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Preface

The development of micro-processors and other electronic components over the last two decades has resulted in their considerable miniaturisation, decreasing prices, and increasing reliability and computing power. As a result, digital controllers are becoming ever more compact and cheaper. Nowadays, digital controllers have almost entirely replaced their analog counterparts in process control.

There are several advantages of using digital instead of analog controllers. They include:

- variability of controller structure,
- simple implementation of additional blocks as anti-windup protection, bumpless transfer feature, linearisation of the process steady-state characteristics, gain scheduling, etc.,
- built-in self-tuning and adaptive control algorithms,
- easy communication between controllers, and supervisory system, etc.

The most frequently used controllers in the process industry are PID controllers (Åström and Hägglund, 1995a), even though they have already been used for more than five decades. The reason lies in the fact that the PID algorithm gives an excellent trade-off between robustness and performance (Clair, 1995).

The most important considerations when designing a PID controller are the following:

- selecting a suitable controller structure (e.g. PI or PID),
- finding appropriate controller parameters (K, T_i, T_d),
- taking into account the physical limitations of a system by adding appropriate anti-windup compensation, and
- using appropriate bumpless transfer protection when switching the control algorithm from manual to automatic mode.

This thesis deals with each of the above four points, where anti-windup and bumpless transfer algorithms are considered relative to PID controllers, as well as for other more general types of controllers, like state-space controllers and controllers given in polynomial form.

The thesis is divided into two main parts. The first part is dedicated to the design of an anti-windup and bumpless transfer compensator.

In control theory there is a common assumption that the controlled process is linear. However, all the real processes are non-linear. Static process non-linearity can usually be linearised by applying certain linearisation functions (see e.g. Juričić et al., 1986; Vrančić and Peng, 1995b, 1996), but linearisation can only be achieved within specified limits. Such limits are called constraints.

All industrial processes are subject to constraints. For instance, a controller works in a limited range 0-10 V or 0-20 mA, a valve cannot be opened more than 100 % and less than 0 %, and a motor driven actuator has a limited speed, etc. Such constraints are usually referred to as plant input limitations. On the other hand, a commonly encountered control scheme is the switching from manual to automatic modes or between different controllers. Such mode switches are usually referred to as plant input substitutions.

As a result of limitations and substitutions, real plant input is temporarily different to the controller output. When this happens, if the controller is initially designed to operate in a linear range, the closed-loop performance will significantly deteriorate with respect to the expected linear performance. This performance deterioration is referred to as windup. Besides windup, in the case of substitution, the difference between the outputs of different controllers results in a large jump in the plant input and a poor tracking performance. This mode switching, which results in such phenomena, is referred to as bump transfer.

A rational way to handle the problem of windup is to take into account the input limitations at the stage of control design. However, this approach is very involved and the resulting control law is very complicated. Moreover, the non-linearities of the actuator are not always known *a priori*. A more common approach in practice is to add an extra feedback compensation at the stage of control implementation. As this compensation aims to diminish the effect of windup, it is referred to as anti-windup (AW).

In the case of mode switching, the method which aims to minimise the jump at the plant input is referred to as bumpless transfer (BT). Yet, minimising the jump is not always preferable, since this may cause a relatively poor tracking performance. Thus, we refer to the method which not only reduces the jump at the plant input but also keeps a good tracking performance as conditioned transfer (CT). This new notion will be shown to be very useful later in this thesis. An anti-windup strategy is usually implemented as a bumpless transfer technique. Indeed, an anti-windup method will usually diminish the jump at the plant input during mode switching. However, it should be pointed out that anti-windup does not necessarily imply bumpless transfer (Hanus et al., 1987).

The topic of anti-windup and bumpless transfer has been studied over a long period of time by many authors, and the most popular techniques are described in Åström and Wittenmark, (1984); Fertik and Ross, (1967); Hanus et al., (1987); Kothare et al., (1994); Morari, (1993); Peng et al., (1996a,b), Walgama et al., (1992). However, although the concept of anti-windup and bumpless transfer is introduced in almost every basic control textbook, it is not clearly illustrated and is sometimes misinterpreted. For instance, many authors think that anti-windup is aimed at reducing the output overshoot in its step response, or that anti-windup is a synonym of bumpless transfer, or that the best transfer transition is to eliminate the jump at the plant input. The aim of this thesis is to correct such thinking.

The second part of the thesis is dedicated to the tuning of the PID controller parameters.

PID controllers are the most often used controllers in the process industry. It has been recognised that in process control, more than 95% of the control loops are of the PID type, where most loops are actually of the PI type (Åström and Hägglund, 1995a). However, in some observations given by Ender, (1993), it was claimed that 30% of installed process controllers operate in manual mode, that 20% of the loops use default parameters set by the controller manufacturer, and that 30% of the loops function poorly because of equipment problems in valves and sensors (see Åström and Hägglund, 1995a). Only about 20% of the control loops were found to be working well and decreasing process variability. It is therefore clear that up to 70% control loops would have improved performance just by applying properly tuned PID controllers.

