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PPI CONTROLLER TUNING FOR USE WITH A HIGHLY OSCILLATING SECONDORDER-LIKE PROCESS

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Abstract: -
A PPI controller is investigated for set-point tracking associated with a highly oscillating secondorder-like process. The controller is tuned using the MATLAB optimization toolbox and five different errorbased objective functions. All the objective functions result in a same time response of the closed-loop control system to a unit step input. The unit step reference input time response of the control system has a zero maximum overshoot and a settling time of 16 seconds. It has an oscillatory nature for a response time up to 10 seconds. The simulation results using the PPI controller are compared with using I-PD, PD-PI, PIPD, PID + first-order lag and PID controllers. The PPI can compete with I-PD, PD-PI and PI-PD controllers regarding the maximum percentage overshoot. However, it cannot compete with all the other five controllers regarding the settling time.

Keywords:- *PPI controller, second-order-like process, controller tuning, control system performance.*

I. INTRODUCTION

Some industrial and engineering applications exhibit an oscillating nature when excited by a reference step input. Such processes can be assumed as a second-order underdamped process. Controller type and tuning is a challenging demand to produce a control system of accepted performance even the process is highly oscillating. A PPI controller is investigated for possible recommendation as a suitable controller for such applications.

Lo,Rad and Tsang (1994) proposed a predictive proportional integral (PPI) controller over standard PI and PID controllers. They compared the controller performance with that of PID one tuned by Ziegler and Nichols and other tuning methods. They derived the conditions for stability and the controller sensitivity to process parameter changes [1]. Rayanallur, Milky and Chen (2002) presented the design, tuning and performance analysis of a predictive fuzzy controller structure for high order plants with large time delays. The designed controller consisted of a fuzzy PI part and a fuzzy predictor. They compared the performance of the proposed controller with that using the conventional PPI controller [2]. Ren, Zhang and Shao (2003) demonstrated the performance of PPI controller and compared with traditional PID controller. They emphasized the application of PPI for long time delay processes and its excellent robust stability [3].

Arousi, Sohmitz, Bars and Haber (2008) derived a single predictive control algorithm using approximation of an aperiodic process by a first-order model with dead-time. They applied a noise model to enhance the robustness properties of the algorithm considering plant-model mismatch. They demonstrated the behaviour of the PPI algorithm and the robustifying effect of the noise filter [4]. Airikka (2011) presented an extension of a PPI controller having a good match to a Smith predictor to improve control performance for delay dominant processes. He covered industrial processes with multiple time constants, integrator or both of them combined [5]. Larsson and Hagglund (2012) presented a performance comparison between PID and PPI controllers. They performed optimization of controller and measurement filter parameters considering load disturbance rejection, robustness and noise sensitivity for a batch of industrial processes [6]. Airikka (2012) presented a modification of a PPI controller to deal with processes with long dead times. His proposed method had resemblance with PID controller and was applicable for industrial dead time dominating processes [7]. Airikka (2013) analysed in details the stability of the PPI control loop for accurate process models having no model mismatch and processes having modelling errors and uncertainties. He has given some preliminary guidelines for the controller tuning [8]. Shrinde, Hamde and Waghmare (2014) proposed a nonlinear PPI controller for processes with varying dead times. They tested the proposed method on process models and compared the performance with that existing linear PPI. They showed that the nonlinear PPI controller removes the oscillatory behaviour of the time response with linear PPI controller [9].

Airikka (2014) considered the stability and robustness of PPI controller without an additional filter for any time-invariant system resulting in tuning rules for an optimal performance with a targeted robustness against model mismatch. He has given tuning rules for a first-order plus dead time and integrating plus dead time systems [10]. Prakash and Alamelumangai (2015) designed and analysed a predictive fractional order PI controller to compensate the effect of dead time present in a process. They evaluated the performance of the control system with the developed scheme using settling time, rise time, peak time, overshoot and ISE through simulation [11].

II. PROCESS

The process is a second-order like one without time delay having the transfer function, $G_p(s)$:

$$G_p(s) = \omega_n^2 / (s^2 + 2\zeta\omega_n s + \omega_n^2) \tag{1}$$

Where:
ω_n = process natural frequency in rad/s
ζ = process damping ratio

To simulate the high oscillations nature of the process, ωn is taken as 10 rad.s and ζ is taken as 0.05. Using MATLAB control toolbox, the process has the following time-based specifications [12]:

- Maximum percentage overshoot: 85.446 %
- Maximum percentage undershoot: 69.760 %
- Settling time: 5.975 s

III. THE PPI CONTROLLER

The block diagram of a linear feedback control system for set-point tracking exhibiting a PPI controller is shown in Fig.1 [5].

