

Signal Smoothing-in-Control-Loops

SIMATIC PCS 7

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SIMATIC PCS 7

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Preface

Objective of the Application

Almost any real sensor device for the measuring of process values of control loops delivers signals, which are disturbed by typically high-frequency noise. Nevertheless the requirements for the control loop with respect to fast dynamics and moderate movements of the actuator are to be fulfilled as good as possible. Therefore signal noise is suppressed by a filter, and the proper choice of the filter time constants is a major issue. Filter implementation and parameter setting as well as consequences of different filter time constants are shown, using the example project "APL_Example_EU".

Main Contents of this Application Note

The following issues are discussed in this application note:

- Interaction between the signal filtering and the controller.
- Simulation example.

Validity

... valid for PCS 7 V7.1, in principal transferable to V7.0 from SP1.

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1 Introduction

1.1 Basic Principles of Signal Smoothing

Process signals are often disturbed by high-frequency noise. The noise may be generated by the physical sensor element itself or by subsequent signal processing. In addition, there is so-called quantization noise from the analog-digital converter. The signals can be smoothed with the help of low pass filters such that the noise does not disturb the control system. Sometimes low pass filters are also applied to analogous measurements which are not used for a control loop e.g. to smooth the display of the measurement or to avoid fluttering alarms.

These low pass filters let signals of lower frequencies pass by nearly unchanged, while fractions with higher frequencies are damped. Therefore high frequency disturbances (e.g. measurement noise) are filtered out and the signal is smoothed.

The simplest low pass filter is a first order time delay element which has, however, a relatively broad transition zone between the pass band and the stop band (at the frequency axis), which means that there is danger of losing considerable fractions of the wanted signal when filtering out the measurement noise. The so-called Butterworth filter is a better solution. Butterworth filters are designed such that the frequency response stays horizontally as long as possible below the cut off frequency ω_g i.e. the wanted signal is passed unchanged. Only shortly before this cut off frequency, at the beginning of the stop band the transfer function is decreasing and moving into the gain reduction of $n \cdot 20$ dB per frequency decade (the order of the Butterworth filter is n).

The Bode diagram of a first order Butterworth low pass filter is shown in Figure 1-1. In the pass band the filter gain is 1 (damping 0 dB). The damping at the cut off frequency is -3dB, i.e. a signal with the cut off frequency is damped to an amplitude

of $\frac{1}{\sqrt{2}} \approx 0,7$ times the original signal amplitude. Butterworth filters have a smooth

(flat) characteristic of the transfer function both in the pass band and the stop band. The Butterworth filter was named by the British physicist Stephen Butterworth who described this kind of filter for the first time.

Further types of low pass filters are known in literature. Bessel filters have a less sharp transition from pass band to stop band, and the particularly sharp transition of the Tschebyscheff filter is bought dearly by a ripple of the frequency response in the pass band. This means that wanted signals of different frequency are amplified differently and measurements are distorted this way. For these reasons PCS 7 offers only the simple first order low pass filter (function block FB 1828 Lag from the Advanced Process Library respectively FB 51 PT1_P from the Standard Library) and a Butterworth filter (function block FB 1890 Smooth from the Advanced Process Library respectively FB 144 SIG_SMT from the Standard Library).

Inside intelligent field devices low pass filters are frequently offered integrated in the device and these can be parameterized by SIMATIC PDM. If the raw measurement signal is not needed anywhere for the automation in unfiltered form, it is straightforward to use these integrated filters. Rules for the dimensioning of the filter time constant in this application note are independent from the implementation of the filter.

High pass filters or band pass filters are hardly used in combination with measurement signals in the process industry because slow, sluggish variations of the signal would be filtered out and this way the absolute measurement value becomes falsified.

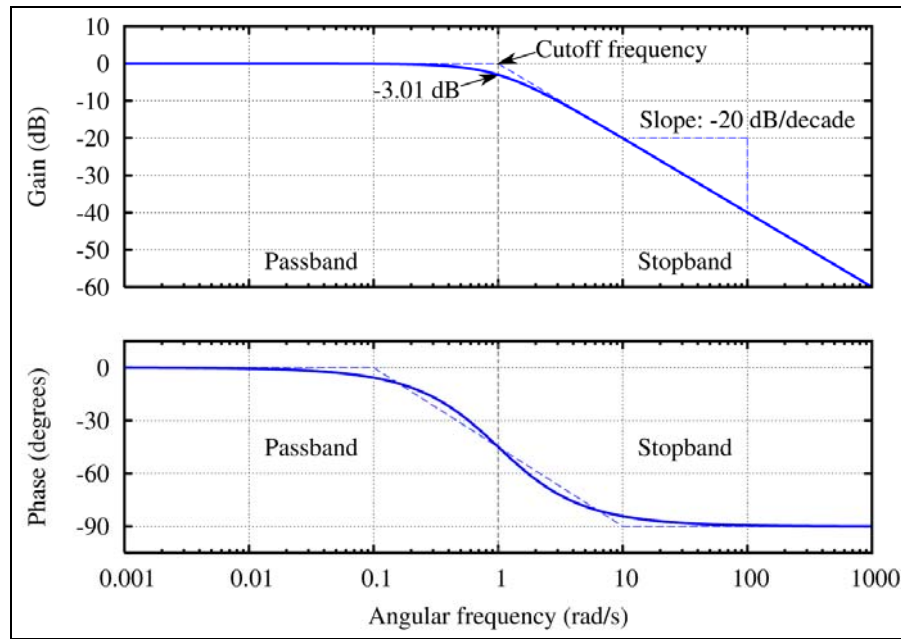


Figure 1-1: Bode diagram of 1st order Butterworth filter. The cut off frequency separates the pass band from the stop band

