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Anti Windup Implementation on Different PID Structures

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ABSTRACT

Although there have been tremendous advances in control theory over the last 25 years, the PID controller remains very popular and is still widely used in industry. A vital aspect of its implementation is the selection of a suitable set of parameters, as an improperly tuned controller might lead to adverse effects on process operation and worse, cause system instability. In industry, there are various types of PID controllers in addition to the 'textbook' PID but most tuning methods were developed based on this ideal algorithm. Another issue that is always associated with PID controllers is integral windup and the most popular method to overcome this problem is to add an anti windup compensator. This article includes the assessment of three anti windup strategies in combination with different tuning methods. The characteristics of PID controllers tuned using these approaches are evaluated by application to simulated FOPTD processes with different time-delay to time-constant ratios. Different measures were used to assess their performance and robustness properties, and the applicability of the tuning relationships to more typical (non-ideal) PID controllers is also considered. In general, the anti windup compensators successfully reduced the degradation effect caused by integral windup. It was found that the effectiveness of the different anti windup schemes varied depending on controller tuning methods and controller structures.

Keywords: Anti windup, PID, saturation

INTRODUCTION

The Proportional-Integral-Derivative (PID) controller remains the most popular control algorithm used in industry despite the continuous advances in control theory. It has a simple and easily understood structure but at the same time, can provide excellent control performance over a wide range of dynamic characteristics. Controllers are tuned to minimize or eliminate offset; to minimize the effect of disturbances; to ensure and maintain stability; and to provide smooth and rapid response. Practically, constraints always exist in any control system and may have negative effects on the closed loop response. Actuator saturation is among the most common nonlinearity in any control system. It is a form of input constraint and should not be neglected in a control design system. When the actuator saturates, the plant input will be different from the controller output, the integrator will continue to integrate the error causing the windup. Windup was initially associated with integral action, which may also occur during switching between controllers. This is because a control scheme has to satisfy multiple objectives, thus needs to operate in a different control mode (Bak, 2000; Astrom and Hagglund, 1995; Seborg *et al.*, 1998; Chau, 2002; Coughanowr, 1981).

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A well known methodology that has been used to counter windup is anti windup compensation. This methodology gave rise to a compensator which during saturation, suppresses the degradation caused by saturation (i.e. large overshoot, long settling time). Anti windup is a popular approach in handling saturation. The main objective of all anti windup schemes is to stabilise the system and to recover as much performance as possible in the presence of actuator saturation (Bohn, Atherton, 1995; Goodwin *et al.*, 2001; Astrom and Hagglund, 2001).

The objective of this research was to investigate how different controller tuning methods fare under the presence of saturation will also be investigated. Focus will be on the classical anti windup strategy and some extension of the classical anti windup structures. The different anti windup structures will be tested on different PID controllers tuned by different methods, to see the effectiveness of anti windup schemes with different tuning methods and different PID structures. The robustness properties of these anti windup compensators will also be studied.

Different PID Structures

There is only one form of PI controller. PID controllers, however, can have different structures.

Ideal PID (PIDI)

The PID algorithm reported in most publications is the "ideal PID" which has the following transfer function:

$$\frac{U(s)}{E(s)} = G_C(s) = K_C\left(1 + \frac{1}{T_I s} + sT_D\right) \tag{1}$$

The proportional gain (K_c), integral time (T_I) and derivative time (T_D) are the tuning constants. $U(s)$ is the output of the controller, while $E(s) = X(s) - Y(s)$ is the error between setpoint, $X(s)$, and controlled output, $Y(s)$ and $G_C(s)$ is the controller transfer function. PID controllers used in industry may not have the same structure though (Astrom and Hagglund, 1995; Goodwin *et al.*, 2001; Astrom, 1996; Clair, 2000).

Series PID (PIDS)

There is a slightly different version of the PID controller, known as the "series" or "interacting" controller.

$$G_C'(s) \;=\; K_C'\left(1 + \frac{1}{sT_I'}\right)\left(1 + sT_D'\right) \tag{2}$$

The controller transfer function is denoted as $G_C'(s)$. The proportional gain (K'_c), integral time (T'_I) and derivative time (T'_D) are the tuning constants for the series controller. It is called interacting because the derivative and integral terms interact with each other (Astrom and Hagglund, 1995; Goodwin *et al.*, 2001; Astrom, 1996; Clair, 2000).

