PID Windup

This Interactive Learning Module (ILM) is part of a sequence of modules that have been designed to make you familiar with PID control. The modules were designed as a complement to the book [1]. They can be viewed as an attempt to make the key pictures in the book interactive. This particular module is designed to develop an understanding for integral windup and one way to avoid it. There are two icons to access *instructions* and *theory*. There are also two associated modules *PID Basics* and *PID Loop Shaping* that gives you additional insight. Instructions give acces to this document which contains suggestions for experiments. Theory gives access to help via internet.

Many aspects of PID control can be understood using linear models. There are however some important nonlinear effects that are very common even in simple loops with PID control. Integral windup can occur in loops where the process has saturations and the controller has integral action. When the process saturates the feedback loop is broken. If there is an error the integral may reach large values and the control signal may be saturated for a long time resulting in large overshoots and undesirable transients.

The module is similar to the module *PID Basics* but it permits simulation of an actuator with saturation. The actuator is assumed to be linear if the controller output is sufficiently small, but it saturates for large control signals.

The exercises are structured as follows:

1. Getting started
2. The windup phenomenon
3. Set point response
4. The tracking time constant

1. Getting Started

Get familiar with the interactive learning module by exploring the `Settings` menu and by clicking on the interactive elements. If you are reading this you are already familiar with the icon *Instructions*.

A default process transfer function is loaded when you start the system. A process transfer function appears on the screen together with buttons for selecting controller types and sliders to change the controller parameters. At the lower right there is a graph which models the actuator saturation.

There are three plots in the right half of the screen showing process output, controller output and integral term. The top plot shows process output, the middle plot shows the controller output and the bottom plot shows the integral term of the controlller. The blue curve shows response for a liner controller and the green curve shows the response of a controller with protection for windup. There are buttons marked `Linear`, `PB Windup`, `PB AntiWindup`, `PB Windup` and `PB AntiWindup`. When the button linear is activated there is a (red) curve showing the linear response, i.e. the response when there is no saturation. When the button `Windup` is activated the system with a linear controller and a process with saturating actuator is simulated (blue curves). Activation of button `Antiwindup` simulates a controller with windup protection and a process with actuator saturation. The buttons `PB Windup` and `PB AntiWindup` shows the proportional bands for the different controllers. A dotted vertical line which makes it easier to compare the times in the plots is also available.

Several options can be chosen from the *Settings* menu which has the following entries

- Process transfer function
- Controller parameters
- Load/Save
- Simulation
- Examples

The process transfer function can be chosen from the entry *Process transfer functions*. Numerical values of the parameters can be using the selection *Controller parameters* in the *Settings* menu. Results can be stored and recalled using the *Load/Save* menu. Data can be saved and recalled using the options *Save design* and *Load design*. The option *Save report* can be used to save all essential data in ascii format. This is useful for documenting your results. The menu selection *Simulation* makes in possible to choose the simulation time, and to activate the *Sweep* option which can be used to show the results for several values of the tracking time constant (`Tt`) simultaneously. It is possible to load a number of figures from the book [1] using the selection *Examples* in the *Settings* menu. In this way you can explore what happens when you change the parameters in the examples.

Controllers of the type I, PI, and PID and their parameters can be chosen from the panel. The controller with anti-windup has an extra parameter, the reset time constant `Tt` which determines how quickly the integrator is reset when the controller saturates. This parameter can be chosen using a slider or from the *Settings>Controller parameters* menu.

2. The Windup Phenomenon

The purpose of this experiment is to give a familiarity with the phenomenon of integral windup. The notion of *proportional band* is useful to understand the windup effet. The proportional band is defined as the range of process outputs where the controller output is in the linear range. For a PI controller we have

$$
\begin{aligned}
y_{max} &= by_{sp} + \frac{I - u_{max}}{K} \\
y_{min} &= by_{sp} + \frac{I - u_{min}}{K}.
\end{aligned}
$$

The same expressions hold for PID control if we define the proportional band as the band where the *predicted output* $y_p = y + T_d dy/dt$ is in the proportional band (y_{min}, y_{max}). The proportional band has the width $(u_{max} - u_{min})/k$ and is centered at $by_{sp} + I/K + (u_{max} + u_{min})/(2K)$.

- Load `Figure 3.12` from from the menu *Settings>Examples* menu. The process transfer function is $P(s) = 1/s$. Change the saturation limit and the controller gains and observe how the changes in behavior. Click on the button `Linear` to show the process output, the controller output and the integral terms for the systems of a system without saturation. Two curves, one red for the linear system, and one green for the system with saturation then appears on the screen. Compare the behaviors of the systems.

