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Optimization of an Alkalinity Control Unit

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Abstract
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The reactor or ACU™ (alkalinity control unit) is a part of a bigger application known as the ADALKA™. Ever since that first installation of the ACU™ the development has been going on and the aim of the thesis was, to check and improve the logics of the ACU™ and the way the reactor is controlled.
Since there are many ACU™s running, but no test unit, only one ACU™ has been examined in this thesis. If not other mentioned the ACU™ refer to the mobile unit currently existing at the M-Real paper mill in Jyväskylä, Finland.
The thesis resulted in a new control program, which included some new ideas based on more advanced control theory together with different logics. Modifications where made to the start up and stop sequences of the reactor as well as to the dilution part before the reactor. A different kind of pressure control for the reactor was implemented, tested and evaluated.
The ACU™ is operated from a panel, which was adjusted and fully configured to this new control program.
The examination of the ACU™'s process image also contributed to the decision to change one of the control valves. This change had a big influence on the process. It became more stable. Since none of the control circuits were tuned prior to this work two of the most significant circuits were tuned.

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Optimization of an Alkalinity Control Unit

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Preface

This Master's thesis is made as a part of the completion of the Master of Physics program and the work was made at AGA and in cooperation with the Department of Automatic Control, Lund Institute of Technology.

The author wants to express his gratitude to several people who have provided their support:

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- Hannu Leino, supervisor, coordinator and technical advisor.
- Ulrika Molin, supervisor, reviewer and the person who supported both a lot of time and knowledge and made this thesis possible.
- Erkki Rinne, skilful SIMATIC® programmer and advisor with a lot of patience.

Table of contents

1 Aim

The aim of this thesis was to improve the logics of the ACU™-reactor and the way it is controlled. Some situations were specified to be investigated including start up, stop and flow changes. The commissioner also wanted the pressure control of the reactor to be reviewed and compared with control theories. From this investigation the problems should be pinpointed and form the base to changes in the existing control program or to a new program.

2 Background

In this chapter the chemistry on which the reactor is founded will be presented together with a visual description of the application. The notation used for the different control loops and equipment will be explained, and last the problems related to the control system for the ACU™ will be listed.

2.1 The process

In the papermaking process sudden pH changes often cause process disturbances, but they could largely be avoided by adding a buffering agent i.e. increase the alkalinity. Powderous sodium bicarbonate, $NaHCO_3$, could be used for this purpose, but with the problem of too high pH at the addition point.

Linde's paper team has developed a solution to this problem by producing sodium bicarbonate solution to which the properties can be changed according to the process requirements. The idea is to mix aqueous sodium hydroxide, NaOH, with gaseous carbon dioxide, CO_2, at different ratios, and according to the following reaction [1] produce sodium bicarbonate:

$$NaOH(aq) + CO_2(g) \Leftrightarrow NaHCO_3 \qquad (2.1)$$

Adjusting the amount of added CO_2, controls the pH of the resulting sodium bicarbonate solution. The ACU™ reactor is built and controlled with respect to the reaction described in (2.1). In the next section the ACU™, which is fully automated and has three output flows through which it can feed sodium bicarbonate, will be described.