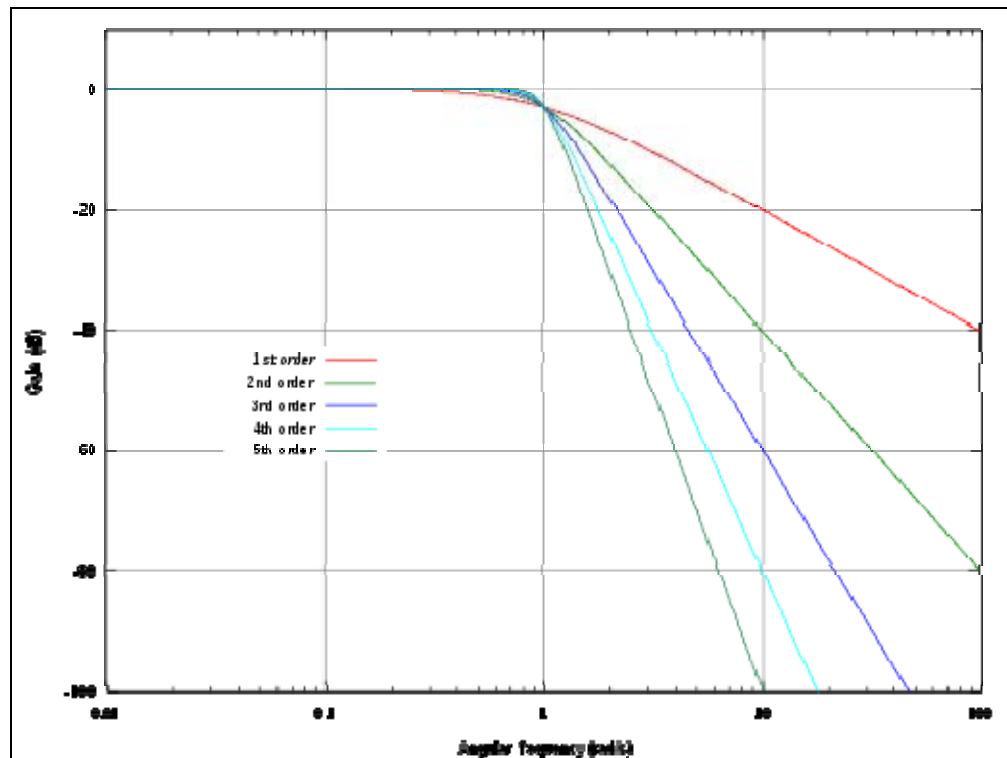


Figure 1-2: Bode diagram (gain) of Butterworth filter for different orders.

NOTE

The block Smooth from the PCS 7 Advanced Process Library contains a Butterworth filter of second order.

The filter is inserted in the signal flow between measurement value acquisition and measurement value utilization (e.g. in a controller).

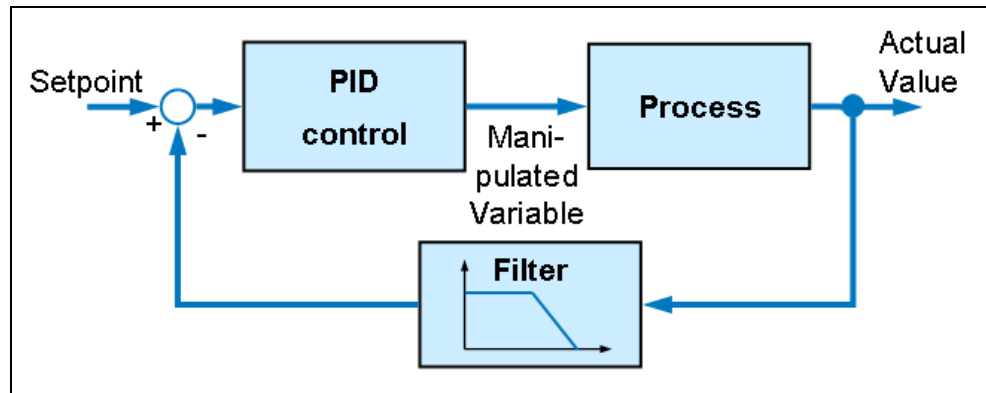


Figure 1-3: Signal flow for low pass filtering in a control loop

1.2 Function Block Smooth from Advanced Process Library

In the PCS 7 Advanced Process Library there is a function block called Smooth from the mathematical block family. This block includes both a Butterworth low pass filter and an outlier detection.

The function block is a time discrete approximation of the continuous Laplace transfer function

$$g(s) = \frac{1}{\frac{b}{\omega_g^2} s^2 + \frac{a}{\omega_g} s + 1}$$

according to [3] with the Butterworth coefficients $a = \sqrt{2}$, $b = 1$. The steady state gain is 1, and the cut off frequency ω_g .

The filter is parameterized by specification of the filter time constant *TimeConstant* which is the reciprocal value of the cut off frequency:

$$\omega_g = 1/TimeConstant$$

Physical measurements, which are affected by inertia (e.g. mass inertia in context of level and flow measurements, or energy conservation in context of temperature measurements) can not suddenly jump. The outlier detection monitors the difference between two adjacent signal samples. If the difference from one sampling value to the next is bigger than a predefined limit *OutThreshold* (depending on the noise level), the last valid value is frozen. The last valid measurement is then kept constant for maximal *OutCycles* sample times.

1.3 Typical Applications

It is generally known that measurement signals of different sensors are differently affected by noise. Temperature measurements usually are less noisy than pressure and flow measurements.

The signal-to-noise ratio is of vital importance. The overall measurement range and the absolute amplitude of the noise signal are often fixed from a physical point of view and can therefore not be modified in a given hardware. If relatively small amplitude variations of the wanted signal (with respect to the measurement range) have to be processed in the automation system, a bad signal-to-noise ratio is resulting and therefore this is a typical application area for a noise filter.

Further reasons for higher noise levels and therefore need for filtering are related to the physical properties of the measuring principle:

- EMC-problems (electromagnetic compatibility) can cause noise effects, especially in combination with badly shielded signal cables, switching operations of large electrical power consumers or particularly sensitive measuring methods.
- If the physical measuring effect generates low-energy signals (e.g. capacitive pressure measuring) the danger to get noisy measurement signals is much higher than in context of measuring methods which generate or modify high-energy signals (e.g. temperature measurement by resistance thermometers.)

Moreover, there are process related reasons for noise signals which depend on the sensitivity of the measuring principle to certain disturbing impacts, e.g.

- Transportation of gas (e.g. air bubbles) in fluids can lead to additional measurement noise of pressure and flow sensors.
- Foam formation or wave movement by stirring appliances or feed flows can lead to additional measurement noise of level sensors.

2 Configuration of Signal Smoothing

There is no separate process tag type for signal smoothing, because the filter block Smooth can be added to any other process tag type which handles analogous signals. The filter is inserted between the analogous input driver and the signal processing block e.g. PID controller.