"Commercial" PID (PIDC)

The derivative term in Eq. 1 causes realization problems, and a more practical form is:

$$G_C(s) = K_C\left(1 + \frac{1}{T_I s} + \frac{T_D s}{1 + sT_D / N}\right) \tag{3}$$

The derivative term in Eq. 1 is cascaded with a low-pass filter with a time-constant, T_D/N is usually chosen to be between 5 and 20. The sensitivity of the algorithm to noise is increased with higher values of N (Astrom and Hagglund, 1995; Goodwin *et al.*, 2001; Astrom, 1996; Clair, 2000).

Setpoint Weighted or Output Filtered PID (PIDF)

Normally, a PID controller is driven by the error between the setpoint and the controlled output. However there is a more flexible structure given by:

$$U(s) = K_C\left[\left(bX(s)\right) + \frac{1}{sT_I}\left(X(s) - Y(s) + \frac{T_D s}{1 + sT_D / N}\left(cX(s) - Y(s)\right)\right)\right] \tag{4}$$

Here, the responses to setpoint changes depend very much on the values of b and c, which are either "0" or "1". By setting them equal to zero, "kicks" in the controller output are avoided when there is a large step-change in setpoint (Astrom and Hagglund, 1995; Goodwin *et al.*, 2001; Astrom, 1996).

Different Anti Windup Schemes

Three anti windup schemes based on 'back calculation' technique are discussed. They are the classical anti windup, alternative anti windup and modified anti windup. The Classical Anti Windup (CAW) is previously known as 'back-calculation' or 'tracking', this anti windup scheme is easily incorporated in PI/D controllers. The principle behind it is to recalculate the integral action when the output saturates and come into effect only when there is saturation and maintain the original 'normal' behaviour when there is no saturation. An extra feedback loop is added by feeding the difference between the control output, u, and the plant input or the saturated plant input, *sat(u)* to the integrator with a gain of $1/T_I$. T_I is the parameter that needs to be specified, and determines the rate at which the controller output is reset (Astrom and Hagglund, 1995).

By limiting the controller output, the speed of actuator response will also be limited, if the actuator is described by linear dynamics, followed by saturation. To account for this, an alternative structure is introduced where an unrestricted control signal is applied to the process and a dead zone is used to generate the feedback signal. The structure is called Alternative Anti Windup (AAW). The dead zone range is the same as the linear range of the actuator. The dead zone gain, b, represents the ratio between integral time and the tracking time, $b = \frac{T_I}{T_I}$ and usually is set equal to 1, as it corresponds with $T_I = T_P$, (the suggested value for classical anti windup). A high value of b may reduce overshoot but at the expense of slower response (Bohn and Atherton, 1995).

Both classical and alternative anti windup are very sensitive to changes to the parameters, T_I and b. In the alternative anti windup scheme, if the dead zone gain is large, a very high initial controller output (due to P and D terms) will give a very large feedback signal to the integrator. Therefore, an additional limit on the proportional and derivative part is introduced. By incorporating the additional limit, another design parameter is introduced, and it is known as 'r', which represents the ratio range of the proportional-derivative limiter and the dead zone range. This structure which is known as Modified Anti Windup (MAW) allows a large value of dead zone gain to be selected, without causing slower response. The responses are relatively insensitive to changes in r (Bohn and Atherton, 1995).

Simulation Studies

To assess the effectiveness of different types of anti windup structures, they have been applied to different controller structures. The design parameter, for classical anti windup has been chosen to be $T_I = T_I$ for PI and $T_t = \sqrt{T_I T_D}$ for PID, while for both parameters for alternative anti windup and modified anti windup; b and r are chosen to be 1, as suggested. The anti windup strategies were applied to all PID structures except the Series PID. The structure of Series PID does not require anti windup, as this PID form can be implemented to counter actuator saturation. The three different anti windup structures were applied to PID controllers that were tuned using different tuning methods. The methods vary from the classical methods, like Ziegler-Nichols (ZN), Cohen-Coon (CC), to more recent methods like Direct Synthesis (DS), Simplified IMC (SIMC), Abbas tuning method (AA) and gain phase mergin method (GPM) (Abbas, 1997; Ho *et al.*, 1999; Coughanowr, 1981; Seborg *et al.*, 1989; Skogestad, 2002). The process considered was first order with process and time delay (FOPTD) with process gain, $K_p = 2$, process time constant, $\tau_p = 4$ and the delay, $\theta = 2$ where R = 0.5. The simulations were done using MATLAB, where the simulation time was 200s.

