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Comparison of Schemes for Windup Protection

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Comparison of Schemes for Windup Protection

Abstract
The purpose of this study is to compare different schemes of anti-windup. The methods are compared for different processes and different disturbances; step response in setpoint, and load and measurement noise. The controller parameters are determined by the MIGO method and the reset time constant. The tests have been done by simulation in Matlab Simulink and the report is divided for PI and PID control and structured by the tested processes. The methods are compared to find pros and cons for the specific processes. The thesis has shown that no method is uniformly best. All methods are reasonably good but they have advantages and disadvantages. The disturbance type and the process dynamics determines which method is most suitable in a specific case.

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Preface

Windup protection is an important part of all practical controllers. This project was initiated by informal contacts with Henry Salomons of Dow Chemical Company [2] and Terry Blevins of Emerson Process Systems [1]. Emerson is one of the leading manufacturers of distributed control systems (Delta V) and Dow has for a long time developed their own process control systems and they have a lot of practical know how. Salomons mentioned a method for integral windup where only the integral is saturated, similar to what is done in analog controllers. Emerson is using a windup protection scheme that is similar to a scheme that has been used for a long time in Foxboro controllers, also based on inheritance of analog control [4]. A special feature, batch unit, has been introduced to improve performance in certain operating conditions.

The purpose of this masters project was to make an assessment of the different schemes for windup protection. At first the project was mainly meant to compare the difference between two methods, but later branched out when other interesting ideas were considered. It has been fun trying to find a good way to model and compare the different methods as well as trying to analyse the reactions of the controllers which has required quite some remodelling. The work has been done at the Department of Automatic Control at LTH in Lund under the supervision of Karl J. Åström.

I would like to thank Tore Hägglund for being my examiner on this project. Henry Salomons at Dow Chemical and Terry Blevins at Emerson who have provided two of the methods through contact with Karl. I would also like to thank Karl Johan for all his help, guidance and invigorating positivity. I would also like to thank my dear fiancée Maria, who has supported me throughout this project. Thank you all!

Contents

1. Introduction

Control theory is a huge exciting area of expertise that can be applied on just about anything, and if its done right you will probably not even think that it is there. Wether its traction control on a car or the conveyor belts in a paper factory, a well tuned controller can save lives and money. Many companies around the world have some sort of controller in their line of work or on their industrial floor, controllers that usually is not anything more complex then a normal PI or PID controller. One of the problems that might occur when using a controller with an integral part is that a saturated actuator leads to windup, which is a problem that might lead to oscillations and long settling times.

1.1 What is windup and how to counter it?

When an actuator gets saturated a normal linear control problem becomes nonlinear since the controller can no longer produce the output needed. This is a problem that any physical actuator can get, since they will always have limits on performance, wether its a valve that cannot be opened more then full, or an engine going at maximum velocity. When the actuator gets saturated a windup effect occurs. The error gets bigger and bigger since the control output can not match the requirements. This becomes a problem when using a PI or PID controller since the integral part of the controller will have the past error in mind, even if the reference signal is finally reached. This will lead to an overshoot that will take quite some time for the system to handle, and might involve several oscillations above and below the wanted value before fully recovered, see figure 1. The problem can be solved in different ways and is usually handled by resetting or limiting the integrated part of the control signal in some way.

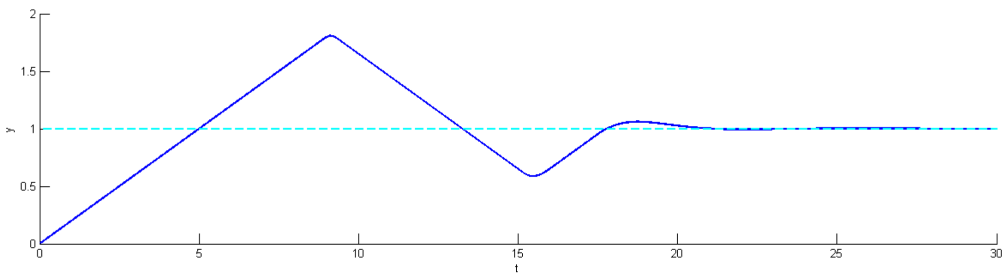

Figure 1: PI control of a single integrator with no windup protection and saturated actuator.

1.2 Master thesis objective

The goal of the master thesis is to compare some methods of anti-windup and conclude which might be better under certain circumstances. The master thesis have been focused on finding pros and cons with these methods. The comparison is done using Simulink [3] in Matlab. First and foremost it's the difference of the method suggested by Karl J Åström and Tore Hägglund in their book *Advanced PID Control* [4] and an alternative version of this where only the integral part of the control signal is regulated. The master thesis was later extended to also compare a series implementation of a anti-windup PI controller also mentioned in *Advanced PID Control*, and an alteration of this method proposed by Terry Blevins where a variable preload control signal is used when the actuator is saturated. Follow up master thesis work could be to further investigate the methods from a analytical point of view, or extending it towards also finding a good anti-windup method for cascaded systems.

2. Methods of Anti-Windup

The master thesis will focus on four methods of anti-windup, two on parallel form and two on series form. The parallel methods are the back-calculation method, and the Dow method. The Foxboro method and Blevins method are instead on series form. The four methods of anti-windup all need to have a model of the actuator saturation in order to reset the integrator windup. In addition, some of the methods require some extra parameters to tune.

2.1 The Back-Calculation method

The back-calculation method (henceforth referred to as the AH method because we use the version described in [4, p.79]) is a PID controller on parallel form with a back-calculation factor calculated from a model of the actuator saturation. This back-calculation kicks in when the entire control signal is saturated according to the actuator model. Taking the overflowing value multiplied with a back-calculation factor, to then be subtracted from the integral part of the controller to reset the integral windup. The AH method has full PID support and the back-calculation leads to one extra parameter T_t, compared to an ordinary PID controller. The AH method can be seen in figure 2, where the blocks marked in red are showing the derivative parts added for PID control.

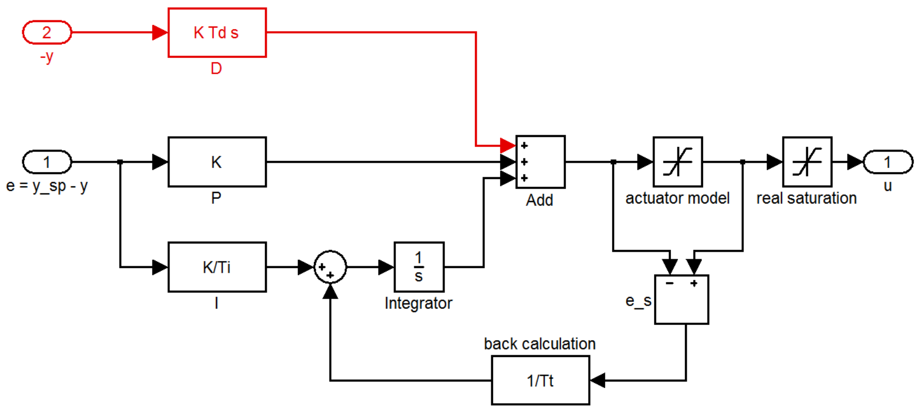

Figure 2: The schematic for the AH method, where the red marked blocks are only used for the PID version of the controller.

2.2 The Dow method

The method suggested by Henry Salomons from Dow Chemical [2] is similar to the AH method, but instead of using the overflow of the whole control signal for back-calculation only the integral part is being back-calculated to reset the integral windup. This makes it more similar to the controller without windup protection since extra measures are only taken when the integrator is saturated. The Dow method has full PID support and have one extra parameter compared to an ordinary PID controller and thus is exactly like the AH method on this regard. The Dow method is shown in figure 3.

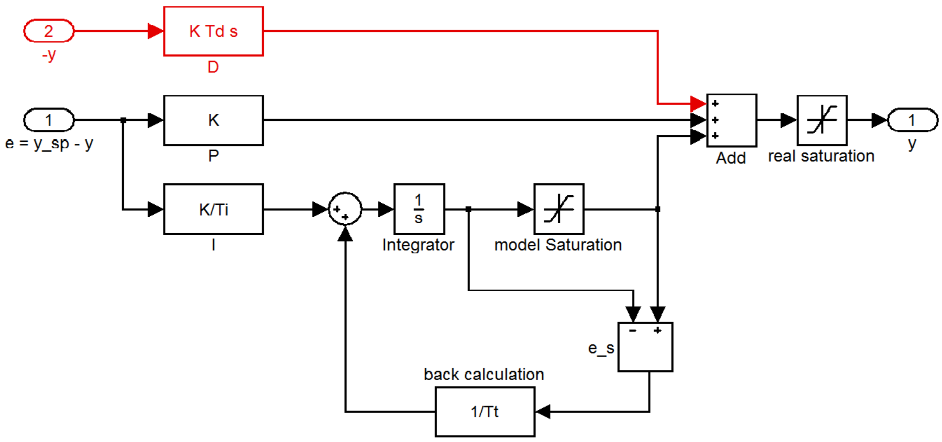

Figure 3: Block schematic of the Dow method, where the blocks marked in red are the derivative part of the controller.

2.3 The Foxboro method

The Foxboro method [4, p.85] is a PI controller using integral action to generate automatic reset. This method only uses the two parameters you normally would use in a PI controller. For PI comparison the Foxboro method equals the AH method for a fixed $T_t = T_i$. The PID implementation of the Foxboro method is more distinct and can not be interpreted as a AH controller. Both the proportional and derivative part are added up for the integrator in the positive feedback loop. A derivative part is added for PID comparison. The Foxboro method is shown in figure 4 .

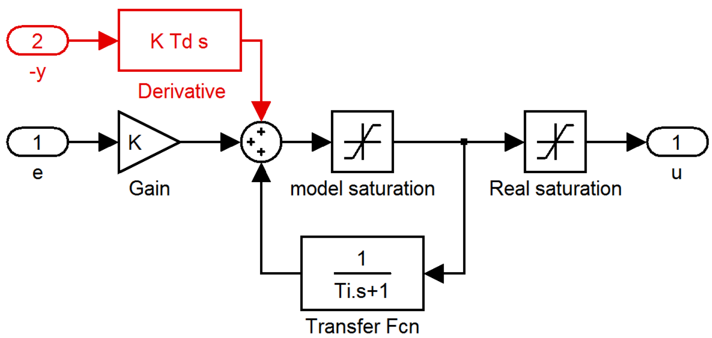

Figure 4: Scheme of the Foxboro method where blocks marked in red corresponds to the derivative part added for PID control. A positive feedback loop is used for windup protection.

2.4 Blevins method

This method, provided by Terry Blevins from Emerson is similar to the Foxboro method but with a calculated variable preload that substitutes the control signal when the controller is saturated [1]. The variable preload is used for faster reset of the integrator, as well as making the actuator able to react before the error changes sign. It is also designed to work better for systems with limits on the control adjustment of the manipulated process input. This method uses three extra parameters, two of which are used in the calculation of the variable preload to get a good transfer of the control signal when switching between saturated and unsaturated control. The third parameter is a user specified parameter *F* that works as a filter on the positive feedback which can be useful for significant measures of noise. *F* has been set to 1 to easier relate to the other methods. The variable preload is set to $(1+sT_{i_{PL}})(1+sT_{d_{PL}})$ plus the constant limit value. This method is only used for the PI comparison even though it could be interesting to test this method further for PID control as well. Blevins method can be seen in figure 5.

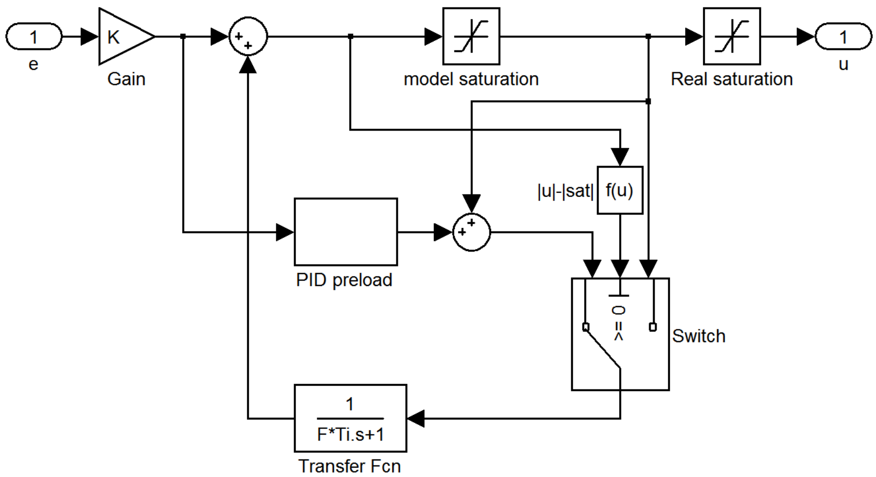

Figure 5: Block schedule of the Blevins method. A switch make sure that the variable preload is used when the actuator is saturated. The integration is made in the positive feedback loop.

3. Processes

Five different processes will be used to compare the methods, two of which have a time delay. The processes will be used to compare the methods for both PI and PID control. Most of the processes are part of a test batch [4, p.226] used in the book *Advanced PID Control*. The controllers are going to be tested on each process for each of the cases:

- An initial setpoint step.
- A setpoint step after a long time of saturation.
- A load disturbance step after long time of a saturated actuator.
- In addition, the PID controllers are also tested with two kinds of measurement disturbances, a pulse and noise.

Process 1

The first process is a simple integrator.

$$P_1(s)=\frac{1}{s}$$

Process 2

The second process has balanced lag and delay dynamics and is made of four equal poles.

$$P_2(s)=\frac{1}{(s+1)^4}$$

Process 3

The third process has four poles and lag dominated dynamics.

$$P_3(s)=\frac{1}{(1+s)(1+as)(1+a^2 s)(1+a^3 s)}\text{, with } a=0.1 .$$

Process 4

The fourth process has a single pole but also introduces a time delay. The dynamics of this time delayed process depends on the ratio τ which can be calculated as $\tau=\frac{L}{L+T}$. For $\tau<0.5$ the process has lag dominated dynamics, and for $\tau>0.5$ it is delay dominated, for $\tau=0.5$ it is simply called balanced dynamics.

$$P_4(s)=\frac{1}{(1+sT)}e^{-Ls}$$

Process 5

The fifth process used for simulations is also a time delayed process, but with two equal poles. The parameters are chosen so that the dynamics of the process is delay dominated.

$$P_5(s)=\frac{1}{(1+as)^2}e^{-Ls}$$

4. PI Control

PI control is widely used and can be sufficient in many situations. The controller parameters have been chosen with the MIGO tuning rules [4, p.217] for PI control where saturation is not a problem. The method specific parameters is then chosen for a good overall performance of the different cases.

4.1 Process 1

The single integrator is a good example on how bad it is to use a PI controller without any anti-windup. All methods use the control parameters $K=3.414$ and $T_i=0.5$ which would lead to a quick response and fast settling time for an unconstrained controller. The controllers used for the methods are however constrained, and will have an actuator saturation of ±0.2 for process 1. Method specific parameters can be seen in the table 1.

Method	***Additional parameters***
AH	$T_t=0.1\ T_i=0.05$
Dow	$T_t=0.1\ T_i=0.05$
Foxboro	
Blevins	$T_{i_{PL}}=3\,T_i=1.5$, $T_{d_{PL}}=0.1$, $F=1$

Table 1: Method specific parameter choices for the PI control comparison of process 1.

Initial step

To begin with we look at how the PI controllers handle the initial step of process 1, which can be seen in figure 6. The setpoint is changed from 0 to 1 at time $t=0$, and in figure 6 the time starts at $t=4.5$ when the system outputs are approaching the setpoint.

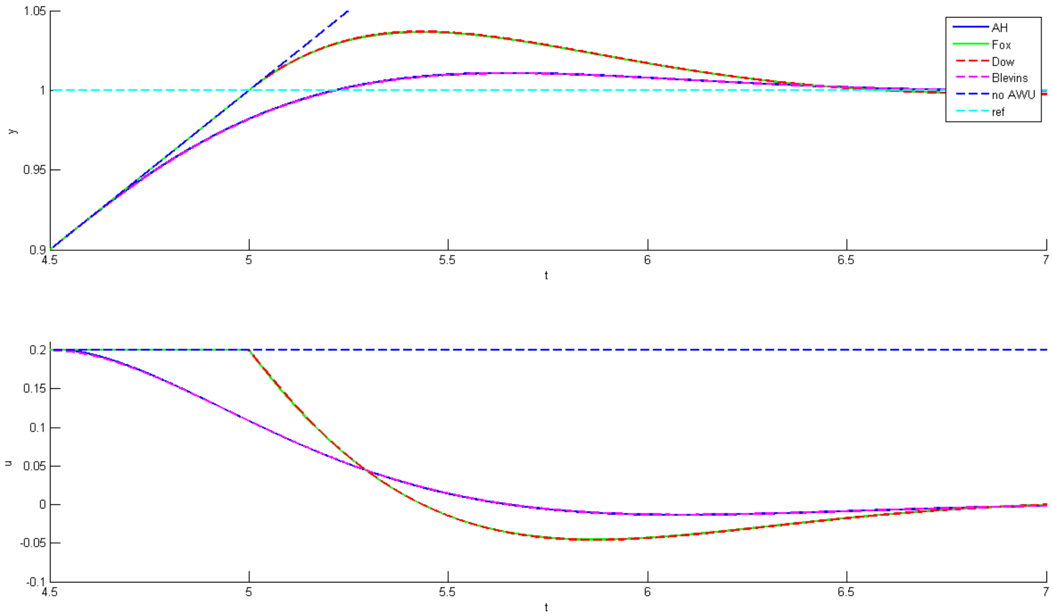

Figure 6: PI control of the initial step for Process 1. Upper plot showing system output, and the lower plot showing the control action.

We can see that the AH method and Blevins method perform almost identically and start reducing the control signal before the setpoint value is reached, and has only a slight overshoot before settling. The Dow and Foxboro methods also perform almost identical for the initial step for this process, but these methods do not reduce the control signal output until the setpoint is reached leading to a larger overshoot. The settling time is however fairly equal for all four methods. To realise why the AH and Blevin methods react before the setpoint is reached, while the Dow and Foxboro methods is not, we need to look at the different parts of the control signal.

For the AH method the proportional part saturates the controller so that the back-calculation reduces the integrator to a value below zero. The integrator then slowly adds up to zero. Since the integrator has a negative value the controller output will go below the saturation level as soon as the proportional part gets low enough. This can be seen in figure 7.

