COMPARISON OF ANTI-WINDUP SCHEMES

***SRIKANTH B**

**Asst. Professor,Department of Electrical and Electronics Engineering,*
AITAM college of Engineering,
Tekkali,srikakulam - 532201
Andhra Paradesh,India

ABSTRACT

Proportional-integral-derivative (PID) controllers are extensively used in industrial systems, despite the significant developments of recent years in control theory and technology. The performance of PID controllers can be severely limited in practical cases by the presence of saturation of the actuators, which causes the phenomenon integrator wind-up. Conditional integration and back calculation are the two approaches used to design the compensator. These techniques can suffer from the presence of a significant dead time in the process or deal with different normalized dead times, they might require an extra tuning effort which is undesirable for industrial regulators. Therefore it is proposed to combine the different approaches to overcome these problems. These approaches are implemented for different process system and performance is compared.

Keywords: *saturation; anti windup; PID controller; overshoot; settling time (Minimum 5 to 8 key words)*

INTRODUCTION

PID control is often combined with logic, sequential functions, selectors and simple functional blocks to build complicated automation systems used for energy production, transportation and manufacturing. PID controllers have survived many changes in technology ranging from pneumatics to microprocessors via electronic tubes, transistors, integrated circuits. These controllers are often the controller of choice due to simplicity in tuning for performance robustness requirements in addition to their ability to achieve zero steady-state error in the presence of constant disturbances.

PID controllers suffer significant loss of performance due to integrator windup when used in systems with actuator saturation. Many of these actuator devices have a limited range of input and output operation. The effects of this saturation nonlinearity can range from degradation of performance to closed-loop instability, even when the nominal linear system predicts acceptable closed-loop performance. The consequence is that any controller with integral action may give large transients when the actuator saturates. Integrator windup may occur in connection with large set point changes or it may be caused by large disturbances or equipment malfunctioning.

The remedy for integrator windup is to switch off the integrator action as soon as control signal enters the saturation region and switch the integral action back on as soon as the controller re-enters linear region of control. This switching is implemented using an anti-windup circuit. Conditional integration and Back calculation are the techniques employed to avoid the integrator windup. With the Conditional integration, the integral term is increased only when certain conditions are satisfied, otherwise it is kept constant. Back calculation is an alternative approach, through which the integral term is recomputed once the controller saturates.

A combined use of conditional integration and back calculation will overcome the above mentioned problem. This combined scheme is compared with the both schemes when implemented for sampled process systems.

ANTI-WINDUP SCHEMES

Many techniques have been developed to avoid the windup. Back calculation and conditional integration are the two impressive methods among them.

A. *Backcalculation*

To avoid windup phenomena, the integration is inhibited whenever the output saturates. i.e. the integral is recomputed so that its new value gives an output at the saturation limit. It is advantageous not to reset the integrator instantaneously but dynamically with a time constant Tt.

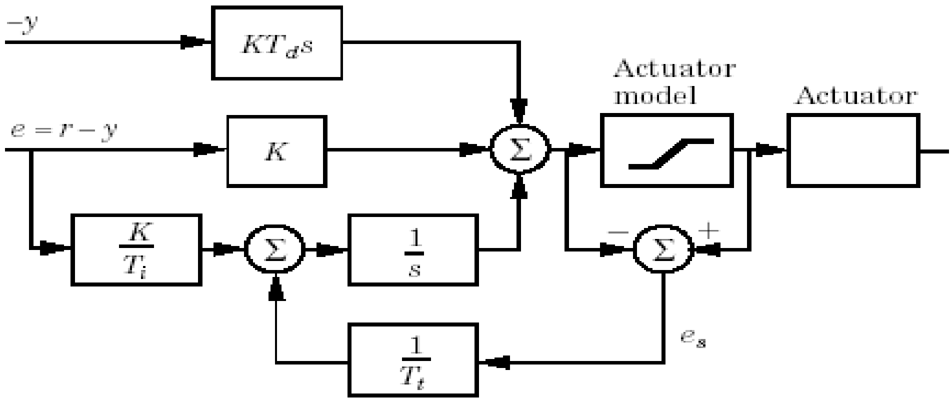


Figure: 1 controller with antiwindup

The integrator input is

$$\frac{1}{T_t} e_s + \frac{k}{T_i} \qquad (1)$$

Where e is the control error. Hence, in the steady state

$$e_s = -\frac{kT_t}{T_i} e \qquad (2)$$

Since $e_s = U_s - U$, it follows that

$$u = u_{\lim} + \frac{kT_t}{T_i} e \tag{3}$$

Where U_{lim} is the saturating value of the control variable. Since the signals e and U_{lim} have the same sign, it follows that U is always larger than U_{lim} in magnitude. This prevents the integrator from winding up.

