Applications for Process Automation

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Multivariable Model Predictive Control - Distillation Column as an Application Example

Application Note

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Preface

Objective of the Application

The objective is fast and tight control of processes with several interacting in- and outputs. In the accompanying example the MPC controls two sub-ordinated PID controllers in a cascade structure. This demonstration with two manipulated and two control variables is only an application example. The procedure to configure an MPC with more or less than two manipulated variables is the same.

This application note is intended for non experienced users in MPC technology; special cases and complex applications are not considered here.

The application example considered here shows the enhancement of a basically automated distillation column with a MPC based temperature control.

Main Contents of this Application Note

The following issues are discussed in this application:

- How to create an instance of the process tag type

- How to collect the necessary measurement data for the MPC

- Configuration using the MPC configurator

- How to handle more than one measurable disturbance variable

- Benchmark simulations with and without MPC, to show the potential benefits

Validity

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

Reference to Automation and Drives Service & Support

This article is from the internet application portal of the Industry Automation and Drives Technologies Service & Support. Clicking the link below directly displays the download page of this document.

http://support.automation.siemens.com/WW/view/en/37361208

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1 Basic Principles of Model Predictive Control

A general overview of model predictive control is provided by the White Paper "How to improve the Performance of your Plant using the appropriate tools of SIMATIC PCS 7 APC-Portfolio?"

https://pcs.khe.siemens.com/efiles/pcs7/support/marktstudien/WP_PCS7_APC_EN.pdf

PCS 7 embedded MPC: Method of Operation und Area of Application

The ModPreCon block is used for multivariable control of dynamic processes (see the online help "Description of ModPreCon"). It can handle up to four dependent manipulated and controlled variables as well as one measurable disturbance variable.

In special situations, the ModPreCon block can also be used for SISO (single-input single-output) controls with particularly difficult dynamics. It performs better than a PID controller, for example, in systems with non-minimum phase or a strongly oscillating response.

The ModPreCon algorithm only works for stable processes with a step response that settles to a fixed value in a finite time. If the process is unstable or includes an integrator (tank level control for example), the corresponding partial transfer function must be stabilized with a secondary controller.

Note	The run time of the multivariable controller is basically longer than that for PID controllers, because large matrices have to be multiplied in the algorithm. The run time is also determined by number of process and manipulated variables in the control algorithm. This is why the multivariable controller is unsuited for rapid control and is usually applied for slow, complex control tasks. The computation time required on the CPU is compensated by the fact that very slow sample times of > 20s are used for the typical ModPreCon applications (see Advanced control templates). The ModPreCon is then typically running in OB30 and can be interrupted by faster OBs.

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2 Implementation of the MPC

The principal approach to configure a model predictive controller is very similar to the computer-based commissioning of a PID controller. Due to the matrix form of the control parameters within the MPC, the interaction between control block and configurator is organised differently. The configuration is done in several steps (see the online help of ModPreCon block) as it is explained in the next chapters:

- Excite the process with the controller in manual mode by applying a series of manipulated variable step changes.

- Record the measured data with the CFC trend display and export it to an archive file.

- Using the MPC configurator, create an SCL source code for the user data block (DB). It contains the models and matrices required for a ModPreCon instance.

- Compile the SCL source code in the engineering system and download it to the AS.

2.1 Installation

The installation of the PCS 7 Advanced Process Library is performed automatically by the PCS 7 master setup V7.1.

Note   There is a MPC process tag type named "MPC_CTRL" already available in the PCS 7 APC Library V7.0 SP1. Although the Advanced Process Library of PCS 7 V7.1 is used in this Application Note, the principal procedure is also applicable to the APC library of PCS 7 V7.0 SP1.

2.2 Configuration: Creating an Instance of the Process Tag Type (CFC Template)

The following steps are carried out for the MPC in the same way as for any other process tag types (CFC templates).

1. Please open PCS 7 Advanced Process Library V71 with the menu "File > Open > Libraries" in SIMATIC Manager.

Figure 2-1: Open the PCS 7 AP Library V71
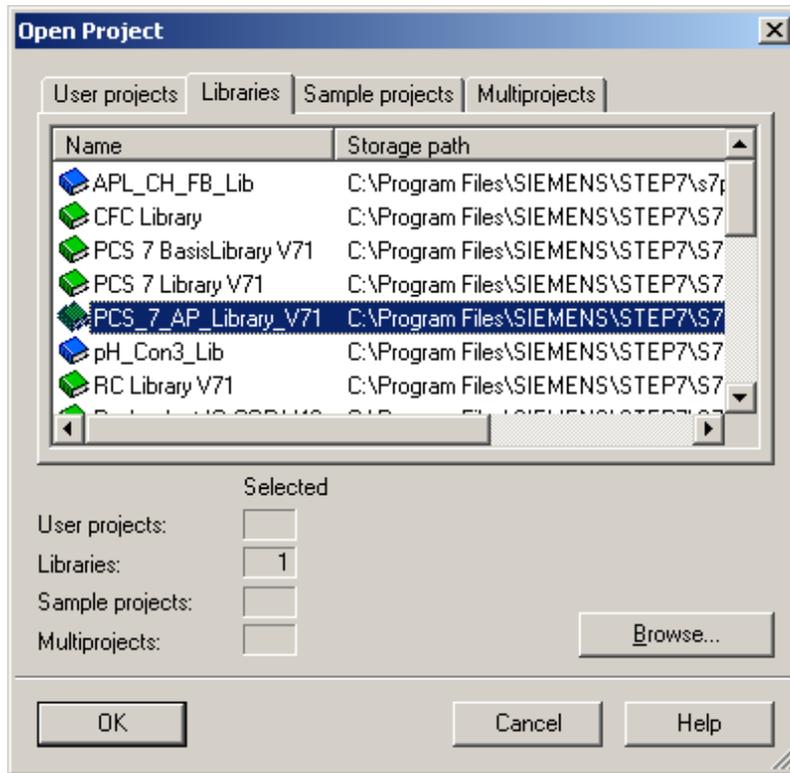
2. Copy the process tag type "ModPreCon" from the subfolder "Templates" into the master data library of your PCS 7 multiproject.

3. Modify it if this is necessary according to your general application requirements.

Figure 2-2: Selection of the process tag type
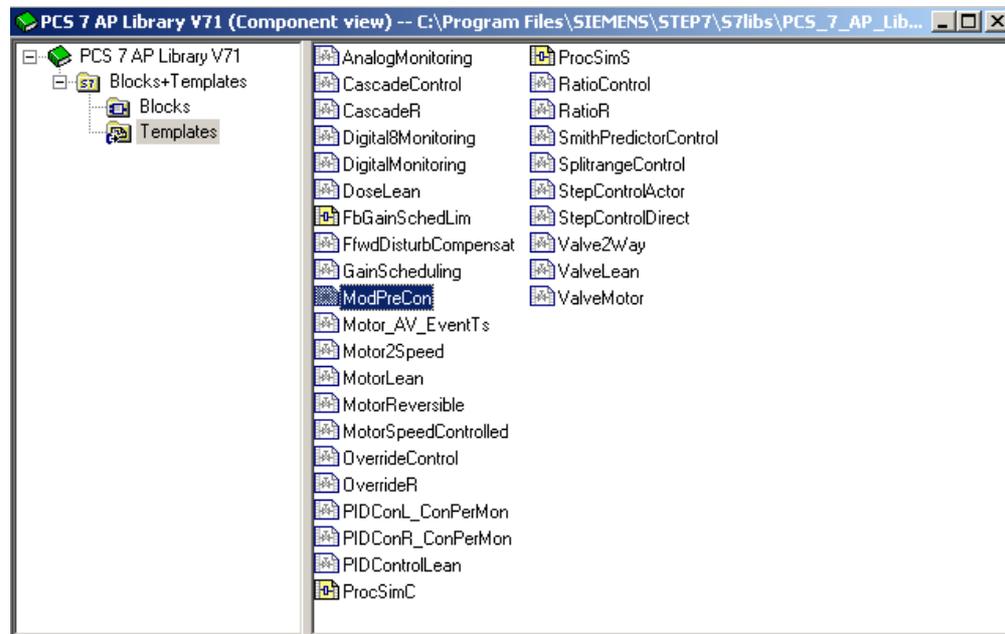
4. Copy the process tag type from the master data library to the target folder (Process cell > unit etc.) in the plant view. You obtain an instance of the process tag type i.e. a CFC chart, which indicates its origin by its symbolic representation.

5. Rename the new CFC chart and check if the cyclic interrupt OB is correct (in the CFC chart "Edit > Open run sequence").

6. Open the CFC chart and implement the following connections:

    *   Control variables: Connect the analog input drivers "Pcs7AnIn" for both control variables "CV1" and "CV2" (see figure Figure 2-3, number 1) with the symbolic names of the corresponding peripheral signals from the hardware configuration. The units of the signals can be adjusted at the input "PV_InUni".

    *   Disturbance variable: The measureable disturbance variable (if available) has to be linked to the input "DV1" of the MPC block (ModPreCon) (see figure Figure 2-3, number 2). If more than one measureable disturbance variable is affecting the process the additional signals can be considered too (see chapter 5).

    *   Manipulated variables: Both manipulated variables "MV1" and "MV2" have to be connected to the periphery via the analog output drivers "Pcs7AnOu" (see figure Figure 2-3, number 3 for the original process tag type). For using the manipulated variables as external set points for the slave PID controllers (as it is done in this example) the connections must be different. The outputs "MV1" and "MV2" of the MPC block must be connected directly to the inputs "SP_Ext" (external set point) of the corresponding PID controllers (see figure

Figure 2-4, number 3 for the cascade control). The inputs "MV1Trk" and "MV2Trk" of the MPC block (see figure Figure 2-3, number 4 and figure Figure 2-4, number 4) must be connected to the corresponding process values of the PID controllers to provide the information of the process values achieved by the PID controllers to the MPC. Therefore, the existing connections from the outputs "MV1" and "MV2" to the inputs "MV1Trk" and "MV2Trk" of the MPC block must be deleted. The units of the signals can be adjusted at the input "PV_InUni" of the analog output drivers "Pcs7AnOu" for the original process tag type (no cascade control) and via the units of the process variables of the slave control loops for cascade control.