Today, the most applied tuning rules for PID types of controllers are those based on the measurement of the process step response or based on the detection of one particular point on the process Nyquist curve (usually detecting the ultimate magnitude and frequency of the process by using the relay excitation). The best known tuning rules are the Ziegler-Nichols tuning rules (Åström and Hägglund, 1995a; Hang and Cao, 1993; Hang et al., 1991; Thomas, 1991). The reason for their popularity lies in their *simplicity*. In real plants, it is usually relatively easy to obtain a process step response and to identify the appropriate process lag and process rise times, which are the input parameters for the calculation of the PID parameters (Clair, 1995).

The drawbacks of these tuning methods stem from the lack of information, since the available process information is based only on measured lag and rise times. Different processes exist with the same pairs of lag and rise times, but they need different controller tuning. Different deficiencies of the Ziegler-Nichols tuning rules are reported in Åström and Hägglund, (1995a); Hang et al., (1991); Hang and Cao, (1993); Hang and Sin, (1991); Thomas, (1991); Vrančić et al., (1995a); Žáková, (1997). Several authors have suggested the introduction of so-called “set-point weighting” (Åström and Hägglund, 1995a; Hang et al., 1991), and refinements of the Ziegler-Nichols tuning rules (Åström and Hägglund, 1995a). The improved closed-loop response of some tested process models have shown that they were quite successful. However, “refined” rules were still based on measurements of the process lag and rise times, so their applicability to a wide spectrum of possible processes remains an open question.

Apart from the very popular tuning rules, based on the measurement of the process step response or detection of the process ultimate point, such as Ziegler-Nichols, Cohen-

Coon, or the Chien-Hrones-Reswick rules, more sophisticated tuning approaches also exist. They are usually based on more demanding process identification (Åström and Hägglund, 1995a; Ho et al., 1993; Thomas, 1991).

Such tuning rules generally give better closed-loop performance at the cost of more extensive computations with longer and more complicated experiments on the testing plant. In some cases, the plant must be driven into self-oscillations, which is sometimes intolerable.

The aim of our research work was to find tuning rules for the PI and the PID controllers which would only require the process open-loop step response in order to satisfy quite demanding frequency criterion, known as the magnitude optimum criterion.

The remainder of this thesis is organised as follows. In **Part I** the anti-windup protection for different types of controllers is given. Part I is divided into four chapters.

Chapter 1 gives some background material about process limitations, several types of controllers, windup phenomenon, and bump transfer. It concludes with a short history of anti-windup and bumpless-transfer techniques.

A review of some anti-windup, bumpless transfer, and conditioned transfer techniques, and a comparison between them is given in **Chapter 2**. It is shown why several well-known criteria for comparing process responses are not suitable for comparing anti-windup, bumpless transfer, and conditioned transfer techniques, whilst the realisable reference proves to be a powerful tool for comparison.

Some issues on anti-windup protection for univariable controllers is given in **Chapter 3**. It is divided into five sub-chapters. First, the time response of the realisable reference, when using the generalised PID controller, is derived. It is determined that the process settling time, after a system leaves the limitation, strongly depends on the integral time constant of the PID controller. In the second sub-chapter, it is explained why strong windup behaviour, such as large overshoot and long settling time, will be produced when the difference between the limited and unlimited process time responses is large during system saturation. How a suitable anti-windup compensator can reduce the windup effect is also outlined. The third sub-chapter combines the results obtained in the previous two sub-chapters by making a prediction of the maximum overshoot of the realisable reference, when no protection against windup is taken, whilst using the PID controller. Disturbance rejection under saturation is presented in the fourth sub-chapter. It is shown that the process response to disturbance equals the sum of the unlimited process response to disturbance and the unlimited process response to changed realisable reference. A proper anti-windup compensator should be relatively inert to process noise. However, in the fifth sub-chapter it is found that some anti-windup techniques are much more sensitive to process output noise than others.

Chapter 4 discusses anti-windup protection for multivariable controllers. A new anti-windup approach is compared to several other existing methods. A new method, based on the optimal design of the artificial nonlinearity, is seen to give the best tracking performance.

Part II of this thesis deals with PID controller tuning using the multiple integration approach. It is divided into six chapters.

An introduction with a short history of PID controller tuning is given in **Chapter 5**.

A theoretical evaluation of the PID controller parameters obtained from the process step response, using the magnitude optimum technique, is given in **Chapter 6**. It is shown that the PI and the PID controller parameters can be derived merely from the process step response by using the multiple integration approach.

In **Chapter 7** some modifications of the PID tuning algorithms are presented. Tuning of the PID controller parameters is given for PID controllers with derivative filters, for the PID controllers by measuring only three areas, and for two-degree-of-freedom PI controllers. It is also shown how to improve certain classical tuning rules by using the new tuning approach. The influence of process noise and no-linearity on the tuning results are also studied. Some stability considerations are also noted.

Simulation examples are presented in **Chapter 8**, where the new tuning approach is compared to several other classical step-response-based tuning methods.

A real-time PID controller tuning algorithm is described in **Chapter 9**, where some real-time experiments on different laboratory set-ups are shown.

A discussion of the new PID tuning method is found in **Chapter 10**.

Finally, at the end of the thesis, some general conclusions are given, including the author's own explicit contributions to the fields of anti-windup protection, bumpless transfer, and PID controller tuning.