic-based set-point weight tuning of PID controller in the modified SP

where f is the Fuzzy Logic System (FLS) output and $w \leq 1$ is a constant parameter to adjust the value of the weighting coefficient *b(t)*. Using tracking error signals, the FLS produces suitable value to ensure rapid converging of the output y(t) towards the reference input r(t). This FLS is designed as follows.

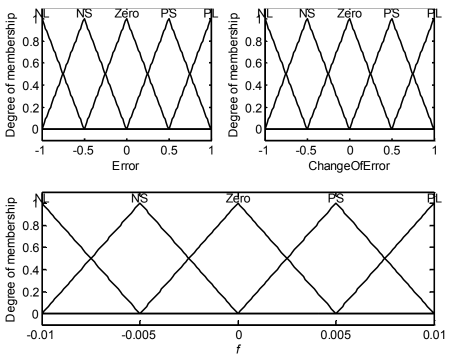

Fig. 4. Membership functions of FLS

Table 1. Rules of FLS

		e				
		NL	*NS*	*ZERO*	*PS*	*PL*
ė	*NL*	NL	NL	NS	NS	ZERO
	NS	NL	NS	NS	ZERO	PS
	ZERO	NS	NS	ZERO	PS	PS
	PS	NS	ZERO	PS	PS	PL
	PL	ZERO	PS	PS	PL	PL

In Fig. 4 (a, b) the range of FLS input membership functions are set as [-1, 1]. In order to finely adjust the proportional control action and avoid oscillation, the range of FLS output membership function is set as [-0.01, 0.01] as shown in Fig. 4 (*f*). Table 1 shows the fuzzy rules.

3.2 Evaluations

The IPDT process plant transfer function is given by Eq. (4), and the modified SP model is defined as

$$G_n(s)e^{-L_n s} = \frac{1}{s+1}e^{-5s} \qquad (7)$$

The modification with a Fuzzy-Logic-Based Set-point Weight Tuning of the PID Controller is evaluated in simulations. At first, the parameter w is set to 1. Then successive simulation trials were conducted by reducing progressively the value of w until there is no further improvement in the system's response. The final value of the parameter w settled at 0.5.

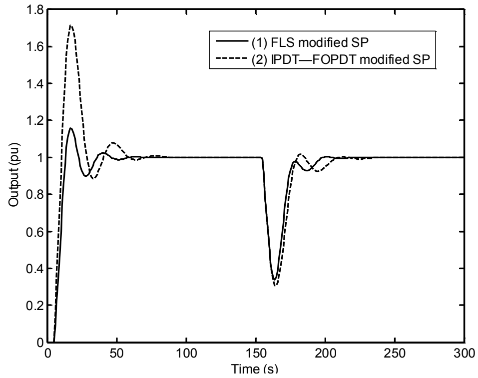

Fig. 5. Response of IPDT—FOPDT SP process

The Response Curve (2) is that of a system with the initial modified SP. An overshoot appears at the beginning of the set-point tracking response. Response Curve (1) is that of the system with the Fuzzy-Logic-Based Set-point Weight Tuning of the PID Controller. It is clear that the overshoot has been dramatically reduced.

By comparing the proposed method with the approach developed by Zhang et al. [10], the system response for 20% dead-time modelling error is obtained. i.e.,

$(G(s)e^{-Ls} = (1/s)e^{-4s} \ and \ G_n(s)e^{-L_n s} = (1/s)e^{-5s})$

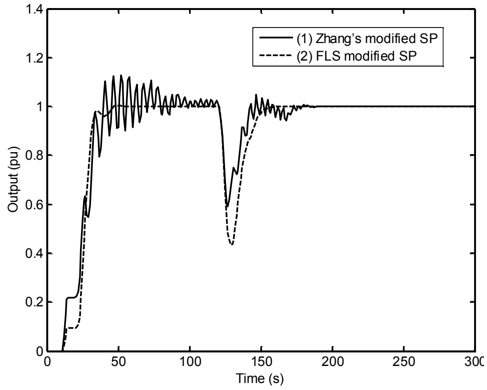

Fig. 6. Comparisons of the system response for 20% time delay modelling error

In Fig. 6, Response (1) presents the system's output of the Zhang modified SP, which shown a large number of oscillations for system input tracking and disturbance rejection. Response (2) is the response of the system using the proposed approach. It is obvious that without complex tuning algorithm the proposed approach provides much better robustness than Zhang's with respect to time delay model mismatch for the IPDT process control.

