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PERFORMANCE ANALYSIS OF PROPORTIONAL INTEGRAL DERIVATIVE CONTROLLER WITH DELAYED EXTERNAL RESET AND PROPORTIONAL INTEGRAL DERIVATIVE CONTROLLER FOR TIME DELAY PROCESS

RAMAVEERAPATHIRAN ARUN[1], RATHINAM MUNIRAJ[2], MARIA SILUVAIRAJ WILLJUICE IRUTHAYARAJAN[3]

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In the developed work, the traditional particle swarm optimization (PSO) technique is utilized to optimize parameters of PID controller with and without delayed external reset. Optimization of controller parameters, considering servo and regulatory performance, input energy usage, and robustness to model uncertainties is performed for the first order plus dead-time (FOPDT) process with various values of time delay. A robust controller is obtained by imposing constraints on the maximum sensitivity and complementary sensitivity functions. The connections between obtained parameters of the controller through optimization procedure and process model parameters have been analyzed. Further, the performance and robustness of PID with delayed external reset and PID controllers have been compared. The results show that the derivative action of PID with delayed external reset controller is not beneficial for the time delay processes where delay in time is greater than process time constant. Therefore, PI with delayed external reset and PID controllers are optimized for industrial time delay processes and performance comparison is presented. The results presented show that the PI controller with delayed external reset performed better for the time delay processes.

1. INTRODUCTION

The proportional integral (PI) and proportional integral derivative (PID) controllers are broadly utilized in the industries owing to its simplicity, simple execution and proven performance with number of conditions for operation [1]. Desborough and Miller [2] carried out an investigation in process industries for more than 11,000 controllers employed in it and it is told that the PID algorithm is employed for more than 97 % of regulatory controllers. Also, reported that most of them are PI only controller. Plethora of tuning procedures is presented in the literature for tuning PID controllers for dissimilar objectives and specifications. Henceforth, while dealing with the complex issues the conventional methods face some challenges theoretically [3]. It is a good choice to use optimization algorithms to design the optimal PID controller for complex problems [4].

Evolutionary algorithms are the widely accepted methods to resolve complex optimization issues. There are variety of algorithms for evolutionary techniques such as genetic algorithms (GA), particle swarm optimization (PSO) algorithm and differential evolution (DE) that are broadly utilized for parameter determination of PID controller systems [3–5]. Among evolutionary computation techniques, PSO algorithm has been popularly used to tune PID controller [6–8]. Due to simple concept, quick convergence and easy implementation PSO have been considered to tuning the parameters of controller. The idea of using PSO to tune a PID controller satisfies the established requirements in a method of minimization of objective function. Implementation of PSO is easy and inexpensive, as its memory and CPU requirements for speed is less. Moreover, gradient information is not required for objective function, which is under evaluation, but only its values. Only primitive mathematical operators are utilized. Therefore, in this work, PSO is considered to tune controller.

The closed-loop performance of PI/PID controllers is not only influenced by engaged optimization method but also by the selected objective function. To tune controllers by utilizing single-objective evolutionary algorithms, different objective functions are given in literature with the inclusion of integral absolute error (IAE), integral time absolute error (ITAE), integral squared error (ISE) and integral time squared error (ITSE) [9]. Generally, it is difficult to define an optimal controller for a system due to many issues such as closed-loop performance, robustness, and usage of input and noise sensitivity. Optimizing the controller with the right choice of objective function can efficiently compensate the robustness and performance requirements of closed-loop systems.

Time delay occurs in a number of types such as from an actual delay in physical transport in various systems processes, communication delays in complex systems and computational delay in embedded systems.The presence of time delay in many industrial processes imposes certain limitations on the achievable feedback performance and may trigger serious stability issues [10]. For time delay dominated process, it is well-known that operation of PI/PID controller is not satisfactory. Smith developed the first dead-time compensation (DTC) technique [11] to increase PI/PID controllers' operation for plants with delay in time. The original Smith predictor (SP) is the most widely utilized DTC algorithm in industrial control applications. Smith's DTC scheme is a model-based scheme, which requires model of the process. A PPI (predictive proportional integral) [12] controller has been proposed for the FOPDT process model, which has all Smith predictor characteristics with three adjustable parameters, whereas Smith predictor has five adjustable parameters. Several DTC techniques are developed in the literature with respect to different process model types and the objectives of closed loop [10–16]. Besides, it is exhibited that if the delay of time is low, the

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[1] Department of Electrical and Electronics Technology, Ethiopian Technical University, Addis Ababa, Ethiopia, pathiranarun@gmail.com

[2] Department of Electrical and Electronics Engineering, P.S.R Engineering College, Sevalpatti, Sivakasi, Tamil Nadu, India. munirajphd@gmail.com [Corresponding author]

[3] Department of Electrical and Electronics Engineering, National Engineering College, K.R. Nagar, Kovilpatti, Tamil Nadu, India. m.willjuice@gmail.com

PID controller performance is good when compared to the time delay compensation techniques [17]. Henceforth, if time delay is large, the DTC will experience better performance than the PID. The alternative to the PID controller provides improved performances but at the expense of sacrificing simplicity.