2.2 ACU™ Hardware description

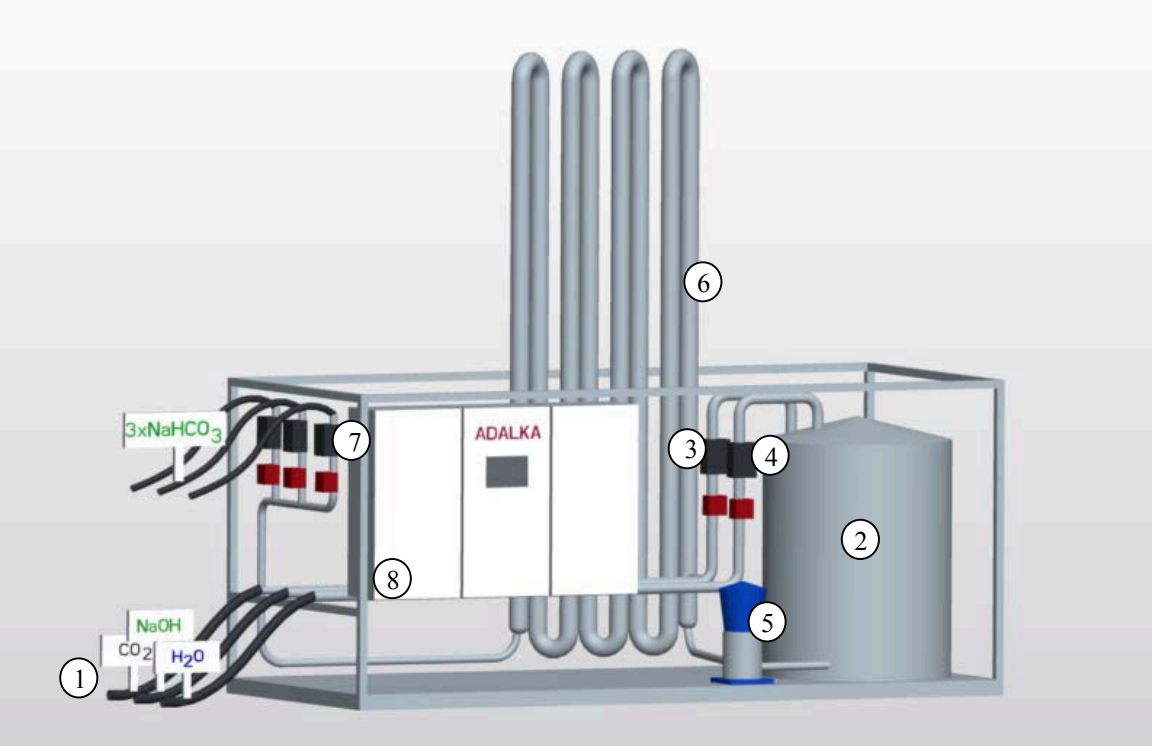

Figure 2.1 *Picture from a 3D-model of the Alkalinity Control Unit (ACU™).*

Figure 2.1 shows a picture from a 3D-model of the Alkalinity Control Unit. The model is not complete but shows the main parts. In this system description some of the abbreviations for the parts used in the control system will be explained.

The ACU™ requires three inputs, water (H_2O), sodium hydroxide (NaOH) and carbon dioxide (CO_2), label 1 in figure 2.1. The water and sodium hydroxide are mixed together in the tank, label 2, under the control of two valves, one for the water (FV014), label 3 and one for the NaOH (FV004), label 4. The pump (PU27), label 5 builds up a pressure for the NaOH flow before it goes into the reactor, label 6, through another control valve (FV037), not seen. The third input, the CO_2 enters the reactor through a perforated lance and the flow is controlled by valve (FV035), not seen. This particular ACU™ has three outputs each one controlled with a different valve (FV051, FV052 and FV053), label 7. There are also two On/Off valves used, but not seen in the picture, one between the reactor and the outputs (HV42) and one used for re-circulation (HV43). HV43 is connecting the back of the reactor with the tank. The white cabin in the front stores all the electronics including the PLC, label 8.

2.3 Control system

Also the control circuits have certain names, and they require an explanation before they can be referred to. The circuits will be represented throughout the thesis according to the following block diagram notation [2], see figure 2.2. For other notation used see appendix III.

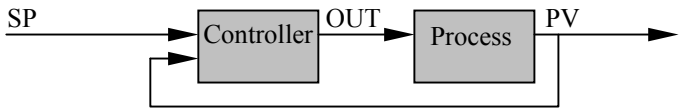

Figure 2.2 *Control circuit represented as a block diagram.*

All of the different control circuits used to control the ACU™ and their abbreviations are found in appendix IV. In appendix IV is also a description of the different measuring equipment used for the feedback to the different controllers.

2.4 Problems with the ACU™

The first installation of an ACU™ was in summer 2000, and since then many changes have been performed to the equipment. The development has been mainly focused on reactor design and other technical issues. In the beginning of this thesis all the problems related to the control system where gathered and are listed below:

- Variations in the outgoing pH, especially noticed at low flows.
- Unstable pressure in the reactor due to variations in flow.
- Undissolved CO_2 in the reactor especially during the start up. This causes big pressure variations as the undissolved gas goes through.
- PID-controllers working without being tuned.

3 Programmable logic controllers

The ACU™ is controlled by a PLC from Siemens with a control program based on the SIMATIC® S7 system. In this chapter some general facts about PLCs will be presented and in the end a small comparison between the PC and the PLC.

3.1 General

A PLC is a user-friendly, microprocessor-based specialized computer that can carry out control functions of many types and levels of complexity. Its two main functions are to control the process itself and to monitor the present process parameters, known as the process image. The PLC can operate any system that has output devices that can go on and off e.g. on-off valves and pumps, as well as it can operate any system with variable outputs e.g. control valves. On the input side the PLC can be operated by on-off (binary) devices or by variable (analog) input devices [3].