2.1 Inserting the Filter into a Process Tag Type

In the application example „SigSmooth“ of the APL example project, a PID control loop with signal smoothing is implemented that is based on the process tag type PIDConL_ConPerMon for standard control loops.

To have a look at it, please open the Project „APL_Example_EU in SIMATIC Manager by clicking on „File“/“Open“/ “Sample projects“ “.

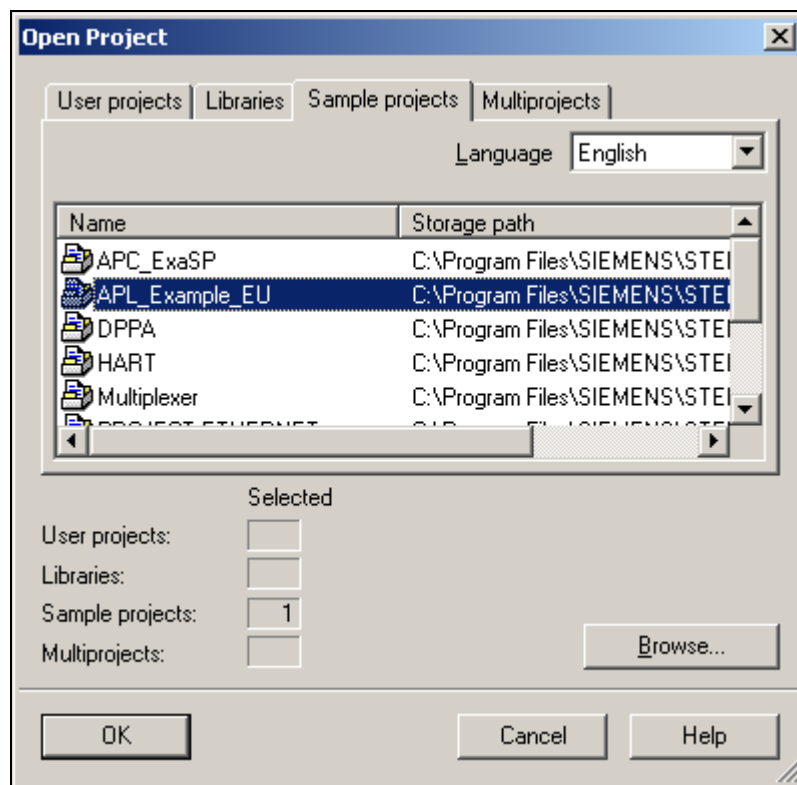


Figure 2-1: Open „APL_Example_EU“

Open the CFC of the unit „SigSmoothSim“ in the chart folder.

2 Configuration of Signal Smoothing

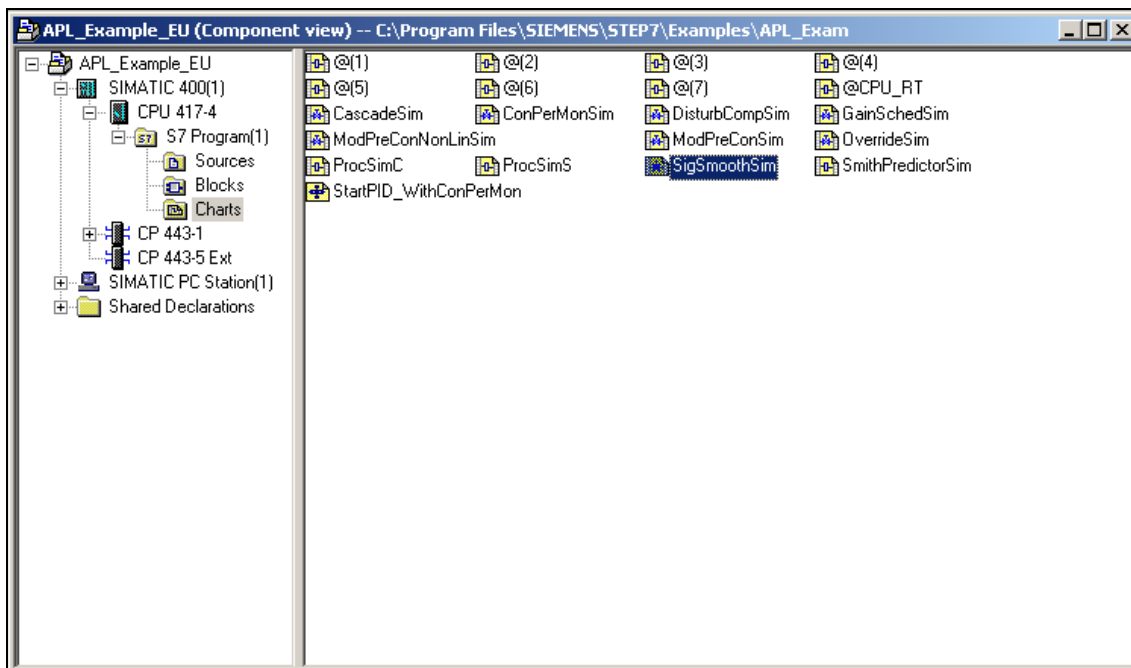


Figure 2-2: Selection of process CFC "SigSmoothSim" in the example project

You can have a look at the principle structure of the signal smoothing: The analogous value coming from the I/O periphery is filtered before it is connected to the process value PID.PV of the controller.