- Monitoring: A further logical OR-block must be inserted for each cascade to monitor the connection inside the cascade. The first input of these OR-blocks has to be connected to the output of the block "CV_Bad" (see figure Figure 2-4, number 5) to monitor the process values of the MPC. The second input must be connected to the output "CascaCut" of the related slave PID controller. The outputs of the OR-blocks must be connected to the inputs "MV1TrkOn" and "MV2TrkOn" of the MPC block.

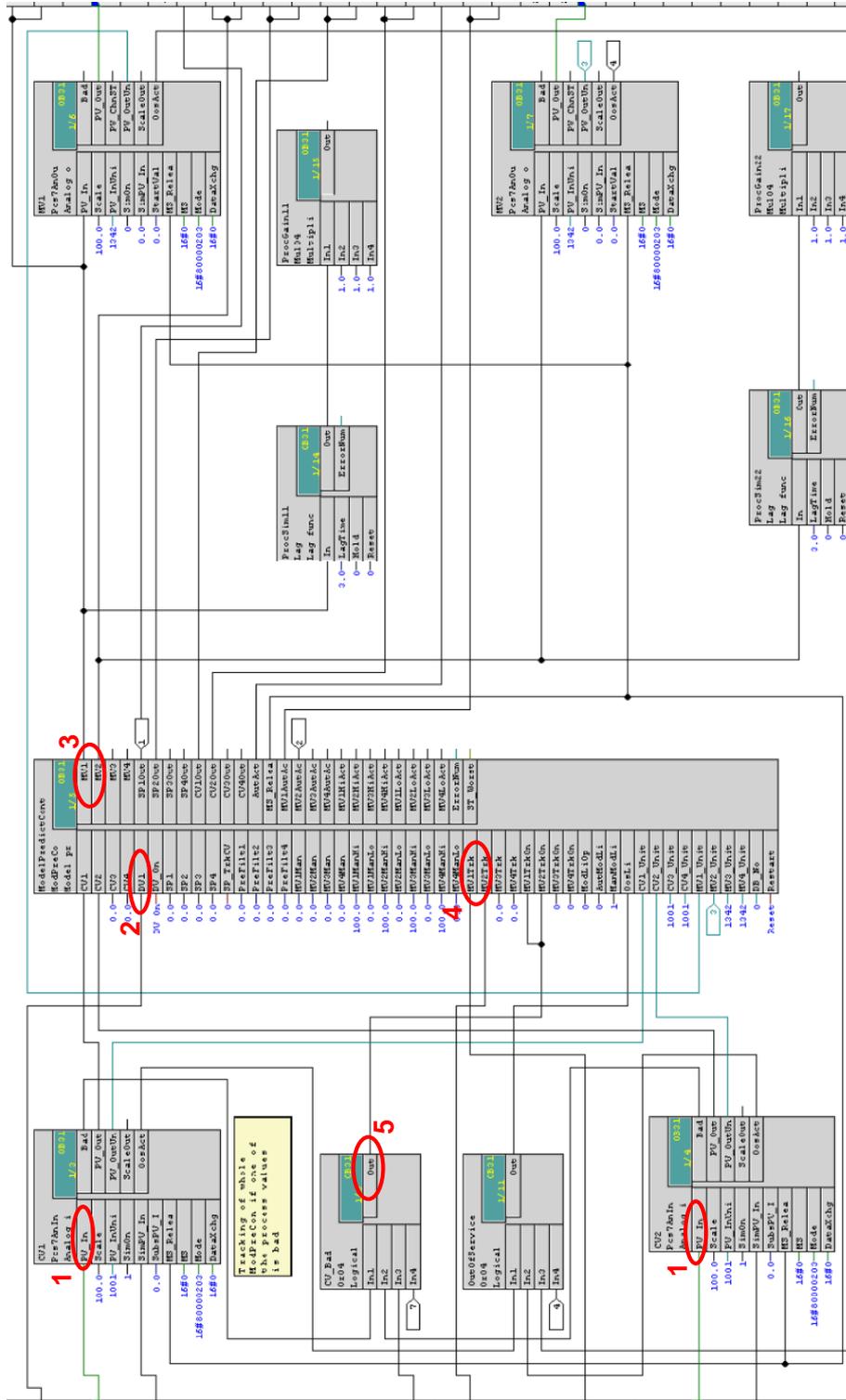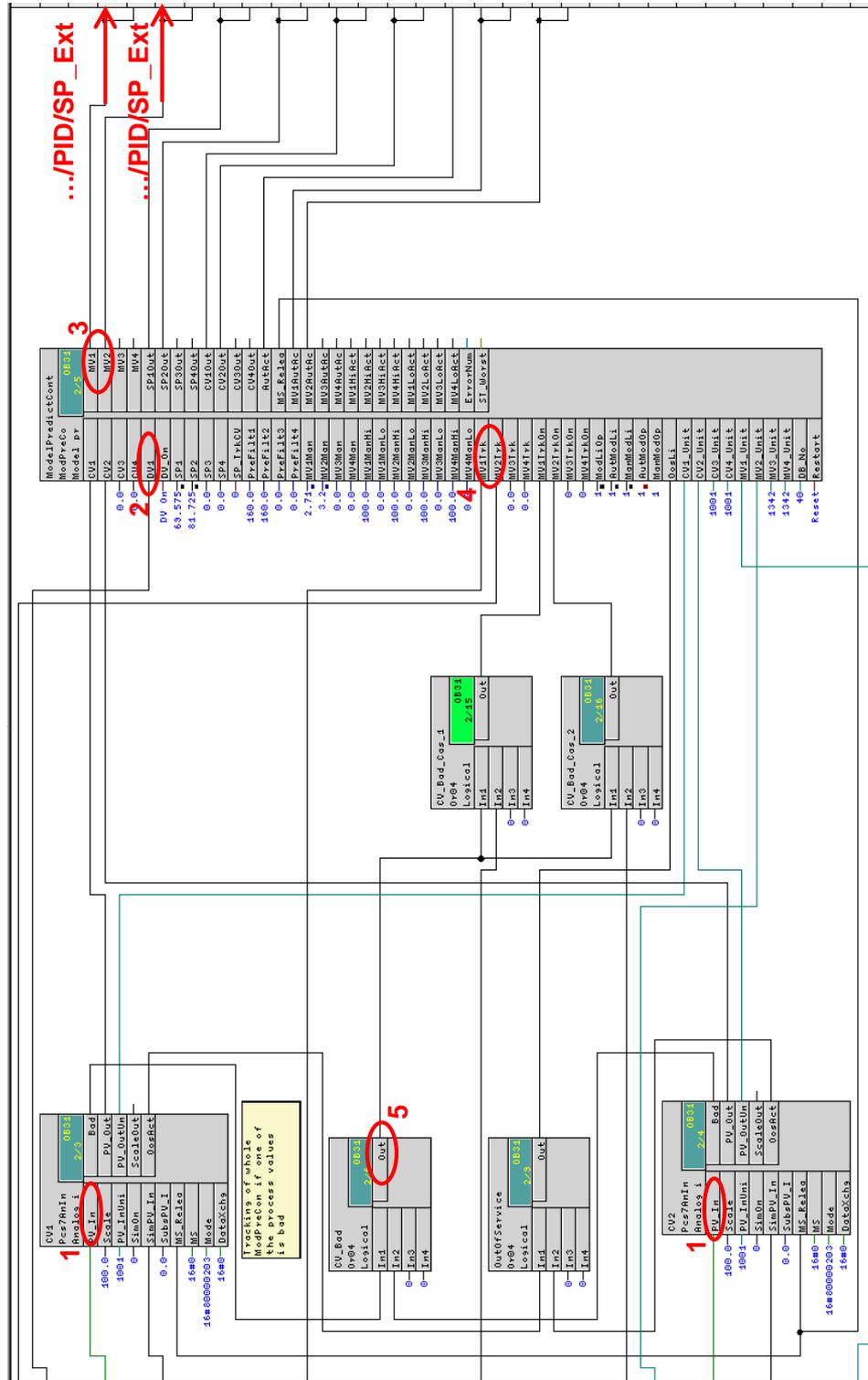Figure 2-3: Important connections of the original measurement tag type with direct access to the actuator

Figure 2-4: Important connections of the measurement tag type with cascade control

Hinweis   As long as the controller is not adapted to the process (no user data block for the underlying application is generated and loaded) it can only be run in manual mode.

7. Compile and download your changes to the AS. Compile the OS again to include the MPC faceplate in your runtime application.

Now you have successfully integrated the MPC to your process. In the next step the MPC must be configured to match your plant behaviour. Therefore, measurement data must be generated to identify the sub process of interest.

3   Generation of Measurement Data for the Identification

Excitation of Process and Recording of Training Data

The process is excited with stepwise changes of the manipulated and if possible of the disturbance variables in manual mode of the MPC. These measurement data is collected with the CFC trend display and exported to an archive file.
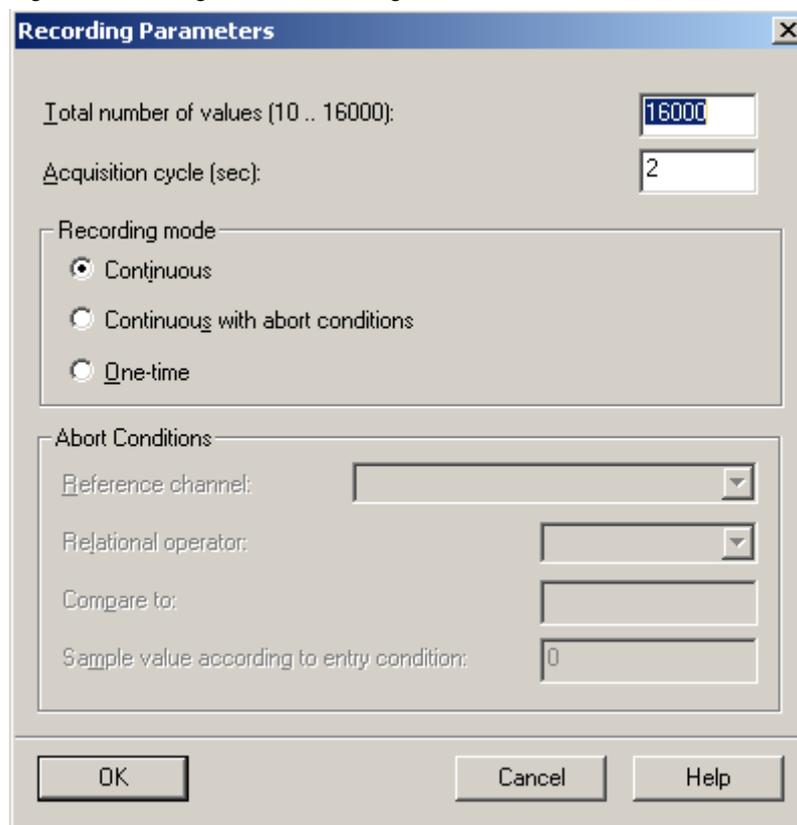
1. Select "Trend Display" in the menu "View" in the CFC to open the trend display.

