Implementation Issues of Industrial PID Controller and Their Remedies

C. B. Vishwakarma

Abstract**—**We elaborated the parallel and series Proportional, Integral and Derivative (PID) controllers, which are being used in industries. Various issues, which are very often faced by control engineers while designing the PID controllers for industrial systems are described. The effect of measurement noise on the actuator due to derivative term of a PID controller has been explained in detail. Similarly, proportional kick, derivative kick, saturation tendency of the actuator and reverse phenomena of an industrial process have been summarized. Moreover, we meticulously explained the remedies of the all issues of the parallel industrial PID controller.

Keywords**—**Band-width limited derivative control, derivative kick, proportional kick, reverse acting controller, series PID controller.

I. Introduction

THE history about the successive development of a PID controller is not very new. The first PID controller was introduced in 1911 by Elmer Sperry [1]. After 22 years, the Taylor Instrument Company (TIC) developed first pneumatic controller with a fully tuneable proportional controller in 1933. The control engineers faced the problems to eliminate steady-state error in the controllers but after few years, the steady-state error was eliminated by introducing an integral term in the control system. The steady-state error tells us about the accuracy the system response. Thereafter, TIC suggested the first PID pneumatic controller along with derivative action in 1940. The derivative action was able to control the overshooting issues. After successive development, the Ziegler and Nichols developed tuning rules to compute PID parameters in 1942. By the mid 1950's, automatic PID controllers were successfully adopted in many industrial applications [1], [2].

The vast use of feedback controllers has no more sense until the development of wideband high-gain amplifiers to use the fundamental concept of negative feedback. This had been accomplished in telephone engineering electronics by Harold [1]. Company introduced a wide-band pneumatic controller by combining the nozzle and flapper high gain pneumatic amplifier, which had been invented in 1914, with negative feedback from the controller output. This considerably increased the linear range of operation and subsequently the action of integral control was also incorporated by use of bleed valve and bellows. The integral term was also known as reset. Thereafter, the derivative action was added by using bellows and adjustable orifice [3], [4].

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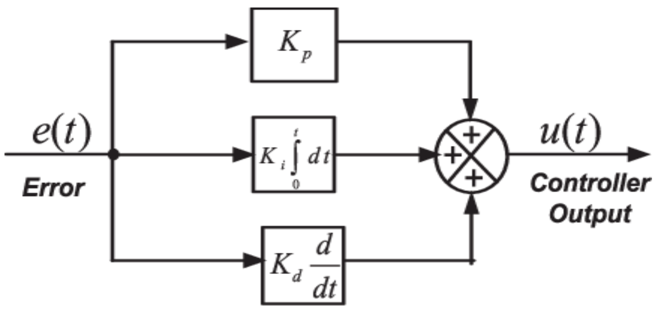
The PID controller became popular in 1950's because of the development of electronic amplifiers, which were not so costly and also were reliable in operation. The pneumatic system was controlled by 10-50 mA and 4–20 mA current loop signals, finally this became the industry standard. Pneumatic field actuators are still popular because of the advantages of pneumatic energy for control valves in process plant environments.

II. Types of PID Controller

In this paper, two structures of PID controller [5]-[7] have been discussed and their parameters are correlated to each other. Two types of PID controllers are as follows:

- Parallel PID controller
- Series PID controller

Parallel PID Controller: In parallel PID controller, all three terms (P, I and D) are connected in parallel. The basic structure of this controller is shown in Fig. 1.



$e(t)$: Error Signal
$u(t)$: Controller Output
K_p : Proportional Gain
K_i : Integral Gain
K_d : Derivative Gain

Fig. 1 Structure of PID Controller

The mathematical equation between the output $u(t)$ and input $e(t)$ can be written as