RESULTS AND DISCUSSION

Integral Absolute Error, (IAE), and the percentage overshoot (PO) were used as performance measurements. The three anti windup schemes were compared based on different PID controllers. Extensive simulations were done to observe the effect of saturation. In general, saturation will degrade the closed loop performance, leading to larger IAE, larger overshoots and longer settling times. Systems with faster responses (i.e. tuned using ZN and CC) tend to result in larger differences compared to the process tuned using the GPM method.

Performance

In general, insignificant differences were observed in PI controlled system. For the Ideal PID controller, all anti windup strategies performed well in reducing the overshoot for all tuning methods. The MAW scheme was designed to provide faster response compared to the classical anti windup (Bohn and Atherton, 1995), explaining the smallest amount of overshoot reduction in comparison to the other two schemes. With the GPM method, responses of the different anti windup are quite identical with about 10% reduction in overshoot.

An analysis of the overshoots in the responses under the different anti windup schemes are shown in *Fig. 1*. Each bar represents a different anti windup method; CAW,

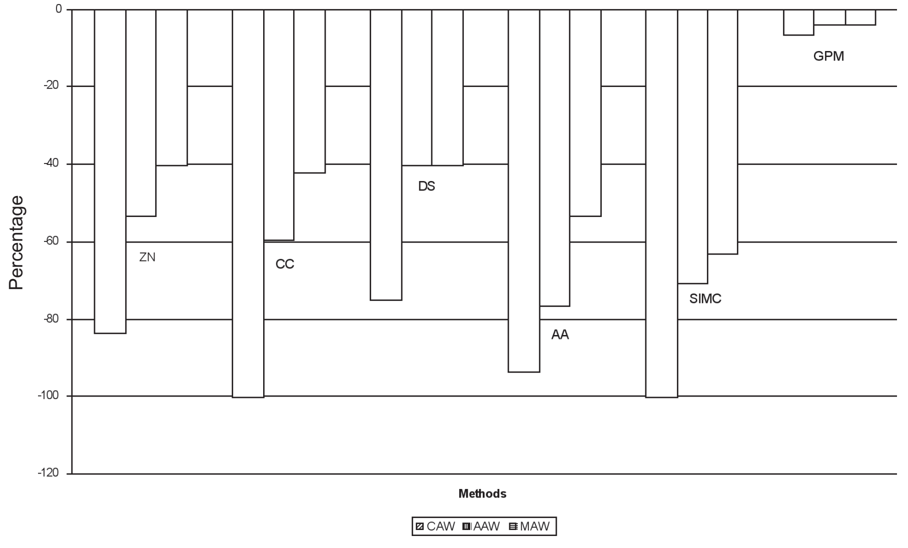

Fig. 1: Differences in overshoots for different anti windup (PIDI)

AAW and MAW. Six different tuning methods were considered and they are indicated as ZN, CC, DS, AA, SIMC and GPM. The y-axis represents the percentage change in overshoot when different anti windup compensators were applied. A negative value means that the percentage of overshoot is reduced by the anti windup scheme, while a positive value means that the percentage overshoot is increased by applying anti windup.

As one of the main objectives of having anti windup is to reduce the overshoot that will occur when there is saturation, the main focus will be in the negative region, as this shows the degree of reduction in the overshoot for a system without anti windup and when different anti windup schemes are applied. The anti windup schemes undoubtedly showed excellent performances in reducing the overshoot, with the CAW consistently yielding the 'best' performance across different tuning methods, for all PID structures.

For the Ideal PID controller, the differences in IAE between the three anti windup structures are more significant (*Fig. 2*). The CAW showed tremendous improvement in reducing or eliminating overshoot, compared to the other two schemes, which consequently reduced largest IAE as well. All the anti windup schemes effectively reduced the IAE. The MAW scheme in general, contributed to the least reduction in IAE, ranging between 0.4 to 26% reductions.

The differences between the three anti windup schemes became more prominent when applied to the Commercial PID. The CAW scheme was clearly the most effective anti windup scheme in terms of reducing overshoot; it reduces overshoots by between 50 – 100% for all tuning methods considered. On the other hand, the MAW only managed to reduce overshoot by 4 to 60%. The AAW showed acceptable performance, where the overshoot was reduced by between 40 to 100% for different tuning methods.