Time delay elements simple insertion in the integral feedback path of conventional PID is called as PID controller with delayed external reset produces a transfer function like IMC and Smith predictor [18]. However, several researchers have pointed that the inclusion of time delay in controller structure may improve its performance [19] for time delay dominated processes. In [18] PID with delayed external reset controller settings have been proposed for distributed lag process. In [20] a time delay element is added to integral term of PI controller and tuning relations are derived based on the IMC formulation. In these methods, the time delay element is considered as tuneable parameter and tuning rules have been devised by the authors.

The time delay inserted in the PID controller also yields prediction capability as like derivative action. The two parameter PI controller is most used structure compared to PID structure. The derivative part is often turned off especially for long dead time processes. Therefore, the addition of time delay element to the PI (D) controller should be analyzed. Most of the DTC schemes utilize a process model and/or its parameters that are related to the model. Hence, relationship between the model and PI/PID controller parameters should be examined for time delay processes.

The main aim of the developed work is to contribute insight into the issues of choosing between PI and PID controllers with time delay compensation. Specifically, in the developed paper a study is performed for the time delay dominated processes, relative to time constant for FOPDT processes. The controllers are tuned for a well-balanced objective function using evolutionary algorithms and the performance of controllers has been evaluated. Further, this work studies the performance comparison between the PID controllers with and without time delay compensation. The regulatory performance of a controller is usually more important that servo response. Differing from other methods the chosen objective function considers both servo and regulatory performance of closed loop system along with their input energy usage. The optimization is performed under robustness constraints on the maximum sensitivity and complementary sensitivity functions. In this work, an effort has been made to illustrate the benefits of time delay compensation in the existing PID control structure as simple as possible.

The proposed tuning method of PID controller with delayed external reset using evolutionary algorithms is more beneficial for industrial systems having time delays such as smart grids [22, 23], aerodynamic systems [24] and chemical processes [25]. The paper is outlined as below: Section 2 introduces PID with delayed external reset scheme in reset configuration, in Section 3 optimization problem is formulated, Section 4 analyzes the operation of PID controller with and without time delay compensation and Section 5 simulation analyses on the industrial processes is exhibited. Finally, section 6 concludes the developed work.

2. **FEEDBACK AND CONTROLLER STRUCTURE**

The unity feedback closed loop system block diagram is exhibited in Fig. 1, where $G_p(s)$ and $G_c(s)$ are open loop process transfer function and transfer function of the controller respectively. The significant objective of closed loop methodology is to maintain the system output y at the specified reference r by manipulating the process input u in the presence of input disturbance d.

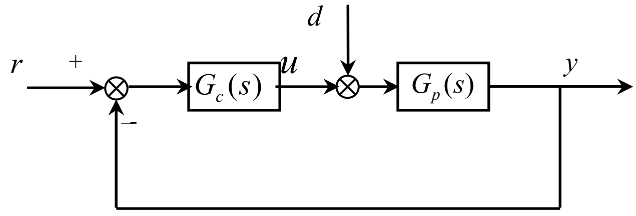

Fig. 1 – Block diagram of unity feedback closed loop system.

The considered PID controller with filter is on series form, the input-output relation is as below:

$$G_c(s) = k_c\left(\frac{\tau_i s + 1}{\tau_i s}\right)\left(\frac{\tau_d s + 1}{\tau_f s + 1}\right), \tag{1}$$

where k_c is the gain in controller, τ_i, τ_d and τ_f are integral, derivative and filter time constants respectively. The PID controller integral action can be evaluated in configuration with reset as exhibited in Fig. 2. This implementation of positive feedback integral action keeps up several significant PID functions likewise dynamic reset limit, wireless enhancement, and time delay compensation [21]. The PID controller output equation is evaluated in a configuration with reset as exhibited in Fig. 2 is

$$u(s) = k_c \frac{\tau_d s + 1}{\tau_f s + 1} e(s) + \frac{1}{\tau_i s + 1} u(s)\,. \tag{2}$$

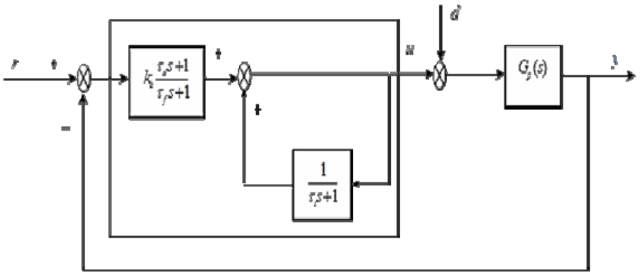

Fig. 2 – Reset configuration of PID controller.