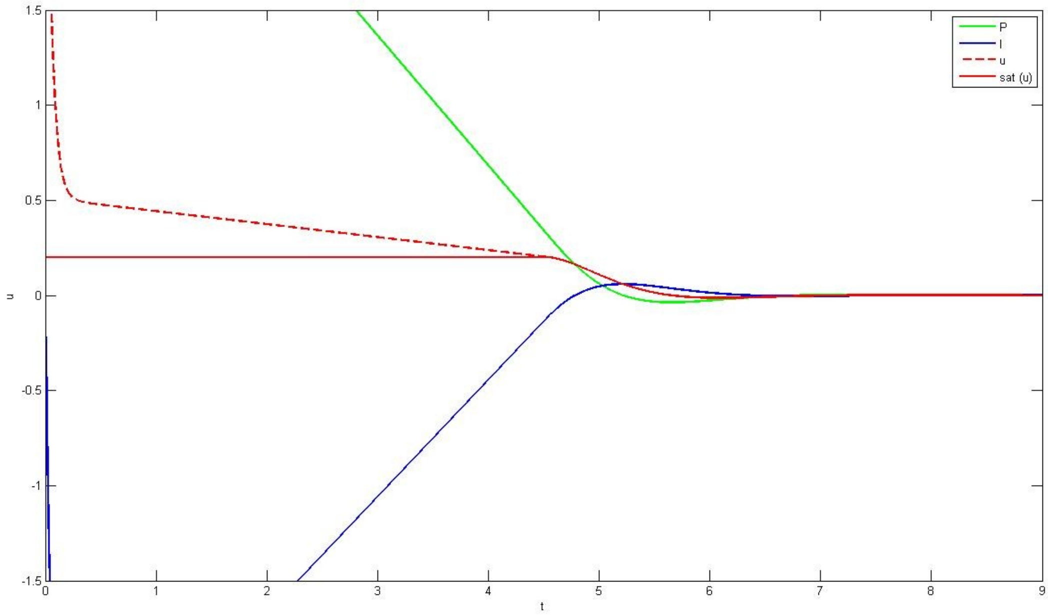

Figure 7: Controller components of the AH method for the initial step of Process 1.

For the Foxboro method the integral part will converge to the saturation level and the control output will not go below the saturation before the setpoint is reached and the proportional becomes negative, as can be seen in figure 8.

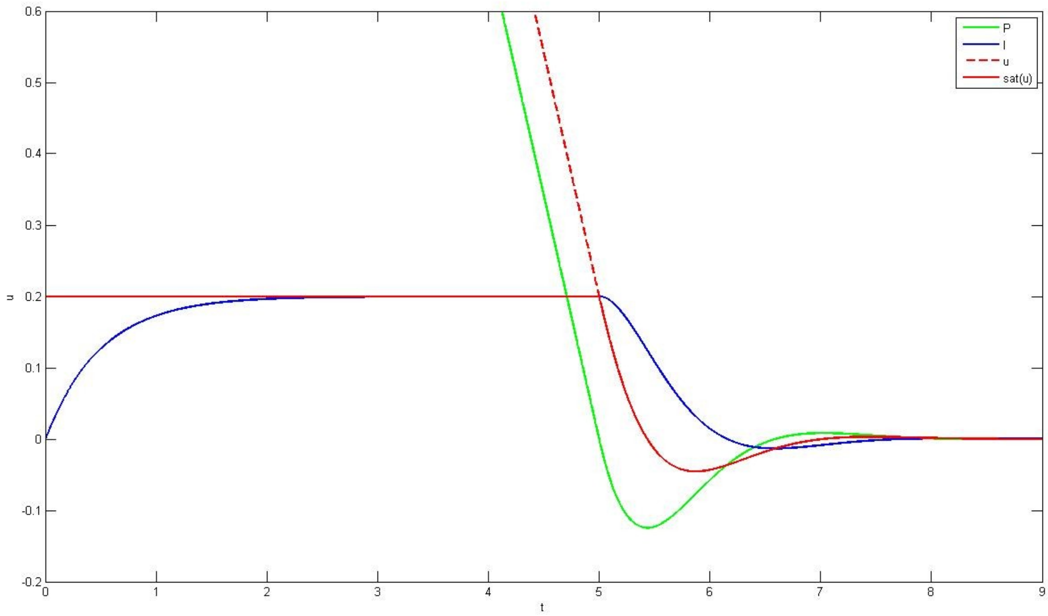

Figure 8: Components of the Foxboro method's control signal for the initial step of Process 1.

The Dow method is similar to the Foxboro method, with the main difference in how the integrator builds up. The proportional part saturates the actuator alone since a setpoint step has occurred at the startup, but as the output signal gets closer to the new setpoint, the proportional part is reduced, however it does not change sign until the the new setpoint is reached. The integrator also saturates the actuator very fast. To counter the integrator saturation the back-calculation kicks in and works actively to reduce the integral part, however it will only reduce it down to the saturation level, hence the control signal of the Dow method wont start dropping below the saturation until the proportional part changes sign which will happen when the setpoint is reached. The different components of the Dow method for this case can be seen in figure 9.

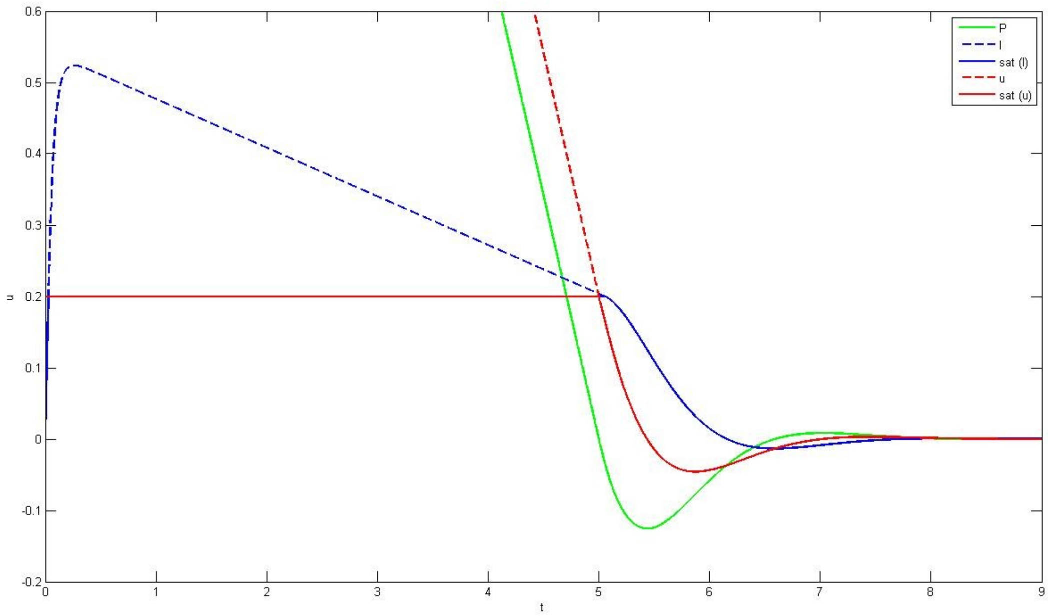

Figure 9: The Dow method controller components contribution for the initial step of Process 1.

The Blevins method resets the integrator and keeps pushing it down, even below zero as long as the controller is saturated and the preload variable is used. When the controller output reaches the saturation level the controller switches away from the variable preload and the controller output can be reduced to sub saturation level as soon as the proportional part is small enough since the integrator now adds a negative part to the controller output. By changing the preload variables, especially $T_{i_{PL}}$, the performance of this method can go from acting as the AH method to acting similar to the Foxboro method. The different components of the Blevins control signal can be seen in figure 10.

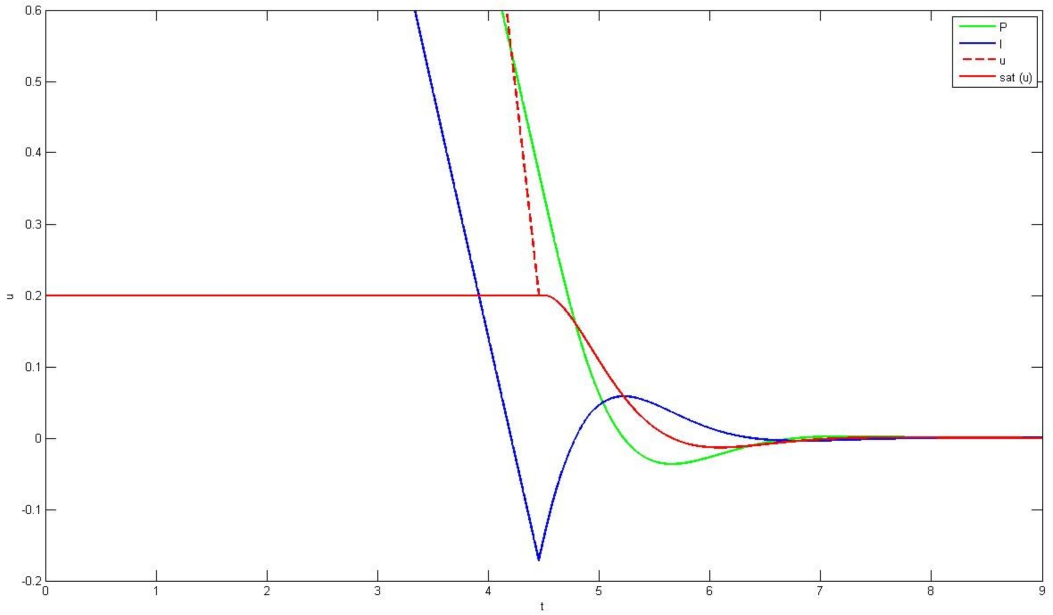

Figure 10: Blevins method's and its controller components for an initial step of Process 1.

Reference step

In figure 11 we also look at a negative reference step when the process has been steady for some time. Just as before we see the methods pairing up and performing almost identically. The AH and Blevins methods leave the saturation before the setpoint is reached, leading to less overshoot.

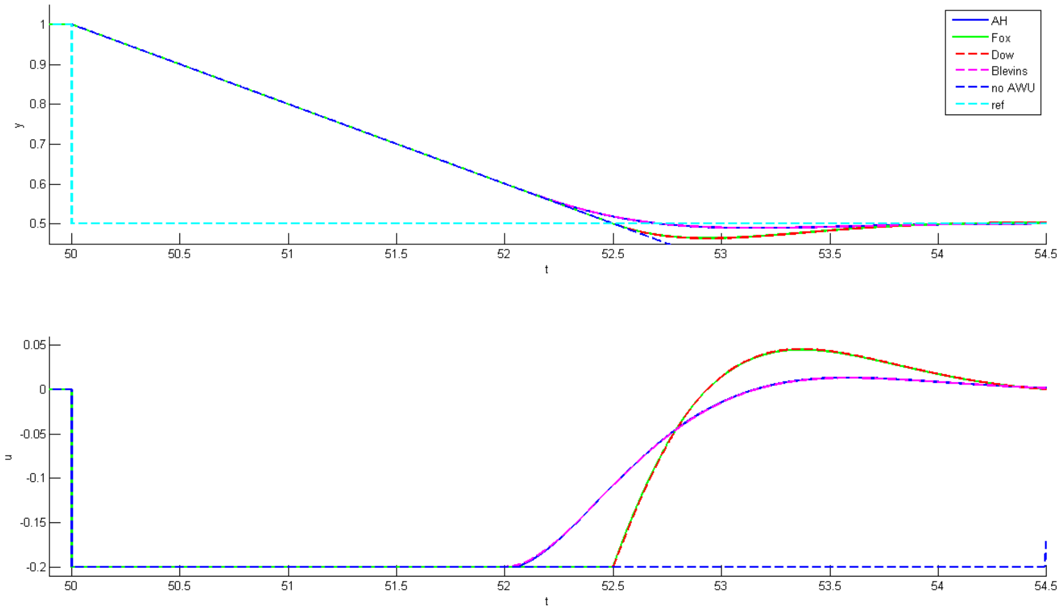

Figure 11: A negative reference step on process 1 after long time of saturation, handled by PI control.

When looking at the different parts of the controller signals we see the same behaviour by the controllers as for the initial step. For the AH method the back-calculation grows large from the big proportional part when the reference step occurs, which leads to the integrator having opposite sign from the proportional part. As a result the control signal changes from the lower saturation limit as soon as the proportional part gets small enough to be cancelled out by the integrator part. This also gives the controller a slower and smoother control signal.

For the Foxboro method the integrator slowly saturates, and has just saturated when the control output leaves the saturation limit, leading to a positive proportional gain needed to leave the lower saturation limit which is first when the reference value is reached. The late reaction results in a slightly larger overshoot.

The integrator saturates on the lower limit for the Dow method quickly, resets to the lower limit of the actuator and the control signal leaves the saturation only when the setpoint is reached and the proportional part changes sign. The real difference between the Foxboro and Dow method is in the way the integrator has been added up, but since the controller was saturated during that build up phase for both methods, the controller output is the same for the methods.

For Blevins method the integrator is saturated instantly, and then quickly added up by the preload variable. When the integrator has been added to a positive number and cancels out the proportional part the preload is switched off. This makes the controller output leave the lower saturation level before the setpoint is reached leading to lesser overshoot and shorter settling time.

Load disturbance

Introducing a load disturbance step for process 1 leads to similar conclusion as for the other two cases, however the Foxboro and Dow method is now separated, as can be seen in figure 12.

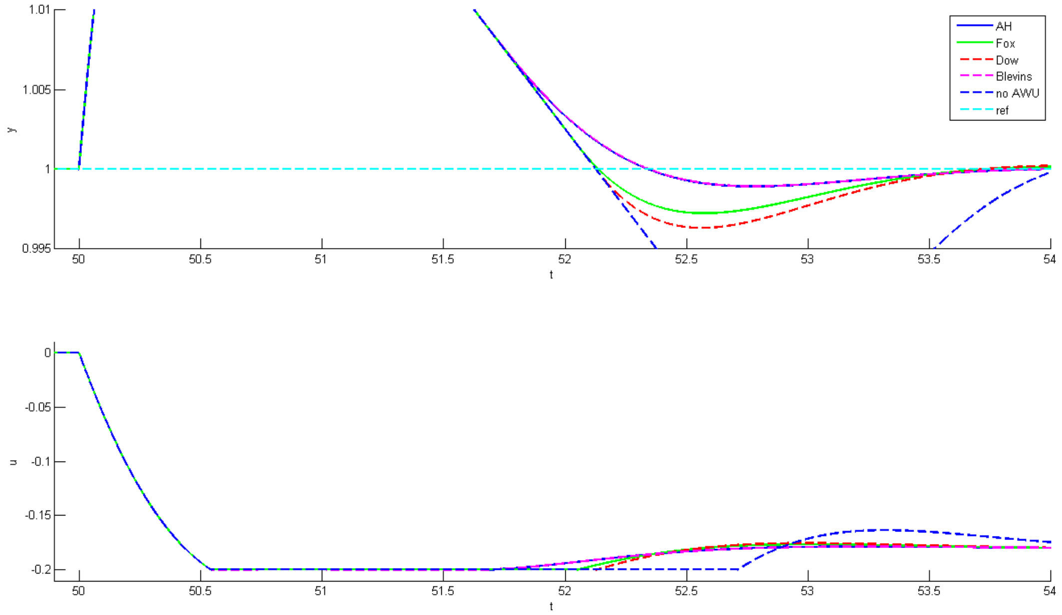

Figure 12: PI control of process 1 with a load disturbance step.

The reason that the Foxboro and Dow method are separated is due to the slower convergence of the Foxboro methods integrator.

For the AH method the integrator first decreases rapidly, however when the controller gets saturated on the lower limit, the back-calculation adds to the integrator, resulting in only a slight decrease so that the integrator does not reach the lower saturation limit, and the controller was therefore able to react some time before the setpoint was reached. The Foxboro integrator is turning slowly towards the lower saturation limit. It does not reach it before the control action is large enough to leave the saturation, which leads to the controller reacting slightly before the proportional part changes sign. The difference between the methods here is how the integrator is reacting, the Dow methods integrator is quickly reduced down to the lower saturation limit.

Blevins method switches a little between using and not using the preload value when the controller reaches the lower saturation limit, and slows the reduction of the integrator. The behaviour is very similar to that of the AH method.

4.2 Process 2

The second process has four equal poles with the transfer function $P_2(s)=\frac{1}{(s+1)^4}$. The MIGO parameters [4, p.249] that the methods controllers have in common are $K=0.432$, $T_i=2.43$, and an actuator saturation of 1.1 for the initial step, and 0.9 used for the step in reference and for step in load. The method specific parameters can be seen in table 2.

Method	Additional parameters
AH	$T_t=0.1\ T_i=0.243$
Dow	$T_t=0.1\ T_i=0.243$
Foxboro	
Blevins	$T_{i_{PL}}=3T_i=7.29$, $T_{d_{PL}}=1$, $F=1$

Table 2: The method specific parameters of the PI controllers for process 2.

Initial step

The MIGO control parameters for process 2 do not saturate the actuator for the initial step, and thus the four methods do not differ from the normal controller in this case, therefore a figure for this case is redundant and we continue straight to the case of a sudden reference step.

Reference step

A negative reference step after the control signal has been saturated can be seen in figure 13. Here we see the AH-method to be slightly faster, the big difference is in initial action taken in control signal when the reference change occurs.

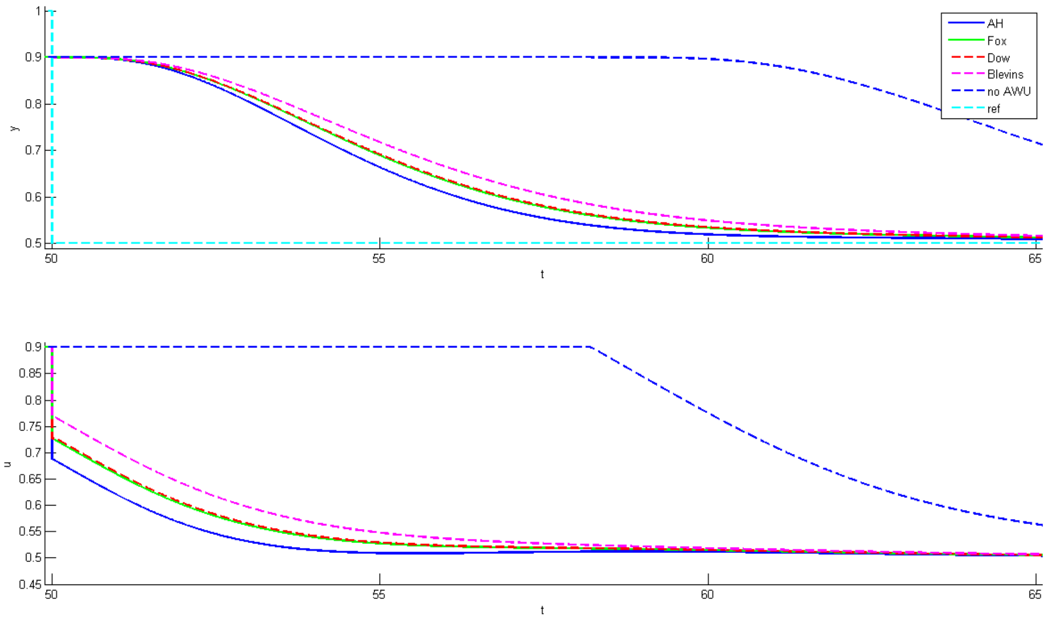

Figure 13: PI control of a negative reference step of process 2 after a long time of saturation.

