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PID Controller Tuning using Online Dynamic Set Point Weighting Scheme

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ABSTRACT

An online dynamic set point weighting technique is proposed for PID controller. The set point weighting factor is calculated online according to the process change of error through a simple sigmoid function. Weighted set point for each sampling instant is applied only for proportional term of the PID controller. The proposed dynamic set point weighted PID controller provides a significant amount of performance enhancement for higher order processes with dead time. Its superiority has been verified through simulation study. Unlike the conventional fixed set point weighting which provides only improved set point response, our proposed technique is capable to provide simultaneous improvement during both the set point tracking as well as load variation with considerable robustness in close-loop behaviour

Keywords: PID controller, ZN tuning, fixed set point weighting, dynamic set point weighting.

INTRODUCTION

Proportional-integral-derivative (PID) controllers are widely accepted in industrial close-loop control due to their simple structure and straightforward tuning techniques [2].Among the reported tuning relations, Ziegler-Nichols (ZN) [3] settings are considered to be most familiar for determining good initial settings of PID controllers. During steady state response, ZN tuned PID (ZNPID) controllers are found to provide improved performance compared to transient response. Another major advantage of ZN ultimate cycle based tuning is that it is independent of process model. But, from practical implementation point of view continuous cycling of a process parameter with the critical gain is not feasible for most of the applications especially for higher order process. This problem can be overcome up to a large extent with the help of relay tuning [4]. Set point filtering and set point weighting techniques [5] are the most well known solutions in this direction as suggested by the researchers.

In any close-loop control, the main objective is to maintain the process output at the desired value i.e., at set point irrespective of the process operating conditions. So, to attain this desired goal set point weighting technique is an effective mechanism which can minimize the overshoot but at the cost of increased rise time. Hence, in literature we can find that various set point weighting schemes have been proposed by the researchers [7-13] to make the set point weighting more effective and easy to implement for single input single output (SISO) control loops. Fixed set point weighting (FSPW) [7] and variable set point weighting (VSPW) [8] are some of the well studied examples of it. In FSPW, a specific weighting factor (usually ranges from 0.4 to 0.6) is used while in case of VSPW instead of fixed set point weighting factor three different values for the weighting factor are used. It is found that, it results better performance in case of VSPW compared to FSPW. Another set point weighting technique is proposed in [9], where the weighting factor is obtained by minimizing the integral square error (ISE) of the controlled variable. To achieve further improvement during transient response fuzzy logic based set point weighting [10] mechanism is also reported in the literature. Continuously varying set point weighting technique is suggested for conventional PI and PID controllers in [11] and [12] respectively. Here, we propose a new set point weighting technique for ZN tuned PID

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controllers where weighting factor is varied online through a sigmoid function. It is found that the proposed scheme is capable to provide performance enhancement during both the set point response and load disturbance rejection.

In the proposed sigmoid function based dynamic set point weighting (DSPW), a continuously varying weighting factor is calculated online based on the current change of error of the process output[1]. The performance of the proposed DSPW is verified for second order integrating and linear processes with dead time. A comparison is made with conventional ZNPID and fixed set point weighted PID (FSPW-PID) controller. Simulation study is performed and the controller performance indices–percentage overshoot (%OS), rise time (t_r), settling time (t_s), integral absolute error (IAE) calculated for each setting for having a clear comparison. Robustness of the proposed controller is also verified by increasing the process dead time by 20% from its nominal value while keeping the controller settings unchanged. From the performance analysis it is found that the proposed DSPW based PID (DSPW-PID) controller is capable to provide a significant amount of performance improvement over the fixed set point weighting technique to provide a significant amount of performance improvement over the fixed set point weighting technique during transient as well steady state performance.

CONTROLLER DESIGN

The dynamic weighting factor is calculated online through a simple sigmoid function based on change of error at each sampling instant. The weighted set point is calculated by the weighting factor which is used for obtaining the proportional control action of the proposed PID controller

Block diagram of proposed dynamic set point weighted PID controller is shown in Fig.1. The dotted boundary shows the computational mechanism of dynamic weighting factor.