This new modified SP has been developed for the attenuation of the effect of disturbance loading in the case of the IPDT process. The predicted model is intentionally represented by a FOPDT transfer function in the proposed approach to successfully remove the steady-state error in the presence of disturbance load. A fuzzy-logic-based method has been applied to reduce the overshoot of the process, which appears in the transient phase of the set-point tracking response. This new modification demonstrates a better performance in the set-point tracking and disturbance rejection for the IPDT process control. It was also demonstrated through simulations that the new modified SP improves the robustness of the system to modelling errors.

4. SP BASED NN FOR PROCESS CONTROL

In the case of FOPDT process control, SP will not have a steady state error in response to a disturbance load as Eq. (3) results to a zero steady state output.

From Eq. (7), $1/(s+1)e^{-5s}$ is considered as the process plant and the predicted model transfer function, which means that an accurate predicted process model is given. The setpoint tracking response with a constant disturbance load $d(t) = -0.1$ at $\mathrm{t} = 250\mathrm{s}$, is shown in Fig. 8 below.

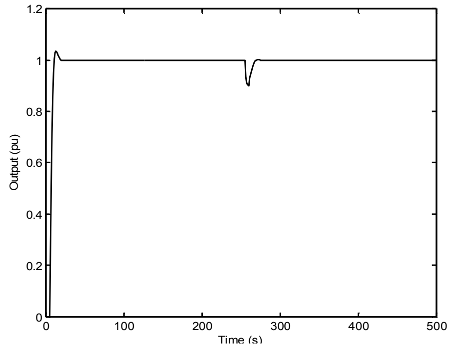

Fig. 7. Response of FOPDT process control

It is clear that from Fig. 7 that there is no steady state error due to the disturbance load.

The Original SP is sensitive to the process modelling error. In the presence of dead time modelling error Eq. (1) cannot be further simplified into Eq. (2). With a -50% dead time modelling error the performance of SP is indicated as Response Curve (1) in Fig. 13 and shows long lasting oscillation with relatively long peaks.

A Smith predictive based neuro-fuzzy compensator control approach developed by the authors is described in [24]. It considerably improves the robustness with respect to process modelling errors. In this paper, a similar SP based neural network is developed in the follow section.

4.1 Smith predictor based neural network design

A BPNN predictive controller for a FOPDT process is developed to be robust to the process modelling errors. The training is conducted off-line using the back-propagation algorithm. The proposed control scheme used in the training phase is given in Fig. 9.

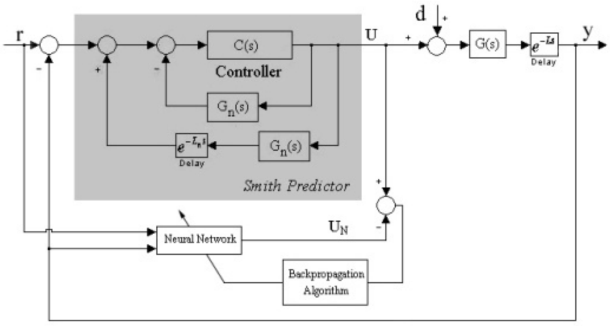

Fig. 8. SP based NN control

The NN controller is trained off-line with SP control structure shown in Fig. 8. As proposed in [24], a PID controller is applied in the feed-forward control loop to reduce the offset when the process gain modelling error occurs.

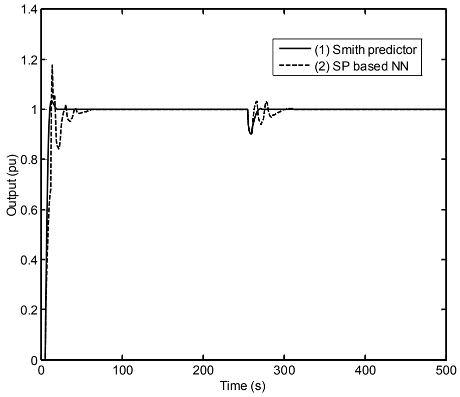

Fig. 9. Comparison of system performance

Initially, simulation is conducted in the case of FOPDT process control in the presence of disturbance load and absence of modelling errors. Response (1) & (2) of Fig. 9 are the system performance of the original SP and the SP based NN. In this control of FOPDT process, both approaches work well as the presence of disturbance load does not lead to a steady state error.