Figure 3-1: CFC trend display
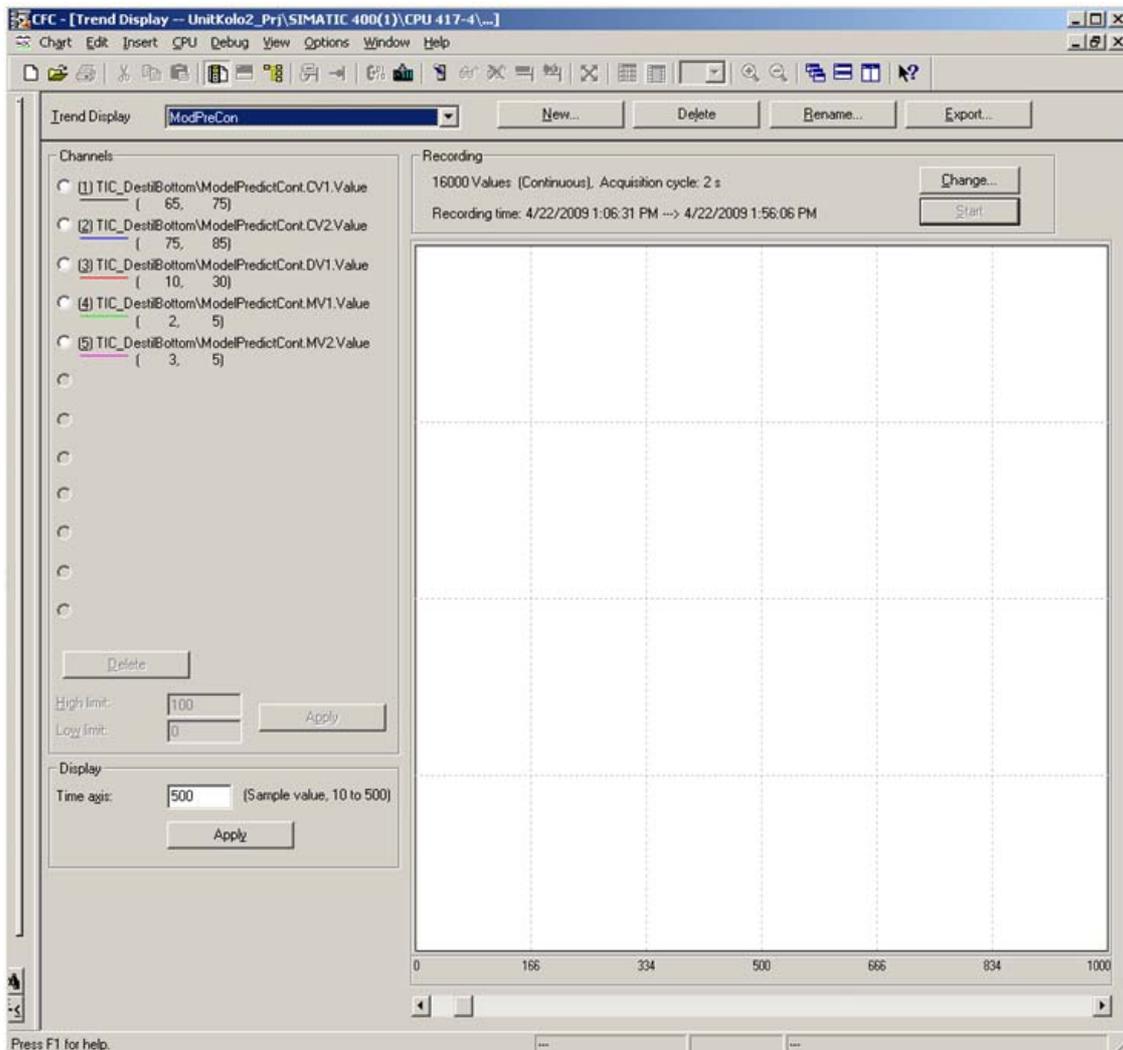
2. Generate a new trend display and specify several parameters with the "Change" button:

- The number of collected measured values;

- The acquisition cycle: It must be an integer multiple of the related interrupt OB and should be large enough to collect sufficient step responses. The rule of thumb says that the shortest transient effect (step response) should be collected within approximately 200 measured values. The maximal time range captured with these settings results from the multiplication of the number of measured values and the acquisition cycle.

Figure 3-2: Settings for the recording

3. In the next step the variables (manipulated, controlled and disturbance variables) to be captured must be selected. Move the corresponding signals via drag&drop from the CFC of the MPC to the trend display.

4. Select the value part of the data structure and apply it to a free channel.

5. Move your process to its operating point and wait for a steady state. Now you can start with the recording of measurement data. Be sure to decide which step changes to the manipulated and disturbance variables you want to apply before starting the recording. Some notes on this topic are given in the following: The measurement data should be symmetrical to the operating point for a successful identification. Therefore, a single step response is not adequate. Another point is that the dynamic of the process should be excited completely. As an example of a possible excitation step responses of the first manipulated variable could be executed first while in-between two changes steady state must be reached. Afterwards the same scenario with the other manipulated and disturbance variables can be carried out. Figure Figure 3-3 shows an example.

Hinweis   Additional remarks to the choice of excitation are given in the online help of the MPC configurator ("The individual design steps in detail > Recording the measurement series").

6. Before starting with the recording be sure to activate the external set points of the slave PID controllers ("SP_ExtOp=1" for "SP_LiOp=0" (default value) or "SP_ExtLi=1" for "SP_LiOp=1").

7. Switch on the test mode of the CFC and start the recording with the trend display. Apply your decided step changes to the manipulated and the disturbance variables successively.

Figure 3-3: Recording of measurement data (clipped in time)
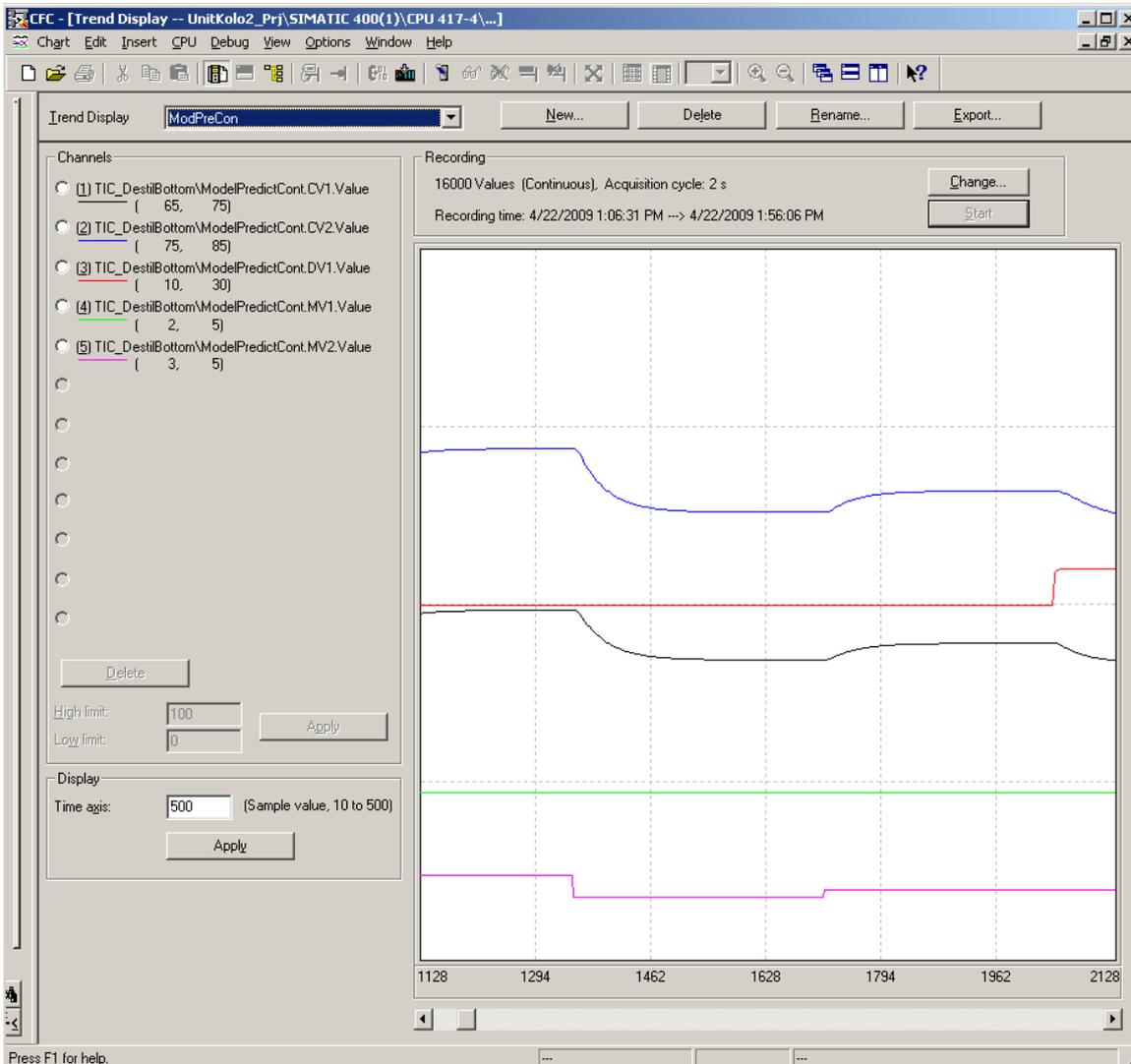
8. If all step changes are finished and the process is in steady state again, the recording can be stopped.

9. Export the measurement data to a csv-file via the "Export" button. Please keep the predefined settings.

10. If a validation of the identified model during the MPC configuration is desired, you have to generate an additional measurement data set in the same way as for the identification, but with a different excitation signal.