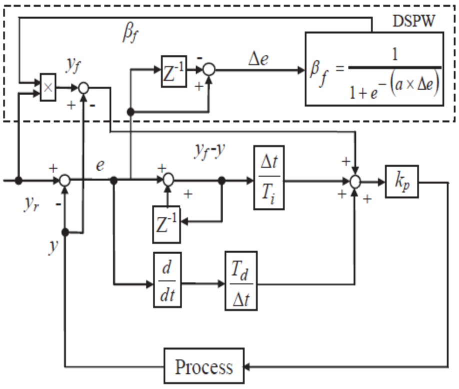


Fig1. *Block diagram of DSPW-PID.*

.Discrete form of fixed set point weighted PID controller [6] at K_{th} sampling instant is given by eq (1),

$$u(k) = k_c\left[\{\beta y_r - y(k)\} + \frac{\Delta t}{T_i}\sum_{i=0}^{k} e(i) + \frac{T_d}{\Delta t}\Delta e(k)\right]$$

$$u(k) = k_c\left[\{y_{fw} - y(k)\} + \frac{\Delta t}{T_i}\sum_{i=0}^{k} e(i) + \frac{T_d}{\Delta t}\Delta e(k)\right] \quad (1)$$

In eq(1), , β is the fixed weighting factor, y(k) is the process output at K_{th} instant, K_c is the proportional gain, T_i is the integral time, and Δ t is the sampling interval, T_d is the derivative time. K_c, T_i and T_d are calculated according to the ZN ultimate cycle based tuning relations [2] given by

$k_c = 0.6k_u$, (2)

$T_i = 0.5t_u$, (3)

$T_d = 0.125t_u$, (4)

Where k_u and t_u are the ultimate gain and ultimate period respectively.

The value of fixed weighting factor β can be calculated by the following relation as in [6]

$$\beta = \frac{15 - k}{15 + k}, \text{ where } 2.25<k<15 \quad (5)$$

Here, k is the normalized process gain. The value of k can be obtained by the following relation based on the normalized dead time [6]:

$$k = 2\left(\frac{11\theta + 13}{37\theta - 4}\right), \text{ for } 0.16<\theta<0.57 \quad (6)$$

But, for the proposed DSPW-PID, its discrete form at k_{th} sampling instant is given by

$$u(k) = k_c\left[\{\beta_f y_r - y(k)\} + \frac{\Delta t}{T_i}\sum_{i=0}^{k} e(i) + \frac{T_d}{\Delta t}\Delta e(k)\right]$$

$$u(k) = k_c\left[\{y_f - y(k)\} + \frac{\Delta t}{T_i}\sum_{i=0}^{k} e(i) + \frac{T_d}{\Delta t}\Delta e(k)\right] \quad (7)$$

In eq (7), y_f is the dynamic set point weighting factor and it is obtained by a simple sigmoid function based on current change of error (Δe)

$$\beta_f(\Delta e) = \frac{1}{1 + e^{-(a\times\Delta e)}} \quad (8)$$

In eq(8), a is the slope parameter of the sigmoid function. Due to multiplicative form of a and Δe in the expression of the sigmoid function, its slope varies continuously depending on Δe. The nature of variation of sigmoid function for different slopes is shown in Fig.2. Here, we have chosen the value of a as 10 through an extensive simulation study. The normalized change of error can vary from -1 to +1 and hence the weighting factor β_f can assume a value ranges from 0 to 1 depending on current process states (i.e., Δe)

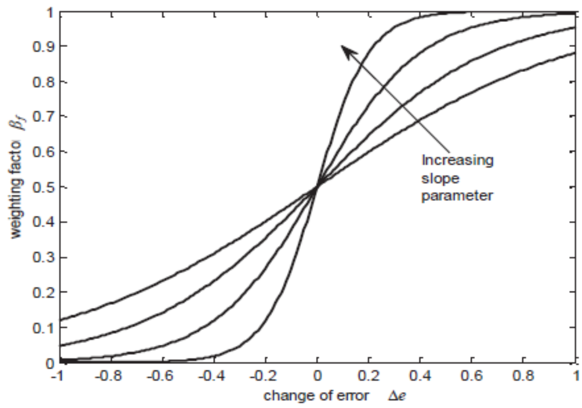


Fig2. *Nature of variation of sigmoid function based on value of Δe.*

The proportional component of DSPW-PID will be continuously adjusted by proposed dynamic set point weighting factor to minimize the process oscillations. For better understanding of the continuous variation in proportional action, some representative operating points are considered on a typical second-order process response curve as shown in Fig.3.