B. ***Conditional Integration***

Conditional integration is an alternative to back-calculation or tracking. With this approach (also called integrator clamping) the integration is switched off when the control is far from steady state. Integral action is thus only used when certain conditions are fulfilled; otherwise the integral term is kept constant.

The different cases can be described as follows:

1. The integral term is limited to a selected value;
2. The integration is stopped when the system error is large, i.e. when $|e| > e^{-}$ where e^{-} is a selected value;
3. The integration is stopped when the controller saturates, i.e. when $U \neq U_{s;}$
4. The integration is stopped when the controller saturates and the system error and the manipulated variable have the same sign, i.e. when $U \neq U_s$ and $e \times U > 0$.
5. Stop integrating and assign a predetermined or computed value to the integrator state when a specified condition is true.

From the different schemes proposed above the conclusions drawn are the following:

Scheme 1) is good for the saturation problem conditions. However, scheme 1) is more complicated due to a fix for chattering.
Scheme 2) may not resume integration for certain initial conditions, and thus gets a stationary error.
Scheme 3) has a slightly larger overshoot than Scheme 4).
Scheme 4) is rated as the best of the four schemes
Scheme 5) is only usable when no load disturbance is present.

C. ***Combined scheme***

The above proposed two techniques conditional integration and back-calculation can suffer from the presence of a significant dead time in the process or, to deal with processes with different normalized dead times, they might require an extra tuning effort , which is undesirable for industrial regulators. Therefore it is proposed to combine the different approaches in order to overcome these problems.

A combined use of conditional integration and the back-calculation approach is adopted. Specifically, the back-calculation is employed when the controller saturates, the system error has the same sign of the manipulated variable and the system output has left its previous setpoint value.

Formally this can be stated as

$$e_i = \begin{cases} \frac{k_p}{T_i} e + \frac{1}{T_t}(u_s - u) & if\ u \neq u_s\ and\ u \times e \succ 0 \\ & and \begin{cases} y \succ y_0\ if\ y_1 \succ y_0 \\ y \prec y_0\ if\ y_1 \prec y_0 \end{cases} \\ \frac{k_p}{T_i} e & otherwise \end{cases}$$

(4)

The aim of equation (4) is to allow an increase in the integral term whilst the process output transient has not started due to the dead time. When the normalized dead time is small, the devised technique basically performs as the standard back-calculation technique. In any case, it is possible to set a unique value for T_t for the different cases and this value can be significantly lower than T_i allowing better performances for small normalized dead times.

SIMULATION RESULTS

CASE A. The effect of windup phenomena in the process control systems can be analyzed with the simulation of an example process system. To illustrate the performances of the different methodologies, as an example, Consider the following process with normalized dead times as

$$p_1(s) = \frac{1.2}{s^2 + 2.5s + 1} e^{-0.5s}$$

(5)

For the process in equation (5), the tuning of the PID parameters has been applied, according to the Ziegler-Nichols formula. Starting from null initial conditions, a positive unit step (i.e. $y_0 = 0$ and $y_1 = 1$) has been applied to the setpoint signal and saturation limits $u_s^{max} = 1.5$ and $u_s^{min} = -1.5$ has been fixed.