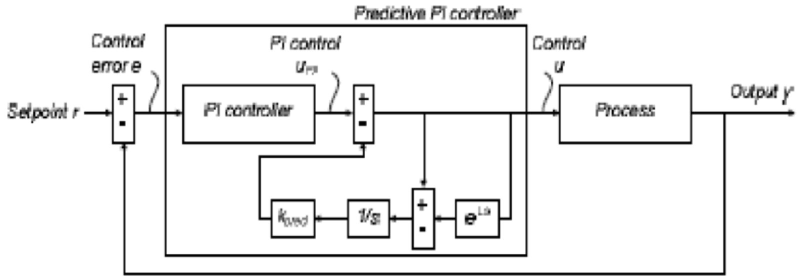

Fig.1 Control system block diagram with PPI controller [5].

The PI controller part in Fig.1 is a standard PI controller having the transfer function, $G_{PI}(s)$:

$$G_{PI}(s) = K_{pc} + K_i/s \qquad (2)$$

According to Airrikka, the PPI controller of the structure shown in Fig.1 has an overall transfer function between its output U(s) and input E(s), $G_{PPI}(s)$ given by [8]:

$$G_{PPI}(s) = s\,(K_{pc} + K_i/s) / \{s + K_{pred}\,[1\text{-}\exp(-Ls)]\} \qquad (3)$$

Where:

K_{pc} and K_i are the proportional and integral gain coefficients of the PI controller. K_{pred} is the predictive gain coefficient of the feedback element shown in Fig.1.

L is the time delay of the PPI controller in the feedback element shown in Fig.1.

This means that the PPI controller has four parameters to be adjusted (tuned) for optimal control system performance in set-point tracking.

To facilitate the dynamic analysis of the control system, the first-order Taylor series is used to replace the exponential term in Eq,3 by a first-order polynomial. That is [13]:

$$\exp(-Ls) \approx -Ls + 1 \qquad (4)$$

Combining Eqs.3 and 4 gives:

$$G_{PPI}(s) = (K_{pc} + K_i/s) / [1+K_{pred}L)s] \qquad (5)$$

The closed loop transfer function of the closed loop control system, C(s)/R(s) is given using the block diagram of Fig.1 and Eqs.1 and 5 by:

$$C(s)/R(s) = (b_0s+b_1)/(a_0s^3+a_1s^2+a_2s+a_3) \qquad (4)$$

Where:

$$b_0 = \omega_n^2K_{pc} / (1 + K_{pred}L)$$
$$b_1 = \omega_n^2K_i / (1 + K_{pred}L)$$
$$a_0 = 1 \quad a_1 = 2\zeta\omega_n$$
$$a2= \omega n2 + \omega n2Kpc / (1 + KpredL)a3 = Kpc \quad a_3 = \omega_n^2K_i / (1 + K_{pred}L)$$

IV. CONTROLLER TUNING

Tuning of the PPI controller allows adjusting the controller four parameters K_{pc}, K_i , K_{pred} and L for optimal tracking of the set-point. The desired steady-state response in this case using Eq.4 equals the amplitude of the step input. This allows us to define an error function e(t) as the difference between the time response and a unit value for a unit set-point step input. That is:

$$e(t) = c(t) - 1 \qquad (5)$$

The controller tuning is performed using the error function of Eq.5 which is incorporated in an objective function to be minimized using the MATLAB optimization toolbox [14]. The objective functions used are ([15][17]):

ITAE: $\int t|e(t)|\,dt$ (6)

ISE: $\int [e(t)]^2\,dt$ (7)

IAE: $\int |e\,(t)|\,dt$ (8)

ITSE: $\int t[e(t)]^2\,dt$ (9)

ISTSE: $\int t^2[e(t)]^2\,dt$ (10)

The tuning results for a control system incorporating the PPI controller and the highly oscillating secondorder-like process are given in Table 1.