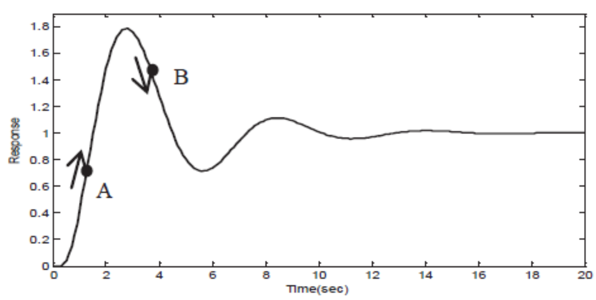


Fig3. *Typical transient response of an under-damped second-order process*

(i) During the process response as given by operating point A, when the process variable is below the set point ($y < y_r$) and is moving towards set value, Δe is negative. From eq(8) it is found that $0 < \beta_f < 0.5$. Thus the proportional action of DSPW-PID is lesser than that of conventional PID controller which will help to restrict the process overshoot within acceptable limit. It is further to note that, as Δe changes with the speed of response of the process, the weighting factor β_f is also got varied.

(ii) In an opposite scenario, when the process output is moving downwards from some higher value ($y > y_r$) towards the set point as given by point B, Δe is positive. It results $1 > \beta_f > 0.5$ as obtained from eq(8). Thus the proportional control action of DSPW-PID will be moderate to reach the set value faster but at the same time it restricts undershoot. Hence, the weighting factor β_f get varied continuously throughout the entire operating phases in such a way that process oscillations get reduced (i.e., damped) around the set value. Hence, during set point change as well as load variation an overall enhanced performance of the process can be expected.

RESULTS

Performance of the proposed DSPW-PID is compared with fixed set point weighted PID controller (FSPWPID) and ZN tuned PID controller (ZNPID). Second-order marginally stable process with dead time 0.3s and 0.36s are considered for simulation as given in following sections.

A. Second-order Marginally Stable Process

Model of a second-order marginally stable process given by

$$G_p(s) = \frac{k_p e^{-Ls}}{s(\tau s + 1)} \qquad (9)$$

A1 second order marginally stable process with L=0.3 s

In this section we consider the open loop process gain $k_p = 1$, time constant $\tau = 1$ s and L= 0.3s, these numerical values are substitute in eq(9),the resultant system is

$$G_p(s) = \frac{e^{-0.3s}}{s(s+1)} \qquad (10)$$

The PID controller will be applied for above marginally stable process as follows

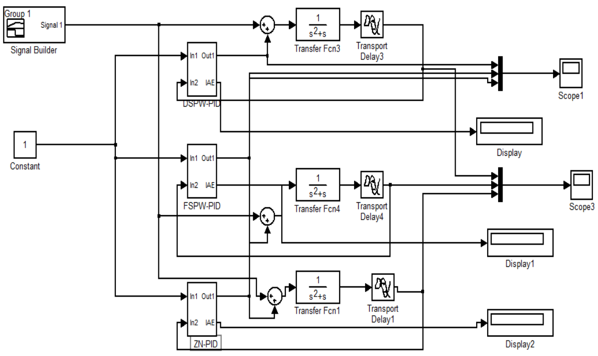
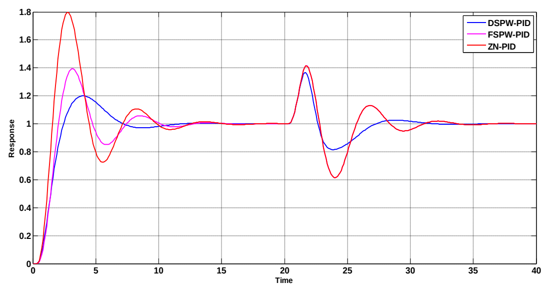


Fig4. *Simulink model for marginally stable process with L=0.3 s*

The corresponding simulation results for marginally stable process is shown in below figure 5.