The first PLC system evolved from conventional computers in the late 1960s. Until then electrical circuits with wires, relays, timers and other components had been used for the same purpose as the PLC today. At this time different automation techniques developed rapidly and the PLC was first used, together with other modernities to shorten the changeover time e.g. when a new car model was about to be produced. A problem in the beginning was that the programs became complicated and only a skilled programmer could make changes.

Nowadays improvements have been made to make PLC programming more user-friendly, an example of this is Siemens development of the high-level language SCL.

3.2 PLC description

The PLC consists of four major parts, see figure 3.1 from left to right:

- Power supply. Part of the system, which supplies the other parts with various operational DC values to ensure proper computer operation.

- Central Processing Unit (CPU). The brain of the PLC, which in turn has three subparts:

    - The microprocessor with ALU (arithmetic/logic unit) and its registers that executes the program carries out mathematical and logical operations.

    - Memory. The basic operating system is stored permanently in the CPU, in the read only memory (ROM), and is not lost when input power is lost. However the control program is stored in the random access memory (RAM) and is not stored permanently.

    - Back up power supply. A battery backup enables the CPU to retain the user program in case of a power loss.

- I/O Modules. The input modules have terminals into which process signals are entered and the output modules create signals to process actuators.

- The rack. The rack on which the PLC parts are mounted.

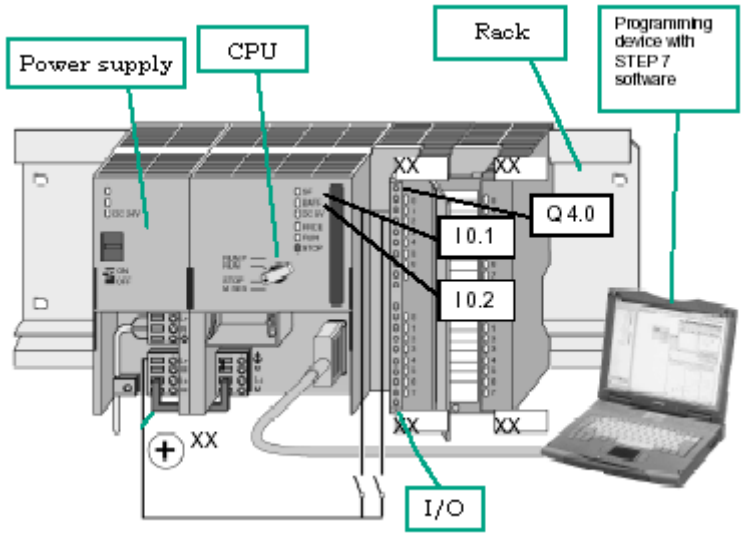

Figure 3.1 *The major parts of the PLC. Slightly modified from figure in [4].*

3.3 Programming a PLC

A PLC can be programmed in different ways and the most common way is to use Ladder Logic. Ladder Logic has evolved from the era before the introduction of the PLC. The three different ways allowed in the S7 system are listed:

- Function Block Diagram, FBD.
  The programming language Function Block Diagram is based on graphic logic symbols also known in Boolean algebra. Complex functions such as math functions can also be displayed directly in combination with the logic boxes.

- Ladder Logic, LAD.
  The graphic programming language Ladder Logic is based on circuit diagrams. The elements of a circuit diagram, e.g. normally open contacts and normally closed contacts, are combined to form networks. The code section of a logic block represents one or more networks.

- Statement List, STL.
  The programming language is a text-based programming language with a structure similar to assembler. Each statement represents a program processing operation of the CPU. Multiple statements can be linked to form networks. The usage of more complex data types requires STL.

A combination of FBD and STL was used for the new control program written as a part of this thesis.

3.4 The PC versus the PLC

Why not using a PC instead of the PLC? Almost any of today's computers have better capabilities than the PLC and can carry out the PLC programming with the right software. When functioning as a full fledged PLC the computer must be able to run PLC software and of course also have some ways to receive and send information to and from sensors and actuators. Both these requirement can be fulfilled on any of today's PC, just hang some I/O capabilities off the back of the PC and there you go-a powerful, fully functional PLC! But why is the PLC still today so much more used than the PC? The answer got to be the history and two separate branches of development. Personally I think that the better CPU power, storage, cost and graphics of the PC soon will bury the PLC.

4 PID Control

In this chapter PID control in general as well as how the algorithm is implemented and used in the SIMATIC® S7 system will be presented.