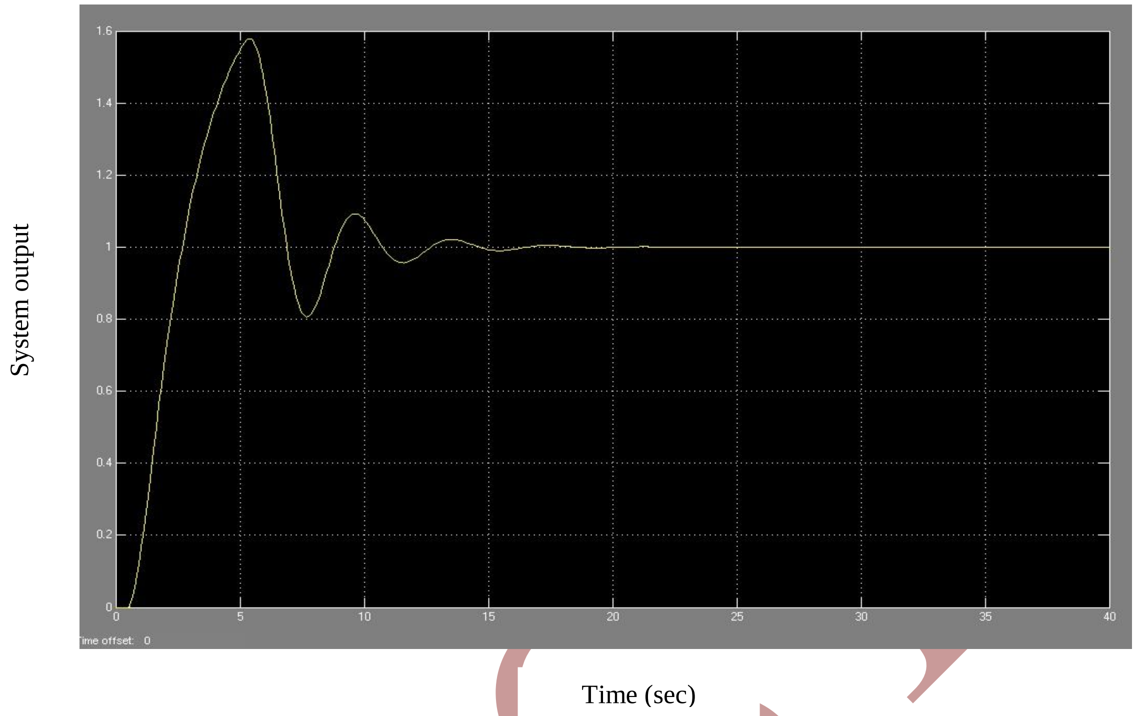


Figure : 2 Step response of process $P_1(s)$ without anti-windup

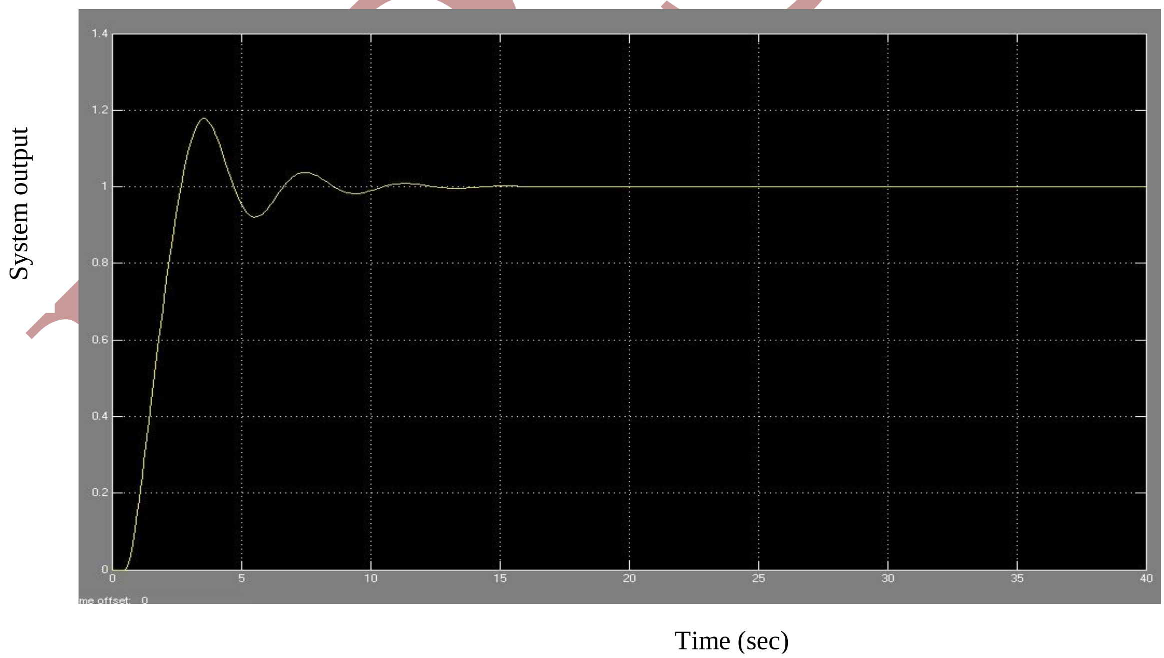