Overall, the CAW scheme was the most effective in terms of reducing overshoot as it eliminated the overshoot for controllers tuned using CC, DS, AA and SIMC methods, but at the expense of longer settling times and larger IAE compared to other anti windup schemes. Insight into the behaviour of different anti windup schemes can be gained by examining the closed loop response in *Fig. 3*. Systems with MAW scheme displayed

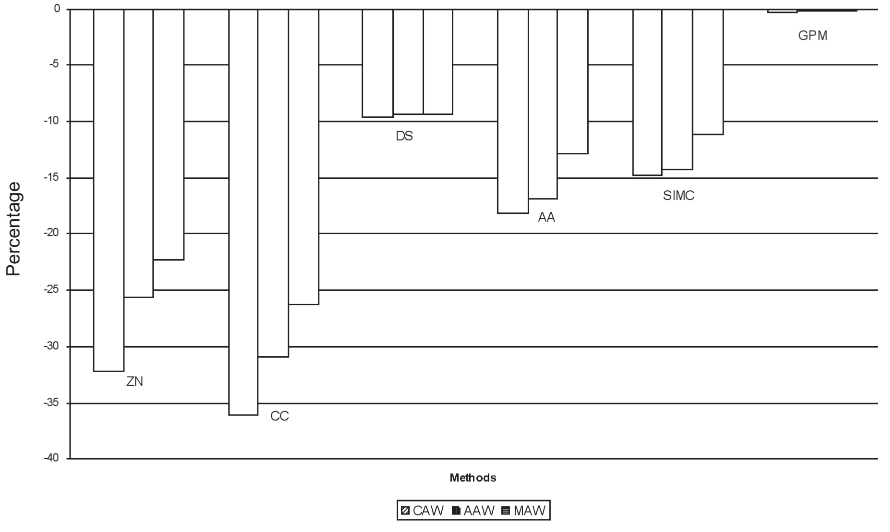

Fig. 2: Differences in IAE for different anti windup (PIDI)

highest overshoot among all other anti windup structures. The CAW scheme portrayed the best performance. Similar trends were observed for different tuning methods ±25% of the nominal case and performances were indicated by IAE values and percentage overshoot.

An increase in gain will definitely make the closed loop response more oscillatory, thus making an anti windup compensator less effective but the CAW scheme still exhibited the best performance on all PID controllers. Table 1 shows the percentage change in overshoot for a PI controller, when the gain is increased by 25%. The table can be divided into three main columns, according to the different anti windup schemes.

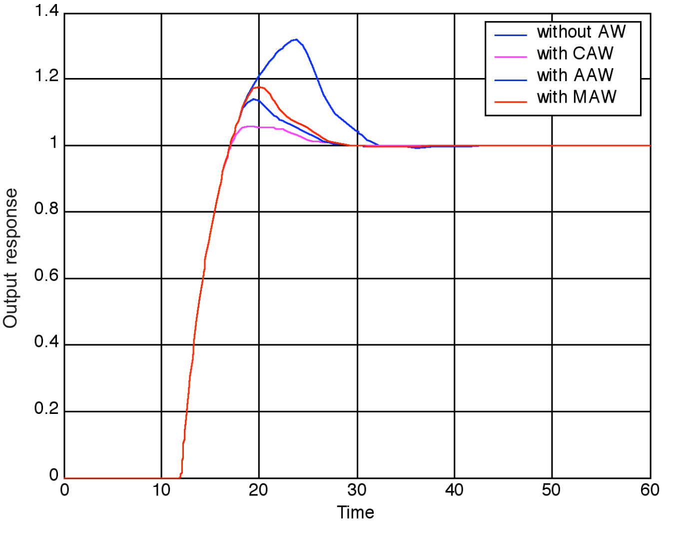

Fig. 3: Responses of different anti windup schemes for ZN tuned PIDF controller

TABLE 1
Percentage overshoot change by different anti windup schemes for PI with mismatch in gain (+25%)

Method	Classical anti windup		Alternative anti windup		Modified anti windup	
	Nominal	PMM	Nominal	PMM	Nominal	PMM
ZN	-99	-20	-99	-20	-65	-20
CC	-55	-40	-55	-40	-48	-40
DS	-20	-8	-20	-8	-20	-8
AA	-75	-25	-75	-25	-75	-25
SIMC	-20	-8	-20	-8	-20	-8
GPM	-44	-14	-44	-14	-44	-14

Each main category can be divided into two, representing the nominal case and when there is process model mismatch, (PMM). They refer to the overshoot reduced by the application of anti windup. Large differences between the nominal case and when mismatch is considered can be seen in the least robust tuning procedures, like ZN and CC, for all anti windup schemes.