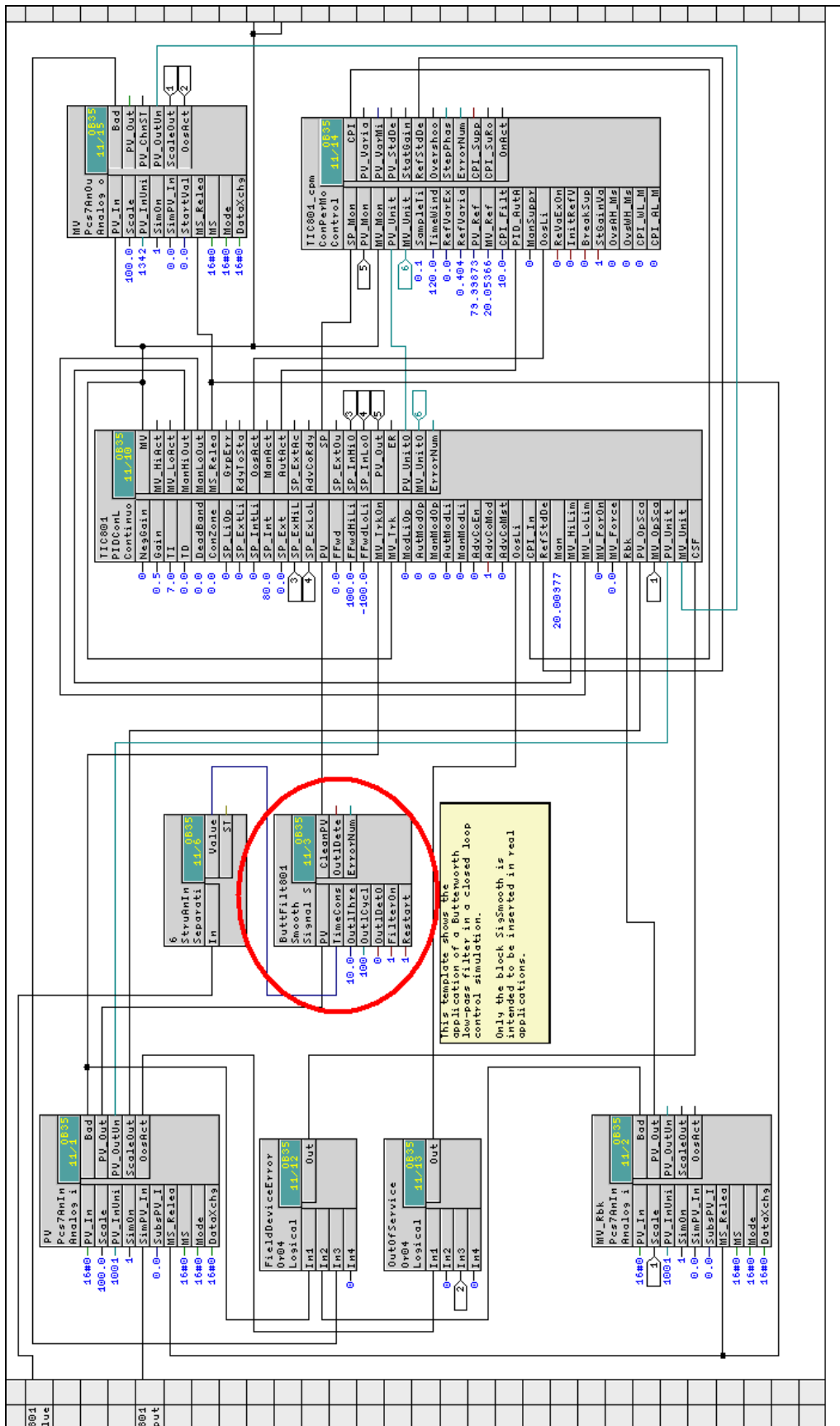


Figure 2-3: PID control loop with signal smoothing

2.2 Procedure for Parameterization and Commissioning

The low pass filter modifies the behavior of the controlled system and therefore belongs to the process model from the controller point of view.

The following procedure is therefore recommended:

- Record the measurement signal with a sample rate as fast as possible. Rather use the CFC trend curve recorder than WinCC TagLogging.
- Zoom a detail of the measurement signal and estimate the cycle duration (periodic time) of the noise signal, e.g. from peak to peak or by counting of peaks over a time interval.

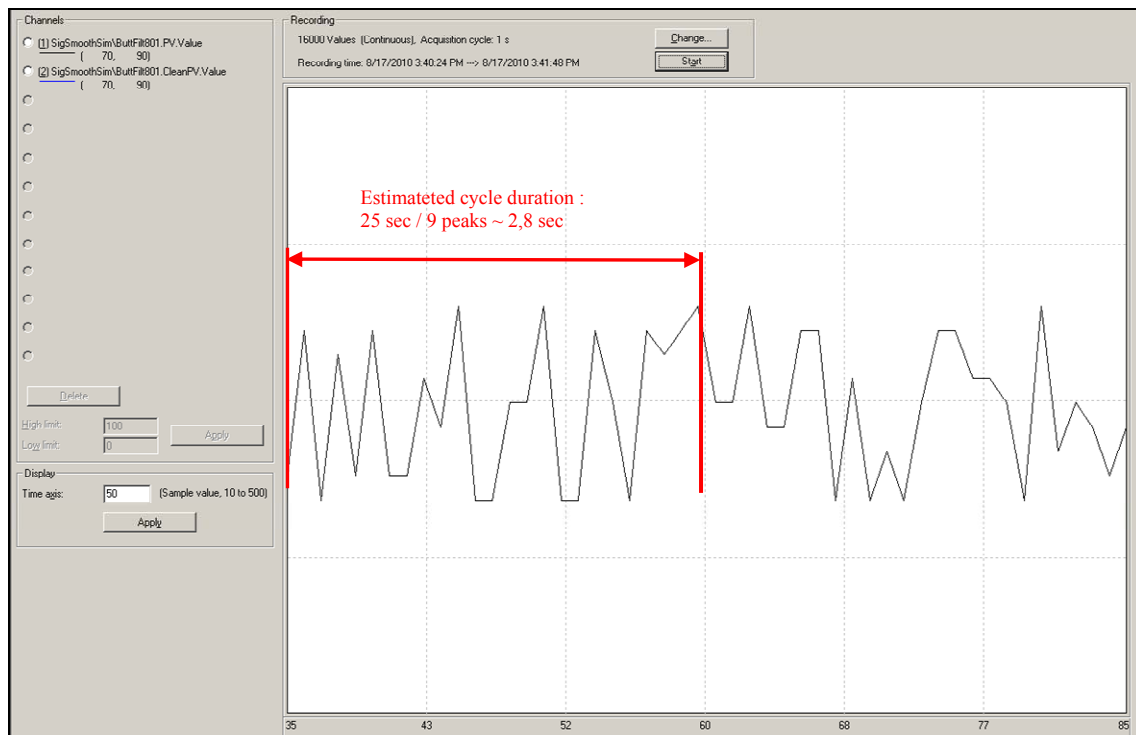


Figure 2-4: Estimation of the cycle duration by counting the signal peaks per time interval

- Set the filter time constant a little bit larger than the estimated cycle duration.
- Test the effect of the smoothing in the trend recorder with steps of the manipulated variable in the hand mode of the controller.