Figure : 3 Step response of process $P_1(s)$ with back calculation

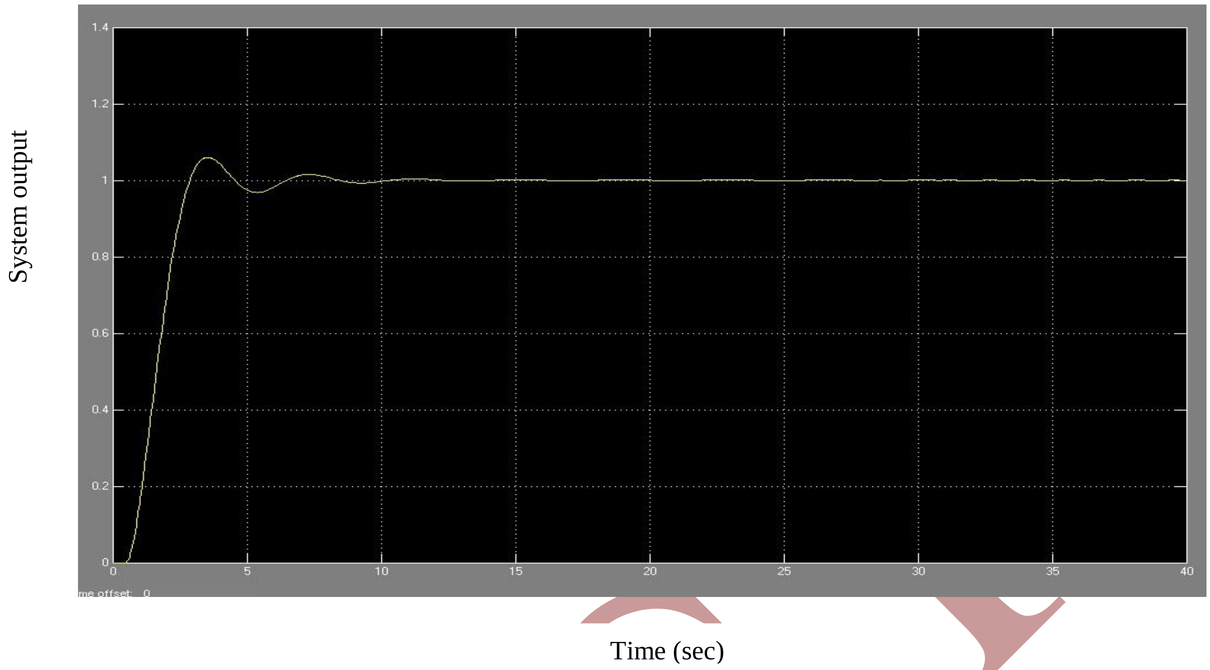


Figure : 4 Step response of process $P_1(s)$ with conditional integration