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{d}{dt} e(t) \tag{1}$$

Taking Laplace transform with zero initial conditions

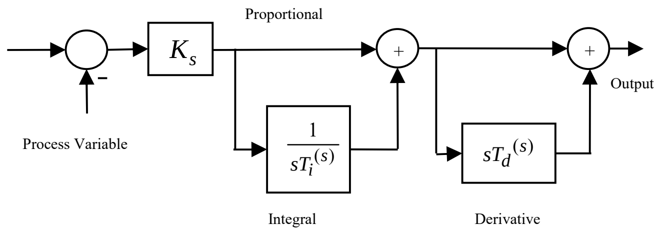


Fig. 2 Structure of a series PID controller

$$U(s) = E(s)\left(K_p + \frac{K_i}{s} + sK_d\right) \tag{2}$$

Now the ratio of controller output and error signal may be written as

$$\frac{U(s)}{E(s)} = \frac{s^2K_d + sK_p + K_i}{s} \tag{3}$$

This is known as transfer function of a parallel PID controller. It consists of one Pole at origin and two Zeros depending upon the values of PID controller parameters (K_p, K_i, K_d).

The transfer function can also be written as

$$\frac{U(s)}{E(s)} = \left(K_p + \frac{K_i}{s} + sK_d\right) = K_p\left(1 + \frac{K_i}{sK_p} + \frac{sK_d}{K_p}\right)$$

$$\frac{U(s)}{E(s)} = K_p\left(1 + \frac{1}{s\left(K_p / K_i\right)} + s\left(\frac{K_d}{K_p}\right)\right)$$

$$= K_p\left(1 + \frac{1}{sT_i} + sT_d\right)$$

$$U(s) = \left(K_p + \frac{K_p}{sT_i} + K_p sT_d\right)E(s) \tag{4}$$

where T_i is known as integral time constant; T_d is known as derivative time constant.

Series PID Controller: Some early PID controllers [8] were pneumatic hardware for which a series transfer function representation was an appropriate mathematical description. To maintain continuity in later analog PID devices, some manufacturers retained this series structure. However, modern PID controllers (parallel controllers) are likely to be digital in nature due to the development in the digital electronics.

The structure of series PID controller is shown in Fig. 2.

$$E(s) \longrightarrow \boxed{G(s)_{series}} \longrightarrow U(s)_{series}$$

where

K_s : Series Proportional Gain

$T_i^{(s)}$: Series Integral Time Constant

$T_d^{(s)}$: Series Derivative Time Constant

$$G(s)_{series} = K_s\left(1 + \frac{1}{sT_i^{(s)}}\right)\left(1 + sT_d^{(s)}\right)$$

$$= K_s\left[\left(1 + \frac{T_d^{(s)}}{T_i^{(s)}}\right) + \frac{1}{sT_i^{(s)}} + sT_d^{(s)}\right] \tag{5}$$

$$U(s)_{series} = \left[K_s\left(1 + \frac{T_d^{(s)}}{T_i^{(s)}}\right) + \frac{K_s}{sT_i^{(s)}} + K_s.sT_d^{(s)}\right]E(s) \tag{6}$$

We compare (6) of series PID controller with parallel PID controller of (4)

$$\left.\begin{aligned} K_p &= K_s\left(1 + \frac{T_d^{(s)}}{T_i^{(s)}}\right) \\ K_i &= \frac{K_s}{T_i^{(s)}} \\ K_d &= K_s T_d^{(s)} \end{aligned}\right\} \tag{7}$$

Similarly, Parallel PID controller can be written in terms of time constants as

$$U(s) = K_p\left(1 + \frac{1}{sT_i} + sT_d\right)E(s) \tag{8}$$

$$U(s)_{series} = \left[K_s\left(1 + \frac{T_d^{(s)}}{T_i^{(s)}}\right) + \frac{K_s}{sT_i^{(s)}} + K_s.sT_d^{(s)}\right]E(s)$$

$$U(s)_{series} = K_s\left(1 + \frac{T_d^{(s)}}{T_i^{(s)}}\right)\left[1 + \left(1 + \frac{T_d^{(s)}}{T_i^{(s)}}\right)^{-1}\frac{1}{sT_i^{(s)}} + \left(1 + \frac{T_d^{(s)}}{T_i^{(s)}}\right)^{-1} sT_d^{(s)}\right]E(s)$$

$$U(s)_{series} = K_s\left(\frac{T_i^{(s)} + T_d^{(s)}}{T_i^{(s)}}\right)\left[1 + \frac{1}{(T_i^{(s)} + T_d^{(s)})s} + \frac{T_i^{(s)}T_d^{(s)}}{T_i^{(s)} + T_d^{(s)}}s\right]E(s) \tag{9}$$