4.1 PID control in general

PID control is by far the most effective and therefore the most common way to control different processes. The process could be anything from a chemical process where a certain concentration should be controlled to a gas throttle used for cruise control of modern cars. The usage of PID control can be separated in two different ways to perform control tasks. First, it can operate as a fixed set point controller and second, where the controller adjusts for continuously changes in the set point, the so-called servo problem.

PID control can be accomplished in many different ways, e.g. by mechanical, pneumatic, hydraulic, or electronic control systems as well as by digital systems including the PLC. The PID controller can be implemented in different ways and two ways are common [2], the serial and the parallel form, see figure 4.1 and 4.2.

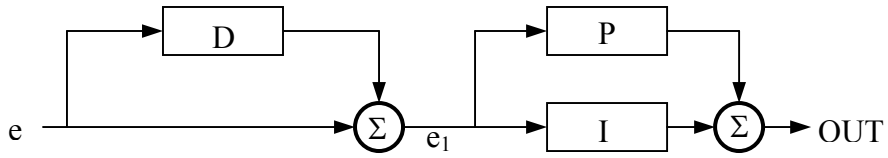

Figure 4.1 *Graphical description of the serial form.*

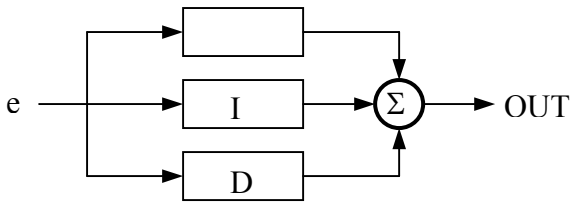

Figure 4.2 *Graphical description of the parallel form.*

It is the parallel form that is implemented in the SIMATIC® S7 system, therefore only this form will be discussed further. Using the parallel structure the output signal (OUT) is given from the equation [5]:

$$OUT = K_c\left(e + \frac{1}{T_i}\int e(t)dt + T_d\frac{de}{dt}\right) \qquad (4.1)$$

Where the first part is the proportional term, the second the integral term, and the third part the derivative term. The controller contains three parameters, which the user can modify, the gain K_c, the integral time T_i and the derivative time T_d.

A discrete version of (4.1) that could be implemented and form the base for a more advanced control algorithm is given from [5]:

$$OUT_n = K_c\left(e_n + \frac{T_s}{T_i}\sum_{k=0}^{n} e_k + T_d\frac{e_n - e_{n-1}}{T_s}\right) \qquad (4.2)$$

From (4.2) it is clear that the different actions (proportional, integral and derivative) could be turned on and off. E.g. by choosing T_d equal 0 and T_i large will give a controller with only proportional action.

4.1.1 PI versus PID control

In many industrial controllers the derivative action is turned off. In the SIMATIC® S7 system it is by default set to off so that it has to be turned on by the programmer in order to be used. It can be shown that PI control is adequate for all processes where the dynamics are essentially of the first order [6], which is the case for controlling different kind of flows [7]. Adequate in the way that the steady state error will always approach zero when the I-action is applied controlling such a process. Introducing the D-action into a first order process is therefore not necessary and the derivative part should only be used in case it could be tuned properly, i.e. the process dynamics are well known.

4.2 PID control with SIMATIC® S7

In the SIMATIC® S7 system the PID control algorithm is implemented in parallel as shown in figure 4.3.

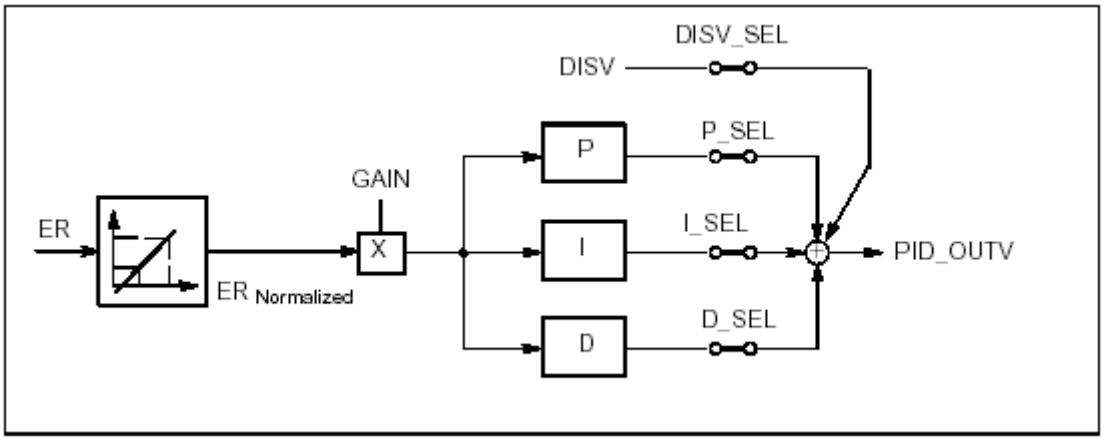

Figure 4.3 *The parallel structure of the PID implementation used in SIMATIC®. Figure from [8], with ER as error, P_SEL choice of proportional action etc and DISV denotes a measurable disturbance to the process.*

4.2.1 General use

The source code for the PID-algorithm is not public, but all of its functions are well described. Some of them, which were used to control the ACU™ are listed below.