Note

A good start value for the filter time constant is five to ten fold of the sample time of the signal input device (sample time of the analogous input driver or sample time of the regulator).

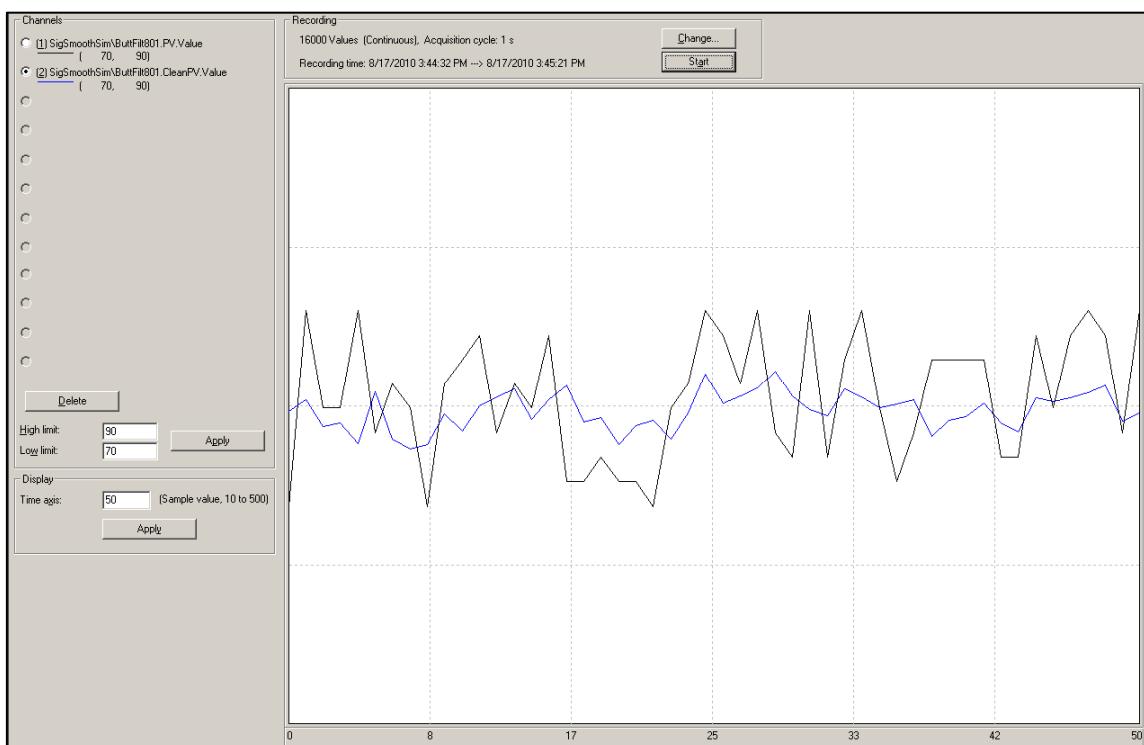


Figure 2-5: Noisy raw signal (black) and filtered signal (blue), filter time constant 3s

- Optimize the parameters of the controller using the PID-Tuner. The low pass filter belongs to the controlled system from the point of view of the tuner, and will be considered as such during modeling from learning data. You will therefore obtain different controller parameters for different filter time constants, if the filter time constant is not several orders of magnitude smaller than the process time constants and therefore can be neglected.

Table 2-1: Controller parameters calculated by PID-Tuner for different filter time constants

	Without filter	Filter time constant 3s	Filter time constant 15s
Gain	0.65	0.33	0.13
TI	9.61s	11.5s	11.2s

Note

If you change the filter time constant considerably during process operation, you have to retune the controller by PID-Tuner.

3 Simulation Example

Signal Smoothing in a PID Control Loop

The plant unit "SigSmoothSim" in the example project APL_Example_EU of the PCS 7 Advanced Process Library contains a simulation model of a control loop with signal smoothing and a noise generator producing a noisy process signal. The signal smoothing is performed by the function block „Smooth“.

Table 3-1: Process parameters of the example project signal smoothing

ProcSimC	Controlled system
Gain	3
TimeLag1	15s
TimeLag2	2s
PV0	20
Noise Variance	2

Table 3-2: Controller parameters of the example project signal smoothing

PIDConL	
Gain	0.5
TI	15s
Sampling time	0.1s

In this example you can see how different values of the filter time constant affect the process signal and thereby the complete control loop. The controller parameters do not exactly correspond to the values from the PID tuner but were selected to demonstrate the described effects.

Signal smoothing with a filter time constant of 3s



Figure 3-1: Signal smoothing with a filter time constant of 3s

Legend

- Blue: Setpoint
- Red: Noisy raw signal
- Green: Filtered measurement value = controlled variable
- Orange: Manipulated variable

With a filter time constant of 3s you achieve a good filtering and a reasonable control response after a setpoint step with a light overshooting of the controlled variable. The gradient of the manipulated variable is relatively smooth (Figure 3-1).