The difference between the methods here is the size of the first step after the setpoint change. The reason for this difference is based on the level of the long term saturated integrator. For the Dow and Foxboro methods the integrator is exactly at the saturation level of 0.9 . The AH method however has balanced out slightly below 0.9 due to proportional part in the back-calculation. For the Blevins method the integrator has balanced out slightly over the saturation due to the preload.

Load Disturbance

For a load disturbance step after a long time of saturation the AH and Blevin methods react earlier and are able to reduce the overshoot more, this can be seen in figure 14.

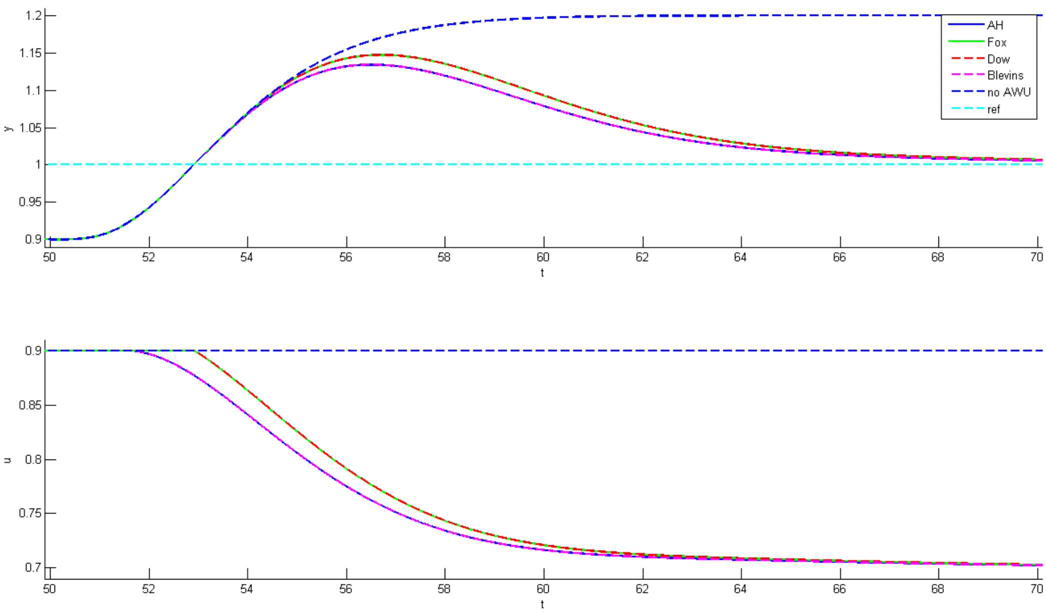

Figure 14: PI control of a load disturbance step on process 2 after a long time of saturation.

A load disturbance step adds to the saturation, resulting in a smaller control signal needed to reach the setpoint. The AH and Blevins methods reduce the overshoot slightly more than the Dow and Foxboro methods by earlier control action, the settling time is however very similar.

When the control signal of the AH controller is saturated the integral part is reduced by the back-calculation and levels below the saturation limit. After the load disturbance step occurs the error reduces, as well as the desired control action. The balance between system output error and back-calculation of the saturated controller makes the integrator rise slightly from the settled value, until the controller is no longer saturated but without reaching the saturation limit. The controller can thus start take action as soon as the proportional part is smaller then the margin between the saturation limit and the integrator value.

The integrator in the Foxboro method settles at the saturation level when the load disturbance step occurs, and remains saturated until the proportional part changes sign, and thus requiring the setpoint to be reached before the controller reduces its control action.

The integral part of Blevins method has settled a little over the actuators saturation due to the preload. After the load disturbance step the preload reduces the integrator until the control signal is no longer saturated, at which point the controller switches to normal control. At the time of the switch the integrator is pushed down to a value below the saturation limit. Since the integrator now is below the saturation limit, control action is taken before the setpoint is reached.

Before the load disturbance occurs the Dow methods integrator is limited to the saturation limit by the saturation model. When the disturbance occurs the integrator alone saturates the control signal, and just like the Foxboro method, it is first when the setpoint is reached that both the control signal and the integrator can be reduced to a value below the saturation.

4.3 Process 3

Process 3 has four poles with lag dominated dynamics. The transfer function $P_3(s)=\frac{1}{(1+s)(1+as)(1+a^2 s)(1+a^3 s)}$, where the parameter a is chosen to $a=0.1$. The shared controller parameters are as suggested by the MIGO design [4, p.247] to be $K=3.56$ and $T_i=0.66$. The different methods parameters can be seen in table 3.

Method	***Additional parameters***
AH	$T_t=0.75T_i=0.495$
Dow	$T_t=0.1\,T_i=0.066$
Foxboro	
Blevins	$T_{i_{PL}}=T_i=0.66$, $T_{d_{PL}}=0.5$, $F=1$

Table 3: Method parameters for PI control of process 3.

Initial step

When looking at the initial step of the different methods, seen in figure 15, the AH and Blevin methods converges to the setpoint with no or almost no overshoot.

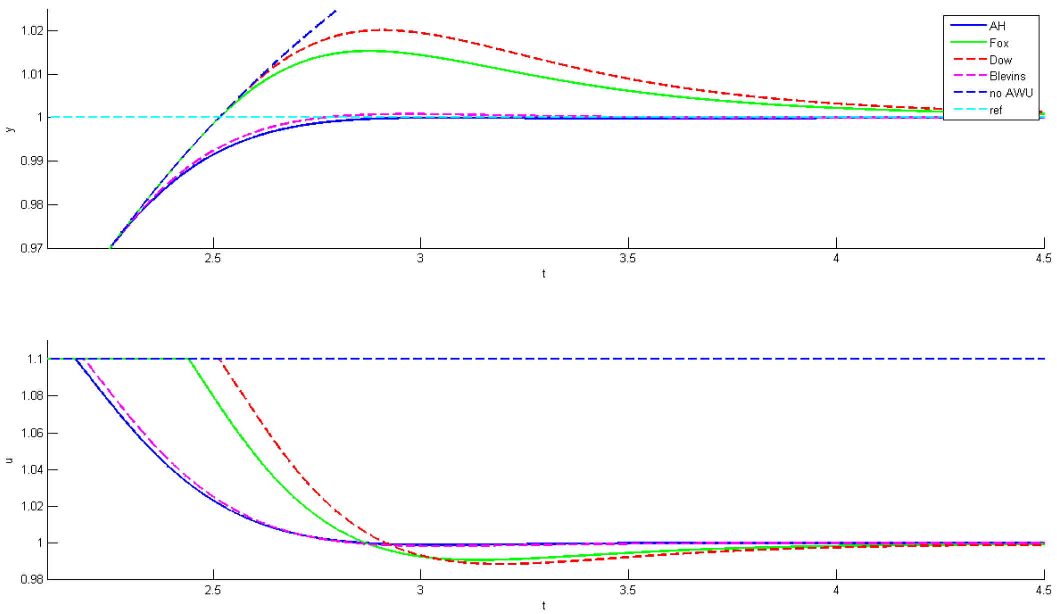

Figure 15: PI control of process 3 comparing the different methods response to startup with an initial step.

The difference between the results of the AH and Blevins methods are very small. Both the Foxboro and Dow methods have an overshoot here, with Foxboro having a smaller overshoot due to a faster reacting control signal.

For the AH method the back-calculation leads to the integrator never saturating and the control signal can react before the setpoint is reached due to both the proportional and integral part being small enough. The higher T_t value used gives the back-calculation a smaller gain, which still holds back the integrator from winding up, but the proportional part does not push the integrator to go below zero as it did for process 1 in figure 7. For a $T_t=0.1$ the AH method would start reducing the control signal much earlier in this case, and by doing so only prolonging the settling time with no apparent benefit. Variations of the T_t parameter is discussed further in section 4.6.

For the Foxboro method the integral part has not saturated when the setpoint is reached, giving a control signal reduction just before the Dow method in this case.

When looking at the different parts of the control signal of the Dow method the integrator resets to the saturation level, and the controller output thus wont reduce to below the saturation until the setpoint is reached and the proportional part adds a negative part to the output.

The Blevins methods integrator saturates very fast after the initial step, the preload will however push it back down, and unlike the Dow method, the reduction of the integrator will not stop at the saturation level, but instead continue until the control signal no longer is saturated. This gives the possibility to earlier reactions similar to that of the AH method.

Reference step

When looking at the case with a negative reference step after a long time of saturation in figure 16, we see that Blevins method is tuning fast in to the new reference step without any overshoot. The other three methods are similar to each other, settling first after an overshoot. The Dow method has a slightly smaller overshoot than the Foxboro, and the AH has a slightly larger overshoot. It is mainly the initial controller step when the setpoint changes that makes the methods differ.

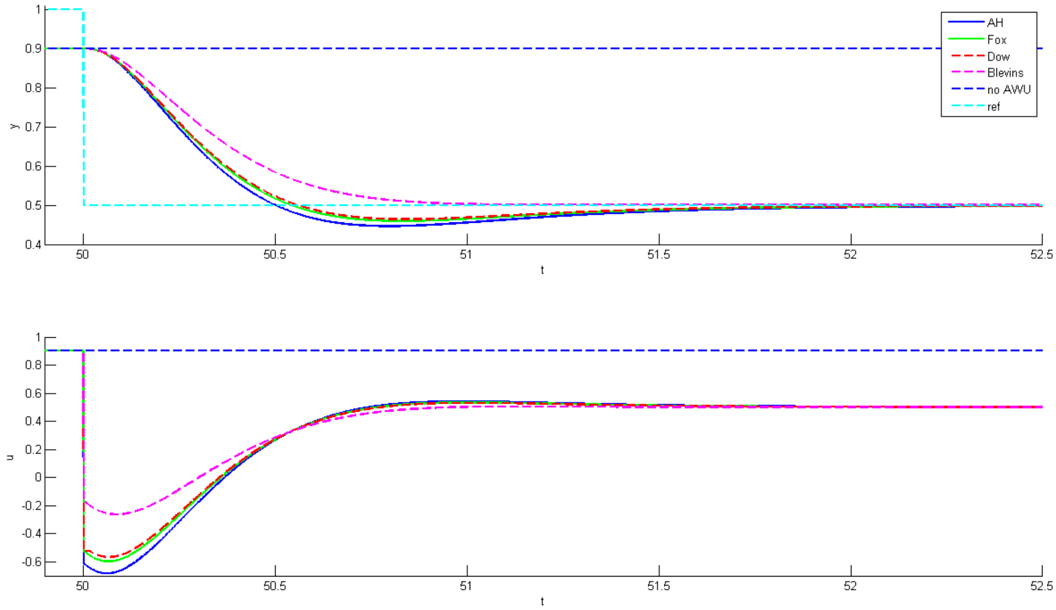

Figure 16: A negative reference step of process 3 after long time of saturation handled by PI control.

The differences in the step that occurs directly upon the setpoint change depends on how the controller has handled the integrator windup. The Foxboro and Dow methods integrators have settled on the saturation level when the setpoint change occurs. The AH method has the integral part slightly below the saturation due to the back-calculation from the proportional part. Blevins method have stacked up the integrator much higher with the variable preload which results in the smaller step, the controller then immediately switches to normal control since the controller no longer is saturated.

Load disturbance

In figure 17 a load disturbance step is added to the controller after a longer time of saturation. Blevins method reacts earlier then the other methods, which leads to less of an overshoot. The AH method reacts slightly faster than the Foxboro and Dow methods.

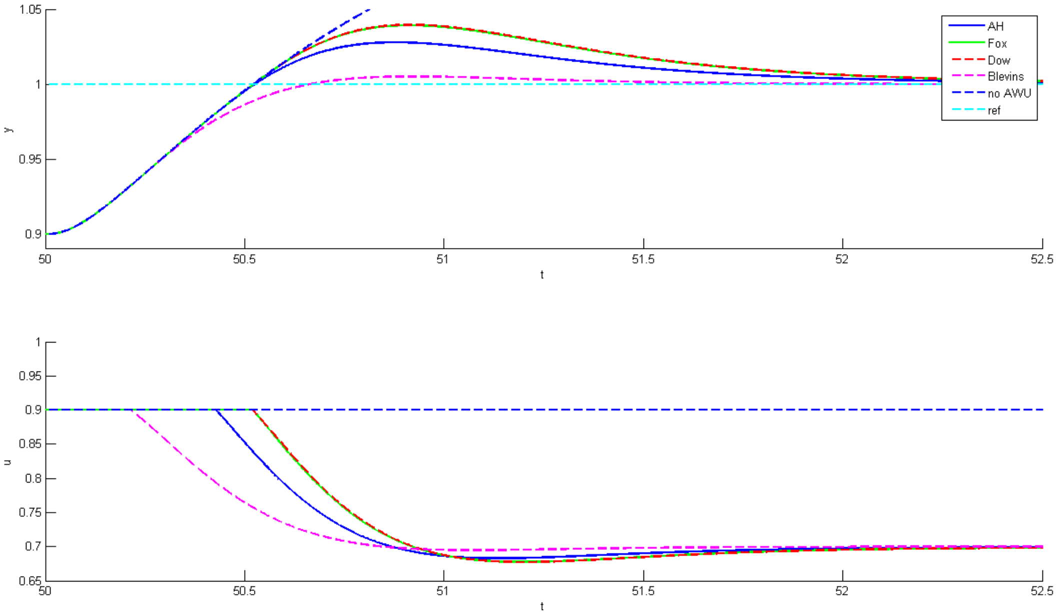

Figure 17: PI control of process 3 when a load disturbance step occurs after long time of saturation.

The Foxboro and Dow method does not react until the proportional part changes sign, leading to the largest overshoot.

Before the load disturbance step occurs, the integrator of the AH method has balanced out beneath the saturation limit, in a balance between integral error trying to increase the error, and back-calculation reducing it. When the disturbance occurs, the boost to the actuator will help to reduce the error. The integrator reset will calculate without the load disturbance, and thus not be able to completely balance out the addition the error does to the integrator. The integrator adds up towards the upper saturation limit during a short while until the proportional part is small enough for the sum of the controller parts to be below the saturation. The integrator is added up to almost the saturation limit by that time, and thus the response is similar to that of the Foxboro and Dow methods. A smaller T_t for the back-calculation of the AH method would result in an earlier response with less overshoot, similar to that of Blevins method, it would however result in slower settling time for the step response, and a larger overshoot for the reference step case.

Blevins methods integrator has instead settled a little over the saturation limit before the load disturbance occurs, however the preload quickly reduces the integrator as soon as it can when the load disturbance occurs, to then switch to normal control as soon as the summarized control action has been reduced back down to the saturation level, leading to earlier response with less overshoot.

4.4 Process 4

Process 4 has a single pole with time delay, and the transfer function $P_4(s)=\frac{1}{(1+sT)}e^{-Ls}$ where the parameters are chosen as $L=0.1$ and $T=1$ leading to $\tau=\frac{L}{L+T}=0.091$ which means it has lag dominated dynamics. The PI parameters is calculated as suggested in the book [4, p.228] for AMIGO tuning [4 p.225] as $K=\frac{0.15}{K_p}+\left(0.35-\frac{L T_p}{(L+T)^2}\right)\frac{T}{K_p L}=2.8236$ and $T_i=0.35 L+\frac{13\ LT^2}{T^2+12\ LT+7\ L^2}=0.6077$. The actuator saturation is chosen as 1.1 for the initial step, and 0.9 for load and reference step. Method specific parameters can be seen in table 4.

Method	***Additional parameters***
AH	$T_t=0.1\mathrm{T}_i=0.0608$
Dow	$T_t=0.1\, T_i=0.0608$
Foxboro	
Blevins	$T_{i_{PL}}=\frac{T_i}{2}=0.3038$, $T_{d_{PL}}=1$, $F=1$

Table 4: Method parameters for PI control of the time delayed process 4.

Initial step

Figure 18 shows the system output and control action of the PI controllers handling an initial step of process 4.

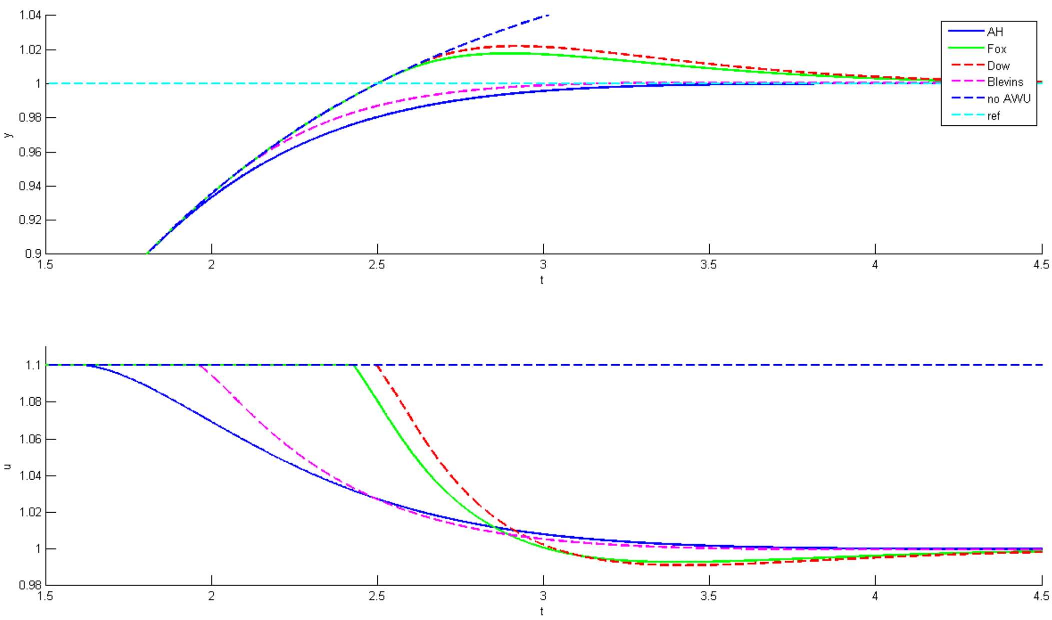

Figure 18: An initial reference step for process 4 handled by PI controllers.

When looking at the integrator parts of the AH method, the back-calculation kicks in due to the proportional part and pushes the integrator to a negative number. The integrator then adds up and reaches zero again almost a second after the step occurred. The controller leaves the saturation when both the proportional part and the integral part are small enough. The slow and smooth control reaction is because the integrator is still growing, while the proportional part is reducing, leading to them partly cancel each other out.

The Dow method has a saturated integrator which is reduced to the saturation level by the back-calculation. The control signal changes first when the proportional part changes sign. The Foxboro method reacts slightly ahead of the Dow method, this is because the integrator does not completely saturate, so that the proportional part only needs to get close to zero for a reduction in control signal below the saturation level to occur.

Blevins methods integrator saturates, to then be pushed down below the saturation level until the sum of the controller parts reaches the saturation level, first then is the preload switched off. This makes it possible for the method to react before a setpoint is reached.

Reference step

In figure 19 is a comparison of the methods way to handle a negative reference step after a longer time of saturation.