By comparing (4) with (9), we have found the following correlation as

$$\left.\begin{aligned} K_p &= K_s\left(\frac{T_i^{(s)} + T_d^{(s)}}{T_i^{(s)}}\right) \\ T_i &= T_i^{(s)} + T_d^{(s)} \\ T_d &= \frac{T_i^{(s)}T_d^{(s)}}{T_i^{(s)} + T_d^{(s)}} \end{aligned}\right\} \tag{10}$$

III. Brief Summary of PID Controller Issues and Remedies

While designing a PID controller for any industrial system/ process, the designer has to consider each and every aspect of the system. For industrial processes, the accuracy has to be maintained and therefore, all kind of disturbances has to be identified and their effects are supposed to be minimized up to the extent of tolerable limit. To perform well with the industrial processes the parallel PID controller requires modifications, some important problems associated with the process and corresponding modification in PID controller to minimize the effects of the associated problems are listed as below:

A. Problem of Measurement Noise and Its Remedy

The feedback control systems require sensors to measure the process output. This signal in electrical form has to be compared with the reference input/set point/command signal. The measurement system includes sensors and signal conditioning circuit to get feedback signal in required form. Very often, the measurement system used in feedback back control system may generate high frequency noise signal and its effect added with the process out signal. Finally, the noise component of the error signal gets amplified by the derivative term of the PID controller. Consequently, the controller output signal with amplified noise fed to the actuator. Under this condition, the actuator behavior becomes detrimental.

Remedy: The replace the pure derivative term by a bandwidth limited derivative term. It will be elaborated in the next section. This will prevent the measurement noise amplification.

B. Problem of Proportional and Derivative Kick and Their Remedy

In parallel PID controller, normally proportional term 'P' and derivative term 'D' are placed in the forward path. The sudden change in the reference signal (Step Signal) results rapid change and spikes in the control signal. This undefined/ abrupt behavior of the control signal creates the problem for actuator's functioning.

Remedy: 'P' and 'D' terms of the parallel PID controller must be shifted in the feedback path. This leads to different form of the PID controller, which are found in industrial applications.

C. Nonlinear Effects in the Process and Its Remedy

The saturation characteristic of the actuator leads to integral wind-up and causing excessive overshoot. The excessive overshoots lead to the plant trips as process variables move out of the range.

Remedy: This problem can be minimized by using anti-windup circuits in Integral term of the parallel PID controller.

D. Negative Process Gain and Its Remedy

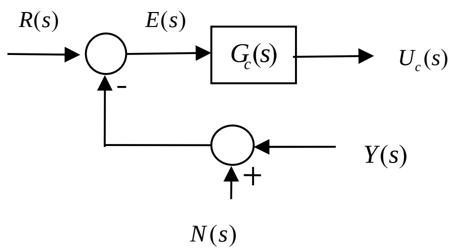
If any plant has negative process gain by its behavior, then a positive step change produces a negative response. The negative feedback control system of such plants/processes may result a closed loop unstable response [5].

Remedy: For such kind of plants, a reverse acting PID controller is used.

IV. Detailed Explanation of the Issues and Remedies

A. Bandwidth-Limited Derivative Control

The measurement process variable of the feedback loop may contain excessive noise. Such noise is modeled as a high frequency phenomenon and this will be amplified by the derivative term in the three terms PID controller.



$R(s)$: Reference Signal
$E(s)$: Error Signal
$G_c(s)$: PID Controller
$U_c(s)$: Controller Output
$N(s)$: Measurement Noise
$Y(s)$: Process Output
$Y_m(s)$: Measured Process Output

Fig. 3 Block diagram with feedback measurement error

The controller in the time domain may be written as

$$\begin{aligned} e(t) &= r(t) - y_m(t) \\ &= r(t) - \left[y(t) + N(t) \right] \end{aligned} \tag{11}$$

In frequency domain

$$E(s) = R(s) - Y(s) - N(s)$$
$$E(s) = (R(s) - Y(s)) - N(s)$$

and

$$\begin{aligned} U_c(s) &= G_c(s)E(s) \\ &= G_c(s)\left[\{R(s) - Y(s)\} - N(s) \right] \\ &= G_c(s)\left[R(s) - Y(s) \right] - G_c(s)N(s) \\ &= U_c^{nf}(s) - U_c^{noise}(s) \end{aligned} \tag{12}$$

where

$U_c^{nf}(s)$: Noise free control term
$U_c^{noise}(s)$: With noise control term

As we have to study the effect of noise on the control action, therefore only the analysis of $U_c^{noise}(s)$ term is important and needed here.