Signal smoothing with a filter time constant of 15s

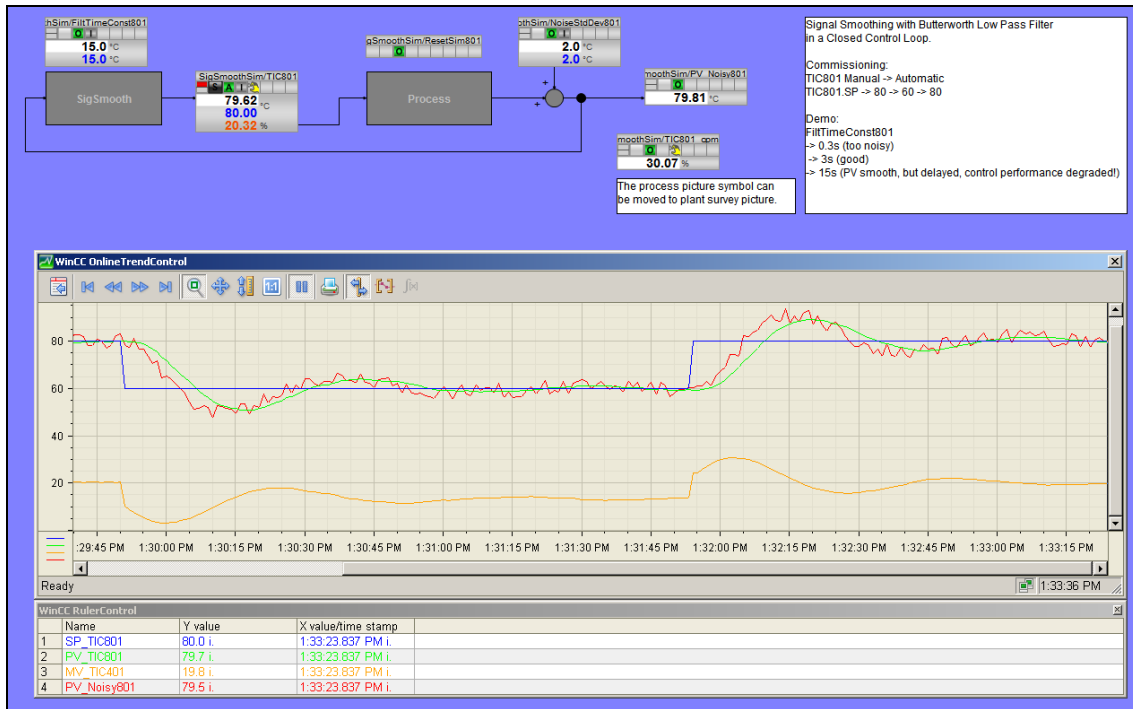


Figure 3-2: Signal smoothing with a filter time constant of 15s

With a filter time constant of 15s the filtered controlled variable as well as the manipulated variable in Figure 3-2 is very smooth i.e. the filter has a stronger effect. However the control loop is more inert, because the filter time constant works as additional time delay ("parasitical time constant") in the controlled system. There is an obvious phase shift between raw signal and filtered signal. The controlled variable oscillates much more after a setpoint step, compared to the control loop with filter time constant of 3s, because the controller does not know about the additional time delay.

Signal smoothing with a filter time constant of 0.5s

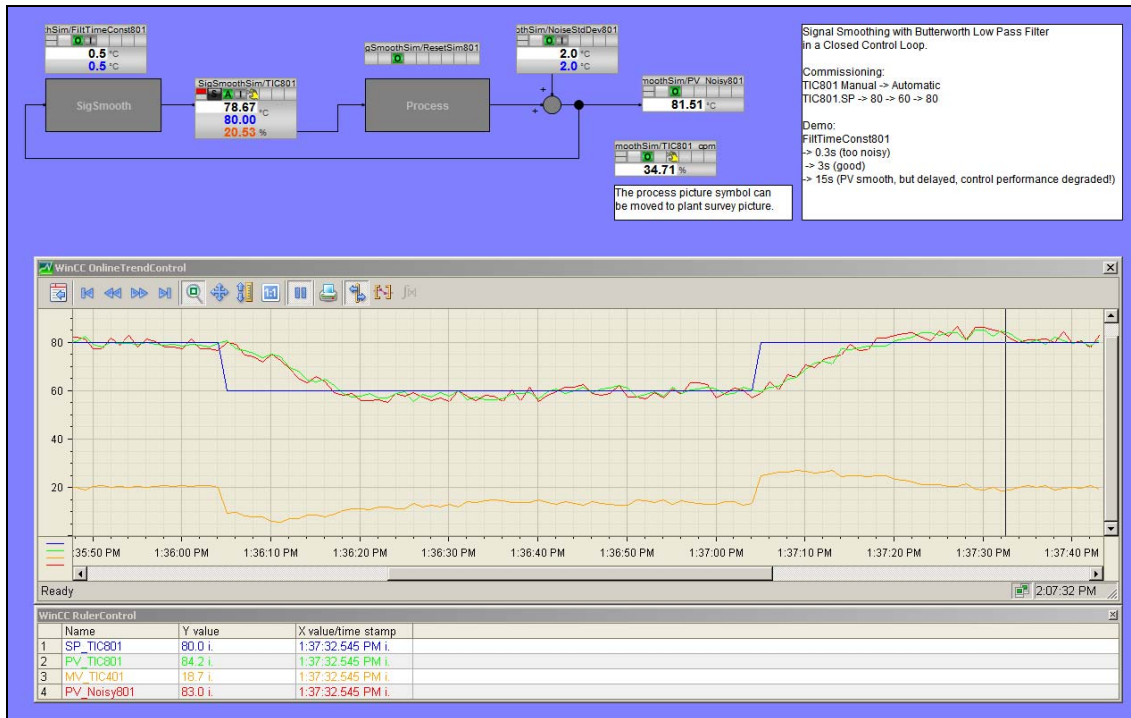


Figure 3-3: Signal smoothing with a filter time constant of 0.5s

A filter time constant of 0.5s implies a low filtering effect on the controlled variable. The filter has nearly no effect at all. The gradient of the manipulated variable is very turbulent, which causes undesirable energy consumption or additional wear and tear depending on the kind of actuator. Especially valves as actuators in control loops are affected. In the example a PI controller is used. Additional differential action of a PID controller would cause even more unsteady movements of the manipulated variable.

4 Signal Smoothing in Advanced Control Structures

Independent of the form of the interaction of different controllers and auxiliary function blocks in a nested control system (e.g. cascade control, ratio control etc.) and independent of the kind of controllers (PID, MPC or others) the following rules always apply:

- The filters are located between measurement value acquisition and measurement value usage (e.g. in a controller).
- The engineering of filters in CFC and the dimensioning of the filter time constants for part loops of advanced control structures are in principle the same as for single loop control systems.
- The filter tuning takes place in an operation mode where the interactions between neighboring control loops are as small as possible. Therefore upstream or neighboring control loops are taken in manual mode.
- The effect of each individual filter is checked in open loop before the next design step will be started.
- Each filter is a part of the respective controlled system from the controller point of view and is considered as such during modeling in the context of controller tuning.