Time delay element (e^{-Ls}) inclusion into PID controller integral feedback path will bring time delay compensation capability to a PID for processes with delay in time. Figure 3 shows off the PID controller with delayed external reset.

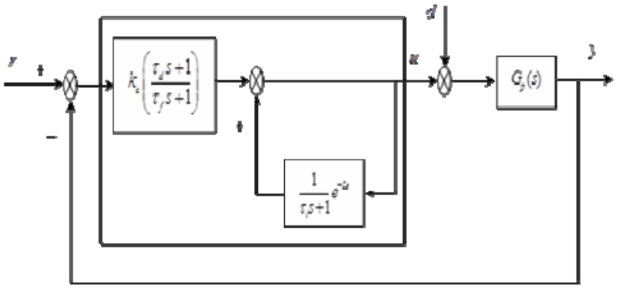

Fig. 3 – PID with delayed external reset control scheme.

The transfer function of PID controller with delayed external reset is as follows:

$$G_c(s) = k_c \left(\frac{1}{\frac{e^{-Ls}}{\tau_i s + 1}} \right) \left(\frac{\tau_d s + 1}{\tau_f s + 1} \right). \quad (3)$$

The PID controller with output equation for delayed external reset is

$$u(s) = k_c \frac{\tau_d s + 1}{\tau_f s + 1} e(s) + \frac{1}{\tau_i s + 1} e^{-Ls} u(s) . \quad (4)$$

By analyzing the structure of controller and equations of PID with and without delayed external reset, it is inferred that integral action is feedback type within controller which resets the input process to follow user specified set point. This reset action regulate the closed loop qualitative behavior. The positive feedback element is a first order model in a PID within the controller whereas in the PID controller with delayed external reset is a first order plus time delay element. A time delay element is inserted in implementation of integral mode positive feedback that brings time delay compensation which is nearly same as Smith predictor. In the PID controller with delayed external reset, the user must set the time delay value (L) in the delay block of time. In the developed work, the delay in time is taken as time delay of the process. It is well known that any controller will not be able to neglect or alter the process time delay in closed loop. Hence, the actual process time delay is used in the reset action of integral mode of the PID controller. Also, this choice makes the number of tuning parameters remains same for both PID with delayed external reset and PID controllers.

The time delay inserted in the PID controller also yields phase advance as like derivative action. The prediction using time delay may enhance the performance better than the derivative action for the time delay dominant processes. In the developed work, the operation of PID controller with delayed external reset which is tuned for a well-balanced objective function is analyzed for FOPDT process for various time delays. The proposed single objective function formulation is discussed in the next section.

3. OPTIMIZATION FORMULATION

Generally, it is difficult to define an optimal controller for a process due to the consideration of many issues. The main issues including:

- Output performance;
- Robustness;
- Input usage;
- Noise sensitivity.

The controller with higher gain favors for good output performance, whereas lower gain for the other three objectives. Output performance (objective 1) is associated with dissimilarity in between the set point (r) and process output (y) and may be computed in many ways. However, to quantify the controller performance in terms of single scalar value, The IAE is chosen as an output performance measure. The closed loop system output should track the specified set point. This set point tracking performance so called servo performance is computed as follows:

$$J_{servo} = \int_0^{T_f} \left| r(t) - y(t) \right| \mathrm{d}t \, . \quad (5)$$

The closed system output deviation from the set point due to disturbances should be rejected by the controller operation. This disturbance rejection performance so called regulatory performance is computed as follows:

$$J_{dis} = \int_0^{T_f} \left| y(t) \right| \mathrm{d}t \, . \quad (6)$$

The controller output performance considering the set point tracking and disturbance rejection is as follows:

$$J_1 = \int_0^{T_f} w_1 \left| r(t) - y(t) \right| \mathrm{d}t + \int_0^{T_f} w_2 \left| y(t) \right| \mathrm{d}t \, , \quad (7)$$

where (T_f) is a finite time, chosen for the steady state value.

The IAE value for both sets point and disturbance is considered when evaluating the output performance. To get a good balance between the set point and disturbance responses, the weights (w_1, w_2) are equally considered in the cost function of Eq. (7).

The input energy usage is usually computed by the metric Total Variation (TV) in the input to evaluate the controller performance. The TV is a good smoothness measure of system input, and it should be as small as possible. The TV is computed using:

$$J_2 = \sum_{k-1}^{N} \left| u(k+1) - u(k) \right| , \quad (8)$$

for input changes due to change in set point and input disturbance.

The servo operation and regulatory operation of closed loop methodology is analysed through their sensitivity functions in the frequency domain. The sensitivity and complementary sensitivity functions are explained below:

$$S(s) = \frac{1}{1 + G_\iota(s) + G_p(s)} , \quad (9)$$

$$T(s) = \frac{G_\iota(s) + G_p(s)}{1 + G_\iota(s) + G_p(s)} . \quad (10)$$

$S(s)$ and $T(s)$ are the sensitivity and the complementary sensitivity functions respectively.