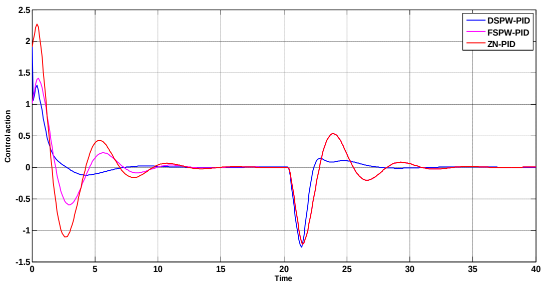


Fig5. *Responses and control actions for marginally stable process*

A number of performance indices like overshoot (%OS), rise time (t_r), settling time (t_s) integral absolute error (IAE) are tabulated below table1

Table1. *Performance analysis* $G_p(s) = \frac{e^{-0.3s}}{s(s+1)}$

	L(s)	%OS	t_r(s)	t_s(s)	IAE
ZNPID	0.3	44%	1.3	12.5	3.26
FSPW-PID	0.3	28%	1.1	11	2.43
DSPW-PID	0.3	16%	0.9	10.5	2.07

A2. Second-order Marginally Stable Process with L=0.36s

In this case we consider the open loop process gain k_p = 1 time constant τ = 1 s and L=0.36, these numerical values substitute in eq(9) , the resultant system is

$$G_p(s) = \frac{e^{-0.36\,s}}{s(s+1)} \tag{11}$$

The PID controller will be applied for above marginal stable process as follows

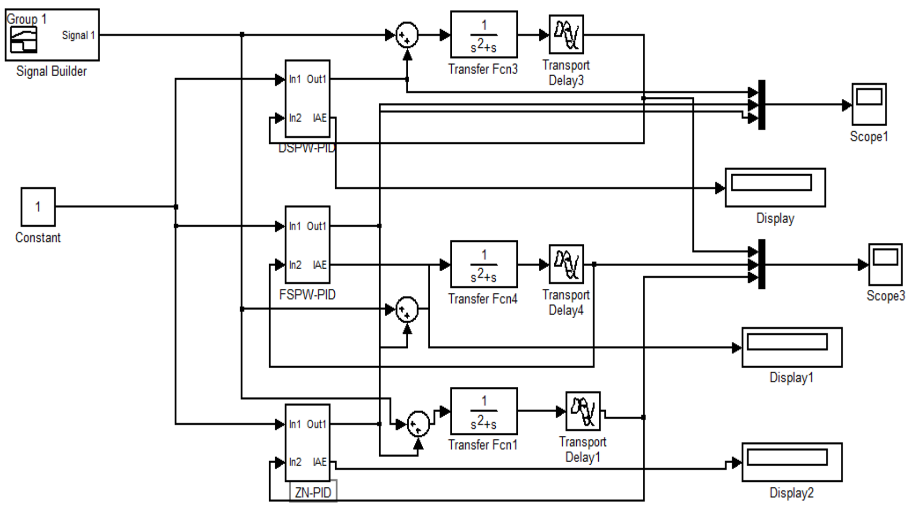
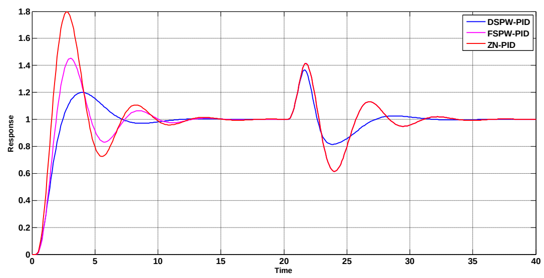


Fig6. *Simulink model for marginally stable process with L=0.36s*

The corresponding simulation results for marginally stable process is shown in below figure 7.



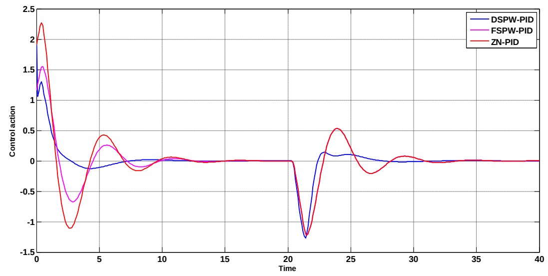


Fig7. *Responses and control actions for marginally stable process*

A number of performance indices like overshoot (%OS), rise time (t_r), settling time (t_s) integral absolute error (IAE) are tabulated in table 2 for above simulation results.