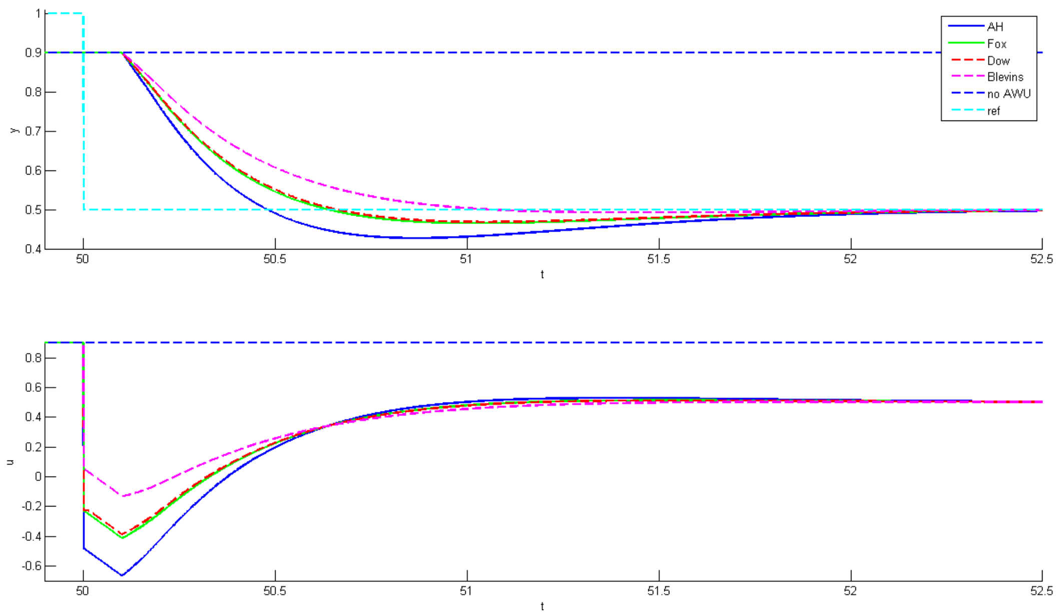

Figure 19: Long time of saturation followed by a negative step in reference for the time delayed process 4.

When looking at the control signals for the different methods for a reference step of process 4 we notice that the methods have similar behaviour, with the big difference being the initial control step when the setpoint is changed. This is similar to the reference step for process 2 and 3, where the level that the integrator has settled on leads to the size of the control action step after the reference change. The control signal is edged due to the time delay of the system.

Load disturbance

The load disturbance response of process 4 can be seen for the PI controllers in figure 20.

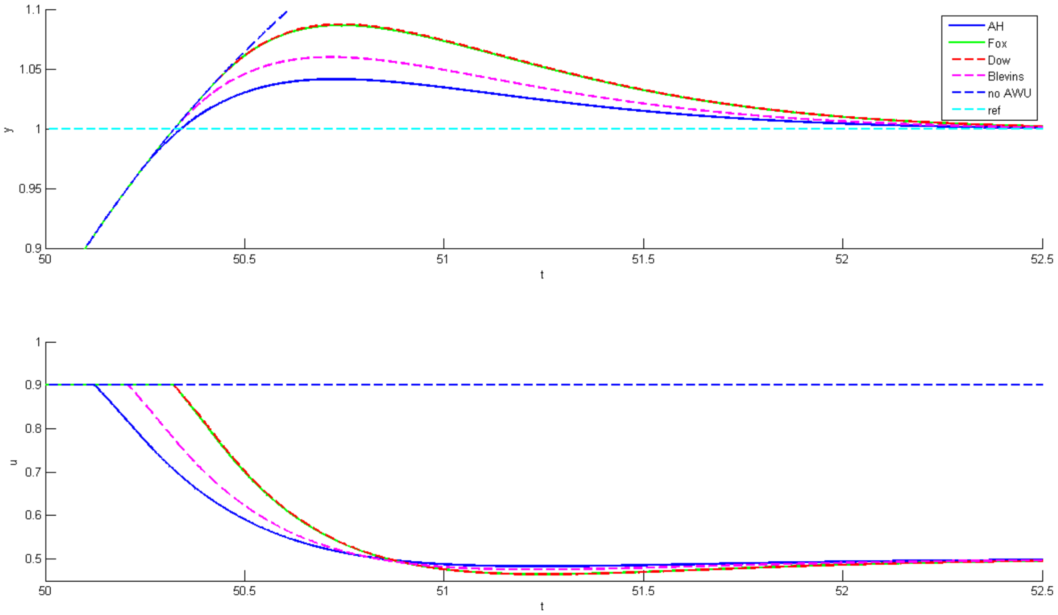

Figure 20: A load disturbance step after a long time of saturation. Note that Foxboro and Dow method is almost identical and plotted on top of each other.

For the load disturbance step we see that the AH method reacts earliest, and can by early control counter the overshoot the most. The reason the AH method can react fast is that the integrator is not saturated thanks to the back-calculation of the entire control signal, which makes the controller react to the proportional part almost directly. The Blevins method do have a integrator part that alone saturates the controller, however the variable preload will reduce the integrator part to below the saturation limit when possible so that the controller still can react fast. Being unable to act before the sepoint is reached is the big problem for the Foxboro and Dow methods when using a PI controller, which we are reminded of here.

4.5 Process 5

Process 5 has two poles and a time delay. The transfer function of process 5 is $P_5(s)=\frac{1}{(1+0.05s)^2}e^{-s}$. This process has delay dominated dynamics and the controller parameters are chosen after the MIGO design [4 p.250] to $K=0.17$ and $T_i=0.404$. The method specific parameters can be seen in table 5.

Method	***Additional parameters***
AH	$T_t=0.1\mathrm{T}_i=0.0404$
Dow	$T_t=0.1\,T_i=0.0404$
Foxboro	
Blevins	$T_{i_{PL}}=T_i=0.404$, $T_{d_{PL}}=1$, $F=1$

Table 5: Controller parameters for the different methods used for PI control of process 5.

Initial step

The controllers do not differ for the initial step of this process since the MIGO design parameters do not saturate the controller, therefor no figures are presented for this case.

Reference step

There is only a small difference between the methods for the reference step of process 5, which can be seen in figure 21.

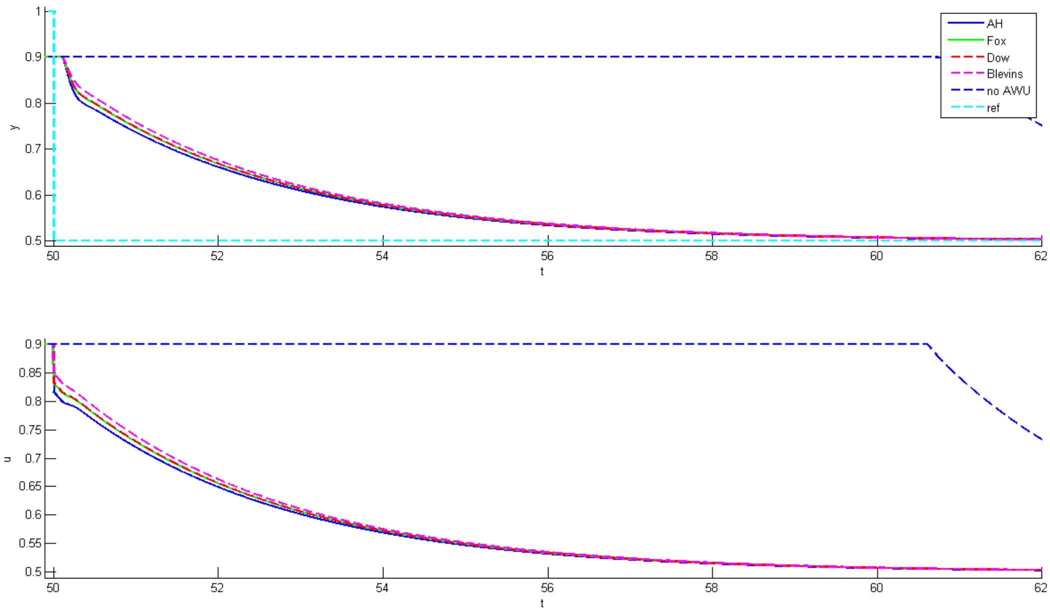

Figure 21: PI control of a reference step change of process 5 after a longer time of saturated actuators.

The methods behave very similar, and the only thing that separates their response to the reference step is where the integrator has settled after the long time of saturation. The Foxboro and Dow methods integrator have settled at the saturation value, while the Blevins methods preload value have balanced the integrator to slightly over the saturation level and the AH methods integrator was slightly below due to back-calculation.

Load disturbance

The difference for the load disturbance step of the PI control of process 5 is also very small, as can be seen in figure 22.

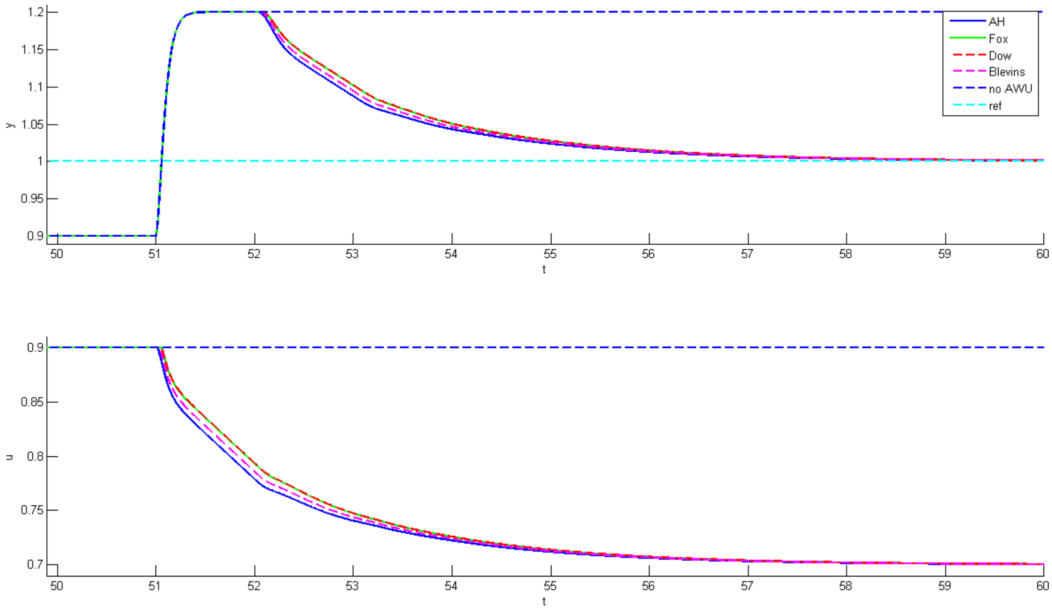

Figure 22: Process 5 with PI control, handling a load disturbance step after a long time of saturation.

The difference between the methods is very small, and the only real difference being the value of the integrator. Here it is shown as earlier control action instead of a larger initial step. The control action is reduced below the saturation limit when the proportional part is small enough so that it together with the relative stable integrator level is below the saturation. One difference here from the reference step change is however that Blevins method now is between the AH method and the two other methods. The reason for this is that the variable preload is used for a short time and is able to repress the integrator to below the saturation level in that time.

4.6 Variations of back-calculation time constant T_t for PI controllers

The back-calculation time constant T_t is used both for the Dow and the AH method. To analyse how this parameter affects the controller performance for the PI controller the control and output signal is simulated for different values of T_t as can be seen in figure 23 for process 3.

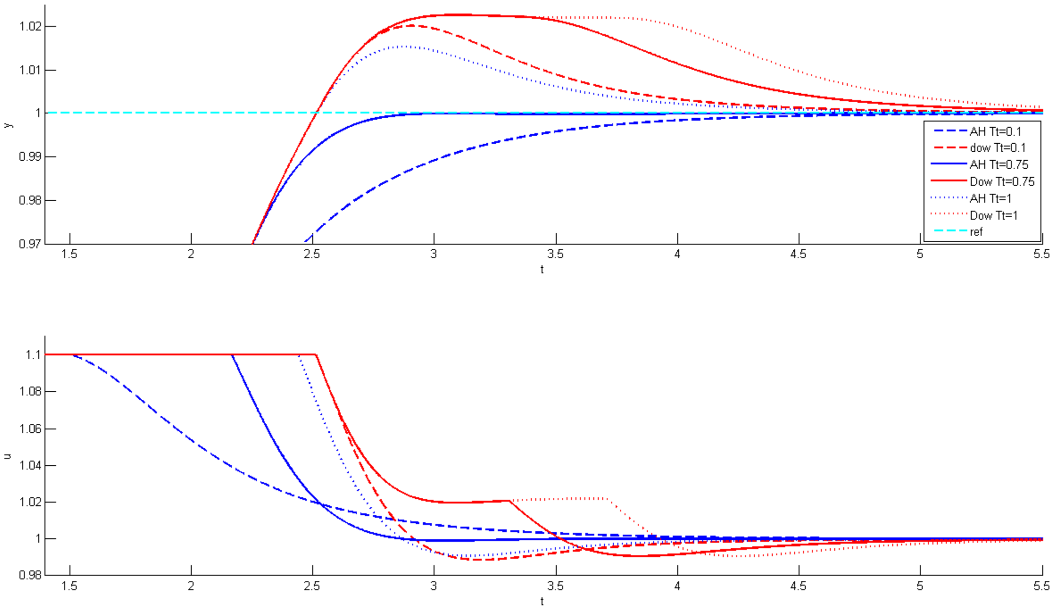

Figure 23: Back-calculation constant T_t *variations for the PI versions of the AH and Dow methods, here seen on the initial step of process 3.*

As can be seen the T_t value affects the two methods quite differently. For the AH method a fast integrator reset leads to a reduced control signal earlier due to being driven by the proportional part mainly, until output signal is close to the setpoint where the integrator part dominates the control signal again. This leading to T_t being a parameter that can help tune the controller.

For the Dow method the T_t parameter however works a little differently. The back-calculation resets the integrator a little slower for the Dow method since it wont kick in before the integrator is saturated, instead of the whole control signal. For larger values of T_t the control signal of the Dow method gets somewhat divided in such a way that the controller takes a step, then is unchanged for a short while, and finally take step to correct the output signal. The reason for this divided behaviour is that the integrator is still saturated, and the proportional part wants to depress the output signal. Since the integrator saturation is set to the same value as the actuator, and then added to the proportional part which will reduce the total output signal to below the saturation value and balance out. The second step of the divided control signal is due to the integrator resetting.

5. PID Control

The AH and Dow methods on parallel form as well as the Foxboro method are also compared for PID control. In addition to the three different cases looked at in the PI comparison, two kinds of measurement disturbances will also be tested for the PID controllers since noise can be a problem especially when using derivate action. The controller parameters are taken as suggested by PID MIGO design, and the method specific parameters T_t is then chosen to get a good overall performance for the different cases at that specific process.

The Foxboro controller has a different parameterization so the parameters should not be the same as for the standard controller. The tranformation is only possible if $T_i > 4T_d$ which is the case for processes 1 and 4 but not for processes 2, 3 and 5. Testing the system with the transformed parametes we get a slight difference of the Foxboro method, shown in figure 25 for the initial step of process 1. The differences of the parameterizations will be discussed in chapter 5.1. Since we can not transform the parameters for all processes used, we will simply use the same parameters for the Foxboro method as for the other methods in the simulations.

5.1 Process 1

Let us again take a look at the single integrator that is process 1, but this time using PID controllers. The control parameters used are $K=3.414$, $T_i=0.5$ and $T_d=\frac{T_i}{10}=0.05$. As for the PI controller, the saturation is set to 0.2. The method specific parameters can be seen in table 6.

Method	***Additional parameters***
AH	$T_t=0.1T_i=0.05$
Dow	$T_t=0.1\,T_i=0.05$
Foxboro	

Table 6: Method specific parameters used for process 1.

Initial step

We start by looking at the step response of process 1. This can be seen in figure 24.

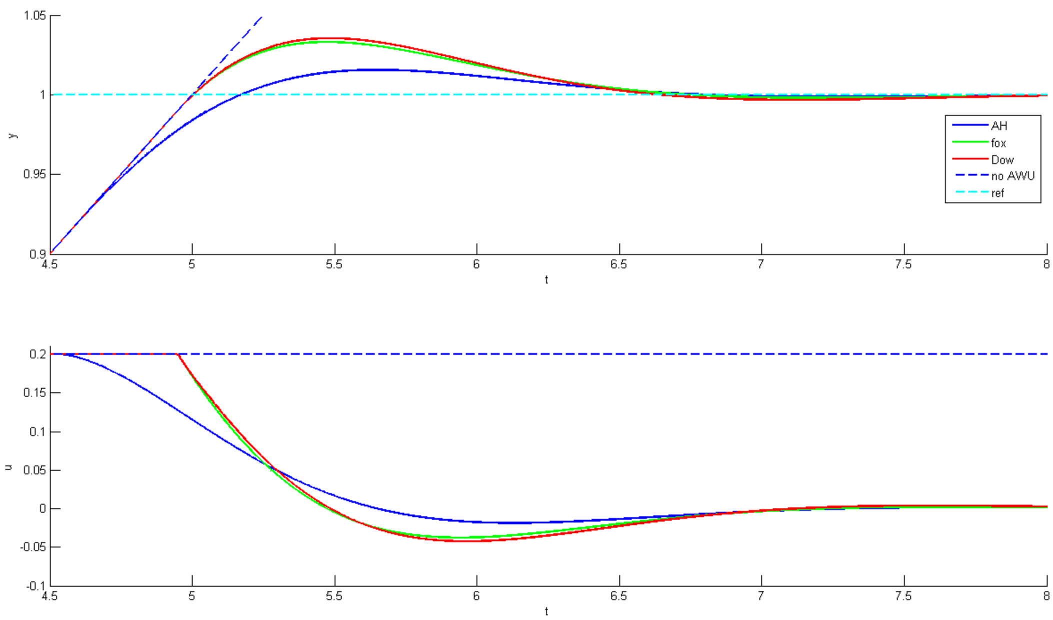

Figure 24: Step response of process 1 by the PID controllers.

The PID controllers are very similar to the PI version for the initial step of process 1 in figure 6, which is reflected in the different parts of the control signal where the derivative only makes a small contribution. For larger derivative gain the AH method is able to react earlier and by doing so, able to reduce the overshoot more than the other methods.

Alternative parameterization for the Foxboro method

The PID Foxboro method is designed a little different compared to the others, leading to a different transfer function which is called interacting form:

$$C(s)=K\left(1+\frac{1}{sT_i}\right)(1+sT_d)$$

The non-interacting form used by the other methods controller has the transfer function:

$$C(s)=K\left(1+\frac{1}{sT_i}+sT_d\right)$$

If the criteria $T_i>4T_d$ is fulfilled a parameter transformation is available to make the two forms correspond [4, p.71]. For process 1 the Foxboro method would then use the parameter $K=3.0292$, $T_i=0.4436$ and $T_d=0.0564$ which is close to the original parameters used. In figure 25 we can see the initial step of process 1 again, now with both the parameter choices for the Foxboro method represented. The plot is also zoomed in more than figure 24, to easier show the differences.