The maximum sensitivity is exhibited by:

$$M_s = \max_{(i)} \left| S(\mathrm{j}\omega) \right| . \quad (11)$$

M_s is associated with gain and phase margins. It establishes lower bounds for the gain and phase margin. The gain margin and phase margins can be expressed as follows:

$$\mathrm{AM} \geq 20 \log_{10} \left(\frac{M_s}{M_s - 1} \right) , \quad (12)$$

$$\mathrm{PM} \geq 2 \sin^{-1} \left(\frac{1}{2 M_s} \right) . \quad (13)$$

Besides, the maximum sensitivity M_s is a measure of robustness in closed loop. The reciprocal of M_s is smallest distance in between transfer function of Nyquist curve loop and critical point. The classic values of M_s are in the range of 1.2–2.0.

The noise sensitivity on the process output can be quantified by the complimentary sensitivity function peak (M_t). The maximum complimentary sensitivity is given by:

$$M_t = \max_{(i)} \left| T(\mathrm{j}\omega) \right| . \quad (14)$$

It is commonly defined that certain useful limits to M_s and M_t values are desirable to conclude least margin of robustness [26]:

$$1.2 \le M_s \le 2.0\,,\qquad 1.0 \le M_t \le 1.5\,. \tag{15}$$

The optimization of controller parameters is subjected to constraint on the maximum sensitivity function and the maximum complementary sensitivity function.

Henceforth the optimization issue is designed to search the solution $\theta = \left\{k_c, \tau_i, \tau_d, \tau_f\right\}$ such that:

$$\begin{aligned} &\min_{\omega}\left(J_1 + J_2\right) && 1.2 \le M_s \le 2.0\,,\\ &\text{Subject to} && 1.0 \le M_t \le 1.5\,. \end{aligned} \tag{16}$$

In this work, the controller parameters are optimized for the above objective function using one of the swarm intelligent techniques called particle swarm optimization. A well-balanced objective function which considers servo and regulatory performance, input usage and robustness constraints is used to optimize the controller parameters.

4. COMPARISON BETWEEN PID CONTROLLER WITH AND WITHOUT DELAYED EXTERNAL RESET

In this section, the PID controller with and without delayed external reset is tuned using PSO algorithm for the objective function given in the Equation 16. Time delay occurs often in several industrial processes including chemical processes, line transmission and telecommunication. A huge count of industrial processes can be approximately modeled by FOPDT transfer function:

$$G_p\left(s\right) = \frac{k_p}{\tau_p s + 1} e^{-Ls}\,, \tag{19}$$

where k_p, τ_p and L are process gain, time constant and time delay. It is commonly known that process time delay and uncertainties in their estimation complicates the control system design task. The presence of uncertainty in time delay plays a significant role in the closed loop system stability. Owed to importance of delay in time, in the developed work, PID controller with and without delayed external reset is tuned using evolutionary algorithm for different values of time delays. To study the effect of process time delay on closed loop performance this analysis has been performed. In this analysis the process gains and time constants were kept unity and the time delay alone is varied from low to high value.

Hence to evaluate processes with least, average, and maximum time delay into account, the range of dimensionless delay in time are evaluated from 2 to 10 as multiples of 2. For all the values of time delay the optimal values of PID and PID with delayed external reset controller parameters are determined using PSO. Further, performance and control schemes robustness are compared.

The following settings are used in PSO optimization routine: size of swarm is 20, highest number of functional evaluations is 1 500, problem dimension is 4, highest velocity is 0.25, inertia weight is linearly decreasing from 0.9 to 0.2 with respect to iteration, accelerate coefficient (c_1 and c_2) is 1 and number of runs is 20. The initial range of parameters of controllers is $\theta = \left\{k_c, \tau_i, \tau_d, \tau_f\right\} \in \left\{0.01, 10\right\}$. The obtained controller parameters with their statistical performance parameters such as mean, standard (Std.), worst values and computation time are listed in Tables 1 and 2 for the PID with delayed external reset and PID controllers respectively.