Table2. *Performance analysis* $G_p(s) = \frac{e^{-0.36s}}{s(s+1)}$

	L(s)	%OS	t_r(s)	t_s(s)	IAE
ZNPID	0.36	44%	1.2	14	3.26
FSPW-PID	0.36	31%	1.25	13	2.53
DSPW-PID	0.36	16%	0.3	11	2.07

B. Second-order Linear Process

Model of a second-order linear process given by

$$G_p(s) = \frac{e^{-Ls}}{(s^2 + s + 1)} \quad (12)$$

B1 second order linear process with L=0.1s

In this section we consider open loop process gain $k_P = 1$ and time constant $\tau = 1$ s and $L = 0.1$s. These values substitute in eq(12) The second order system is

$$G_p(s) = \frac{e^{-0.1s}}{(s^2 + s + 1)} \quad (13)$$

The PID controller will be applied for above second order linear process as follows

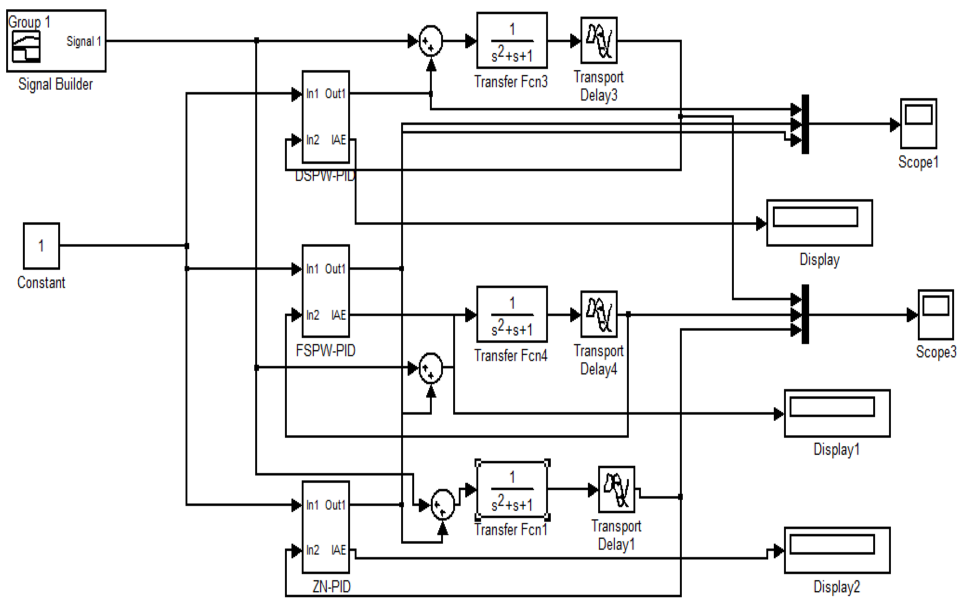


Fig8. *Simulink model for second order linear process L=0.1s*

The corresponding simulation results for marginally stable process is shown in below figure.9.

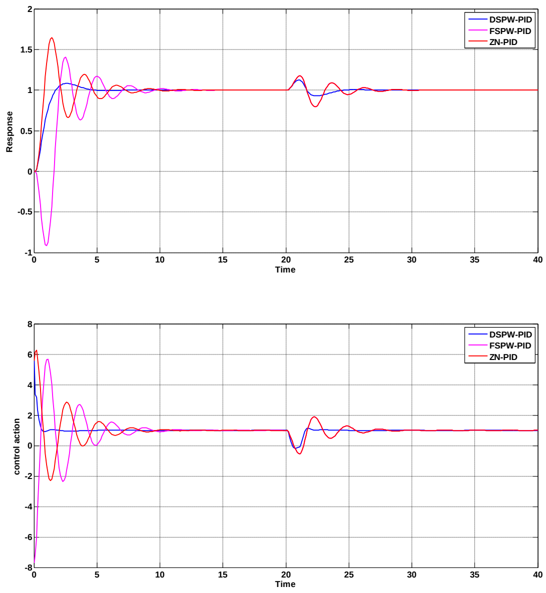


Fig9. *Responses and control actions for linear process*

A number of performance indices like overshoot (%OS), rise time (t_r), settling time (t_s) integral absolute error (IAE) are tabulated in table for above simulation results.