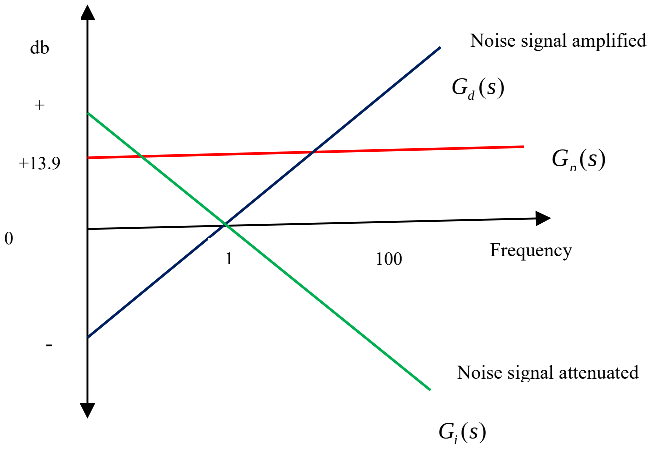


Fig. 4 Bode Plots of PID gains

$$U_c^{noise}(s) = G_c(s)N(s) \quad (13)$$

Let us consider the transfer function of PID controller as under

$$G_C(s) = K_p\left[1 + \frac{1}{sT_i} + sT_d\right]$$

$$U_c^{noise}(s) = K_p\left[1 + \frac{1}{sT_i} + sT_d\right]N(s)$$

$$U_c^{noise}(s) = K_p N(s) + \frac{K_p N(s)}{sT_i} + sT_d K_p N(s)$$

$$= G_p(s)N(s) + G_i(s)N(s) + G_d(s)N(s)$$

$$= U_p^{noise}(s) + U_i^{noise}(s) + U_d^{noise}(s)$$

Here

$$G_p(s) = K_p; \qquad G_i(s) = \frac{K_p}{sT_i}; \qquad G_d(s) = sT_d\, K_p$$

$U_p^{noise}(s)$: Controller Output due to Proportional term only in presence of noise

$U_i^{noise}(s)$: Controller Output due to Integral term only in presence of noise

$U_d^{noise}(s)$: Controller Output due to Derivative term only in presence of noise

To observe the effects of measurement noise on the controller output some typical values are taken as follows:

$$K_p = 5$$
$$T_i = 5$$
$$T_d = 0.2$$

Hence, open loop transfer functions are obtained as:

$$G_p(s) = 5; \qquad G_i(s) = \frac{1}{s}; \qquad G_d(s) = s$$

Following are the observations from Fig. 4 about PID effects with noise signal:

- Noise amplification occurs due to proportional term but it is fixed and constant across the frequency range. It has no major impact on the noise amplification.
  There is a decrement of noise effect by 20 db/decade due to Integral term. Thus, high-frequency measurement noise is attenuated by the integral term.
- The derivative term shows a roll-on of gain +20 db/decade. This produces increasing amplification as the noise frequency increases.

Therefore, it may be concluded that the derivative term of the parallel PID controller is fully responsible for measurement noise amplification by 20 db/decade increment of the noise frequency. This significant noise amplification has to be minimized by some means to have efficient control system. Hence, first order low-pass filter is associated with the derivative term 'D' of the PID controller. The mathematical description and design are explained as follows:

Let the low-pass filter transfer function be

$$G_f(s) = \frac{1}{1 + T_f s}$$

where T_f is the time constant of the filter. Now, controller output with noise may be written as

$$U_c^{noise}(s) = \left[G_f(s)G_d(s)\right]N(s)$$

$$= K_p\left(\frac{sT_d}{1 + sT_f}\right)N(s)$$

$$U_c^{noise}(s) = G_{md}(s)N(s)$$

where $G_{md}(s) = K_p\left(\frac{sT_d}{1 + sT_f}\right)$; gain of derivative term with low-pass filter.