Table 1

Optimal PID controller with delayed external reset parameters

Time delay	**Controller parameters**				**Statistical parameters**				
	k_c	τ_i	τ_d	τ_f	Best	Mean	Std.	Worst	Computation time
2	1.11	1.00	7.78	7.79	7.74	8.375	0.50	9.00	254.735
4	1.02	0.99	10.0	10.0	11.9	12.54	0.90	14.2	242.4258
6	1.01	1.01	5.89	5.93	15.97	16.55	0.893	18.9	247.4977
8	1.01	1.01	7.721	7.735	20.02	21.60	1.629	24.1	251.1883
10	1.00	0.99	3.89	3.87	24.0	26.55	5.05	42.6	253.72

Table 2

Optimal PID controller parameters

Time delay	**Controller parameters**				**Statistical parameters**				
	k_c	τ_i	τ_d	τ_f	Best	Mean	Std.	Worst	Computation time
2	0.76	2.44	2.44	3.72	9.302	9.436	0.21	10.09	227.7351
4	0.60	3.608	3.54	5.19	14.97	15.36	1.06	18.38	230.6406
6	0.58	4.937	5.22	7.74	20.36	21.26	1.430	24.60	230.1508
8	0.31	3.539	1.72	0.88	25.28	27.865	5.32	45.02	222.4914
10	0.34	4.693	2.485	1.415	30.074	31.904	3.203	41.424	232.6516

The convergence rate of objective function performance is shown in Figs. 4, 5 respectively for PID with delayed external reset and PID controllers respectively.

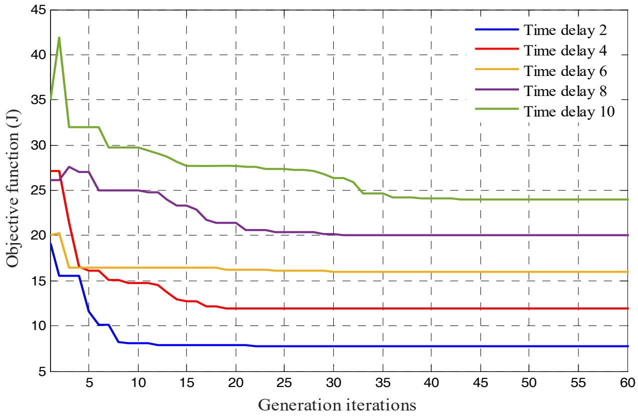

Fig. 4 – Convergence test for PID controller with delayed external reset.

In Fig. 5 the initial high value is limited to ensure the visibility of other generation iterations.

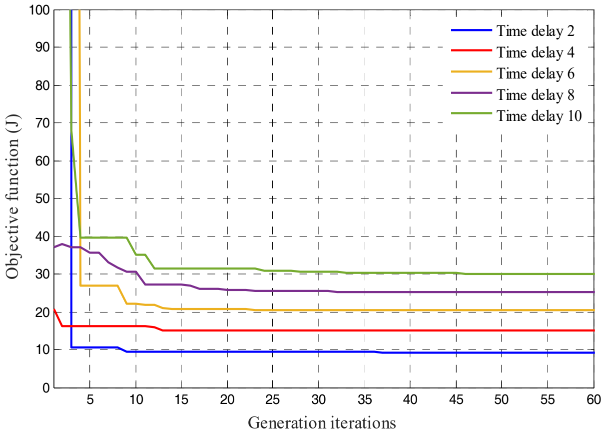

Fig. 5 – Convergence test for PID controller.

From Figs. 4 and 5 it is inferred that the convergence iterations increase as the process time delay increases. One more important thing is PID controller converges quickly as compared to PID controller with delayed external reset. These results show that the design complexities increase for increasing the values of process time delay and controller complexity.

From Fig. 5, it is inferred that the objective function value is increasing with higher values of delay time. This shows that the closed loop performance is decreasing with the higher values of process delay. Extensive investigation has been done for non-unity value of the process gain and time constants. This extensive analysis shows that the obtained controller gain value is close to the inverse of process gain and the controller integral time constant is equal to the process time constant. From the Table 1, it is inferred that derivative and filter time constants of PID controller with delayed external reset is almost equivalent for all values of time delay. The variation in controller parameters with respect to variation in time delay is shown in Fig. 6 for PID controller with delayed external reset (since the derivative and filter time constants are equal, they are not exhibited in figure). Moreover, the controller gain and integral time constant values are almost same for all time delay values. This indicates that the closed loop performance of time delayed processes depends on the time delay and controller tuning have less effect.

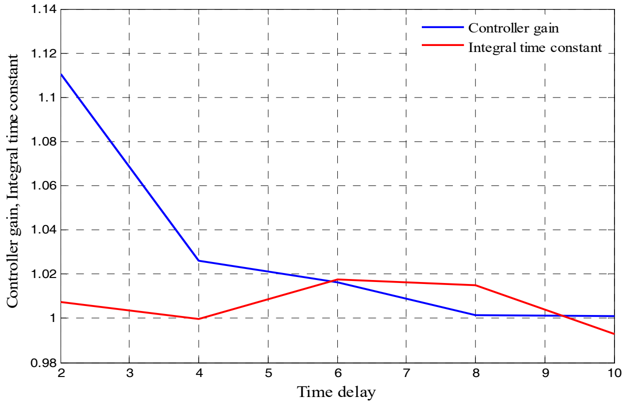

Fig. 6 – Time delay *vs* PID with delayed external reset parameters.