TABLE 1
I-PD CONTROLLER TUNING AND CONTROL SYSTEM PERFORMANCE

	ITAE	ISE	IAE	ITSE	ISTSE
K_{pc}	0.2082	0.2012	0.2007	0.2054	0.211
K_i	0.4923	0.4918	0.4918	0.4921	0.4925
K_{pred}	2.5005	2.5009	2.5010	2.5007	2.5004
L (s)	0.6022	0.6039	0.6060	0.6029	0.6015
OS_{max} (%)	0	0	0	0	0
T_s (s)	16.0464	16.0620	16.063	16.0527	16.0403

It is clear from the tuning results in Table 1 that the type of the objective function has minor effect on the tuning process since the controller parameters have very close values.

CONTROL SYSTEM TIME RESPONSE

The time response of the control system for a unit step reference input gain and a second-order-like process having 10 rad/s natural frequency and 0.05 damping ratio for the five objective functions of Eqs.6 to 10 is shown in Fig.2.

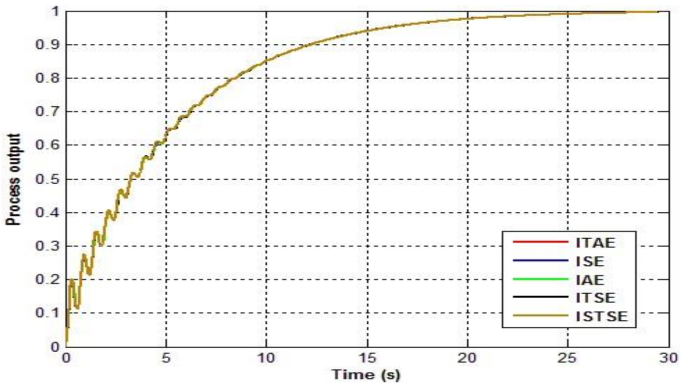

Fig.2 Unit step input time response using a PPI controller.

Fig.2 indicates that the control system is not sensitive to the objective function type used in the tuning process of the PPI controller. The step time response is oscillating around an increasing trend. The oscillations damp down after about 10 seconds.

V. Comparison with other research work

The results of the present research using a PPI controller to control a second-order–like process is compared with that of using I-PD, PD-PI, PI-PD PID plus first-order lag and PID controllers for the same process of 10 rad/s natural frequency and 0.05 damping ratio ([18] – [22]). The unit step reference input time response of the control system is shown in Fig.3.

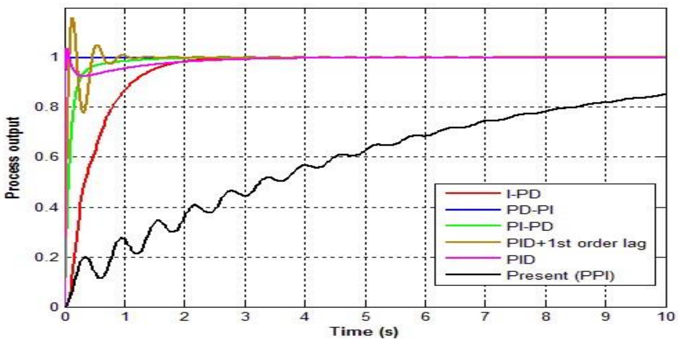

Fig.3Comparison of the unit step reference input time response.

The control system performance is compared in Table 2 between the PPI and the other controllers.

Table 2 performance comparison

	OS_{max} (%)	T_s (s)
I-PD controller	0	1.5000
PD-PI controller	0	0
PI-PD controller	0	0.3714
PID + first-order lag controller	15.924	0.5643
PID controller	3.648	0.8550
Present (PPI controller)	0	16.0403

VII. CONCLUSIONS

- A PPI controller was investigated to control a second-order like process of 85.4 % maximum overshoot and about 6 seconds settling time.
- The controller was tuned using the MATLAB optimization toolbox and five different objective functions were examined.
- The time response of the control system to a unit step reference input had an oscillating nature about an increasing trend for up to 10 seconds.
- The type of objective function did not affect the time response of the control system.
- The PPI controller succeeded to cancel completely the maximum percentage overshoot.
- The settling time of the time response was about 16 seconds.
- Comparing with the research work using I-PD, PD-PI, PI-PD, PID + first-order lag and PID controllers, the PPI controller could not compete with the other controllers regarding the resulting settling time.
- It could compete with the I-PD, PD-PI and PI-PD controlling in having zero overshoot.
- The PPI controller was not so successful compared with the other controllers. The reason for this may be because it was initially applied to deal with delayed processes while the process in hand was undelayed. However, it could eliminate completely the high overshoot of the process.

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