High frequency gain of $G_{md}(s)$ is calculated as

$$K_d^{\infty} = \lim_{x \to \infty} G_{md}(s) = K_p\left(\frac{T_d}{T_f}\right) = K_p.n$$

Typical values of 'n' for parallel PID controller may be taken as $5 \le n \le 20$. To see the effect of low-pass filter on measurement noise, a bode diagram may be plotted against frequency as

$$G_{md}(s) = K_p\left[\frac{sT_d}{1 + \left(\frac{T_d}{n}\right)s}\right] = 5\left(\frac{0.2s}{1 + \left(\frac{0.2}{5}\right)s}\right) = \frac{s}{\left(1 + \frac{s}{25}\right)}$$

So, $K_d^{\infty} = 25$

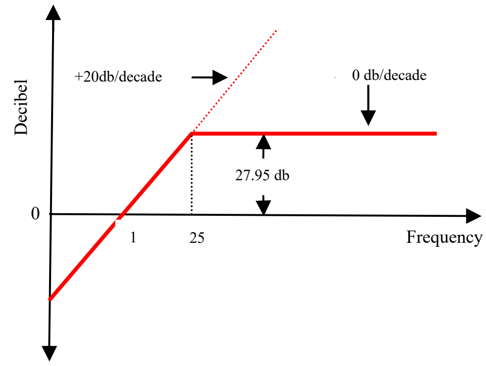


Fig. 5 Bode plot of derivative term with low-pass filter

From Fig. 5, it is clear that amplification of noise effect has been stopped at frequency 25 rad/sec in this example and became constant beyond frequency of 25 rad/sec. Hence, derivative term of PID controller with low-pass filter only passes low frequency signal and stopped high frequency noise components. Overall, derivative term with low-pass filter is capable to stop amplification after certain frequency depending upon the design parameters.

Inserting the new derivative term gives a new PID controller structure as

$$G_c(s) = K_p + K_i\left(\frac{1}{sT_i}\right) + K_d\left(\frac{sT_d}{1 + s\left(\frac{T_d}{n}\right)}\right)$$

Proportional Kick: The proportional kick is the term given to the observed effect of the proportional term of the parallel PID Controller in the usual structure on the quick changes in the reference signal (step signal).

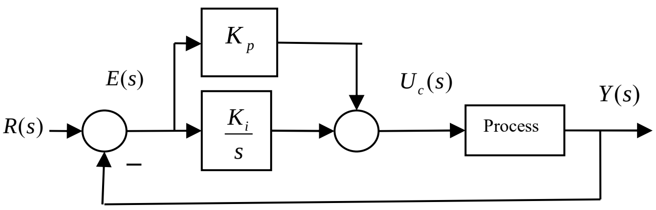


Fig. 6 PI structure of controller

If the process is under control and output is at steady-state then error $E(s) = R(s) - Y(s)$ will be zero. Due to sudden change in the reference input $R(s)$ there will be an immediate step change in $E(s)$ and hence, the controller will pass this signal directly to the actuator via proportional term $K_p E(s)$. In this situation, the actuator unit will experience a rapidly changing command signal that could be harmful to operation of actuator unit. We can say that the actuator will receive a proportional kick because of sudden change in the reference signal [8], [9].

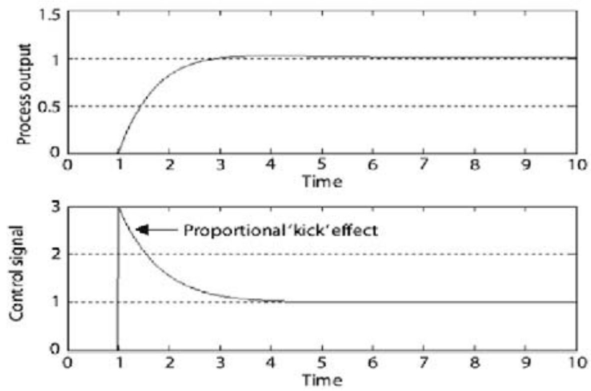


Fig. 7 Proportional kick with process output

In Fig. 7, it is observed that control signal peak is approximately three times more than steady-state value. This rapid large change in control signal can be detrimental for the actuator unit. Therefore, it is necessary to minimize or eliminate the proportional kick for smooth operation of the control system. To remove the proportional kick, there is a need to restructure the PID controller by shifting proportional term into the feedback path. Hence proportional term could be free from error signal. The modified restructure of the PI controller is termed as I-P controller.