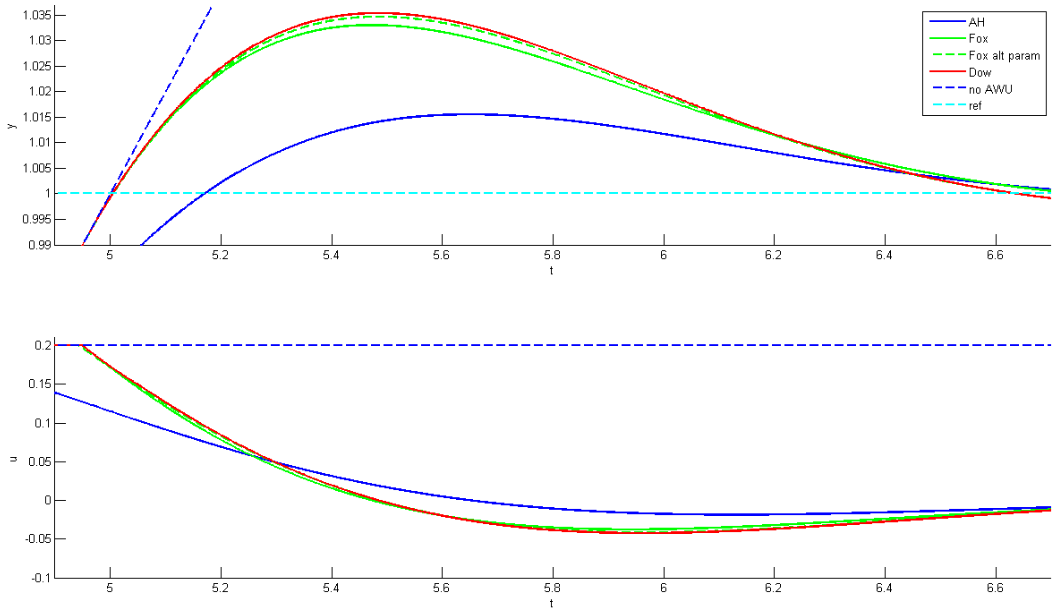

Figure 25: Initial step of process 1 for PID control, comparing the parameterization differences for the Foxboro method.

Above we can see that the difference between the parameter changes seen as dashed lines is similar to the standard parameters used. The alternative parameters makes the Foxboro method approach the curve for the Dow method, this occurs also to the other cases for both process 1 and 4.

Reference step

Figure 26 shows PID control for a negative reference step of process 1.

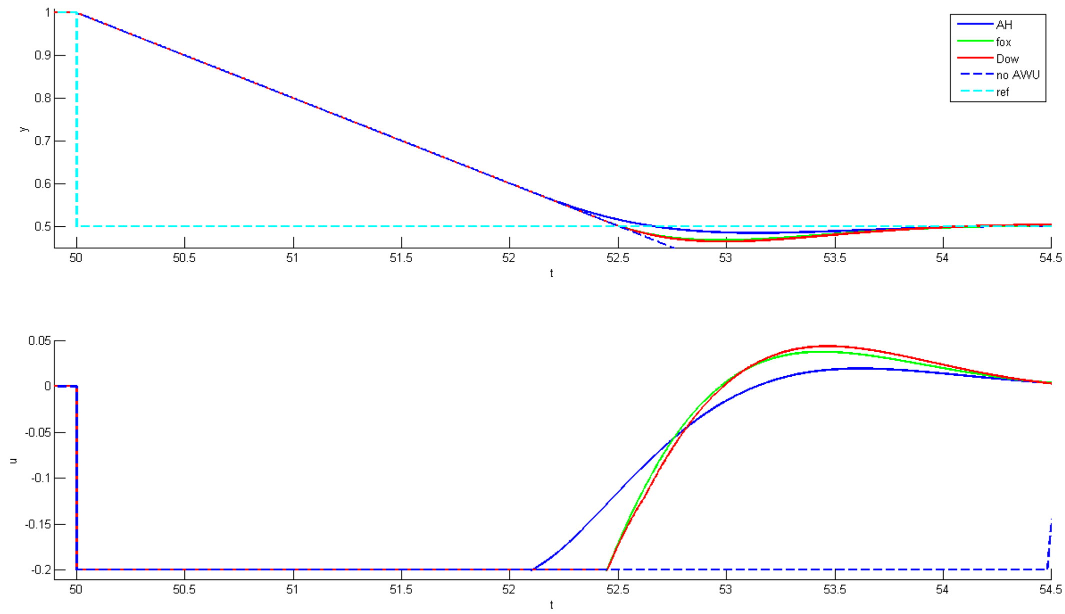

Figure 26: PID control on process 1 for a negative reference step.

The derivative gain is small, so the behaviour is very similar to that of the PI version, where the AH method reacts earlier, and by doing so is able to prevent as large of an overshoot. The Foxboro control signal varies a little from the Dow methods within the working range of the actuator, the variation is however very small.

Load disturbance

When looking at the PID version of the load disturbance step of process 1, the PID controllers perform similar to the PI controller, however the Foxboro method varies some for the PID case as can be seen in figure 27.

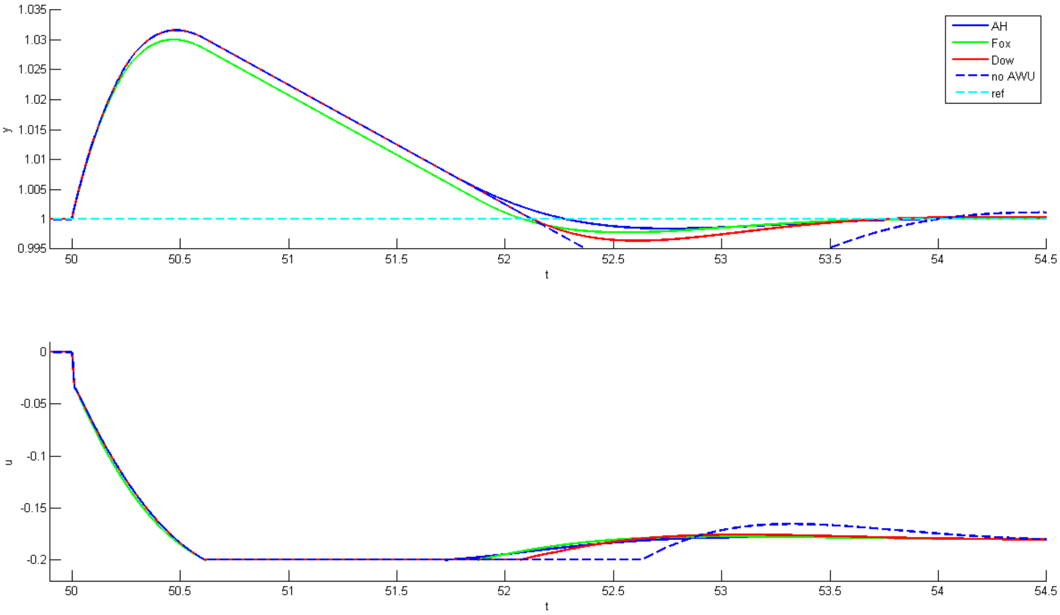

Figure 27: PID control on process 1 with load disturbance.

For the load disturbance case of process 1 the performance of the the PID controllers are similar to the PI version. The noticable difference is in the Foxboro method, where the system output varies from the other methods in the first overshoot after the disturbance is applied. The reason of this variation is the parametrization differences. By changing the parameterization the Foxboro follows the other methods for the first overshoot, and draws closer to the Dow method for the second overshoot, but maintain between the two. The Foxboro method integrates the saturated control signal instead of the system error, which also leads to some of the differences between the Foxboro and Dow method. When looking at the settling after the bump made from the load disturbance, the AH method is able to reduce the overshoot the most, mainly by its early reactions just like in the PI case.

5.2 Process 2

Process 2 has balanced dynamics and four equal poles, with a transfer function $P_2(s)=\frac{1}{(s+1)^4}$. We use the PID MIGO controller parameters $K=1.19$, $T_i=2.22$ and

$T_d = 1.21$ as suggested in the book [4, p.249]. In table 7 the additional parameters used by the various methods can be seen.

Method	***Additional parameters***
AH	$T_t = 0.1 T_i = 0.222$
Dow	$T_t = 0.1\, T_i = 0.222$
Foxboro	

Table 7: Parameters for the PID methods of process 2.

Initial step

In figure 28 is the step responses for process 2 of the PID controllers shown.

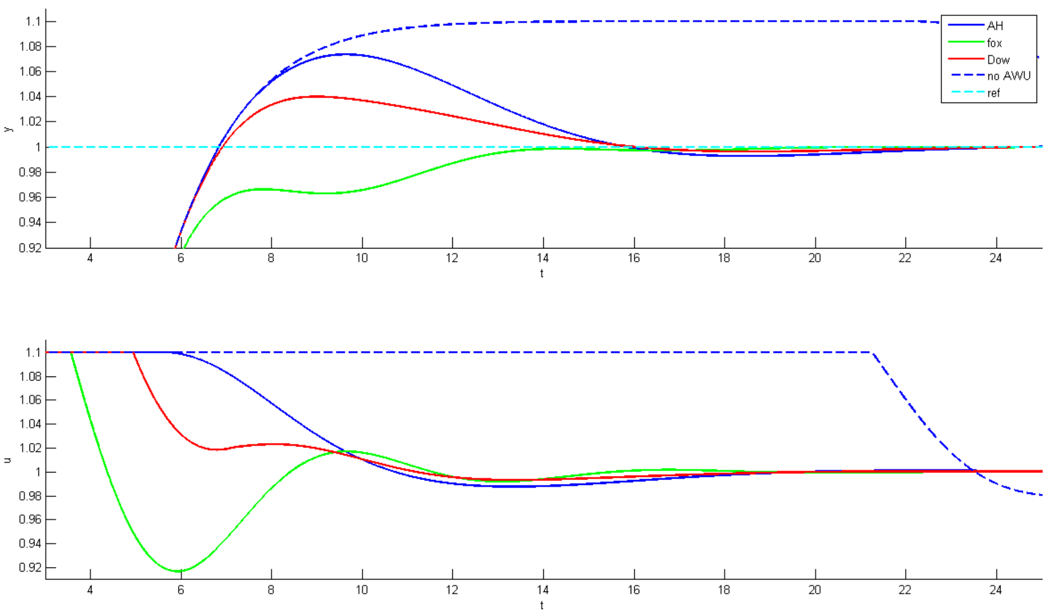

Figure 28: PID control for the initial step of process 2.

For the PID comparison of the initial step of process 2 we find that the Foxboro method reduces its control signal 1.5-2 seconds earlier than the other methods, and by doing so avoids the problems with overshoot. After some small oscillations the Foxboro method also settles a little faster than the other methods. The big thing that differs between Foxboro and the other two methods is that the Foxboro method keeps its integral part below saturation limit during the rise, while the other two methods do not. The Dow method does however limit its integrator to exactly the saturation limit, which then results in a step slightly before setpoint is reached, due to a negative derivative part just slightly outweighs the proportional part before the setpoint is reached. The AH method do also react before the setpoint is reached, however the integrator is over the saturation limit, which means the derivative part has to counter both the proportional part and the overshoot from the integrator before any action is taken.

Reference step

The Foxboro method also has a more aggressive and fluctuating control action for the reference step of process 2, as can be seen in the comparison of the PID methods of this case, in figure 29.

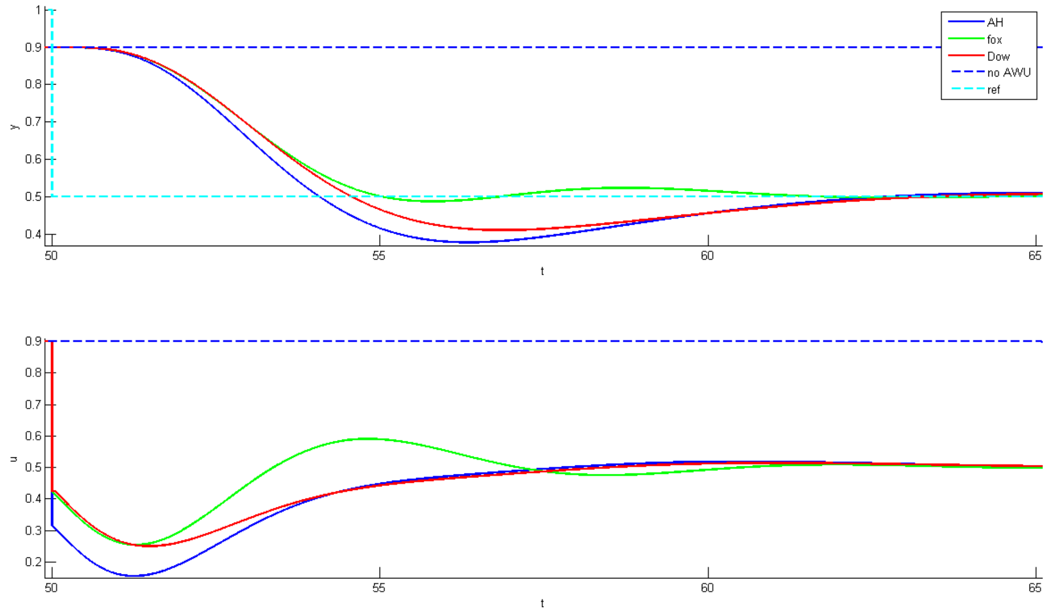

Figure 29: PID control for a reference step on process 2.

For a reference step we see that the first action taken after the reference step looks like that of the PI control case, where the only thing really separating the methods results being the amplitude of the control action, which differs since the integrator is reset to different values after a long time of saturation. The Foxboro method does however not react the same as the other two methods slightly after the initial step is taken. The PID version of the Foxboro method adds the derivative part to the control signal before the filter which acts as the methods integrator has made its integration, compared to the other methods which integrates only the error. The Foxboro method has a much smaller overshoot and settles faster, however with some oscillations still taking place.

Load disturbance

When adding a load disturbance step on the PID controlled process 2 the overshoot is reduced and the settling time shorter, the biggest difference is in the behaviour of the Foxboro method. The load disturbance response can be seen in figure 30.

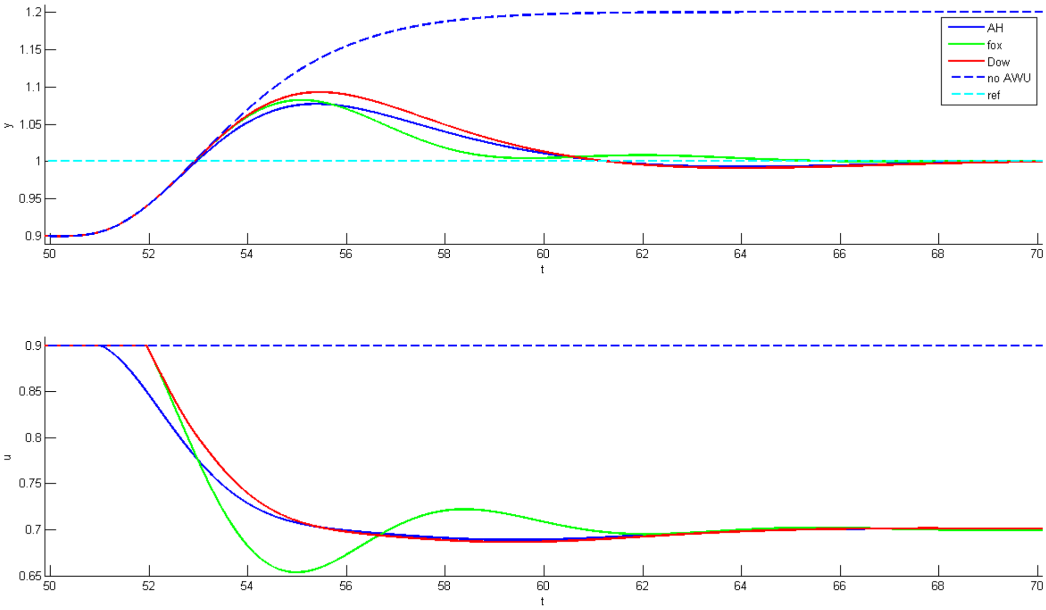

Figure 30: PID control for a load disturbance step on process 2.

For the load disturbance step we see that the AH method starts reducing the control signal earliest. This happens because the AH methods integrator has settled below the saturation level before the disturbance takes place, while the other two methods are at the saturation. For the AH method, the derivative part thus does not have to counter the whole proportional part before the control signal starts reducing, which would be the case for the other two methods. The Foxboro method reduces its overshoot faster with more aggressive control action. The integrator starts reducing earlier for the Foxboro method, since it also integrates the derivate part, which at that point is negative.

5.3 Process 3

Process 3 has four poles and is lag dominated. PID MIGO parameters [4, p248] are used for the controllers, which is $K=56.9$, $T_i=0.115$ and $T_d=0.0605$. The controller specific parameters are set as can be seen in table 8. The transfer function for the lag dominated process is $P_3(s)=\frac{1}{(1+s)(1+0.1s)(1+0.01s)(1+0.001s)}$.

Method	***Additional parameters***
AH	$T_t=0.1\mathrm{T}_i=0.0115$
Dow	$T_t=0.1T_i=0.0115$
Foxboro	

Table 8: Method parameters for PID control of process 3.

Initial step

In figure 31 the step response for the PID controlled process 3 can be seen.

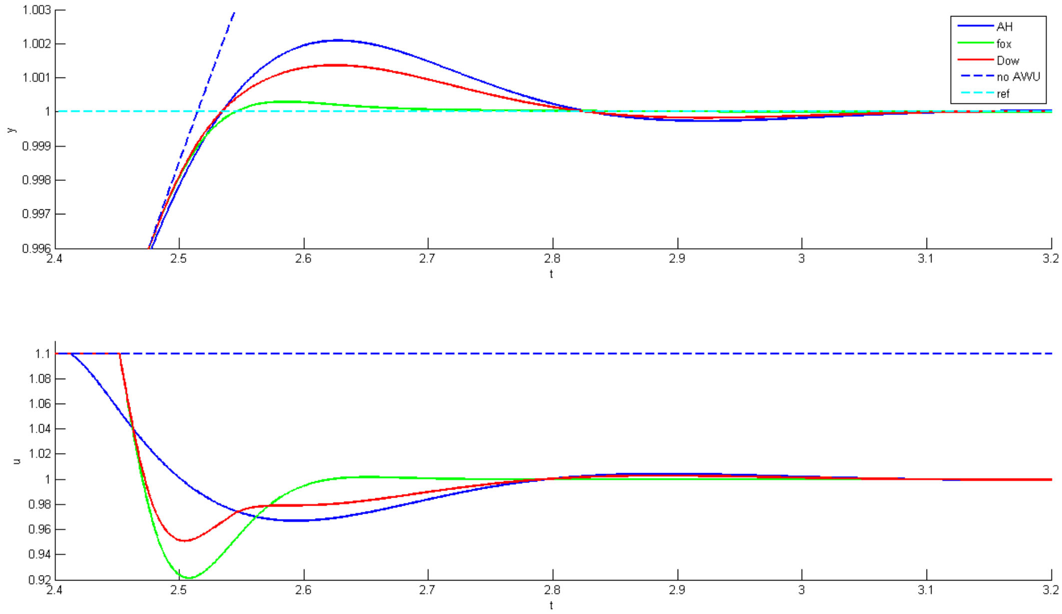

Figure 31: PID control on process 3 for the initial step.