4   Configuration and Implementation of the MPC

4.1   MPC Configurator

The configuration is done with the MPC configurator. Select the MPC block in the CFC and start the configurator via the menu "`Edit > Configure MPC`".

Figure 4-1: Start window of the MPC configurator
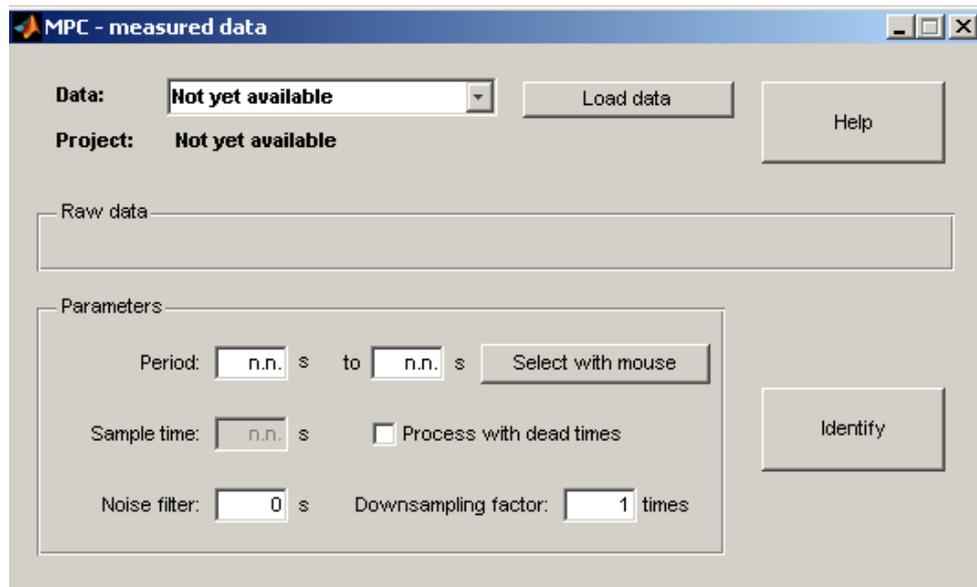
1. Select your recorded measurement data via "load data". Thereupon all captured variables are displayed in the window.

Figure 4-2: Settings for the measurement data
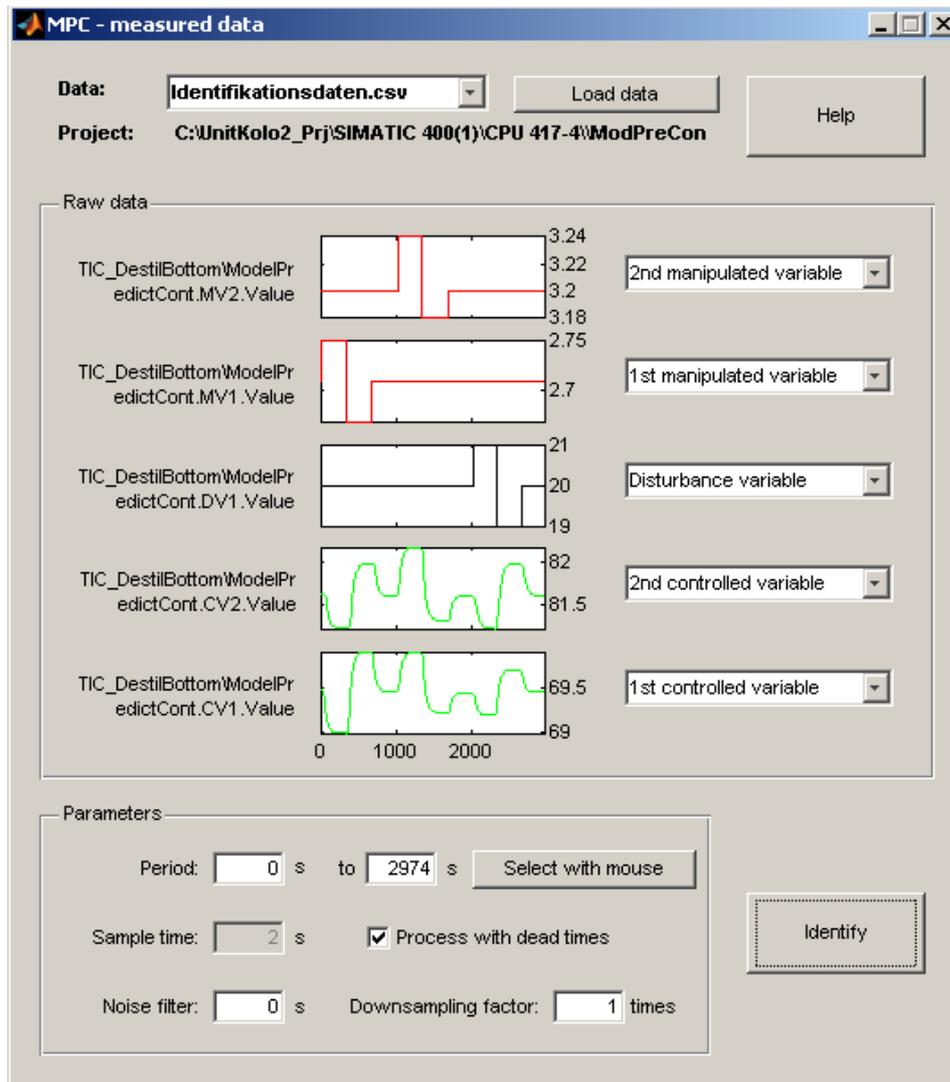
2. Assign its role to each variable and specify if it is a manipulated, controlled or disturbance variable or if it is not relevant.

3. In the lower part of the window the time range of the measurement data can be adjusted. If your process has dead times, mark the appropriate tick mark. Moreover it is possible to smooth the measurements with a noise filter and to downsample the data to reduce the amount of data.

It is possible to load several different data sets, or equal data sets with different time ranges. All loaded data is considered for the identification.

4. Right click on the name of the corresponding file in the data selection to remove a data set from the identification.

5. The identification can be started via the "Identify" button. The results of the identification are shown in a new window (see figure Figure 4-3).

Figure 4-3: Results of the identification
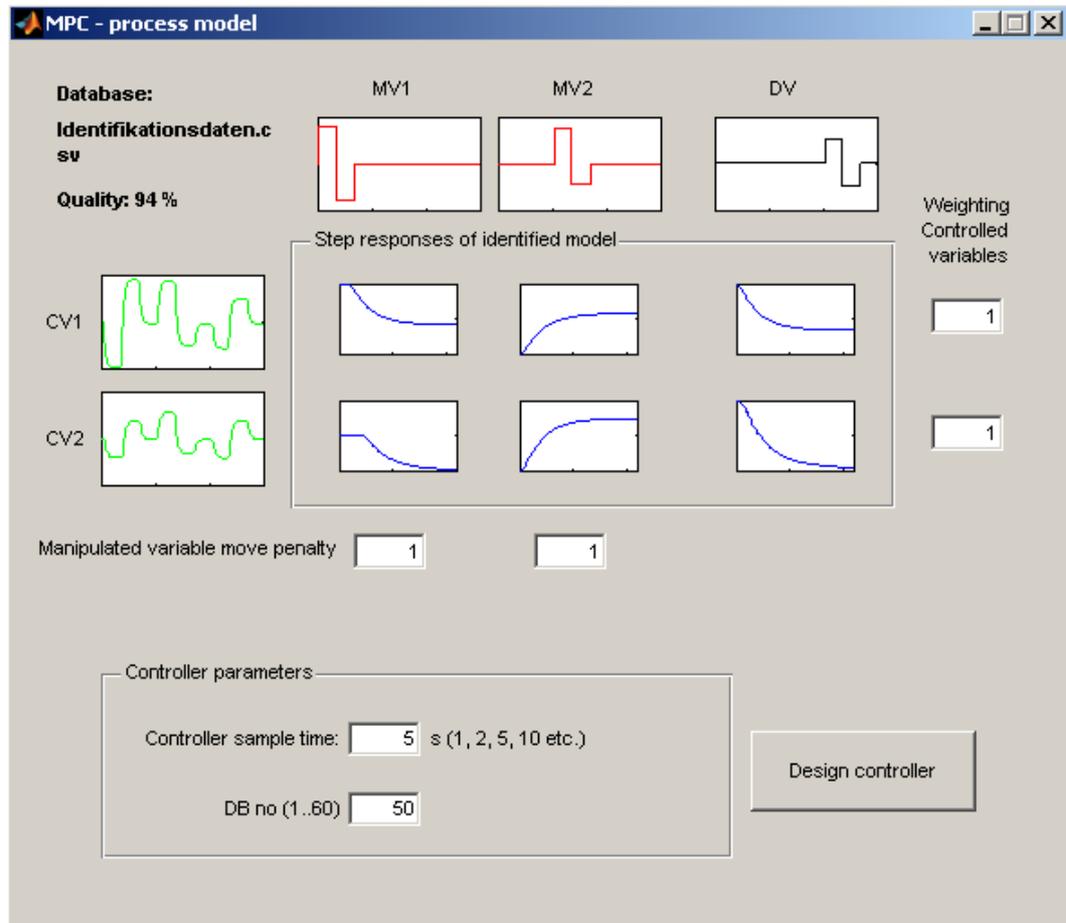
6. Evaluate these results carefully and decide if this model has the adequate accuracy for the MPC design.

- The Bode diagrams can be analysed by clicking on the step responses.

- A click on the control variables shows a comparison of measured and calculated data of the model as can be seen in figure Figure 4-4.

- Altogether the model accuracy should be as high as possible but more than 50%, the dynamic should be covered adequately and the step responses should be stable.