4.2 Evaluation of SP based NN

Simulation results are provided to compare the robustness of the original SP with SP based NN by considering dead time modelling error in process plant.

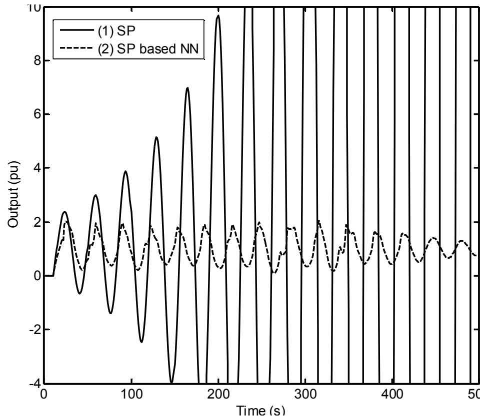

Fig. 10 Comparison of system performance with delay modelling error

Fig. 10 above shows a comparison of the systems performance by considering the presence of a disturbance load and concurrent modelling errors, i.e. -40% in process gain, -100% in time constant and -100% in dead time (where $K = 1.4$, $\tau = 2s$ & $L = 10s$ for the plant and $K_n = 1$, $\tau_n = 1s$ & $L_n = 5s$ for the model). Response (2) is the response of the SP based NN which outperforms the original SP whose response is represented by Response (1), in the presence of the simultaneous modelling errors.

5. PROPOSED NN TO CONTROL IPDT PROCESS

This developed SP based NN scheme is used to control the IPDT process plant by slightly tuning the PID controller without redesigning of the neural controller.

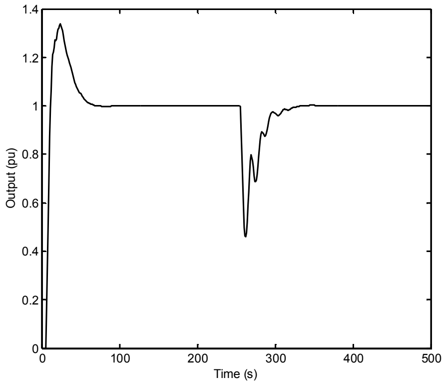

Fig. 11. Performance of SP based NN for IPDT process control

In Fig. 11, the performance of the new developed neural controller is shown for an IPDT process control in the presence of a disturbance load.

Simulations are conducted to evaluate this NN modified SP by considering process dead time modelling errors.

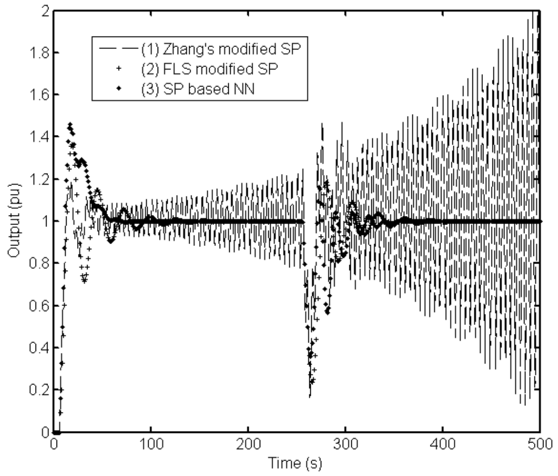

Fig. 12. Comparisons of the system response for -20% time delay modelling error

In Fig. 12 Response (1) is the system's output of Zhang's modified SP[10], Response (2)&(3) are the responses of the FLS modified control and the proposed NN modified SP. These two new modifications markedly outperform the Zhang's modifications in the presence of process dead time modelling errors. In terms of simulation results, this new NN modified SP control gives superior robustness with respect to the process modelling errors and good adaptability to the control of IPDT processes using designs for FOPDT processes.

6. CONCLUSION

In this paper, two novel modifications of SP have been developed. By intentionally converting the predicted model from IPDT to FOPDT and introducing a fuzzy logic method, this first proposed approach presents very good performance for the rejection of disturbance load. Based on the converted predicted model in the first development, the second modification is developed by using back-propagation NN to rebuild the SP. This designed NN controller dramatically improves the robustness to the process modelling errors. It also presents a good adaptability to control different processes (IPDT process) and eliminate the steady state error in the presence of disturbance load without any redesign.

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