When looking at the AH controller signal, the step taken by the proportional part with the large K used drives the integrator down to negative by the back-calculation. The integrator then builds up and gets positive, but not saturated before the whole controller signal leaves the saturation. The derivative part is negative during the rise and helps reduce the control output to below the saturation level earlier.

For the Dow method the integrator saturates and resets down to the saturation level. The control signal changes sign before the setpoint is reached because of the negative derivative part, so that the control output begins to fall under the saturation level when the derivative outweighs the proportional part. The integral part is still saturated when the actuator takes its larger negative step and reduces below the saturation about the time for the small peak after the big dip.

The Foxboro method is similar to the Dow method in the way that integrator is saturated, and the control signal is reduced below the saturation when the derivative part outweighs the proportional part. The difference is that the integral part immediately starts reducing for the Foxboro method when the actuator no longer is saturated instead of the 0.1 seconds delay that the Dow method had. This difference is that the Foxboro methods integral part starts reducing when the derivative counters the error, instead of when the error changes sign.

Reference step

In figure 32 a negative reference step is added to process 3, controlled by PID controllers.

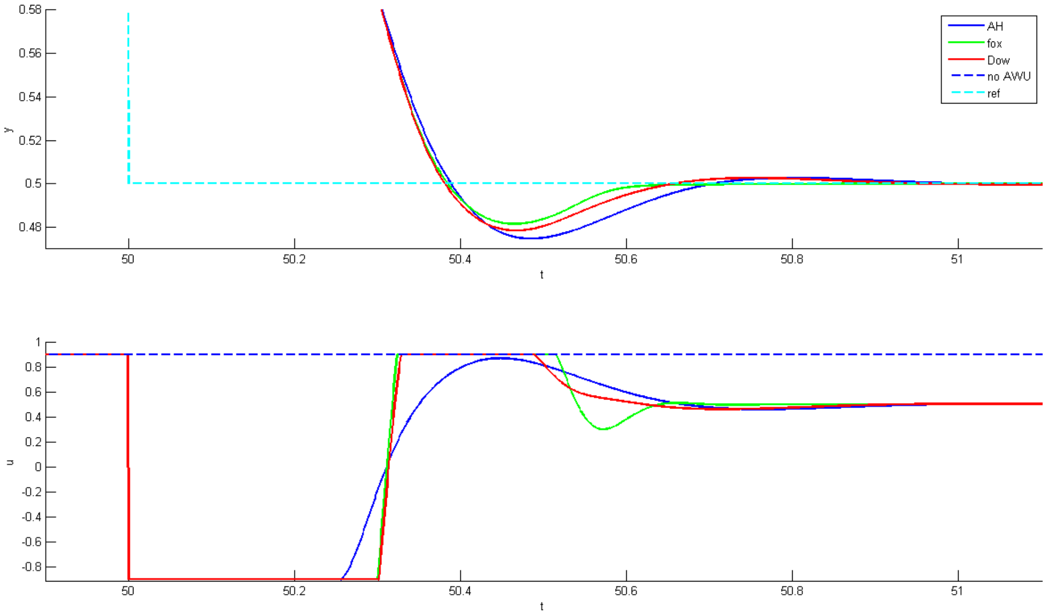

Figure 32: PID control for a negative reference step on process 3.

We can see that the Foxboro method also gives a slightly better output for a reference step after a longer time of saturation. When looking at the control signal the AH method shows a smoother behaviour rather then the bang-bang like behaviour shown by the other two methods. The reason for this is that we have a very strong proportional gain that with the help of the back-calculation will build up the integrator which will counter the proportional part. When the new setpoint is reached and the proportional part changes sign, the integrator has just been pushed down to negative, and again somewhat counters the proportional part.

When looking at the integral windup of the Foxboro and Dow method they behave more predictable. The Dow methods integrator quickly becomes negative when the reference step occurs, but is limited by back-calculation to the lower actuator limit. The Foxboro methods integrator decline more slowly, but has almost reached the lower actuator saturation when the controller output is increased again. The increase of the control signal starts before the setpoint is reached due to derivative action. The reason for the difference in correction of the overshoot between the Dow and Foxboro methods originates from the integral part where the Foxboro methods integral part is closer to zero when the control signal changes.

Load disturbance

When looking process 3 with a load disturbance step, the AH method uses smoother control action, however the more aggressive Foxboro method is able to produce a much better system output than the other methods, as can be seen in figure 33.

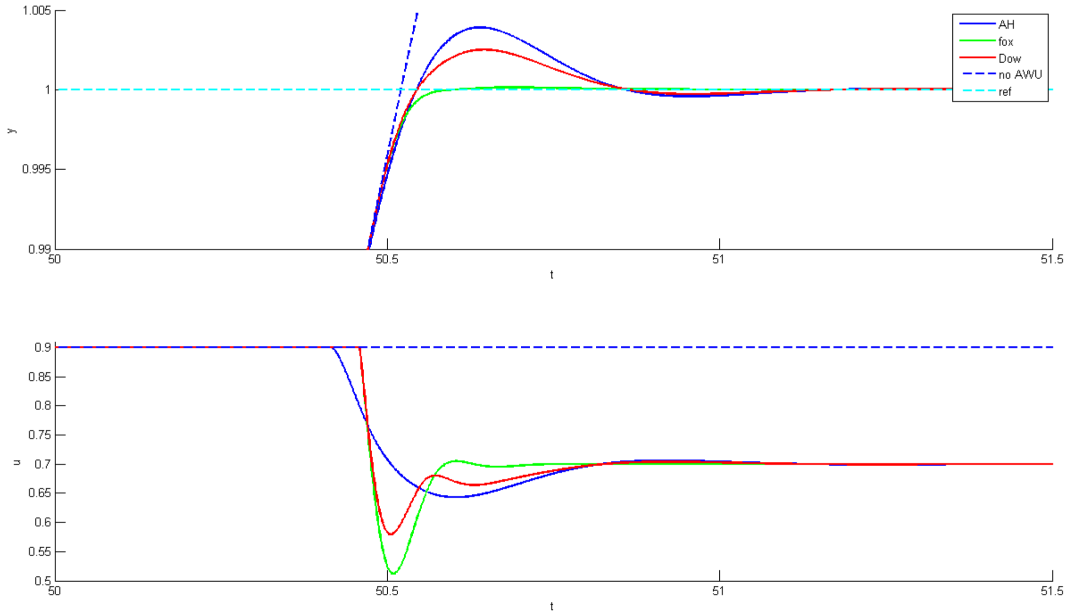

Figure 33: PID control for a load disturbance step on process 3.

In the case of load disturbance, the AH methods back-calculation has pushed the integrator to a negative number by the proportional gain. The integrator is then building up while the proportional decreases, it has not yet saturated when the proportional gets small enough for the derivative part to reduce the control signal. Since the AH methods integrator is not at the saturation level, but the other two methods integrator still is, it can react earlier. The smoother behaviour of the AH method origins from the integrator that is building up and overshoots the saturation limit for a short while during the control signal reaction takes place.

For both Foxboro and Dow method the integrator is saturated when the derivative part outweighs the proportional and integral part, which results in the same reaction time for these methods. The difference is that the Foxboro methods integrator starts reducing to below the saturation limit as soon as the control signal is no longer saturated. The Foxboro integrator also converges faster towards its new desired value, leading to a much better load disturbance response.

5.4 Process 4

The delayed single pole lag dominated process uses the simple tuning rules of AMIGO for its PID parameters [4, p 233].

$$K=\frac{1}{K_p}\left(0.2+0.45\frac{T_p}{L}\right)=4.7\ ,\ T_i=\frac{0.4L+0.8T_p}{L+0.1T_p}L=0.42 \text{ and } T_d=\frac{0.5LT_p}{0.3\text{L}+T_p}=0.0485$$

The actuator saturation is chosen as 1.1 for the initial step, and 0.9 for load and reference step. Method specific parameters can be seen in table 4.

Method	Additional parameters
AH	$T_t = 0.1\ T_i = 0.042$
Dow	$T_t = 0.1\ T_i = 0.042$
Fox	

Table 9: Method specific parameters for PID control of the time delayed process 4.

Initial step

The PID step response for the different methods of process 4 which has delay dominated dynamics can be seen in figure 34.

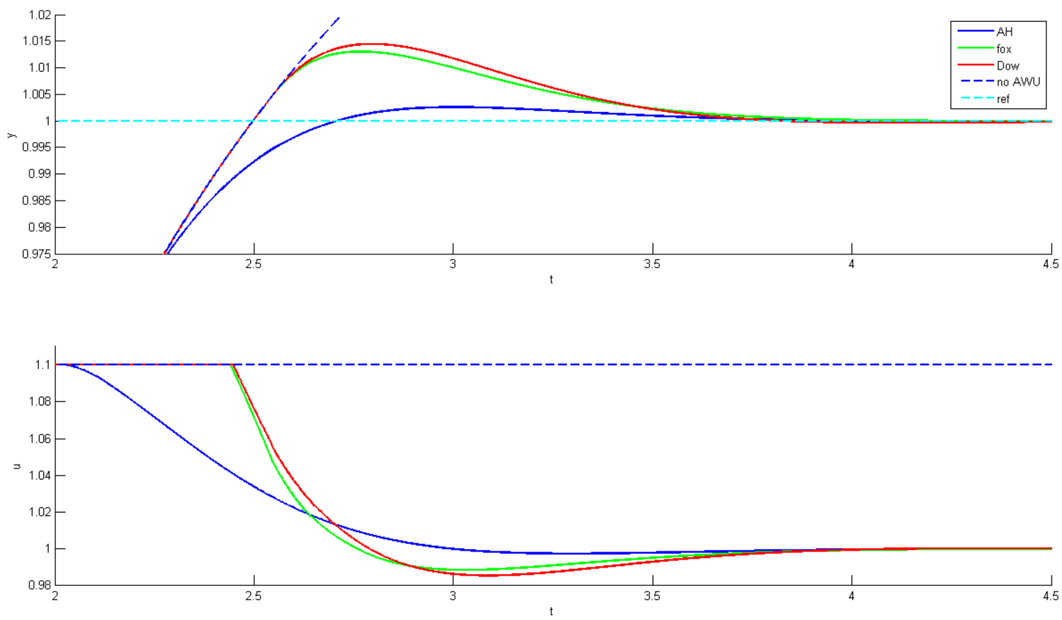

Figure 34: PID control of the initial step of process 4.

When looking at process 4 which has a time delay, we notice that the smoother control action taken by the AH method leads to less overshoot. The reason for the AH method's early reaction is that the integrator builds up much slower than for the other two methods, this is because the proportional part pushes the control signal into saturation, and the back-calculation of the integrator is actively trying to reduce the integrator.

Reference step

When a reference step occurs after a long time of saturation on process 4, the control action behaves somewhat jerky slightly after the reference step occur, which can be seen for the AH method, this can be seen in figure 35.

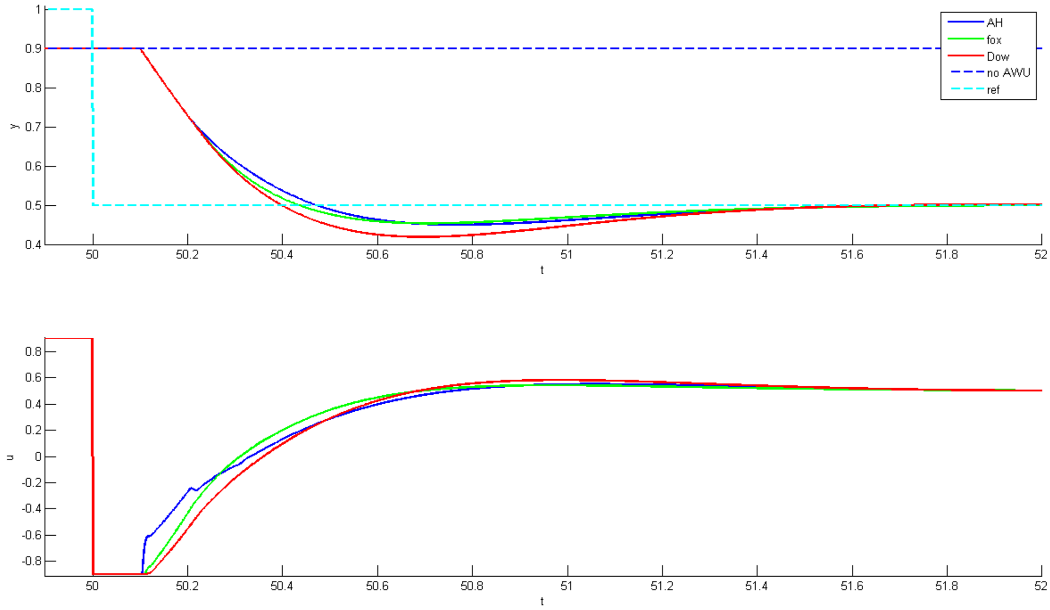

Figure 35: PID control of process 4 with a sudden negative reference step for saturated controllers.

When a negative reference step occurs for process 4 the methods behave quite alike in the performance, with Dow being slightly behind the other two methods. The AH methods control signal does however show on some strange behaviour caused by the derivative part on this time delayed process. The reason why we only see this behaviour for the AH method is that the proportional part has pushed the controller into the lower saturation limit, which for the AH method means that the integrator builds up, and the derivative anomaly takes place within the saturation instead of just outside the saturation area.

Load disturbance

The jerky control action of the AH method can also be seen for the load disturbance response, as seen in figure 36.

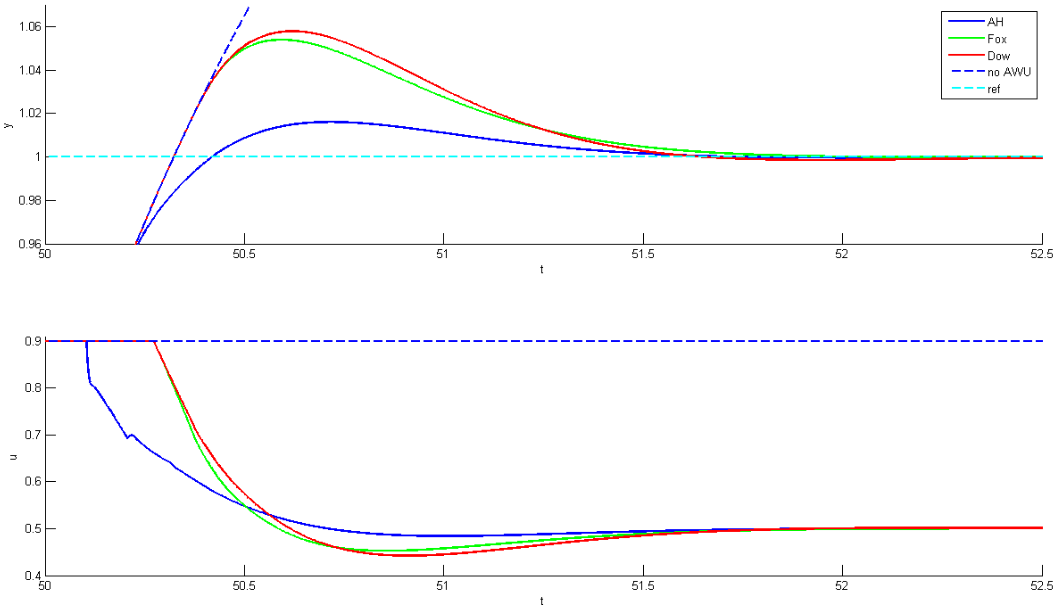

Figure 36: PID control on process 4 with a load disturbance step by saturated controllers.

For the load disturbance we see again the control signal for the AH method having some abnormalities due to the derivative part and process delay. With the help of the back-calculation the AH methods integrator is not saturated when the disturbance occurs, which leads to earlier control response. The AH methods control signal is also not as aggressive since the integrator builds up and counteracts the proportional and derivative parts. As can be seen a less aggressive controller can be preferred when dealing with delays. The Foxboro method's integrator starts decreasing from the saturation level slightly ahead of the Dow method, and the decrease is not as steep, which gives a small advantage over the Dow method.

5.5 Process 5

The shared controller parameters are set to the PID MIGO parameters [4, p.250] suggested in *Advanced PID Control*, being $K=0.216$, $T_i=0.444$ and $T_d=0.129$. The method specific parameters are set as seen in table 10. Process 5 is a time delayed process with two equal poles and the transfer function $P_5(s)=\frac{1}{(1+0.05s)^2}e^{-s}$.

Method	***Additional parameters***
AH	$T_t=0.1\mathrm{T}_i=0.0444$
Dow	$T_t=0.1\,T_i=0.0444$
Foxboro	

Table 10: Parameters for the PID controllers for process 5.

For this delay dominated process we notice that the difference between the methods is very small, and for the reference step and load disturbance step it varies only in the first step the proportional part takes, which is a little different depending on what level the specific methods integrator had settled on. However when looking at the initial step of this process, we can see that the Foxboro method can vary a little from the other two even though the controller does not saturate. The initial step is seen in figure 37, the reference step in figure 38 and the load disturbance step of this process can be seen in figure 39.

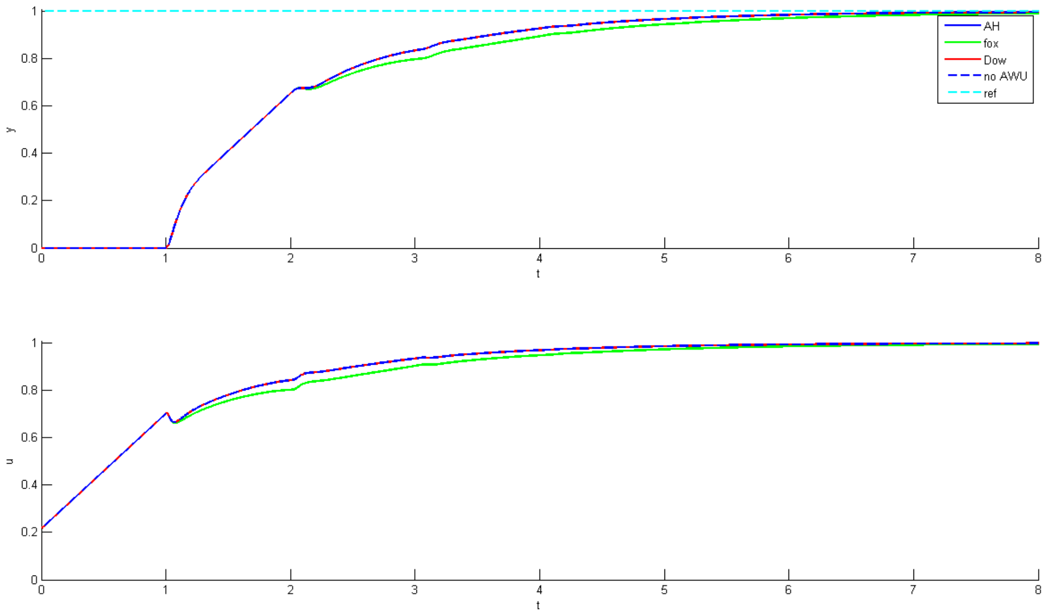

Figure 37: A step response for the PID controlled process 5.