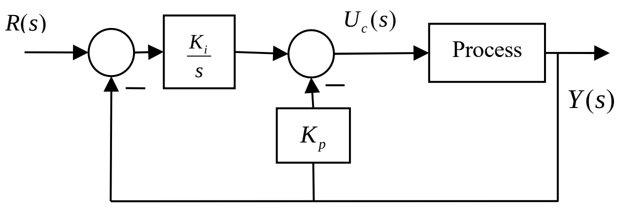


Fig. 8 I-P controller Structure

The integral term (I) will remain connected on the forward path while proportional term will be kept in feedback loop side.

The controller output of restructured controller is found as

$$U_c(s) = \left(\frac{K_i}{s}\right)\left[R(s) - Y(s)\right] - K_p Y(s)$$

$$U_c(s) = \left(\frac{K_i}{s}\right)E(s) - K_p Y(s)$$

The process output and control signal are obtained as shown in Fig. 8. After modification, the process output became slow or sluggish in nature but the proportional kick in control signal has been reduced significantly.

Derivative Kick: The derivative kick is very similar to proportional kick. We consider an ID-P controller structure as shown in Fig. 10.

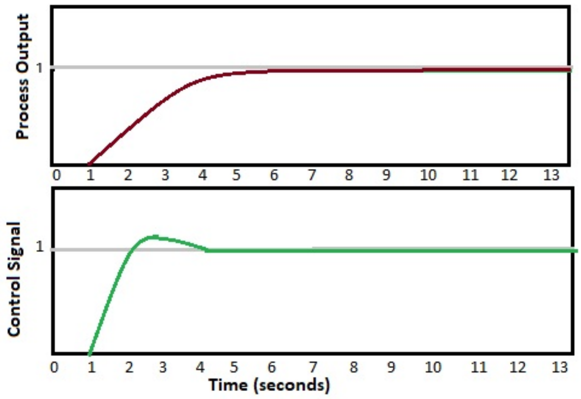


Fig. 9 Responses after rectification of proportional kick

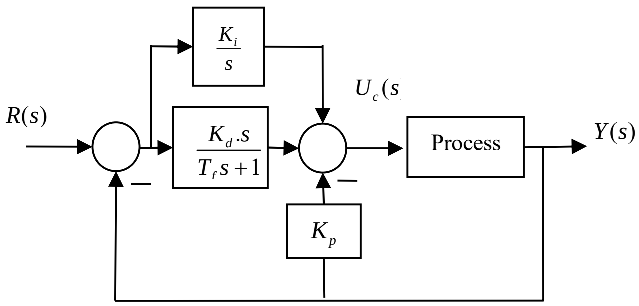


Fig. 10 ID-P Controller Structure

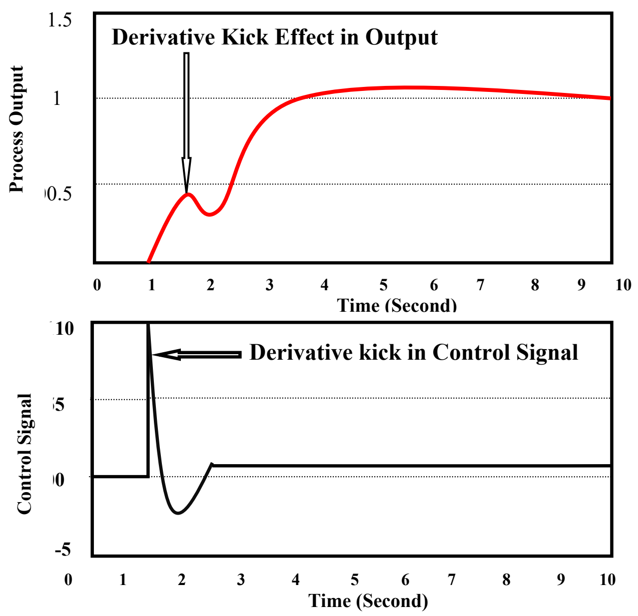


Fig. 11 Derivative effects on Output and Control Signal

The equation for this controller can be written as

$$U_c(s) = E(s)\left[\frac{K_i}{s} + \frac{sK_d}{sT_f + 1}\right] - K_p Y(s)$$

A sudden step change in the reference signal $R(s)$ will result in an immediate step change in error signal $E(s)$. In this control structure, the proportional term of the controller only operates on the output of the process $Y(s)$, hence proportional kick will not be occurred in the control signal. However, the output of the derivative term cannot be ignored. As we know that differentiation of a step is an impulse signal, hence the instant when step magnitude changes, an impulse (spike) of high magnitude generated. This high magnitude surge may be harmful for the actuator.