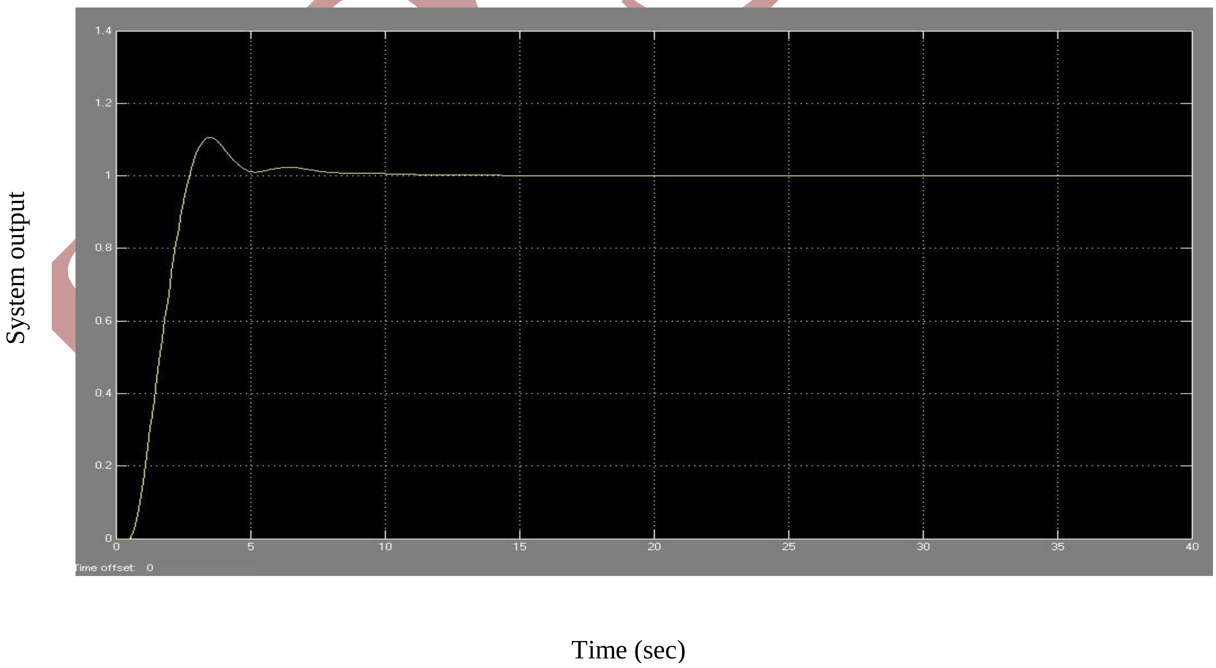


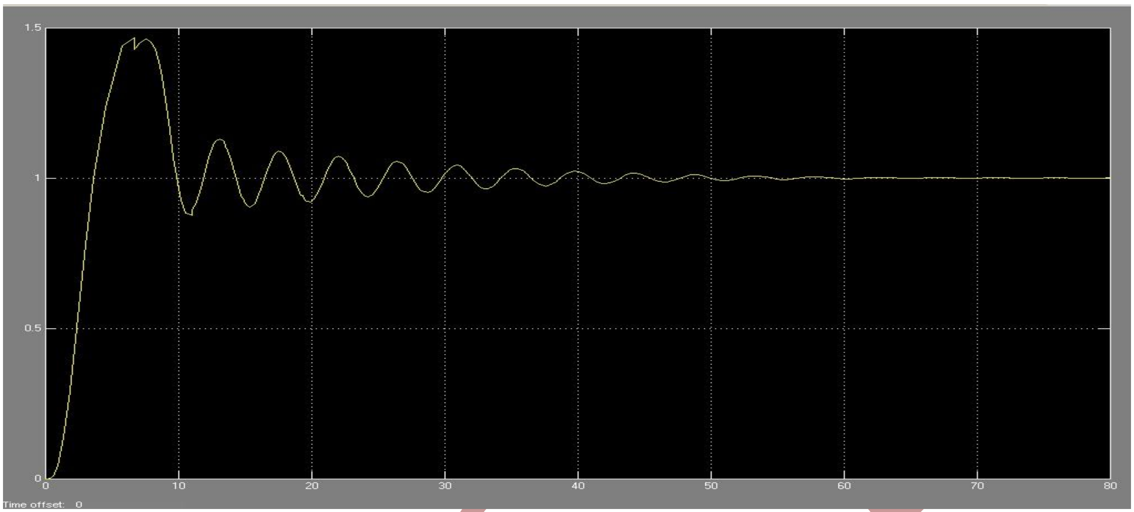
Figure : 5 Step response of process $P_1(s)$ with combined scheme