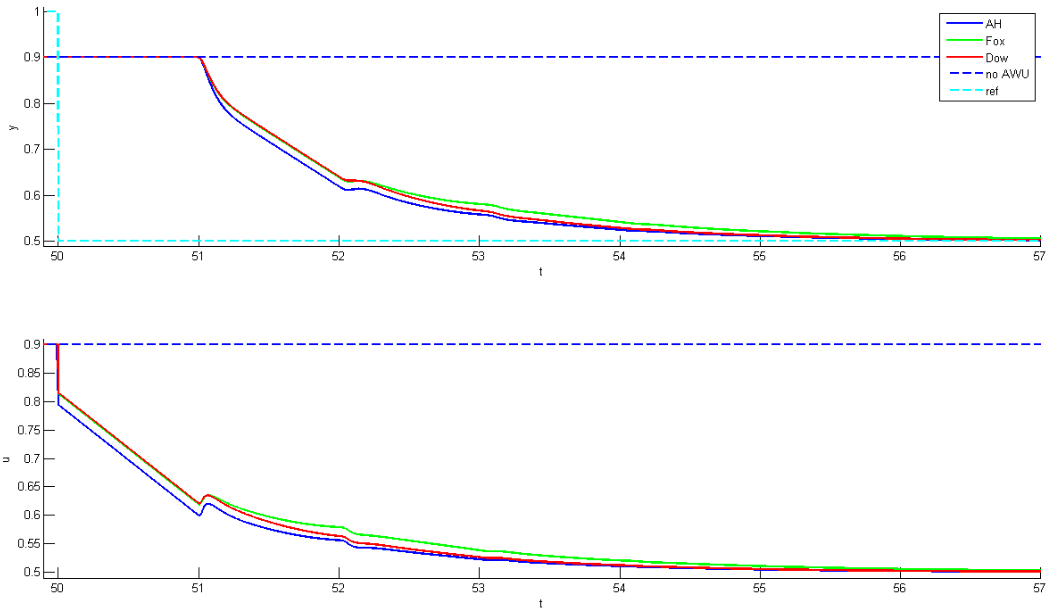

Figure 38: PID control on process 5 with subject to a negative reference step for a saturated controller.

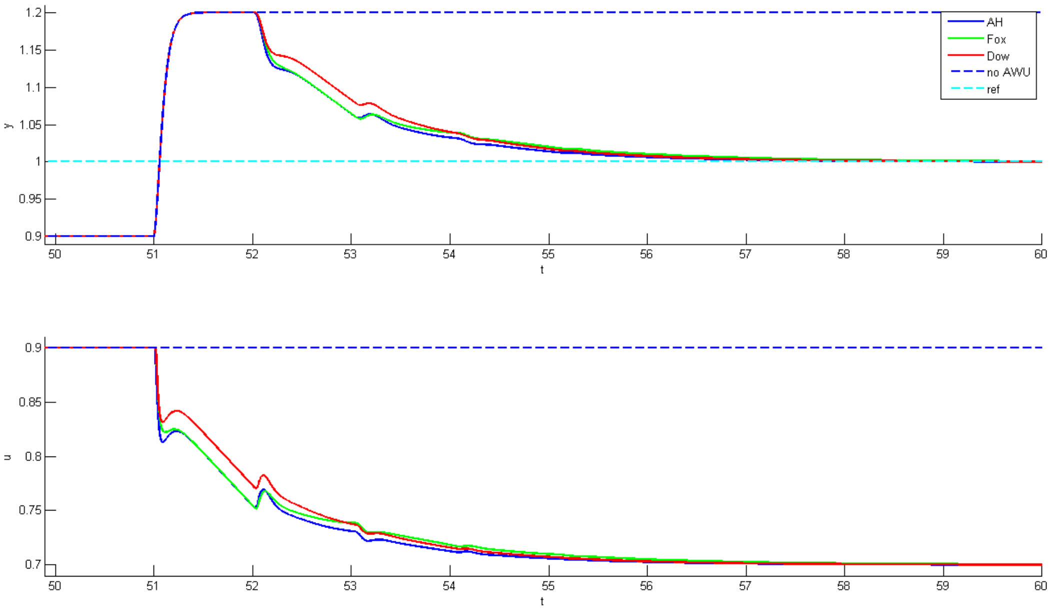

Figure 39: PID control of a load disturbance step for the delay dominated process 5.

The difference is small between deadtime dominated processes both for PI and PID control, which makes it less interesting for comparison.

5.6 Measurement noise

To further test the methods two kind of measurement disturbances were tested, both with band limited white noise and a pulse disturbance. The measurement disturbances displayed similar behaviour and relative ranking regardless of process, and therefor only some examples will be shown.

Band limited white noise

By adding band-limited white noise as measurement disturbance while the controller is at its setpoint close to the saturation limit, one side of the noise will push the controller into saturation where the control signal is adjusted to return to the controllers working area. This leads to some skewing and the methods can get problem keeping the process evenly balanced around the setpoint. When no anti-windup is used the mean value of the system output will be very close to the setpoint value, since the integrator does not reset due to saturation. The mean value will however be very slightly below the saturation since the actuator gets saturated for one side of the white noise, this is more or less as good as we can get the methods to handle this problem. Measurement noise is being shown for process 2 in figure 40.

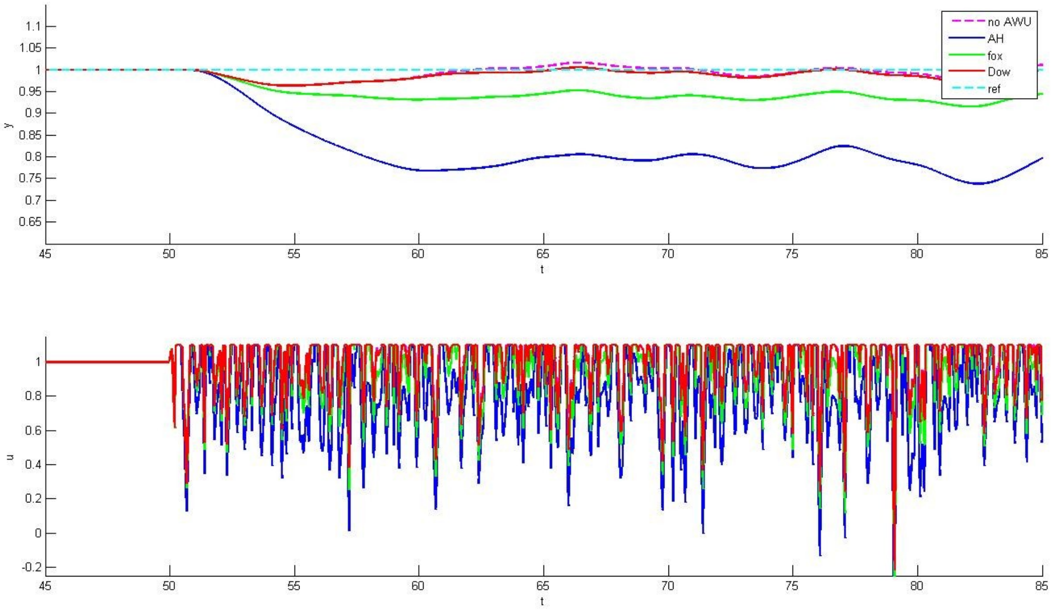

Figure 40: PID control of process 2 with added measurement noise that saturates the signal in one direction.

The Dow and Foxboro methods are both very close to keep the average system output balanced around the setpoint. The AH method does however have a harder time since the back-calculation reduces the entire control signal quite drastically each time the noise saturates the actuator, as can be seen in figure 41. By increasing the back-calculation time constant T_t the AH method can counteract some of this decrease. A larger back-calculation constant would however reduce the controllers performance in regards of the various other cases that has been tested, and the AH method would still only barely keep up with the performance of the other methods when facing measurement noise.

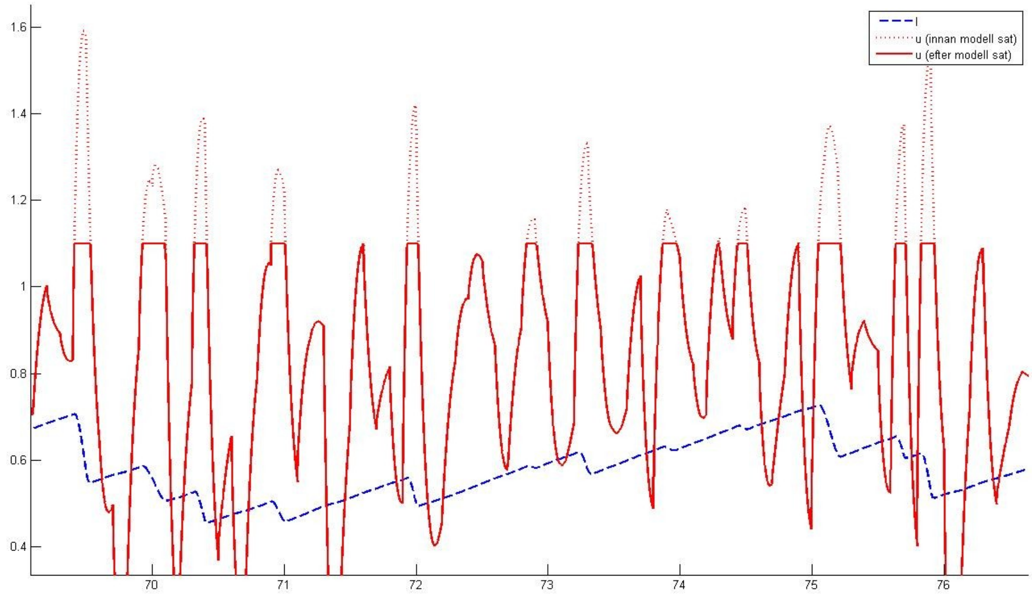

Figure 41: The control action and integrator values of the AH method for the PID controlled process 2 with measurement noise. The integrator is reduced by back-calculation when the control signal saturates.

The Foxboro method lets the desired control signal go through the saturation model before it is added to the integrator, which leaves a noise with uneven amplitude since the signal is only saturated in one direction. For both the AH and Foxboro methods the decline is balanced out by the proportional part when the error is big enough, which is very similar to an ordinary P controller which balances around a small error.

For the Dow method the white noise adds up to the integrator evenly distributed, regardless of saturation level, however the error in system output that is the effects of the white noise on the saturated actuator will be integrated and build up towards the saturation limit. The back-calculation will only reset the integrator down to the saturation limit. Compared to the AH method the integrator of the Dow method is not compromised as much, and not at all until it starts getting saturated, and can thus help balance average of the system much more then the integrator of the Foxboro and AH method can. In the analogy where the AH method acted as a P controller, the Dow method acts more like a PI controller.

Impulse measurement disturbance

A negative measurement disturbance pulse forces the controller to increase the control signal and saturate the controller. The reaction of this disturbance is quite similar for the different processes. The response for process 3 can be seen in figure 42.

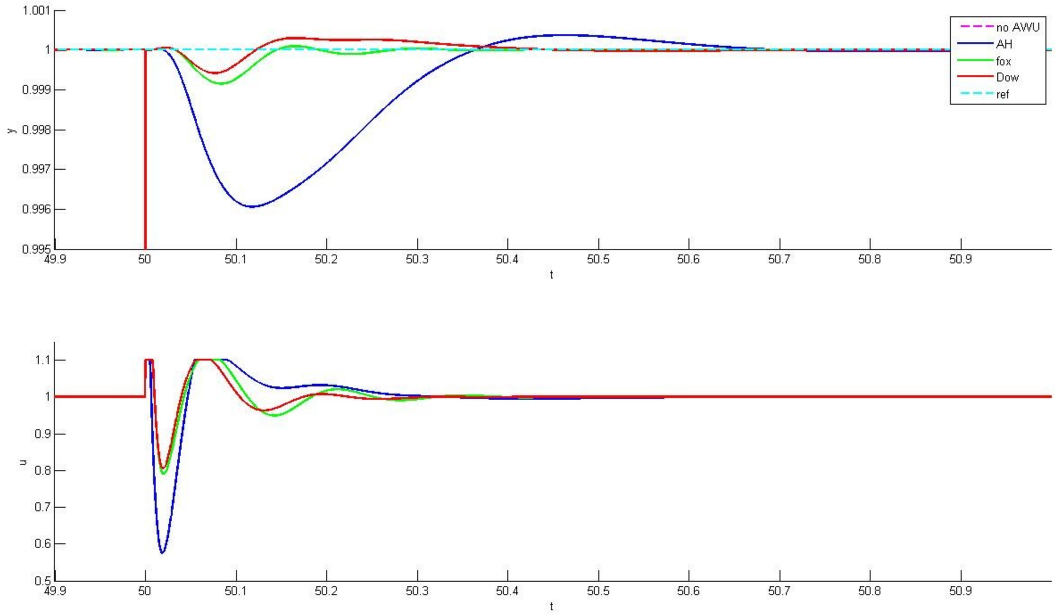

Figure 42: An impulse is added as measurement disturbance for the PID controlled process 3 where the control action taken after the disturbance occurs saturates the controllers.

We can see that the the Foxboro and the Dow methods have less overshoot and settle faster than the AH method here. Since the controller saturates to compensate when the disturbance pulse occurs, the integrator of the AH method resets and pushes it down a little. The controller is then slowly building up the integrator again when the pulse is gone and the setpoint is no longer reached.

Both the Dow and Foxboro methods integrator builds up during the pulse, and performs similar. The difference is that the Dow method gets a smaller initial overshoot, but receives a second overshoot with similar size, while the Foxboro method gets a little larger initial overshoot, but settles faster and with much smaller secondary overshoots. The difference is in the behaviour of the integrator where the Foxboro method follows the control signal, and the Dow method follows the system output.

When looking at process 2 in figure 43 we see that the difference between the Foxboro and Dow methods are smaller, but the same pattern of all three methods can be distinguished.

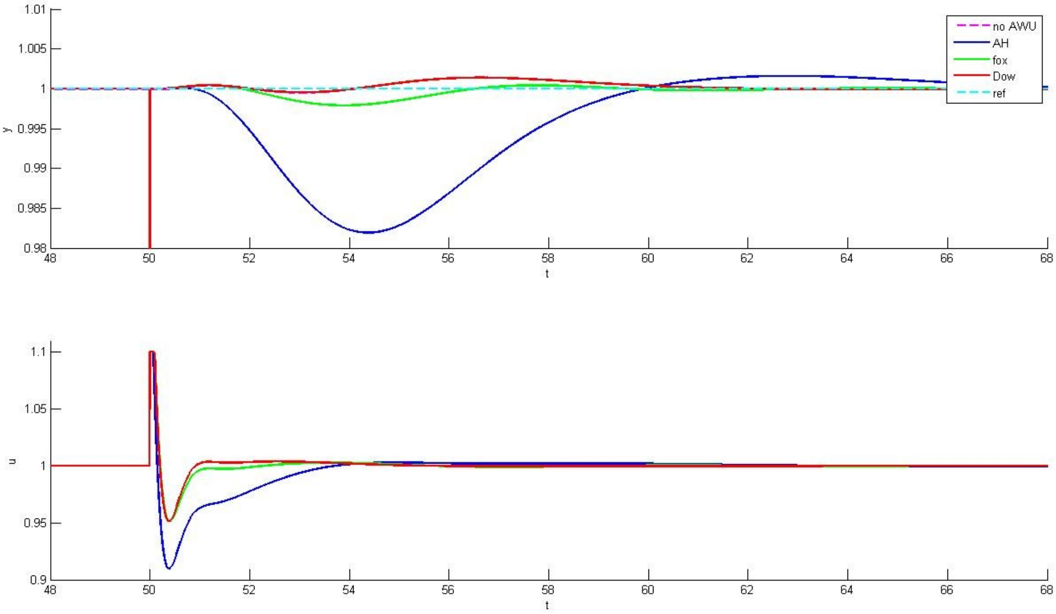

Figure 43: A measurement disturbance pulse added to the PID controlled process 2. The control action response to the pulse saturates the controllers.

The Dow method performs exactly like the method without anti-windup protection since its integrator never saturates when the pulse is added. In figure 44 we increase the width of the pulse to let the integrator saturate for the Dow method.

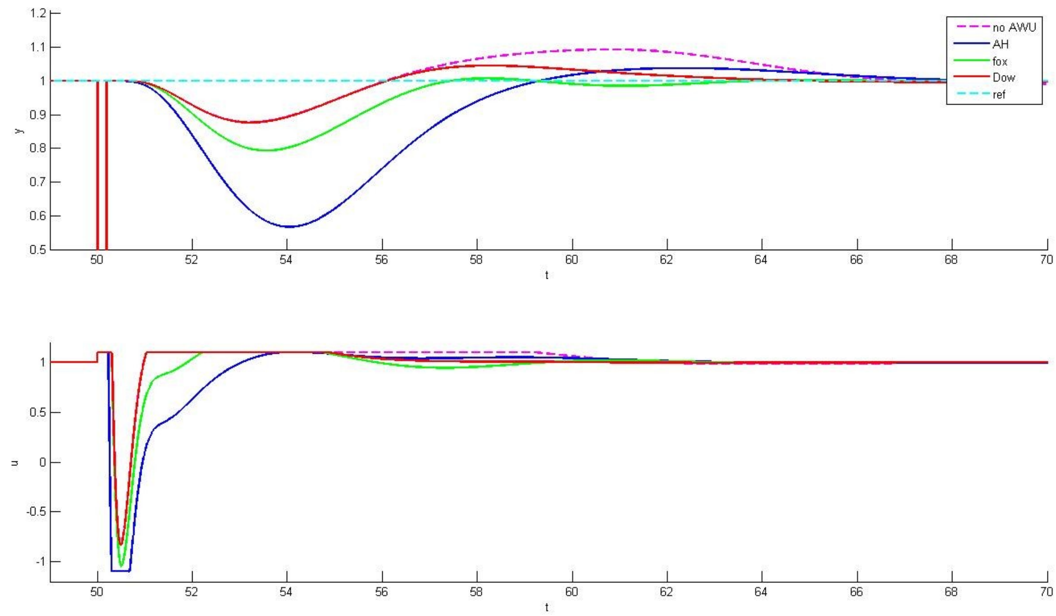

Figure 44: PID control of process 2 subject to an impulse measurement disturbance with increased width compared to that of figure 43. The increased size is made to separate the Dow method from the controller without anti-windup.