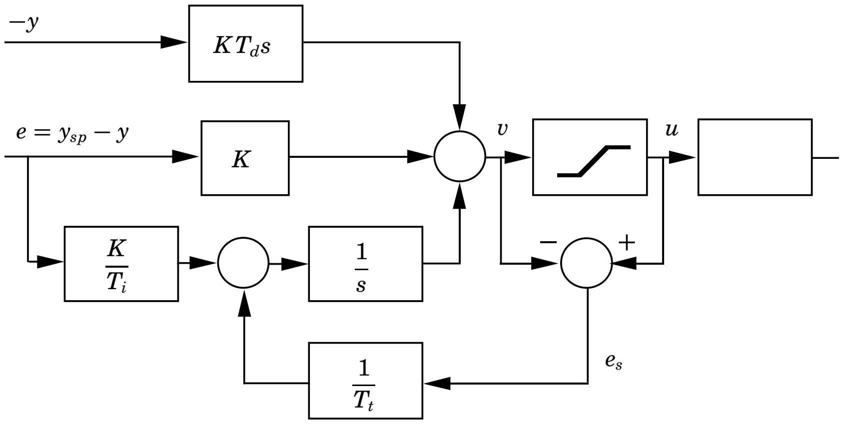
- What happens to the process output at the time where the integral term has its maximum?
- What happens to the control signal at the time where the process output has its maximum? Use the vertical line to better see what happens at synchronized times.
- Keep the setting from the previous exercise and click on the button `PB Windup`. The proportional band now appears in dashed lines on the screen.
  - Change controller gain and observe what happens to the proportional band. What happens to the control signal inside and outside the proportional band?
- The windup effects in the system you have studied are extreme. Investigate the windup effects in a process with the transfer function

$$P(s) = \frac{1}{(s+1)^4}$$

  Pay particular attention to the proportional band. Explore how the windup effects depend on controller gain.
- When controlling the process with the transfer function $P(s) = 1/s$ the controller acted almost like relay feedback in the initial time. Can you characterize processes where you expect this behavior?

3. Anti-Windup

There are many different ways to protect against windup. Tracking is a simple method which is illustrated in the block diagram below. The system has an extra feedback path around the integrator. The signal e_s is the difference between the nominal controller output v and the saturated controller output u.



The signal e_s is fed to the input of the integrator through gain $1/T_t$. The signal e_s is zero when there is no saturation. Under these circumstances it will not have any effect on the integrator. When the actuator saturates, the signal e_s is different from zero and it will try to drive the integrator output to a value that such that the signal v is close to the saturation limit.

Here are some exercises that show the effect of windup protection.

- Load `Figure 3.14` from the menu *Settings>Examples* menu. The process transfer function is $P(s) = 1/s$. Set the tracking time `Tt` to 1 and observe the differences in the behavior of the closed loop with anti-windup (the green curves) and a linear PI controller (the blue curves).
- Click on `PB Anti-windup` and investigate the proportional band. Compare with the proportional band for the linear controller `PB Windup`. Change the scales so that the transient is more clearly visible. Investigate how the process output, the controller output and the integral, and the proportional band change with changing tracking time constant `Tt`. Compare with a controller without protection for windup which corresponds to a very large value of `Tt`.

4. The Tracking Time Constant

Protection against windup is obtained by resetting the integral term. The tracking time constant is an important parameter because it determines the rate of resetting the integral term of the controller. The following exercise illustrates the effect of the tracking time constant.

- Load `Figure 3.15` from the `Settings/Examples` menu. You will then see the behavior of the system for three different values of the tracking time constant `Tt`. Change the values of `Tt` by dragging the sliders and observe the changes in the behavior of process output, controller output and the integral term.

This exercise indicates that it may be advantageous to have a very small value of the tracking time constant. This is not true because measurement errors may accidentally reset the integral term if the tracking time constant is too small. This is illustrated in the following exercies where there is a measurement error in the form of a short pulse.

- Load `Example noise` from the `Settings>Examples` menu. The process transfer funciton is
$$P(s) = \frac{1}{(0.5s+1)^2}$$
and the controller is a PID controller. Notice the large transient after the pulse. Increase the value of the tracking constant and observe the behavior of the system. Notice in particular the behavior of the integral part of the controller.
- Some simple rule that have been suggested for the tracking time are $T_t = \sqrt{T_i T_d}$ and $T_t = (T_i + T_d)/2$. Try these rules.

5. Reference

[1] Karl Johan Åström and Tore Hägglund. *Advanced PID Control*. ISA - The Instrumentation, Systems, and Automation Society, Research Triangle Park, NC 27709, 2005.