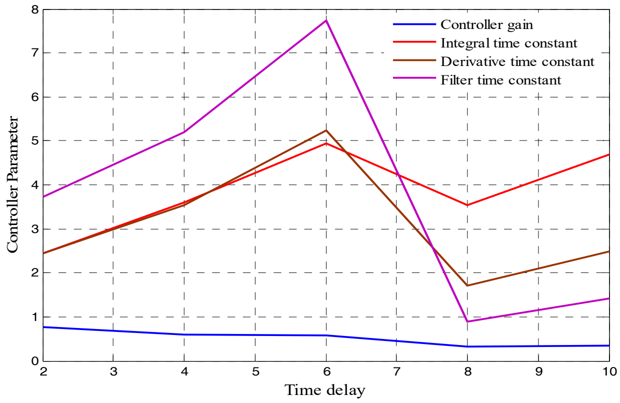

Fig. 7 – Time delay *vs* PID controller parameters.

The variation in controller parameters with respect to variation in time delay is shown in Fig. 7 for PID controller. The PID controller parameters have non-uniform variations with the process time delay. Also, it is inferred that PID controller parameters do not have any relation with the process model parameters. The computation time reported in Tables 1, 2 revels that controller parameters computation times are almost equal for all values of time delay process. On other hand PID controller computation time is less compared to PID controller with delayed external reset. This shows that the computation time increases with the controller complexity.

Further, this analysis shows that the parameters of PID controller with delayed external reset have certain relation with the process model parameters. Due to same time constant values of derivative and filter part there is a pole zero cancellation in the controller transfer function. This analysis clearly shows that the derivative action of the PID controller with delayed external reset is not beneficial for the processes with time delay because the prediction is already provided by the time delay element that presents in the controller. Therefore, derivative action may be disabled for the time delay dominant processes. In overall the process time delay has a limitation on controller tuning to the closed loop performance improvement and the controller parameters can have a direct relation with the process parameters for the PID controller with delayed external reset. This analysis shows that the controller gain is close to the inverse of process gain and integral time constant is close to the process time constant for FOPDT process models.

Further, it is inferred that the PID controller with time delay compensation shows better performance with less objective function value is analyzed to PID controller for all range of time delay. The performance/robustness indices are reported in Table 3. Table 3 compares the robustness of the schemes, and it reveals that the PID controller has slightly higher robustness for lower values of time delay and has equal robustness for higher values of time delay. It can be concluded that the PID controller with delayed external reset has equal robustness and improved closed loop performance compared to PID controller. By evaluating Table 3 it is concluded that PID controller with delayed external reset shows improved performance than PID controller for all values of time delay process. The robustness measure maximum sensitivity M_s values are comparable for both the schemes. This is the well-known trade-off between performance and robustness. The performance improvement exhibits marginal decrease in robustness. But the robustness is within the specified desired limit only. The maximum complementary sensitivity M_t is equal for both the schemes. It is summarized that prediction using process time delay shows improved performance than the prediction using derivative action.

Table 3

Performance and Robustness Indices of PID controllers with delayed external reset and PID

Time delay	**PID with delayed external reset**			**PID**		
	J	M_s	M_t	J	M_s	M_t
2	7.7749	1.828	1.0	9.3023	1.7956	1.0054
4	11.9085	1.91	1.00	14.9727	1.8432	1.000
6	15.9766	1.9444	1.0	20.3626	1.8566	1.00
8	20.0238	1.9697	1.0	25.2840	1.8827	1.00
10	24.0080	1.975	1.0	30.0746	1.9716	1.00

The insertion of element time delay in the PID controller may eliminate need of derivative action. This exclusion of derivative action reduces the number of tuning parameter and avoids the problems associated with the derivative action such as derivative kick, noise amplification, *etc.* Therefore, the PI controller with delayed external reset (*i.e.*, without derivative action) and PID controller parameters are optimized for industrial time delay processes. The attractive feature of a PI controller with delayed external reset has a smaller number of tuning parameters and having time delay compensation. This controller is more useful when time delay processes are frequently changing due to operating conditions. The estimated time varying delays can be openly used in controller to provide optimal performance.

5. SIMULATION ANALYSIS

In this section, the operation of PI controller with delayed external reset and PID controller is compared for an industrial process. Both controller parameters are determined using PSO for the same objective function given in the eq. 16. The paper machine dynamic model is designed for controlling basis weight objective is

$$G_m(s) = \frac{5.15}{1.8s+1} e^{-2.8s} . \tag{20}$$

Table 4

Controller parameters, performance and robustness indices for paper machine

Controller	Controller Parameters					Servo		Reg.		*Ms*	*Mt*
	k_c	τ_i	τ_d	τ_f	Time delay	IAE	TV	IAE	TV		
PI-Time delay	0.2579	1.854	—	—	2.8	4.15	0.34	1.83	0.13	2.0	1.09
PID	0.1429	3.1794	4.5729	5.2304	-	5.10	0.35	2.3	0.14	2.0	1.11

The convergence rate of objective function performance is exhibited in Fig. 9 and it exhibits that PI controller with delayed external reset has quick convergence when evaluated to PID controller. The obtained controller parameters, operation and robustness indices are reported in Table 4. Like previous analysis the parameters of PI controller with delayed external reset have relation with the process model parameters, *i.e.*, the controller gain is close to the inverse of process gain and integral time constant is close to the process time constant of FOPDT process model.