Hence, derivative term may be shifted from forward path to feedback path to avoid derivative kick. The modified structure is shown in Fig. 12 and termed as I-PD controller.

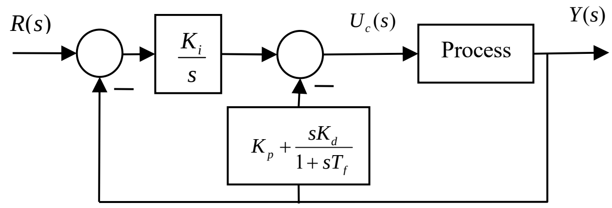


Fig. 12 I-PD structure of PID controller

The responses of the process output and control signal are modified according to the above structure and shown in Fig. 11. It is observed that the process output became sluggish in nature and control signal spike has been reduced drastically [8].

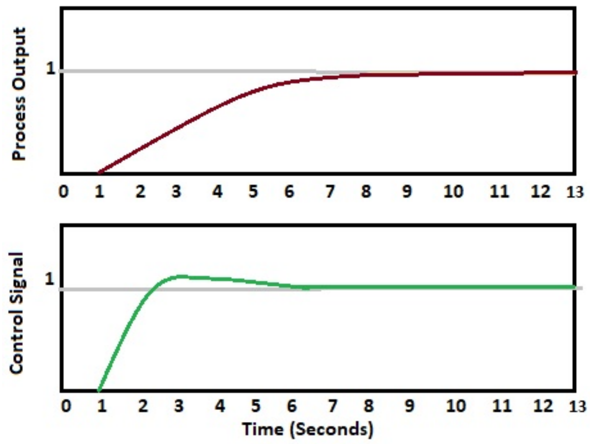


Fig. 13 Responses after rectification of derivative kick

Integral Anti-windup circuit: Non-linearity occurs in almost all industrial process in many ways. Therefore, at different operating conditions, we have different process models and their different dynamics. Hence, only one controller is sufficient to control the dynamics in the nonlinear operating range. The solution of this problem is to schedule a set of PID controllers where each has been designed to achieve good performance for a specific operating point. Many actuators are having nonlinear behavior pose the difficulties for PID controllers, like some are having limited range of input and output operation. For example, valves have a fully closed position and a fully open position and a flow characteristics in-between that could be linear or nonlinear [8].

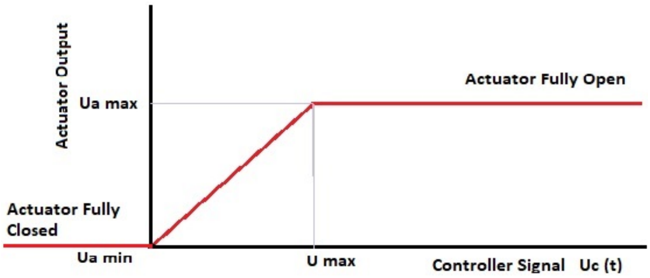


Fig. 14 Actuator Output

If Uc (t) > U max, then actuator output will not be changed because, it is in saturation region. Hence, the system is in open loop control because the control signal is having no effect on the actuator output. This kind of situation is common in industrial processes that create a wind-up effect.

To understand the integral wind-up effect, a simple saturation of a switched step response of a pure I-controller with a saturating actuator may be used.