Table3. *Performance analysis* $G_p(s) = \frac{e^{-0.1s}}{(s^2+s+1)}$

	L(s)	%OS	t_r(s)	t_s(s)	IAE
ZNPID	0.1	37%	1	9.8	1.71
FSPW-PID	0.1	28%	2.5	11	3.47
DSPW-PID	0.1	9%	2	5	0.94

B2 second order linear process with L=0.12s

In this section we consider open loop process gain k_P = 1 and time constant τ = 1 s and L = 0.1s. These values substitute in eq(12) The second order system is

$$G_p(s) = \frac{e^{-0.12s}}{(s^2+s+1)} \qquad (14)$$

The PID controller will be applied for above second order linear process as follows

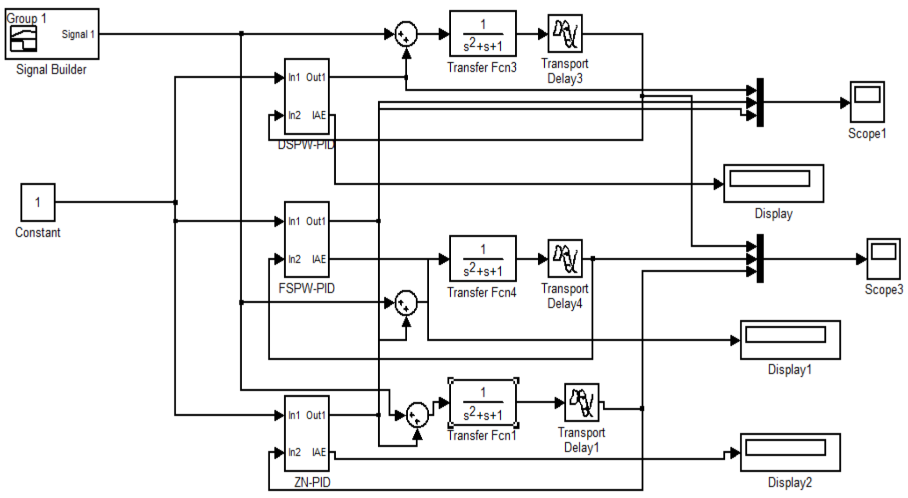
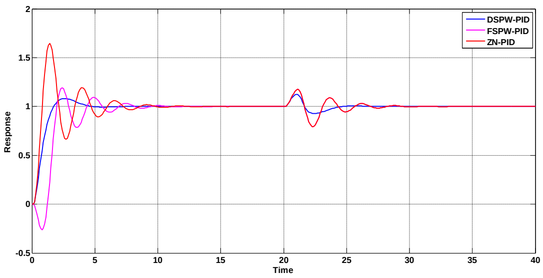


Fig10. *Simulink model for second order linear process L=0.12s*

The corresponding simulation results for marginally stable process is shown in below figure.11.



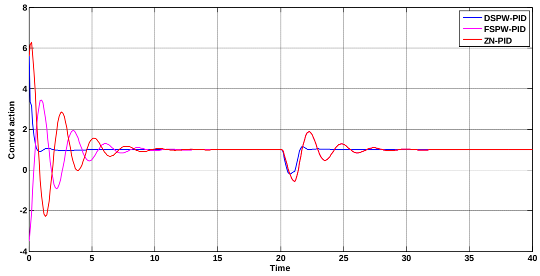


Fig11. *Responses and control actions for marginally stable process*

A number of performance indices like overshoot (%OS), rise time (t_r), settling time (t_s) integral absolute error (IAE) are tabulated in table 4

Table4. *Performance analysis* $G_p(s) = \frac{e^{-0.12s}}{(s^2 + s + 1)}$

	L(s)	%OS	t_r(s)	t_s(s)	IAE
ZNPID	0.12	39%	0.8	9.8	1.71
FSPW-PID	0.12	15%	1.9	10	2.24
DSPW-PID	0.12	8%	1.4	4	0.94

CONCLUSION

In this paper, we propose a function approximation based dynamic set point weighted PID controller where weighting factor is calculated online based upon process operating condition in terms of change of error. This dynamic weighting factor is obtained by a simple sigmoid function. The proposed controller is capable to provide simultaneous improvement during transient as well as steady state response. Robustness feature of the proposed technique is observed against the wide variation of process dead time.

The mechanism of such proposed controller is so simple and straightforward that it can be easily be implemented on practical systems. Due to model independent approach of the propose mechanism the proposed controller may also be applied to non-linear systems. So, there is a future scope to verify and analyze performance of the proposed controller on nonlinear processes.

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