As we can see the Dow method now separates from the method without windup protection. The increased pulse size in conjunction with the back-calculation saturates the AH method also in the negative direction.

5.7 Variations of back-calculation time constant T_t for PID controllers

Testing of different values of back-calculation was also made for the PID controller. Here we notice that the AH and Dow methods react in different ways for higher values of T_t, where the AH method can use the T_t parameter to help regulate the overshoot and get an earlier retraction from the actuator saturation, whereas the Dow methods overshoot does not increase in size, but takes longer to settle due to having the integrator resetting more slowly. The behaviour for the two methods can be seen for process 2 in figure 45 and for process 3 in figure 46.

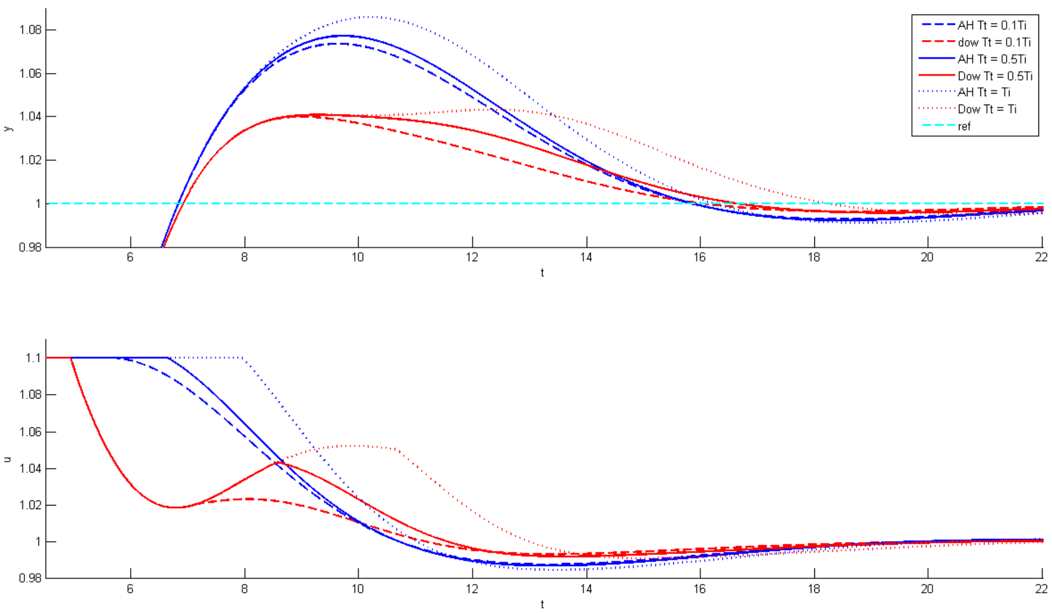

Figure 45: T_t variation for the AH and Dow PID methods of an initial step of process 2.

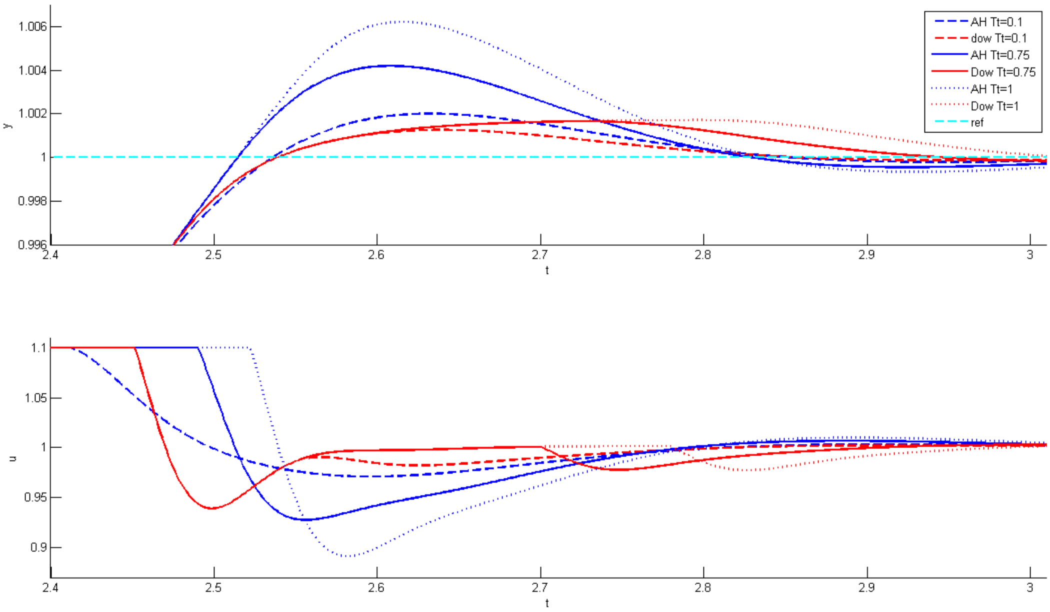

Figure 46: T_t variations for the initial step of process 3 for the PID controllers on parallel form.

A larger T_t helps the AH method counteract measurement disturbances, but also often leads to slower control reaction, and more overshoot. For the Dow method however the back-calculation time constant does not change the reactions of measurement noise.

6. Discussion

At the beginning of the master thesis the objective was to compare the AH and Dow methods. The Foxboro and Blevins methods, both on series form was added later on, just as processes and cases has popped up during the works progress. A major part of the master thesis has focused on PI controllers to be able to compare the methods on even ground. Since Blevins method was added long after the other methods it is likely that this method can gain more from further fine tuning.

The controller parameters was based on the MIGO parameters suggested in *Advanced PID Control* for an unsaturated actuator. The control design can most likely be improved with the control saturation in mind, but I wanted to compare the methods where as little extra control theory as possible was needed to handle the controller compared to one without windup protection. The method specific parameters where tuned for good overall performance for the different cases of each process. Since the methods are quite close in performance some tuning of the parameters can change which method seems better, especially for individual cases. I was surprised to find that the T_t parameter worked so differently for the two parallel methods, and I think similar comparisons can be interesting for the other control parameters as well to find the best controller parameters with the saturation in mind.

When looking into the different parts of the controller signal, the AH method was the most illogical to me, since a large proportional or derivative bump can make the integrator switch sign, which is something the method often uses to its advantage. A problem with the Foxboro method is that it does not give the option of separating the tracking time constant from the integrator time constant, which is something that this master thesis have not looked much into.

When considering how I would want to approach the windup problem, there are some parts of the various methods that are intriguing, such as the Dow methods excellent handling of measurement noise, or the Foxboro methods aggressive control, yet constrained integrator. Both Blevins and the AH method are instead good at reducing the integrator when the controller is saturated to get early response, and especially the way Blevins method accomplishes this could be nice to add, assuming it would be possible to escape the problems that arises when repressing the integrator based on the entire control signal when dealing with measurement disturbances. With this in mind I tried to think of a way to to combine some of these benefits, and my most succesful variation can be seen in figure 47.

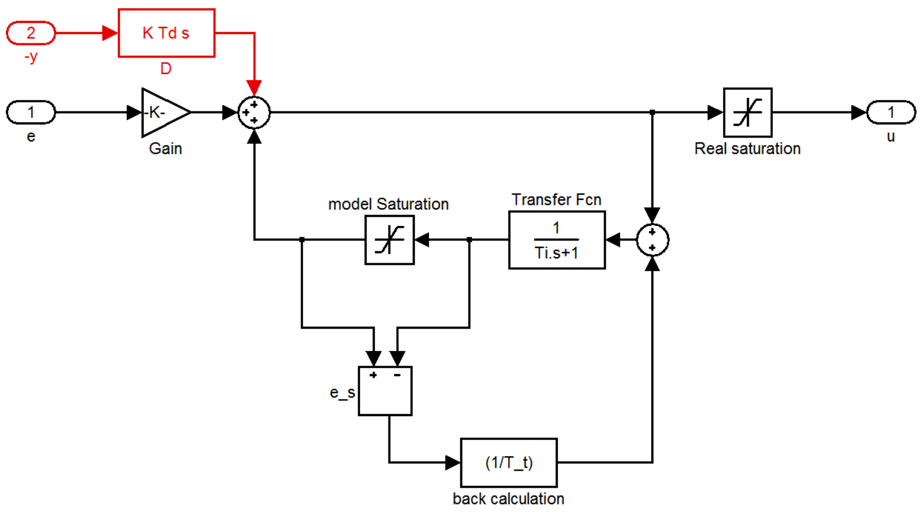

Figure 47: A mixed method suggestion, based on the Foxboro method, with influences of the Dow method's integrator reset.

The method is based on the Foxboro method, with the difference that this method integrates the unsaturated control signal. The integrator is instead regulated by a back-calculation which kicks in when the integrator is saturated, just like the Dow method. The hopes of this variation was to mimic the excellent results of the Foxboro method, but add the Dow methods way to avoid problems with measurement noise. I have only done some initial testing of this method, and some early glances indicates that this mixed method, aswell as other combinations can be interesting for future work in the area. The step response of the PID controlled process 3 where this method is included can be seen in figure 48.

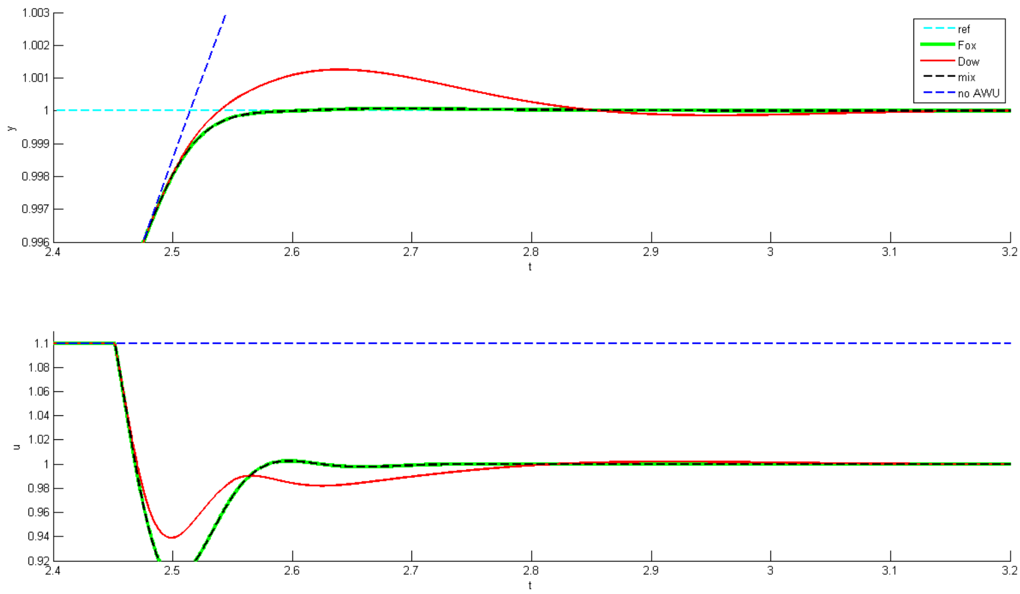

Figure 48: Step response of process 3. The mixed method follows the Foxboro method, which was the intention of the design.

The mixed method's integrator has reset before the control signal leaves the saturation, which makes the method behave just like the Foxboro method. In figure 49 the mixed method's response to measurement noise is displayed.

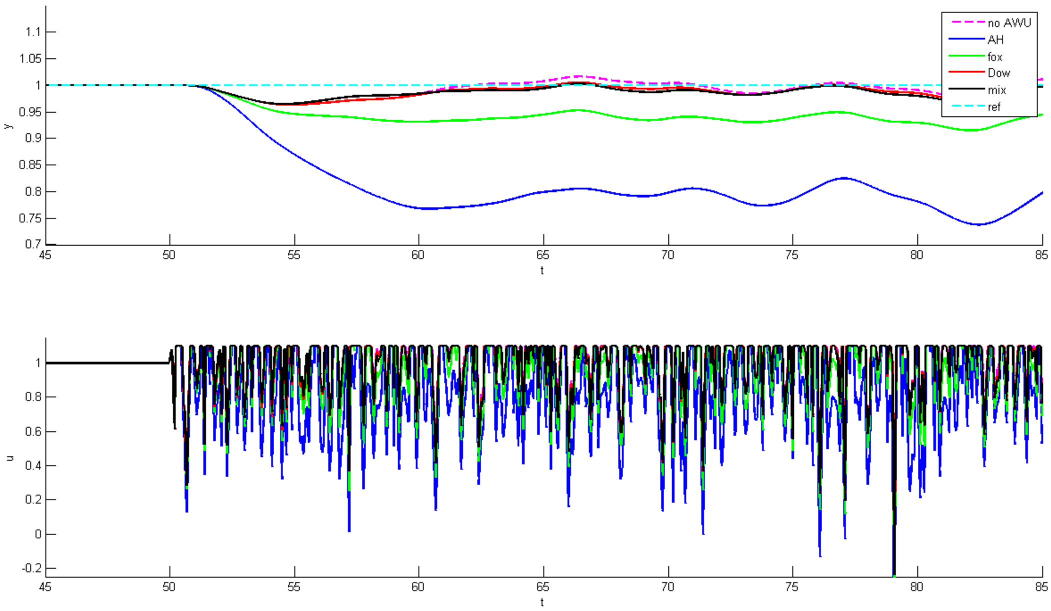

Figure 49: Measurement noise for process 2. The mixed method behaves similar to the Dow method.

The mixed method is almost as good as the Dow method on ignoring the effects of the saturated noise disturbance.

The mixed method, and other variations is something that could be interesting for future work, as well as comparing the methods for cascade controllers and selectors. Finding more optimal control parameters for the methods, and systems with saturation in general is something that can be looked at more in the future with more analytical approach.

7. Conclusion

As this master thesis progressed it became clearer that no method was uniformly superior, they all had some strengths and weaknesses depending on the given scenario. The simplicity and good performance of the AH method for PI control makes it the suggested controller choice. For PID the Foxboro method was the superior alternative. The Dow method was very strong when measurement noise was added to the system. Even if an all-round optimal method would be more appealing, the methods have their individual strengths and a fitting controller can be chosen and tuned to work well with a given problem at hand. A short lucid summary for the various methods can be seen in table 11. More detailed observations and conclusions for all the methods can be found below in the upcoming paragraphs.

	AH	***Dow***	***Foxboro***	***Blevins***
PI	+ Early control + T_t tune	- Late control	+ No extra parameter - Late control - T_t unchangeable	+ Early control - More parameter
PID	+ Time delay + Process 1 & 4 - Noise	+ Noise	+ Aggressive + Process 2 & 3	

Table 11: A table of pro and cons for the various methods for both PI and PID control.

7.1 Method summary

AH method

The AH method tends to bring the control signal away from the saturation limit earlier, but reacts with gentle, less-aggressive control action then other methods. This smoother control action can be particularly beneficial when working with processes that have time delays. The AH method and the Blevins method resemble each other in most cases for the PI controller, where the two are the overall best working methods. The AH method has fewer parameters, but the Blevins method is slightly better and favored for some cases. For the PID version it was especially for process 1 and 4 that the AH method was better then the other methods, while falling behind slightly on process 2 and 3. The AH method had, however, big problems with measurement noise. The method is relatively easy to use with just one extra parameter needed compared to a controller without anti-windup control. The extra parameter can be used for tuning.

Dow method

The Dow method behaves similarly to the Foxboro method for the PI case. The problem that these two method have for the PI controller are that if the integrator is saturated, their back-calculation only brings the integrator back to the saturation limit, which means that the proportional part has to change sign in order to push the control signal into the unsaturated area, which only happens when the setpoint is reached. The same happens for the PID version, however, the derivative part can make the control signal to change slightly before the setpoint is reached. The Dow method has one extra parameter, which requires tuning. For the PID controller the method is not extraordinary good for any of the tested processes, it is nevertheless very good at handling measurement noise.

Foxboro method

The Foxboro method is very easy to apply since it does not have extra parameters that need tuning. When looking at the PI controller, a saturated actuator will make the integrator converge towards the saturation level and thus the error must change sign for the PI controller to reduce the controller output below the saturation limit. The late reactions of the Foxboro method results in overshoots. Performance-wise it is very similar and often equal to the PI version of the Dow method. The Foxboro PID controller it performs very well overall for the different processes and cases, especially for process 2 and 3. The Foxboro method is almost as good as the Dow method for handling measurement noise. The combination of aggressive controller output together with the slow and smooth behaviour of the low pass filter integrator makes the Foxboro a strong choice for most processes and cases.

Blevins method

Blevins method was only tested as a PI controller, where it performed very well, being able to react before the setpoint is reached due to the integrator being pushed down to below saturation level while the actuator is saturated and the preload value is used. This makes it posible for the controller to act before the proportional part changes sign. The control signal will consist of the declining proportional part, together with the reduced but growing integral part. The method performed close to, or identical to, the AH method for many of the processes, and a little better on a few resulting in it being the best overall PI controller, with the downside of being more complex to set up due to more control parameters. The method could probably be used with good results even for a PID controller, which is something that was not fully tested during this master thesis project.

7.2 PI Control

All four methods are quite similar in performance, with the AH method and the Blevins method mostly ending up being slightly better. The main advantage of these two methods is that they reduces the control signal earlier leading to less overshoot. For the negative reference step these methods take a bigger step as soon as the reference step is noticed, which leads to slightly faster settling time. This larger step can be to a disadvantage as seen for process 4, where the AH method takes a large initial step which leads to a large overshoot. The Dow method is performing equal to or worse then the Foxboro method and can be seen as the worst method to use out of these four for PI control, the difference is however slight. The tracking time constant T_t is a better tuning parameter for the AH method then it is for the Dow method.

7.3 PID Control

For the PID controller the AH method tends to react earlier, but with more gentle control actions then the other methods which has its advantages, especially for time delayed systems like process 4, but also for the single integrator in process 1. The Foxboro method is quite aggressive with "roller coaster-like" tendencies on the control signal, it does, however, perform very well and really outperforms the other methods on several occasions, especially for process 2 and process 3. The Dow method is similar to the Foxboro method, but slightly less aggressive, which puts it somewhere in the middle. It really shines when measurement noise is present. The two methods on parallel form have the same number of parameters to tune, however the T_t parameter is less intuitive for the Dow method then for the AH method. When T_t approaches T_i the control signal of the Dow method begins to split up in two parts with a time of unchanged control signal in between. This characteristic leads to T_t being a better and easier tuning parameter to use for the AH method then it is for the Dow method. The Foxboro method does however not require any extra parameter to tune even for the PID controller, and is still performing very good, which makes it the overall recommended method to use. The Dow method can be recommended for systems with a lot of noise, and the AH method especially for systems with time delay, where a less aggressive control signal can help.

A key conclusion is that it may be possible to improve the traditional methods for windup protection for PID controller. One possibility is given in figure 47 but this scheme has to be explored further. Its behaviour for systems with cascade control, mid ranging and selectors must also be explored.

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