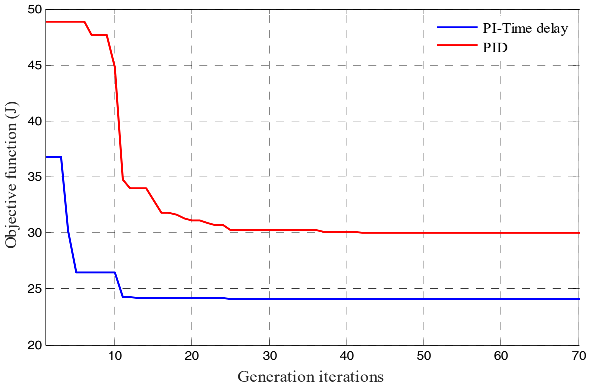

Fig. 9 – Convergence test for paper machine.

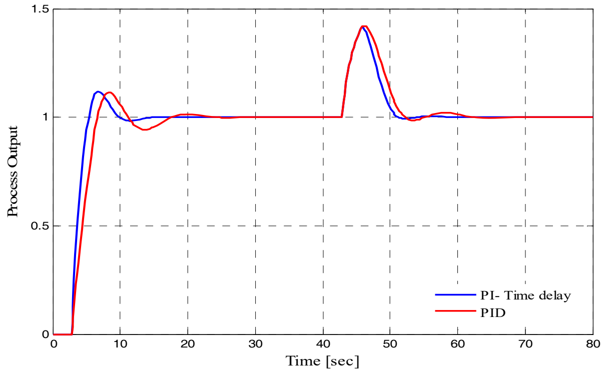

Fig. 10 – Servo-regulatory response for paper machine.

The unit step servo response and regulatory response due to step input disturbance amplitude of 0.1 is exhibited in Fig. 10. From operational evaluation and closed loop performance, it is concluded that PI controller with delayed external reset shows better servo and regulatory performance with same input energy differentiated to PID controller. Also, number of tuning parameters in the PI controller with delayed external reset is lesser than the PID controller. It should be noted that controller parameters of both schemes are optimized for the same objective function using PSO algorithm. Further, the robustness measures such as, M_s and M_t values are same for both the schemes. This example shows that the inherent capability of PI controller with delayed external reset better performance without compromising the robustness and input energy usage compared to PID controller.

6. CONCLUSIONS

A robust PID controller with and without time delay compensation is tuned using PSO algorithm for the FOPDT process with various values of time delay. The optimal controller parameters are obtained considering the servo-regulatory performance with minimum input energy subject to a robustness constraint. By analyzing the parameters of PID controller with delayed external reset, it is inferred that the derivative and filter time constant is almost equivalent to all values of time delay, but it is unequal for PID controller. The derivative action of PID controller with delayed external reset is not beneficial for the process with time delay. The performance of PI with delayed external reset and PID controller is compared for the industrial time delay processes. The result shows that the PI controller with time delay compensation provides an improved performance compared to PID controller without compromising robustness and input energy usage. Further, it is inferred that the PI controller with delayed external reset parameters obtained using optimization procedure has a close relation with the process model parameters such as the controller integral time constant which is equivalent to time constant process and the controller gain which is close to the inverse of process gain.

Additional time delay compensation in the existing PI structure enables industrial applications of the control schemes to increase the performance of loop. PI controller with time delay compensation can be easily implemented with slight modification in the existing controller. Practical implementation aspects of control scheme such as anti-windup, bump less transfer, and noise filtering can be easily addressed. Time delay presents in practical systems are time varying in nature. Most of the chemical processes have number of inputs and number of outputs with multiple time delays. The tuning method of PI controller with delayed external reset can be extended for systems with time varying time delays and multivariable systems with multiple delays.

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REFERENCES

1. D.B. Santosh Kumar, R.P. Sree, *Tuning of IMC based PID controllers for integrating systems with time delay*, ISA Trans., **63**, *1*, pp. 242, 2016.
2. L.D. Desborough, R.M. Miller, *Increasing customer value of industrial control performance monitoring – Honeywell's experience*, *Chemical Process Control-VI*, AIChE Symposium, USA, 2002.