As expected, by lowering the process gain, the closed loop response will become slower. Therefore, the anti windup schemes were more effective in reducing the overshoot. It can be seen that the CAW scheme still gave the best performance, even with mismatch in the gain.

As the process time constant is set 25% higher than the nominal value, the closed loop response was faster for controllers tuned using certain methods. The PI controller with CAW scheme gave quite a consistent performance with small differences between nominal and when mismatch was considered. The AAW and MAW schemes were severely affected. The detrimental effects in all PID controllers are more significant, with the classical anti windup scheme being the most affected in the Ideal PID controller. As the process time constant is reduced by 25%, the closed loop responses are slightly affected. The effectiveness of the anti windup schemes were slightly reduced for the PI controller. However, the change is more significant in other PID controllers; with certain tuning methods showing some reduction in the effectiveness while some portrayed slight improvements. For a slower system (tuned using DS, SIMC, and GPM methods), reducing the process time constant may not deteriorate the performance as much as for controllers tuned by other methods.

Mismatch in time delay does not have a significant overall impact on the effectiveness of the three anti windup compensators. The effect of lowering the dead time was not very significant in the PI controller. A similar observation was made for other PID controllers. Generally, in all PID controllers, the change is between 10%-20% for the three anti windup schemes.

CONCLUSIONS

Actuator saturation undeniably will cause deterioration to a closed loop performance but the degree of degradation differs according to tuning method. Overall, the GPM method was the least affected when there is saturation. Generally, the classical anti windup scheme showed the most preferable performance in reducing the adverse effect caused by saturation while the modified anti windup exhibited the least preferable performance. The CAW scheme also portrayed consistent performance through out the different PID structures. However, the responses of different anti windup also differ according to different controller settings, although the CAW scheme was generally suitable for all tuning methods. The tuning methods that yield more aggressive response like ZN and CC methods may not be suitable with the MAW scheme that resulted in faster responses. However, for a conservative method like the GPM method, applying MAW scheme may still provide a good and acceptable response. The alternative anti windup scheme resulted in similar response with CAW scheme for the PI controller, because the tuning parameters chosen for both CAW and AAW schemes resulted in the same value for the PI controller.

When process model mismatch is considered, the CAW scheme was the least robust, as it was the most affected especially for the Ideal PID controller. Even though the CAW scheme was the most affected when there is model mismatch, it still exhibited the best performance, especially in reducing the overshoot.

REFERENCES

Abbas, A. (1997). A new set of controller tuning relations. *ISA Transactions, 36*(3), 183-187.

Astrom, K. and Hagglund, T. (1995). *PID Controllers: Theory, Design and Tuning* (2nd ed.). New York: Research Triangle Park.

Astrom, K. (1996). *PID Control. The Control Handbook.* Florida: CRC Press.

Astrom, K. and Hagglund, T. (2001). The future of PID control. *Control Engineering Practice, 9,* 1163-1175.

Bak, M. (2000). *Control of Systems with Constraints.* Denmark: Department of Automation, Technical University of Denmark.

Bohn, C. and Atherton, D.P. (1995). An analysis package comparing PID anti-windup strategies. *IEEE Control System Magazine, 2,* 34-40.

Chau, P. (2002). *Process Control.* UK: Cambridge University Press.

Coughanowr, D. (1981). *Process Systems Analysis and Control.* New York: McGraw Hill.

Clair, D.W. (2000). The PID algorithm. Retrieved from http://members.aol.com/pidcontrol/pid_algorithm.htm

Goodwin, G., Graebe, S.F. and Salgado, M.E. (2001). *Control System Design.* New Jersey: Prentice Hall.

Ho, W.K., Lim, K.W., Hang, C.C. and Ni, L.Y. (1999). Getting more phase margin and performance out of PID controllers. *Automatica, 35,* 1579-1585.

Seborg, D., Edgar, T. and Mellichamp, D. (1989). *Process Dynamics and Control.* New York: John Wiley.

Skogestad, S. (2002). Simple analytic rules for model reduction and PID controller tuning. *Journal of Process Control, 13,* 291-309.