CASE B

Consider the following third order system with normalized dead time as

$$p_2(s)=\frac{1}{s^3+3s^2+3s+1}e^{-0.3s} \quad (6)$$

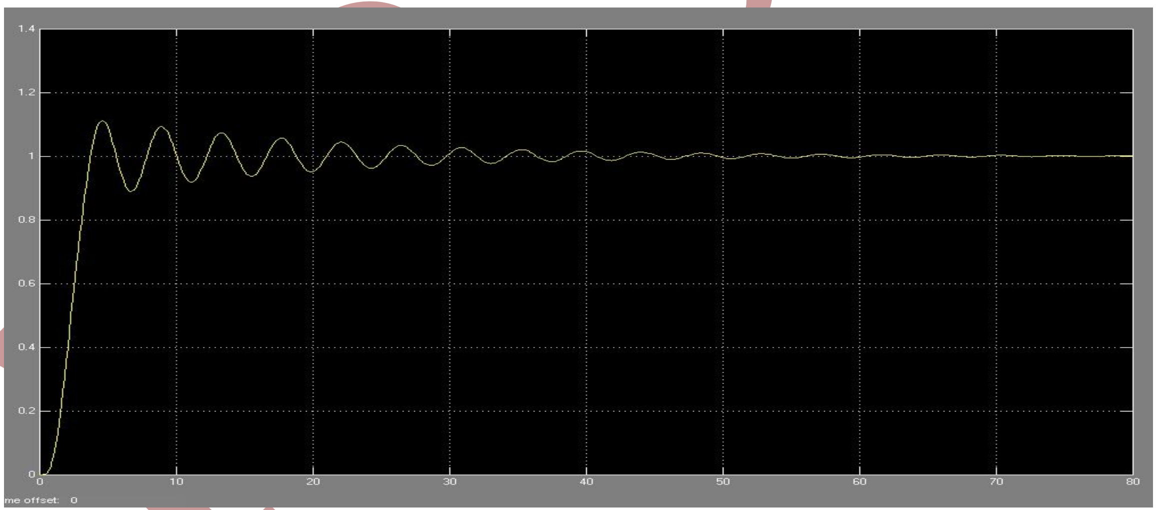
System output



Time (sec)

Figure : 6 Step response of process $P_1(s)$ without anti-windup

System output



Time (sec)