Figure 4-4: Accuracy of the model (Model qualities of 99% can only be achieved with simu-
lated data.)
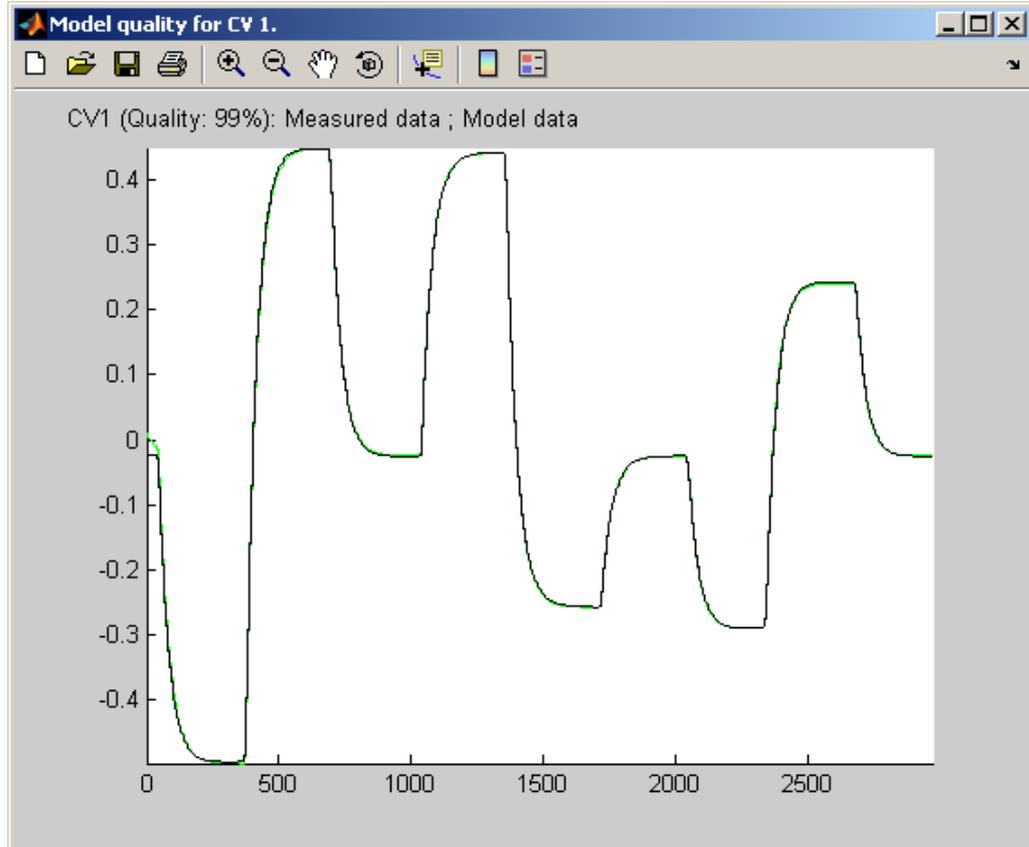
If the model identification is finished, the design of the MPC can be started.
The MPC algorithm is based on a quality criterion of control error and
movement of manipulated variables:

$$J = \left(\vec{w} - \vec{y} \right)^T \cdot \underline{R} \cdot \left(\vec{w} - \vec{y} \right) + \Delta\vec{\underline{u}}^T \cdot \underline{Q} \cdot \Delta\vec{\underline{u}} \, .$$

The diagonal weighting matrices R and Q affect the intensity of the control-
ler action.

Controller parameterization

In figure Figure 4-3 some settings can be specified to parameterize the controller:

- Weighting of the controlled variables: These are the diagonal elements of matrix R corresponding to the related controlled variable over the whole prediction horizon. The weighting indicates the importance of each controlled variable. E.g. higher weighting of controlled variable 1 than controlled variable 2 leads to a faster and more accurate reduction of the control error for the first controlled variable than for the second one.
- Penalization of the manipulated variable: These are the diagonal elements of matrix Q corresponding to the moves of the related manipulated variable over the whole control horizon. If you increase the weighting, the changes in the manipulated variable are penalized more strongly and the controller moves its manipulated variable more cautiously resulting in a slower but more robust control action.
- Controller sample time: The MPC configurator recommends a suitable value for the sample time based on the identified model to cover the slowest step response within at most 100 samples. In general these recommendations should not be changed. Move the CFC runtime group of the MPC measurement tag type in the interrupt OB with the recommended sample time. If the controller sample time is displayed in red, you will need to install the function block in OB30 although the controller sample time is higher than 20 s. The function block is then called every 20 s but the controller is activated with the displayed sample time only due to an internal downsampling.
- DB no.: The data block number relating to this parameterization has to be set manually. Please choose a DB number not used in the project before to avoid overwriting of an already existing block.

After selecting all settings the MPC matrices can be calculated via the button "Design Controller" (Figure 4-3).

Controller design

1. The window for the validation of the model and the controller is opened automatically. In the upper part of the window the recorded measurement data for the validation of the model can be loaded. A comparison between the measurement data and the simulation results of the corresponding model is done automatically.

2. The results can be seen in more detail by clicking on the plot.

Abbildung 4-5: Validation
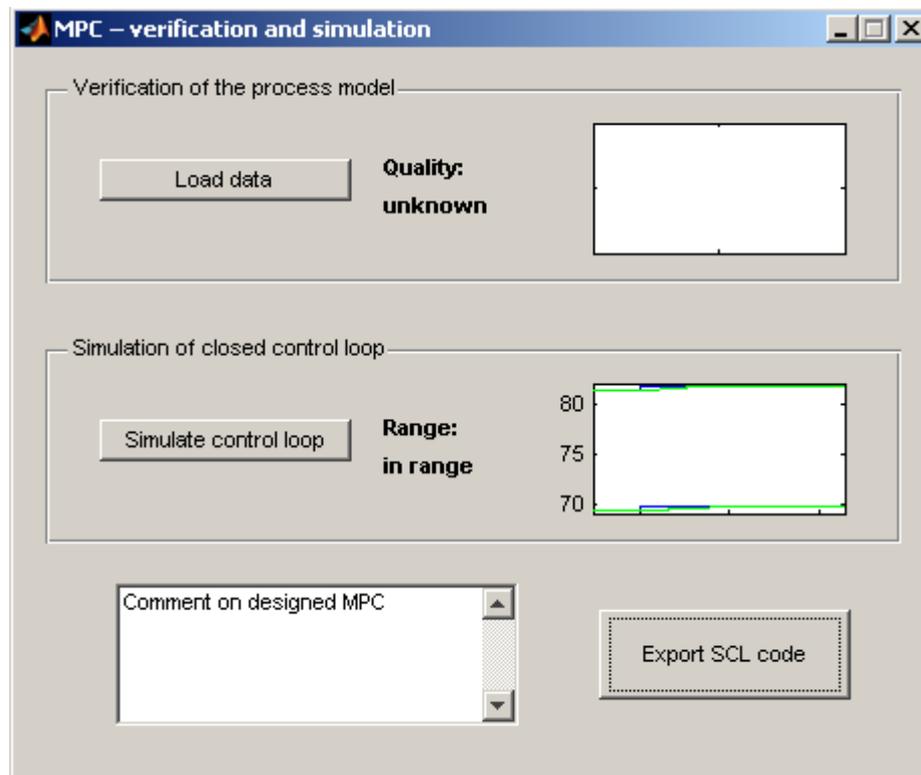
3. In the middle part of the window the controller can be simulated in closed loop via the "Simulate control loop" button.

4. Clicking on the right plot provides the results.

5. If the model as well as the controller shows an adequate behaviour, the user DB for the MPC can be exported via the "Export SCL code" button.

4.2 Integration of Control Parameters

In a first step the SCL source generated by the MPC configurator must be imported.

1. Therefore, use the component view of the SIMATIC Manager as can be seen in figure Figure 4-6. Select the folder "Source" of the S7 programs in your CPU.

2. Select the desired SCL source via "Insert new object > External source" of the context menu.

Figure 4-6: Import the SCL source
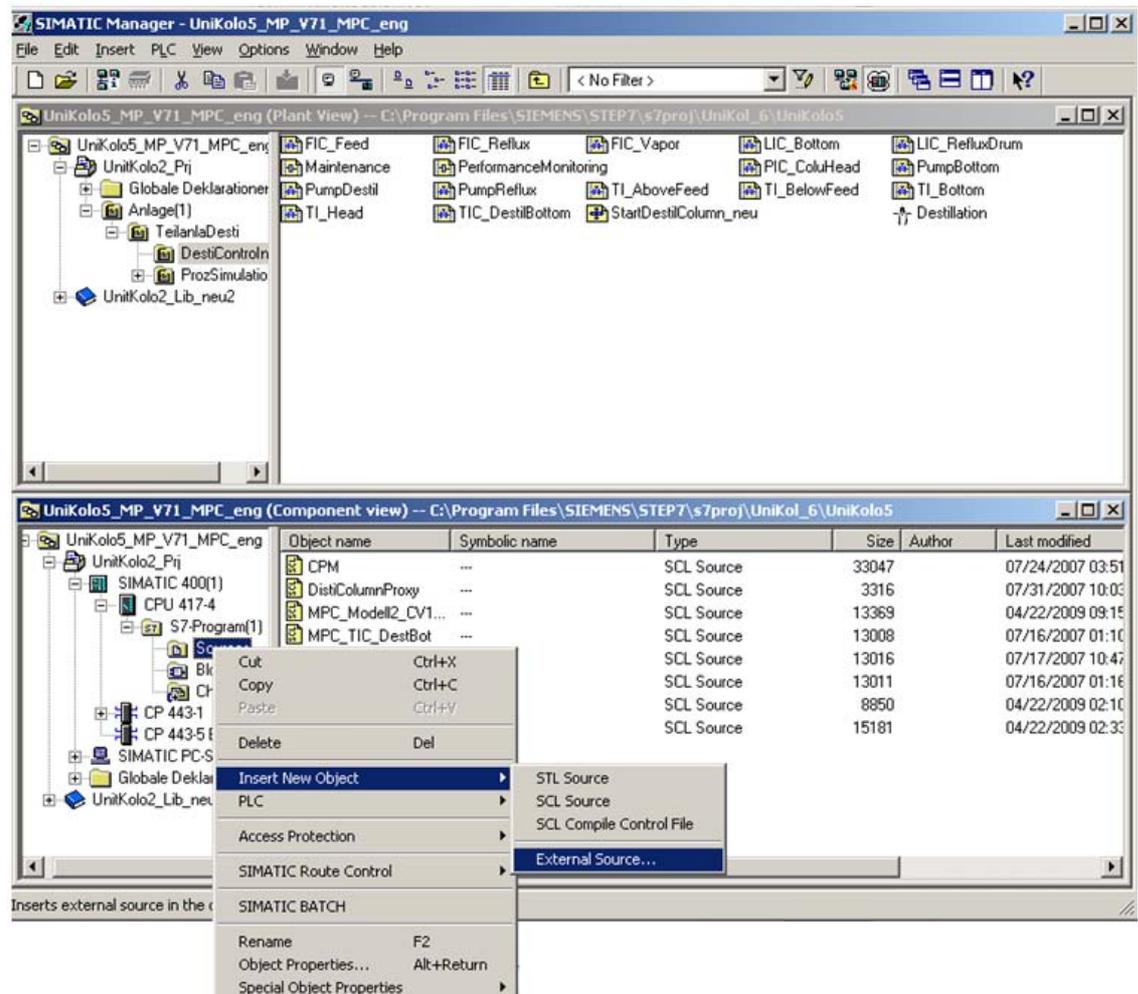
3. Compile the source code via the context menu of the inserted SCL source.