- The proportional, integral, and derivative actions are connected in parallel and can be activated or deactivated individually. This allows P, PI, PD, and PID controllers to be used.
- It is possible to switch over between manual and automatic mode. This requires that the manual value is updated with the last output given in automatic mode.
- The I-action retains the value that was set when the limit was reached (anti wind-up) if the OUT variable range limits are exceeded.
- A disturbance variable (DISV) can be fed forward, see figure 4.3.
- Action can be chosen to be reversed or direct depending on if the OUT variable should increase/decrease while measurement is increasing/decreasing.

4.2.2 Specific use

To use PID control in the SIMATIC® S7 system a certain function block, FB 41, together with a specific data block, should be called repeatedly. This is done by calling the control function from a so-called organization block, which cyclically interrupts the execution of the main program. The time between every cycle will therefore determine the sampling rate, and those should be the same. All of the parameters used in the PID algorithm are stored in the data block and could be updated between every cycle.

5 Hardware changes

In this chapter the decision to change the control valve used for controlling the CO_2 flow going into the reactor will be discussed.

5.1 Change of control valve

After having noticed a relatively unstable pressure control at low flows together with variations in pH in the outgoing product, the aim was to try to get a more clear view of the process image at all time. To be able to analyze the process image at a better resolution than what is given in the operator's panel a PC with logging abilities was connected to the PLC. Ten channels could be used on the logger so all the signals that are related to the pressure control of the reactor were logged. Among these was the signal controlling the CO_2 valve and the signal measuring the CO_2 flow.

Previously the CO_2 flow was controlled using a so-called ball valve with a control range of 20:1 [9], defined as the ratio between the biggest and the smallest flow that can be controlled. Another important characteristic of the ball valve is that it remains closed, without leakage if the control signal is less than 17% (observed from logger data).

5.2 Evaluation of hardware changes

After having the process image logged the following graphs could be plotted from data stored in the database.