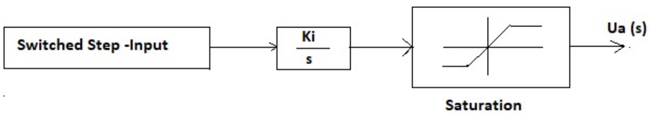


Fig. 15 Integral windup

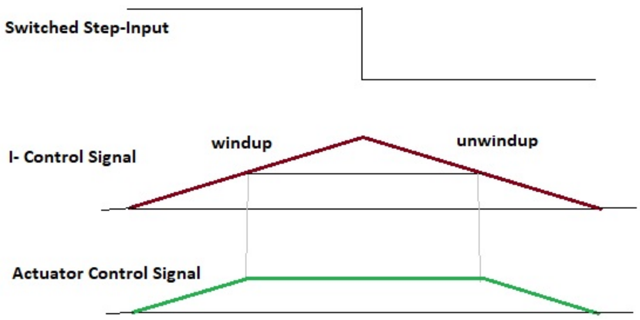


Fig. 16 Actuator signal & I-control signal

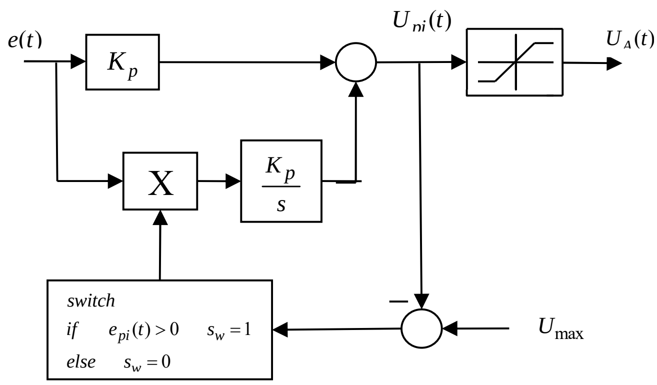


Fig. 17 Anti-windup circuit for PI control

The Remedy: The integral action should be switched off as soon as the control signal enters in the saturation region and switch on the integral action back on as soon as the controller re-enters in the linear region of the control domain. This strategy may be used to remove the problem. The switching operation is implemented by incorporating anti-windup circuit as shown in Fig. 17.

Reverse Acting Controller: Some of the industrial processes produce inverse response. These kinds of processes have negative gain, which results the step response going to negative direction for first few seconds. The non-minimum phase systems belong to this category. The major problem related to the control of such system is that if negative feedback is used then negative process gain generates positive feedback. The positive feedback may not ensure the stability of the system. Therefore, this problem has to be removed for better performance of the control system [8], [10]. The step response of the reverse system is shown in Fig. 18.

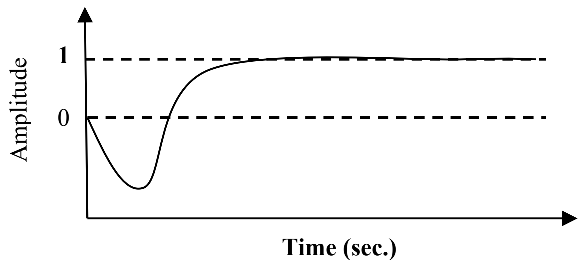


Fig. 18 Response of the inverse system

The Remedy: To maintain the feature of negative feedback, a control engineer has to put a gain of '-1' at the output of the controller. This type of the controller is known as a reverse – acting controller. The block diagram of reverse-acting control system is considered as

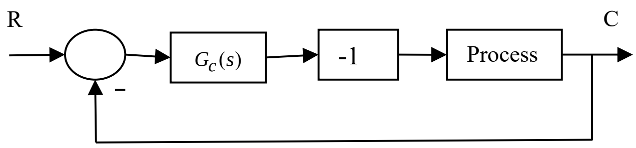


Fig. 19 Reverse acting control system where C, R and $G_c(s)$ are the output, input and controller respectively

V. Conclusion

We discussed the construction and parameters comparison of the parallel and series PID controllers. Few issues usually faced by the control engineers during the synthesis of the industrial PID controller, are described with the proper illustrations. Further, we elaborated the remedies for the issues or problems faced by control engineers during design of the control system. The aim of this paper was to summarize the issues/problems and their remedies at a glance.

Conflict of Interest

We have no conflict of interest.

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