4. Afterwards the new DB can be downloaded to the AS directly from the SCL editor.

5. Parameterize the correct DB number at the input "DB_No" of the MPC block in the CFC chart to assign the correct parameters to the MPC. The contents of the new or modified DB are loaded by initializing the controller. Therefore, set the input "Restart" of the MPC block in the online mode.

6. The last step is to select the correct setpoints for the MPC and to change into automatic mode.

4.3 Parameterization during Operation

The behaviour of the MPC can be slowed down by a setpoint filter, if the controller is too aggressive. Step changes in the setpoint are replaced by an asymptotical trajectory. It can be parameterized by a time constant (input "PreFilt" of the MPC block), which corresponds to the desired settling time of the corresponding control variable after a step change in the setpoint.

5 Model Predictive Control with more than one Measureable Disturbance

If there is more than one measureable disturbance variable and not all four possible manipulated variables of the ModPreCon block are used, you can "rededicate" the first manipulated variable channel that is not used.

Example (see figure Figure 5-1)**:**

1. You currently apply only two manipulated variables "MV1" and "MV2".

2. The additional measureable disturbance "DV2" can be connected to the input "MV3Trk" of the MPC block and the corresponding parameter must be set to "MV3TrkOn=1".

Figure 5-1: CFC with an additional disturbance variable connected to input "MV3Trk"
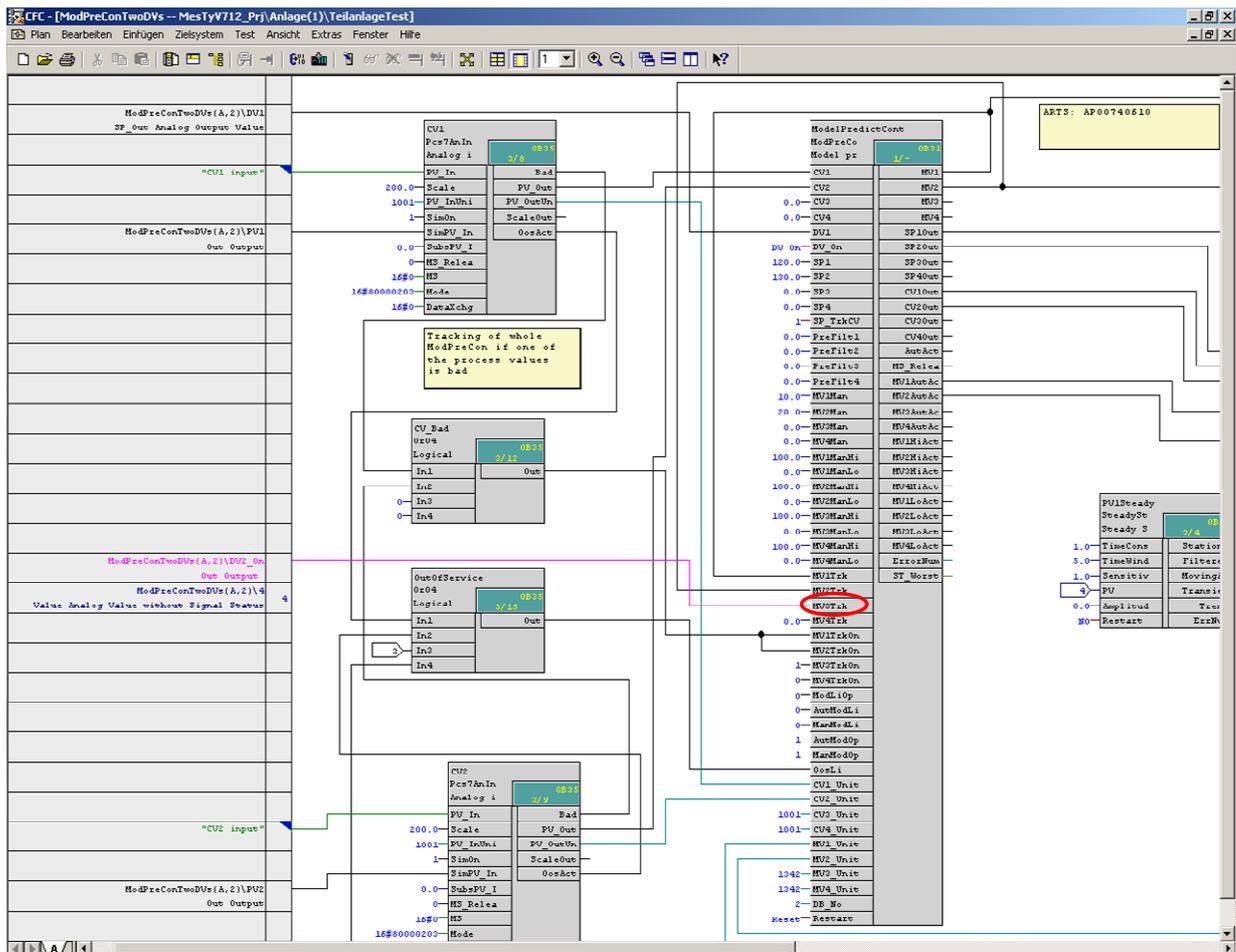
3. Assign "MV3Trk" as the third manipulated variable during the recording of the measurement data for the MPC and additionally capture this variable with the CFC trend display.

4. Identify a model of the process with the MPC configurator, which also describes the impact of "MV3=DV2".

5. The penalty of changes in manipulated variables has to be much higher for "MV3" (e.g. factor 100) than for the two real "MVs" (MV1 and MV2) in the controller design within the MPC configurator. Due to this parameterization "MV3" will hardly be moved by the controller. In fact a changing of "MV3" by the controller is not possible at all, as "MV3" is an external disturbance.

The impact of changes in the disturbance "DV2" are considered in the prediction of the future process behaviour via the input "MV3Trk" in automatic mode of the controller and can be compensated foresightedly. The quality of this disturbance compensation is exactly as high as using the standard feedforward compensation via the input "DV" and "DV_On=1".

The disturbance compensation with the rededicated manipulated variable "MV3" can be deactivated during operation via the connection of the input "MV3Trk" with a selector block "SelS02In". Switching to a constant zero instead of the "DV2" measurement as input "MV3Trk", the influence of "MV3" on the prediction is disabled ("MV3Trk" has to be always "true" to prevent the controller from moving "MV3").

6 Simulation Example

6.1 Distillation Column

Figure Figure **6-1** shows a basically automated distillation column as it is used in the following. More information about the control of a distillation column can be found in [1.] .

Figure 6-1: A basically automated distillation column
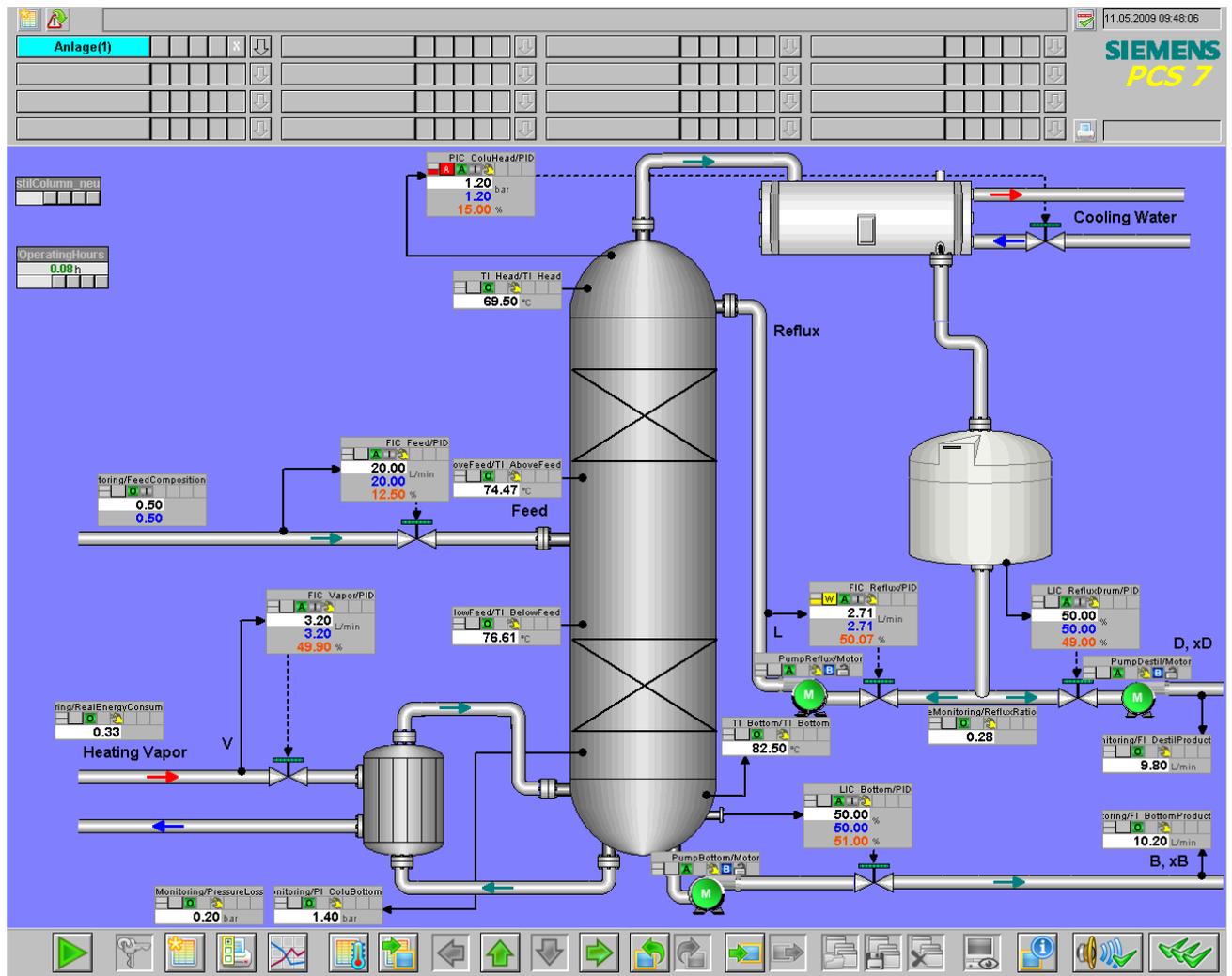
The enhancement of this system by feedback control of the distillate temperature will be the topic. Due to the correlation between temperature and concentration during phase equilibrium (vapor and fluid), the temperature control provides control of concentration (quality control) for the separation of substances during the distillation. Therefore, a cascade control with a slave PID controller for the reflux is used. In a first step the master tem-

perature controller is realized by a single PID controller. Afterwards the interaction between the temperature of the distillate and the temperature of the bottom as well as the perturbation by the feed load are considered by application of MPC. Both versions are compared in a simulation with two test scenarios: a step change in the setpoint and in the disturbance.