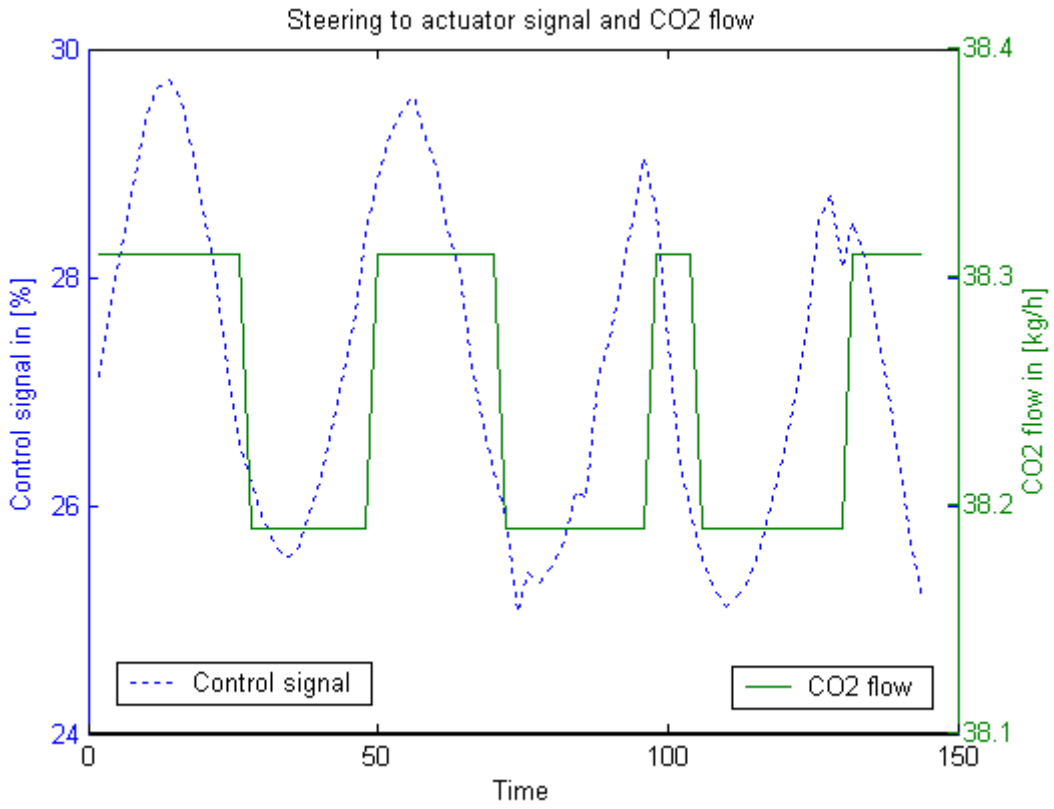

Figure 5.1 *The ball valve controlling the CO_2 flow is only acting between two levels.*

Figure 5.1 shows how the ball valve that is controlling the CO_2 flow going into the reactor only is acting between two levels, despite of how the signal is changing. This situation could

arise if the set point for the CO_2 flow is somewhere between the two levels. The controller is trying to eliminate the error and keeps accumulating until the actuator overcomes the friction [2] and the valve jumps to the upper level. Now the error changes its sign and the signal is decreasing until the valve jumps back to the lower level.

The precise flow jumps have nothing to do with the resolution in the CO_2 flow measurement, since the range of the CO_2 meter is 0-400 [kg/h] and the analog/digital conversion handles 16 bits, which gives the resolution:

$$\frac{(400-0)}{2^{16}} = 0.0061 \text{ [kg/h]} \qquad (5.1)$$

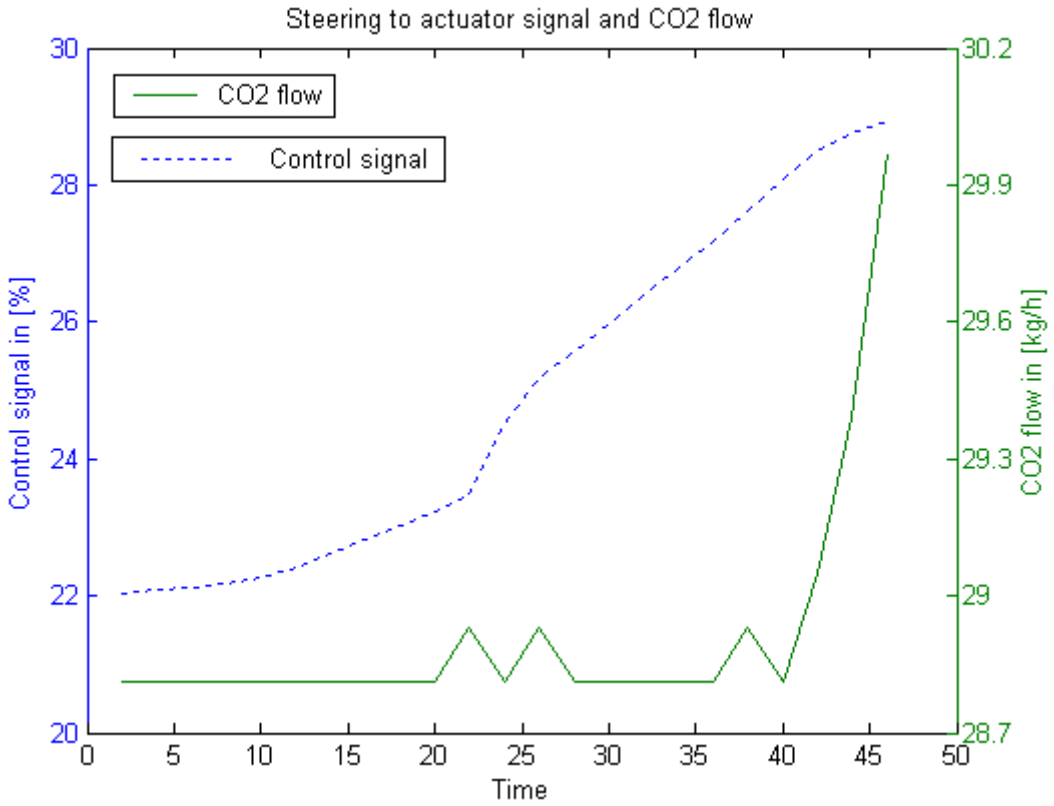

Figure 5.2 *The ball valve controlling the CO_2 flow is not responding to the signal.*

Figure 5.2 shows a graph with the same two signals, and it is observed how the control signal increases from 22-28% without any flow change, and then finally the valve reacts and the CO_2 starts to flow. This of course causes problems, while trying to control something that is not behaving as it is meant to do. "A control circuit is only as strong as its weakest point" - in this case the CO_2 valve is not working properly. The reactor pressure at the time was 4.5 bar and did not prevent the CO_2 to flow accordingly.