Figure : 7 Step response of process $P_1(s)$ with back calculation

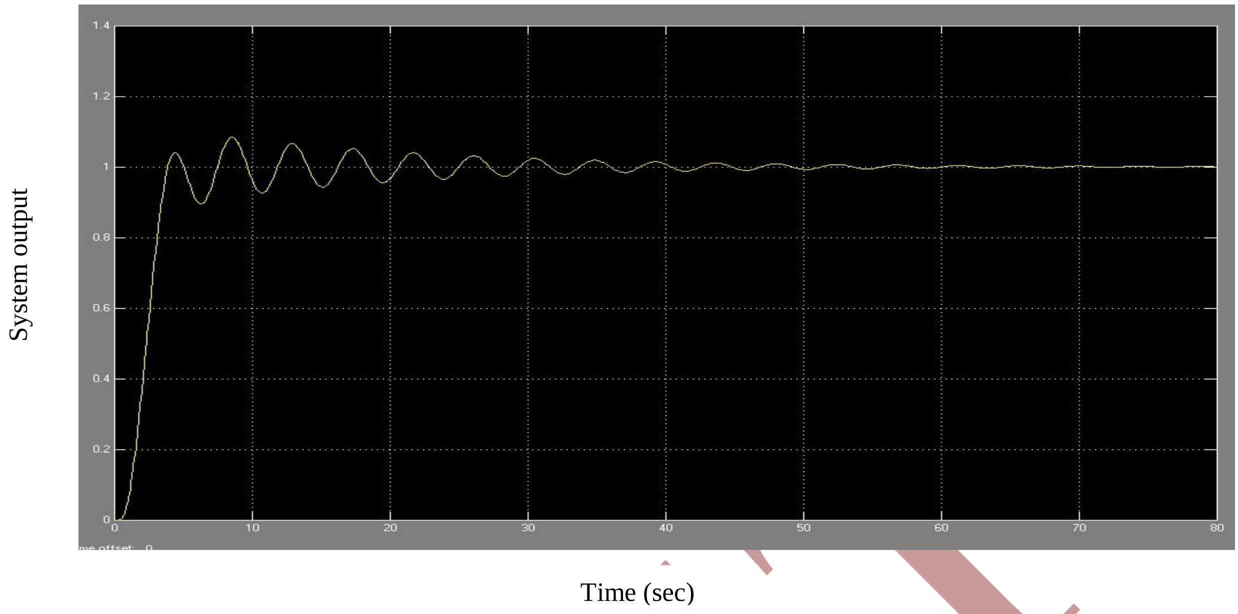


Figure : 8 Step response of process $P_1(s)$ with conditional integration

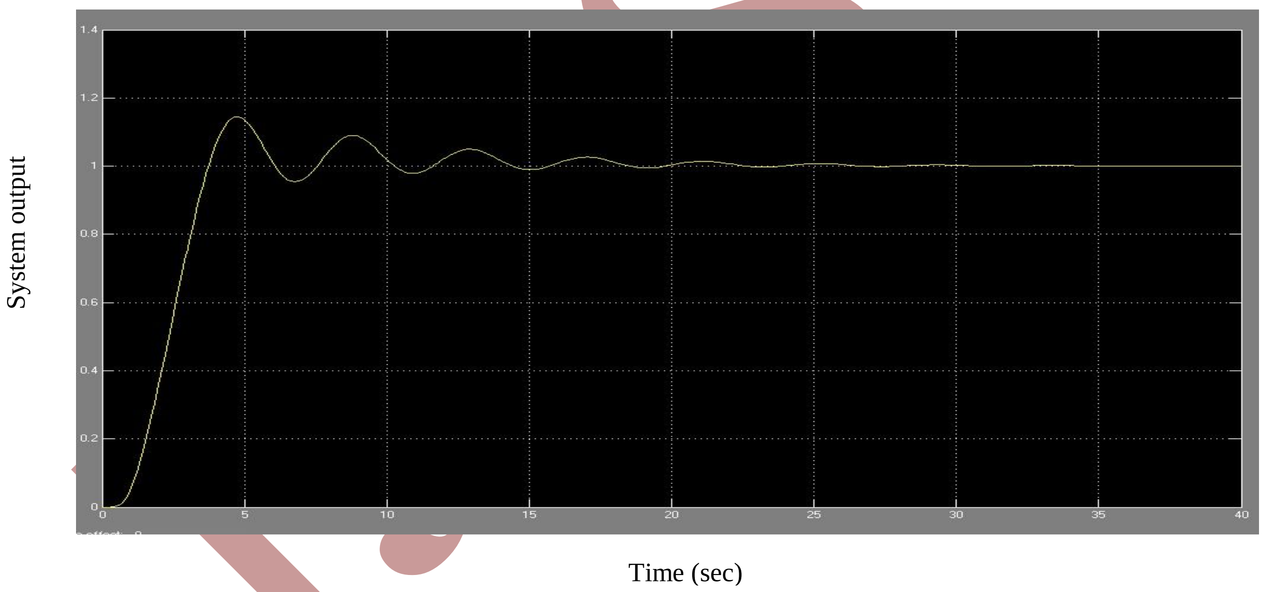


Figure : 9 Step response of process $P_1(s)$ with combined scheme

From the observations of the above anti-windup techniques for different order process systems the results are tabulated as below

Table : 1 comparison of the different anti-windup schemes

Anti-windup techniques	Second order		Third order	
	Overshoot %	Settling time(sec)	Overshoot %	Settling time(sec)
Without antiwindup	58	25	46	78
Back calculation	18	18	12	72
Conditional integration	7	20	9	78
Combined scheme	9	14	11	34

For a second order system, without any anti-windup technique it is found that the overshoot is 58% and the settling time is 25 sec. In Back calculation, the overshoot is reduced to 18% and settled at t = 18 sec. In Conditional integration, the overshoot is reduced to 7% and the settling time is 20 sec. In Combined scheme, the system output overshoot is 9% and the system settled at t = 14 sec.

For a third order system, without anti-windup it is found that the overshoot is 46% and the system settled at t = 78 sec. In Back calculation, the overshoot is reduced to 12% and the settling time to 72 sec. In Conditional integration, the overshoot is reduced to 9% but the system settled at t = 78 sec. In Combined scheme, the overshoot is 11% and the system settling time is 34 sec.

CONCLUSION

Anti-windup schemes are modeled and implemented in MATLAB/SIMULINK environment. The simulation results of anti-windup shown that, these schemes are able to improve the system performance by reducing the overshoots and the settling times for different process systems. From this it is clear that, the back calculation is preferred for better settling of the system.The conditional integration reduces the overshoot very much when compared to back calculation but the settling of the system is too slow. The Combined scheme meets the both factors, with the overshoot is almost same as that attained by conditional integration and the system is settling with in a less time.

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