Signal smoothing in a cascade control loop

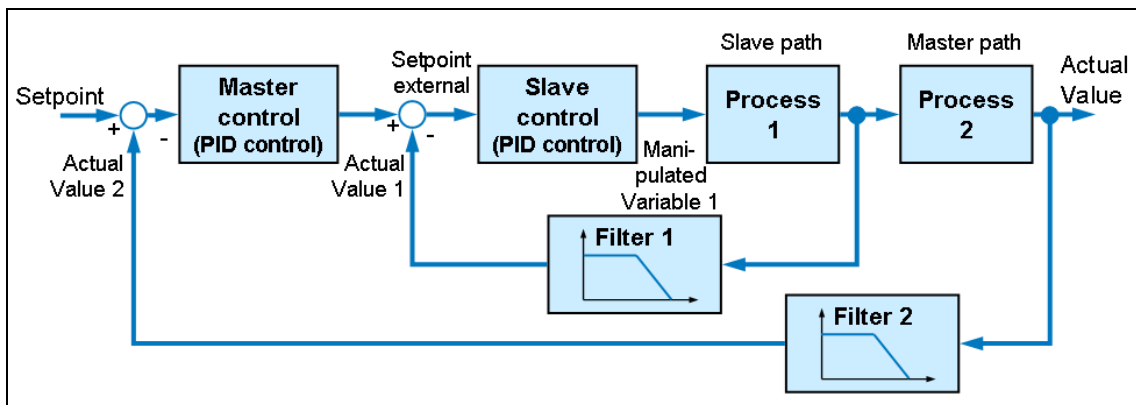


Figure 4-1: Signal smoothing in a cascade control loop

Filter 1 belongs to process 1 and therefore to the controlled system of the slave controller.

Filter 2 belongs to process 2 and therefore to the controlled system of the master controller.

In general the closed slave control loop is also a part of the controlled system of the master controller.

Signal smoothing in an override control loop

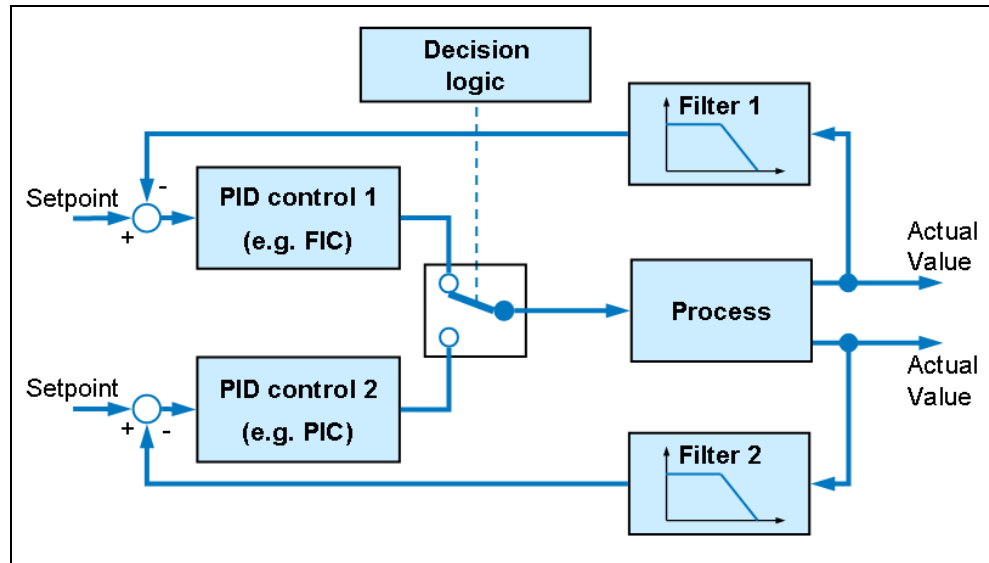


Figure 4-2: Signal smoothing in an override control loop.

Both actual values can be smoothed independently or only one of them.

Signal smoothing in a control loop with feedforward disturbance compensation

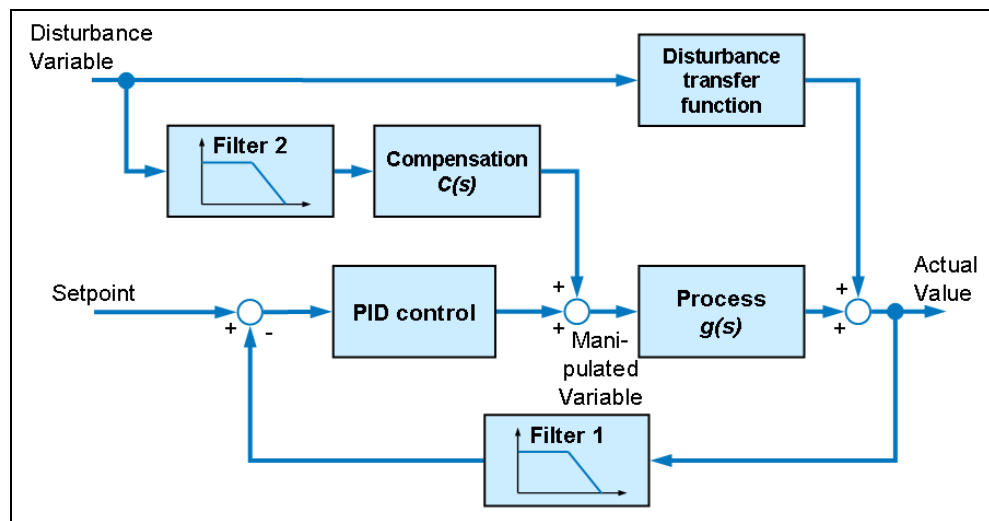


Figure 4-3: Signal smoothing in a control loop with feedforward disturbance compensation.

The physical effect of a disturbance variable to the actual value can not be affected by smoothing, but only the signal way via compensation block to the actuator. The design for the compensation block must be modified accordingly.