6.2   Conventional Single-Input Single-Output Control

The extension of the basic system from figure Figure 6-1 with a master PID controller can be seen in the following figure.

Figure 6-2: Automation with PID master controller for head temperature
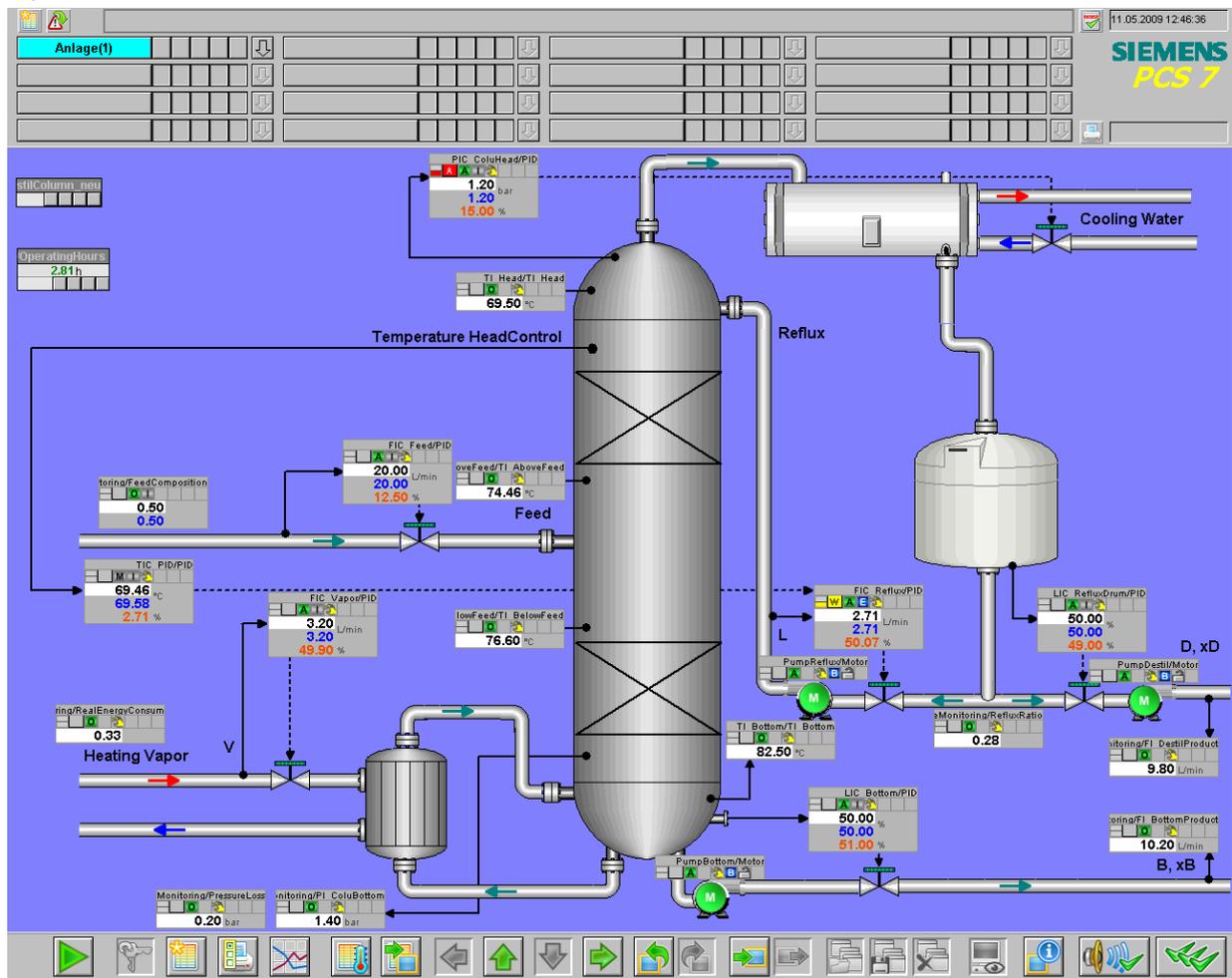
Based on the measured temperature of the distillate, the PID controller calculates the external setpoint for the slave flow controller. The temperature controller was designed with PID tuner for good tracking behaviour.

The results of a step change in the setpoint for the temperature of the distillate (in red) can be seen in figure Figure 6-3. The transfer to the new temperature without oscillations is only possible due to slow controller tuning. At the same time the bottom temperature is drifting away in an undesired way, as there is no controller to keep this temperature constant.

The impact of a stepwise change in the disturbance feed flow can be seen in figure Figure 6-4. Both temperatures are significantly influenced while the PID controller traces only the temperature of the distillate slowly back to its setpoint.

Figure 6-3: Step change in setpoint of distillate temperature (head temperature) with PID master controller
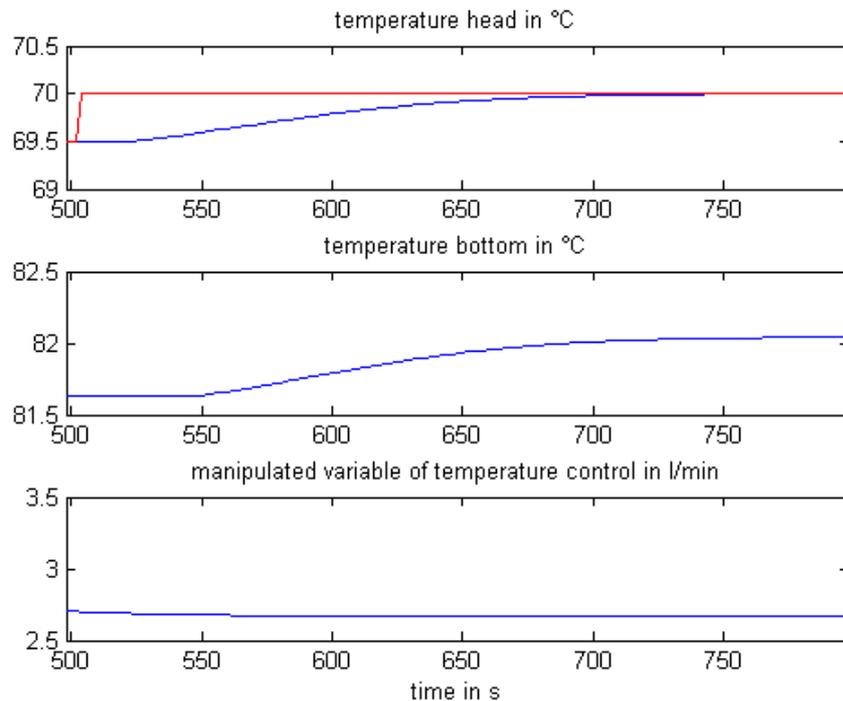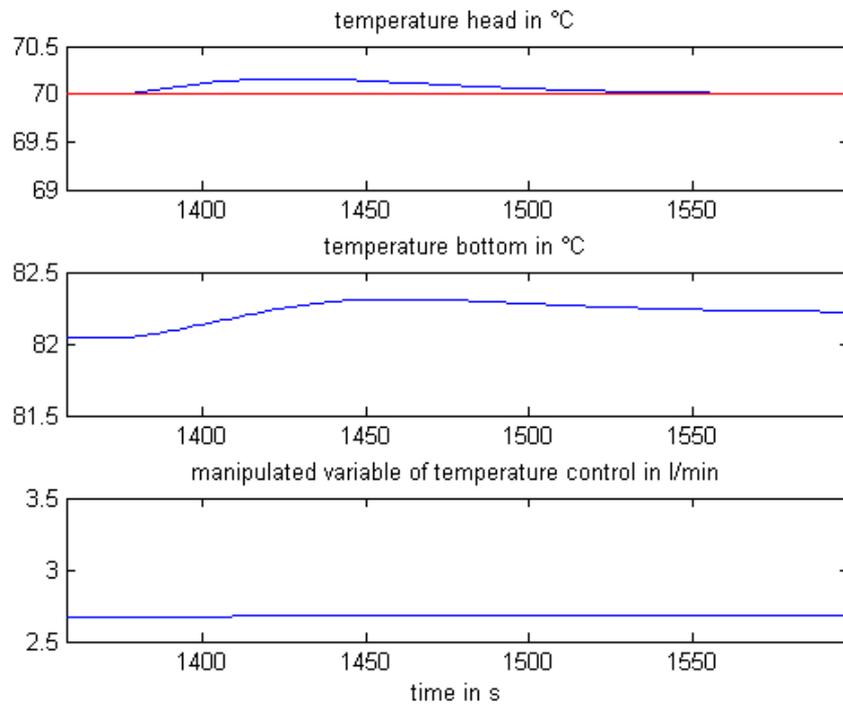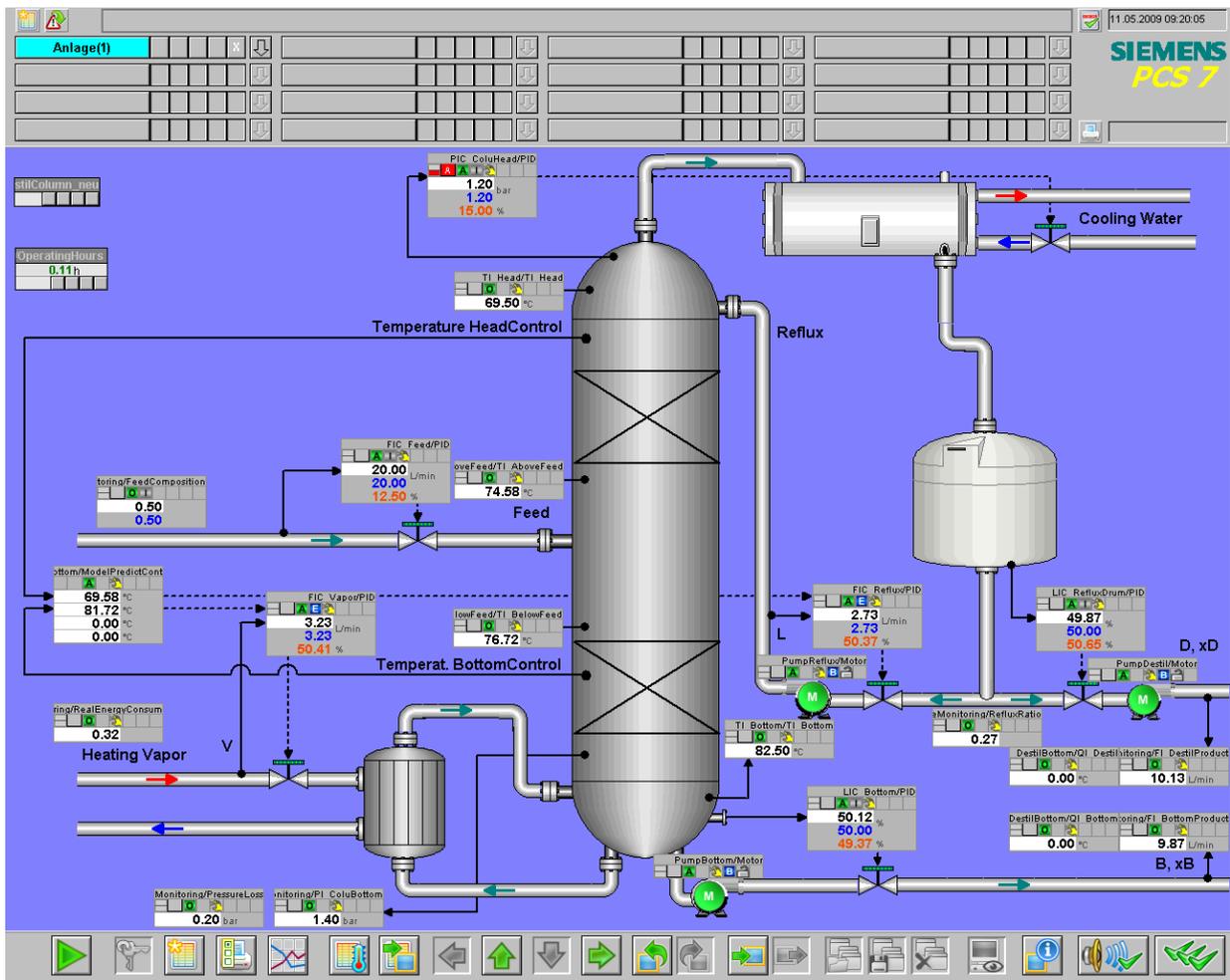
Figure 6-4: Stepwise feed disturbance with PID master controller