Before the logger was installed and the problems with the valve were known manually tuning was tried to stabilize the process. The gain was decreased and reset time increased, which slowed down the variations. In this case where mixing NaOH and CO_2 flow at high accuracy is needed this is only a temporary solution. A decision to replace the valve was taken. A so-called seat valve replaced the previously used ball valve.

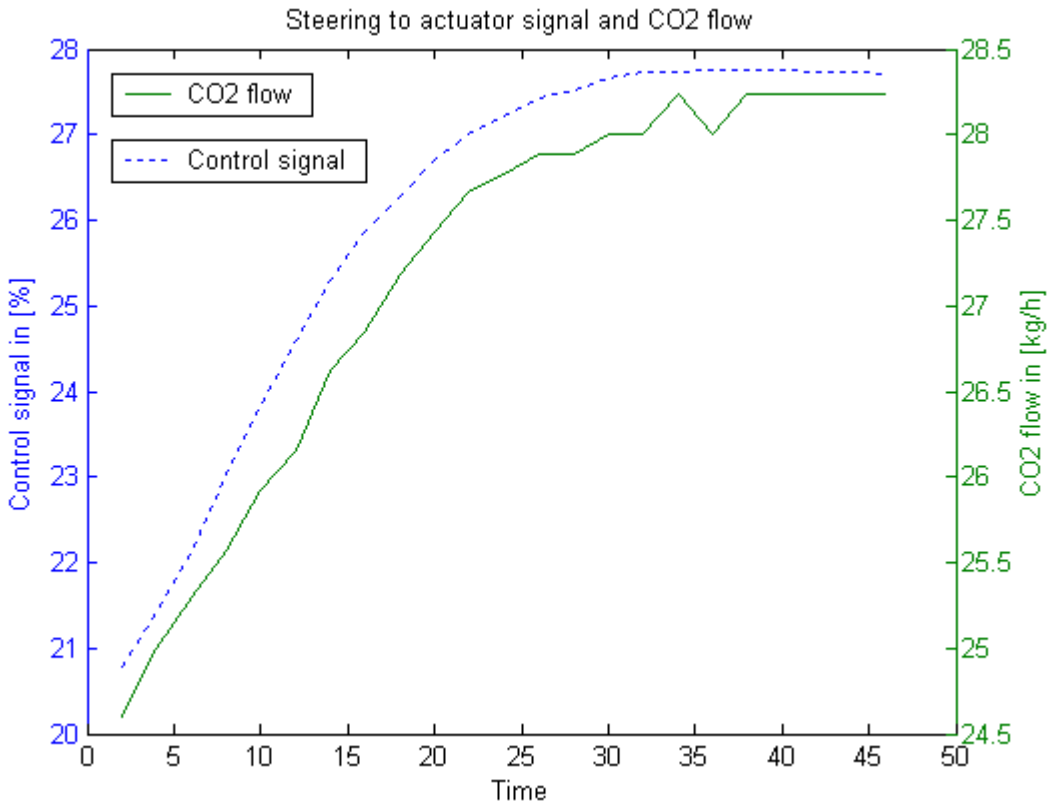

Figure 5.3 *The CO_2 flow follows the control signal to the seat valve.*

In figure 5.3 the relation between the control signal and the CO_2 flow for the new valve is shown. The flow follows the signal in a linear way, which makes life of the controller easier.

For control purpose the change of valve was satisfactory, the behavior of the seat valve is more linear than for the ball valve and also with a larger control range, 50:1. But there is also a small leakage, about 7-8 [kg/h] while the seat valve is in closed position. This causes some problems since the leakage will fill up the reactor with gas when the ACU™ is stopped, and finally level out the pressure difference between the CO_2 line (~12 bar) and the reactor.
A solution to this problem could be to place an On/Off valve just before or after the seat valve, which can be opened and closed during start and stop.

Now when the accuracy of the CO_2 flow was increased another way to measure the influence on the process is to compare the actual ratio that is mixed in the reactor. The actual ratio was defined as:

$$Actual\_ratio = \frac{100\% NaOH\_flow}{CO_2\_flow} \qquad (5.2)$$

A non-varying actual ratio in presence of a stable pressure is of course important for the resulting pH not to vary. The actual ratio was logged both before and after the valve change and the result is presented in figure 5.4.