Note

During the design of compensation blocks for disturbance feedforward the filter is considered as a part of the controlled system and design equation has to be modified accordingly. If the transfer function of the filter is $g_f(s)$ the compensation block will be

$$c(s) = -\frac{g_z(s)}{g_f(s)g(s)}$$

Signal smoothing for a Smith Predictor

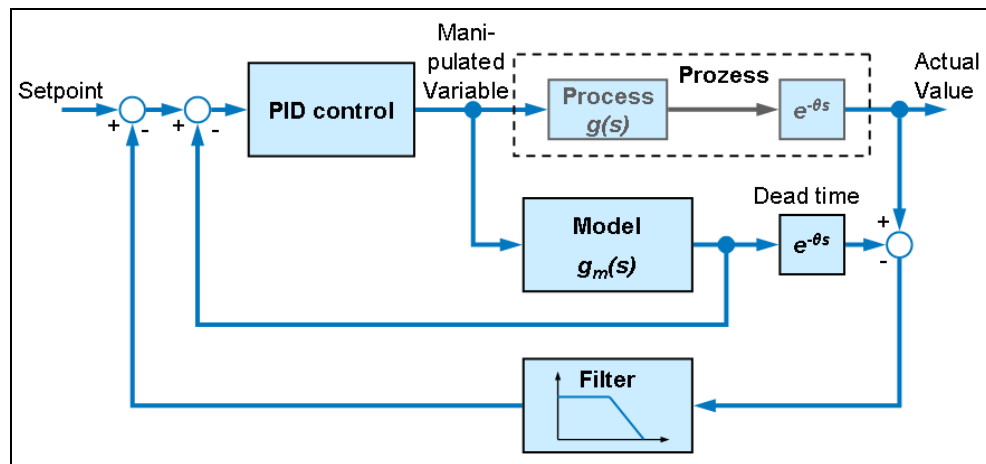


Figure 4-4: Signal smoothing for a Smith Predictor

The filter is located after the subtractor which calculates the difference between the real actual value and the model output, such that two comparable values (i.e. both un-filtered) are compared to each other at the reference junction.

Note

For the Smith predictor the control design applies to the "virtual" process value free of dead time, which is taken from the process model and therefore not filtered. As opposed to all other control system structures, in this case the filter is not considered during controller design! Anyway it delays feedback of model errors to the controller a little bit further - this feedback is anyway afflicted by the dead time. If this should lead to stability problems in exceptional cases because of large model errors, two identical filters must be located at two positions: after the real actual value and after the output of the model $g_m(s)$. Now the filters must be considered during controller design.

Signal smoothing for gain scheduling

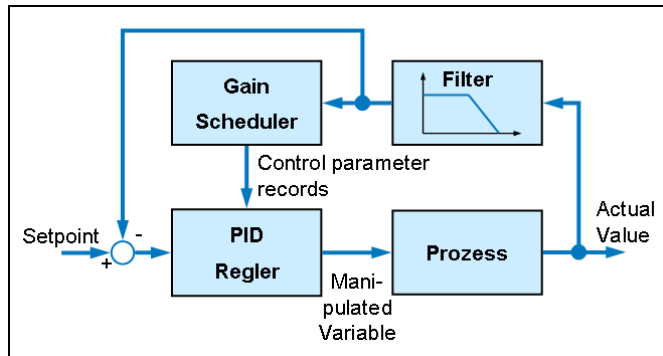


Figure 4-5: Signal smoothing for gain scheduling

Of course the filtered actual value is not only used for the controller but also for the gain scheduling block.

Signal smoothing for an MPC

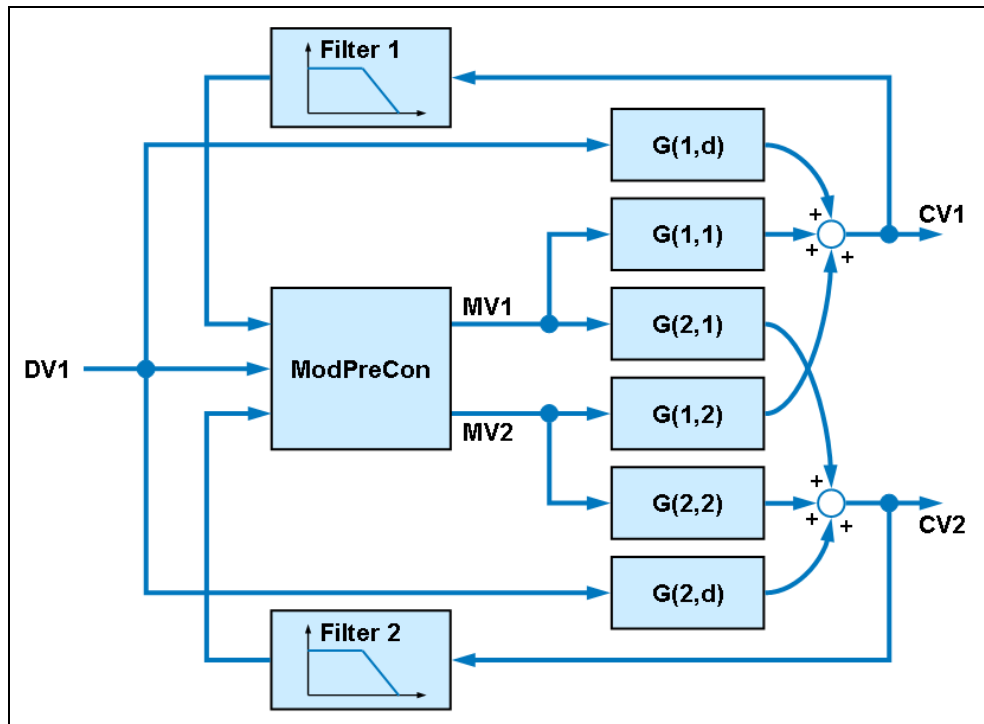


Figure 4-6: Signal smoothing for an MPC

Each controlled variable (CV1...4) can be filtered independently from the others, all of them or some of them as desired. The tuning of all filters has to be finished before the learning data for the MPC configurator are recorded. Measurable disturbance variables (DV1) can be filtered similar to other measurements if necessary.

5 Conclusion

Undesired noise components in the upper frequency domain can be filtered out from an analogous signal by a low pass filter. The selection of the filter time constant is decisive for signal smoothing. If the filter time constant is selected too small the filter effect is too weak. If the filter time constant is selected too large parasitical time constants in the controlled system are generated and included in the dynamics of the control loop. The system response slows down and eventually the controller parameters do not match anymore to the controlled system. This can even lead to instabilities.

Therefore keep in mind to parameterize first of all the filter and afterwards the controller.

6 Related Literature

This list is not complete and only represents a selection of relevant literature.

Table 6-1

	Title
/1/	Online-Help PCS 7 Advanced Process Library Chapter "Templates/process tag types"
/2/	Wikipedia – The Free Encyclopedia http://en.wikipedia.org/wiki/Butterworth_filter
/3/	Tietze, U., Schenk, Ch. Halbleiter-Schaltungstechnik Springer, Berlin, 9. Auflage, 1989.

7 History

Table 7-1

Version	Date	Modifications
V1.0	September 2010	First version