3. W. Zhu, S. Qixin, L. Xionglin, *A novel HTD-CS based PID controller tuning method for time delay continuous systems with multi-objective and multi-constraint optimization*, Chem. Eng. Res. Des., **115**, *A*, p. 98, 2016.
4. A. Moharam, M.A. El-Hosseini, H.A. Ali, *Design of optimal PID controller using hybrid differential evolution and particle swarm optimization with an aging leader and challengers*, Appl. Soft. Comput., **38**, *1*, p. 727, 2016.
5. R. Muniraj, M. Willjuice Iruthayarajan, R. Arun, T. Sivakumar, *Parameter optimization of multi objective robust proportional integral derivative controller with filter using multi objective evolutionary algorithms*, Rev. Roum. Sci. Techn. – Électrotechn. et Énerg., **64**, *3*, p. 259-265., 2019
6. A. Lari, A. Khosravi, F. Rajabi, *Controller design based on μ analysis and PSO algorithm*, ISA Trans., **53**, *2*, p. 517, 2014.
7. A. Belkadia, H. Oulhadjb, Y. Touatic, S.A. Khan, B. Daachic, *On the robust PID adaptive controller for exoskeletons: A particle swarm optimization-based approach*, Appl. Soft Comput., **60**, *1*, p. 87, 2017.
8. Y. Ye, C.B. Yin, Y. Gong, J.J. Zhou, *Position control of nonlinear hydraulic system using an improved PSO based PID controller*, Mech. Syst. Signal Pr., **83**, *15*, p. 241, 2017.
9. M.H. Fini, G.R Yousefi, H.H. Alhelou, *Comparative study on the performance of many-objective and single-objective optimisation algorithms in tuning load frequency controllers of multi-area power systems*, IET Gener. Transm. Dis., **10**, *12*, p. 2915, 2016.
10. J.E. Normey-Rico, E.F. Camacho, *Unified approach for robust dead-time compensator design*,. J Process Contr, **19**, *1*, p. 38, 2009.
11. O.J.M. Smith, *Closed control of loops with dead time*, Chem. Eng. Prog, **53**, p. 217, 1957.
12. T. Hagglund, *An industrial dead-time compensating PI controller*, Control. Eng. Pract., **4**, *6*, p. 749, 1996.
13. J.E. Normey-Rico, C. Bordons, E.F. Camacho, *Improving the robustness of dead-time compensating PI controllers*, Control. Eng. Pract., **5**, *6*, p. 801, 2007.
14. A. Ingimundarson, T. Hägglund, *Robust tuning procedures of dead time compensating controllers*, Control. Eng. Pract., **9**, *11*, p. 1195, 2001.
15. K. Kirtania, A.S. Choudhury, *A novel dead time compensator for stable processes with long dead times*, J. Process. Cont., **22**, *3*, p. 612, 2012.
16. J.E. Normey-Rico, C.C. Rodolfo, T. Flesch, L.M. Santos, *Unified dead-time compensation structure for SISO processes with multiple dead-times*, ISA Trans., **53**, *6*, p. 1865, 2014.
17. A. Ingimundarson, T. Hägglund, *Performance comparison between PID and dead-time compensating controllers*, J. Process. Contr., **12**, *8*, p. 887, 2002.
18. F.G. Shinskey, *PID-dead-time control of distributed processes*, Control Eng. Pract., **9**, *11*, p. 1177, 2001.
19. A.B. Rad, W.L. Lo, K.M. Tsang, *Adaptive time-delay controller*, IEEE T. Ind. Electron., **47**, *6*, p. 1350, 2000.
20. J. Lee, T.F. Edgar, *Improved PI controller with delayed or filtered integral mode*, AIchE J, **48**, *12*, p. 2844, 2002.
21. R. Vilanova, A. Visioli, *PID Controller in the Third Millennium*, 1sted., New York, Springer, 2012.
22. H.H. Alhelou, M.E.H. Golshan, M. Fini, *Multi agent electric vehicle control based primary frequency support for future smart micro-grid*, Smart Grid Conference (SGC), Tehran, Iran, 2015.
23. H.H. Alhelou, M.E.H. Golshan, *Hierarchical plug-in EV control based on primary frequency response in interconnected smart grid*, 24th Iranian Conference on Electrical Engineering (ICEE), Shiraz, Iran, 2016.
24. E. Steed, E. Quesada, L. Rodolfo, G. Carrillo, A.N. Ramirez, S. Mondie, *Algebraic dominant pole placement methodology for unmanned aircraft systems with time delay*, IEEE T. Aero. Elec. Sys., **52**, *3*, p. 1108, 2016.
25. S. Mehrkanoon, Y.A.W. Shardt, J.A.K. Suykens, S.X. Ding, *Estimating the unknown time delay in chemical processes*, Eng. Appl. Artif. Intel., **55**, p. 219, 2016.
26. G. Reynoso-Meza, J. Sanchis, X. Blasco, R.Z. Freire, *Evolutionary multi objective optimization with preferences for multivariable PI controller tuning*, Expert. Syst. Appl., **51**, *1*, p. 120, 2016.