6.3   Control via MPC

In the following temperature control via MPC is considered.

Figure 6-5: Automation with MPC

Based on the measured temperatures of head and bottom and the known perturbation by feed flow the MPC calculates external setpoints for two slave PID controllers, which control the reflux and the heating vapor flow.

The results during a setpoint step change in the head temperature using the MPC are shown in figure Figure 6-6. The distillate temperature is adjusted rapidly and without oscillation while the bottom temperature remains at its original level.

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Figure 6-6: Step changes in head temperature setpoint of using MPC
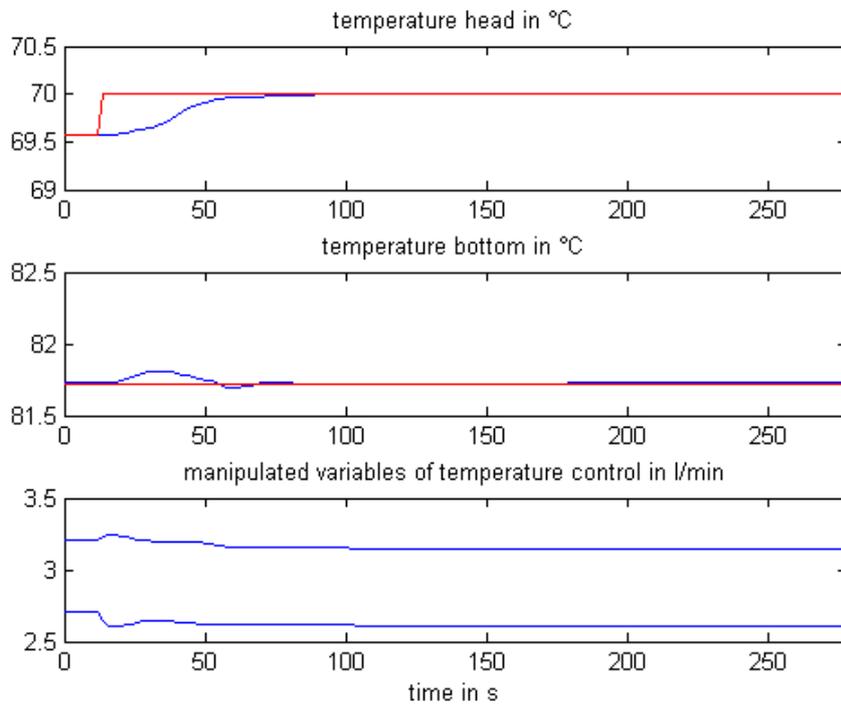
The same disturbance scenario as before using the PID controller is done with the MPC too. The results are shown in figure Figure 6-7. The disturbance is compensated almost ideally with nearly no drift in the temperature signals.

Note For easy comparison, the ordinate scale and the length of the abscissa are the same in all diagrams.

Figure 6-7: Stepwise feed disturbance using the MPC
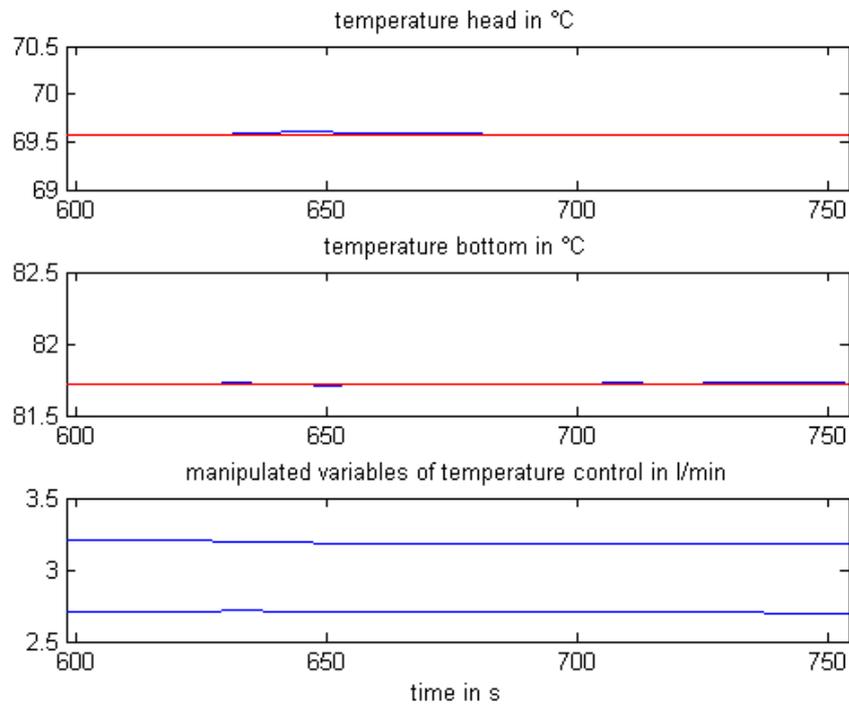
The advantages of the MPC compared to the PID master controller can be
seen clearly. By considering the multivariable case the thermodynamic in-
teraction between head and bottom of the column is taken into account.
Due to the feedforward of the measureable disturbance the perturbing in-
fluence of the feed load can be compensated. The present example is
based on a process with dead times and therefore the MPC can reach its
goals faster (without oscillations) than the PID controller.

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7   Conclusion

A comparison of the conventional PID controller and the MPC can be found in table Table 7-1. An additional comparison to a PID controller with Smith predictor is described in the Application Note dealing with Smith predictor.

Table 7-1: Comparison of SISO PID controller and MIMO MPC applied to a distillation column

	PI(D) controller (conventional)	MPC
SISO/MIMO case (single-input single-output / multi variable case)	SISO only	SISO or MIMO
Control performance	low	very good
Engineering-effort	low	medium
CPU resource-consumption (memory, calculation time)	low	high
Control of processes with dead times	sluggish	very good
Feedforward disturbance compensation	can be supplemented	already integrated

Alternative Hardware Structure to Evaluate the MPC

If you want to test the MPC on a process running an older PCS 7 version than V7.0 SP1 (i.e. without MPC software) you have the following possibility for a temporary test configuration:

- Connect an up-to-date PCS 7 BOX V7.1 to your legacy PCS 7 system (PCS 7 V5.x or higher). The communication from the ModPreCon-function block in the Slot-CPU to the function blocks of the existing system is engineered via AS-AS communication.

Figure 7-1: Test configuration for temporary evaluation of APC functionalities

8 History

Table 8-1 History

Version	Date	Modification
V1.0	July 2009	1st release

9 Literature

[1.] Pfeiffer, B.-M., Lorenz, O.: Unit-orientierte Musterlösungen für Advanced Control (Unit-oriented solution templates for advanced control) – Beispiel Destillationskolonne (Example distillation column). Automation 2008, Baden-Baden. VDI-Berichte 2032, S. 11-14, VDI-Verlag, Düsseldorf.