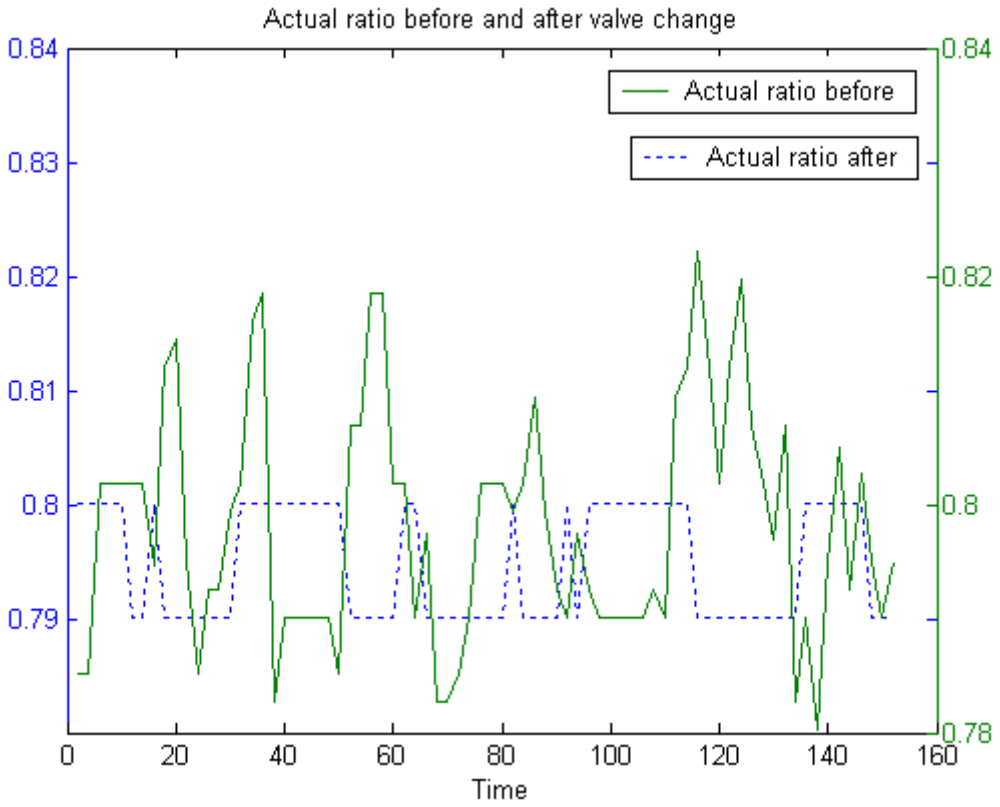

Figure 5.4 *The actual ratio that is mixed in the reactor, setting was 0.8.*

From figure 5.4 it is observed that the actual ratio was varying more before the valve was changed. Therefore with the new valve the mixing conditions became better which in turn results in a more stable pH and better performance. The better mixing presented in Figure 5.4, is also a result from tuning the CO_2 circuit. This will be discussed in chapter 7.

Note that in the old program no variable was declared for the actual ratio and it had to be calculated from the logged CO_2 flow, NaOH flow and density measurement. In the new program the actual ratio was calculated and could be logged. It is the resolution of the logger that creates the précis jumps.

6 Software changes

In this chapter all the software changes made to the ACU™ will be presented and evaluated.

6.1 Start and stop sequences

There are two main differences between the start up and stop sequences described here and in the previous implementation:

- There is no re-circulation of $NaHCO_3$ from the reactor back to the tank.
- NaOH flow will follow a ramp to pressurize the reactor.

The re-circulation of $NaHCO_3$ during the start up will increase the carbonate content and decrease the pH in the tank and therefore it should not be done. If the reactor during a stop shouldn't be pressurized re-circulation is used to depressurise the reactor.

To pressurize the reactor the NaOH valve follows a ramp with the CO_2 following. This is done to prevent a big overshoot of undissolved CO_2 going through the reactor, which in turn causes pressure variations.

A more precise explanation of the start and stop sequences is given in appendix II.

6.2 Tank dilution

6.2.1 On/Off control

Previously the filling of the tank was controlled from its diluted NaOH level. But since the output from the ACU™ sometimes is very small ~0.5 l/s this makes the control valves FV014 and FV004 to control at the lower end of their working area. Instead if On/Off-control is used both set points for the water and NaOH flow could be chosen to dilute in a more accurate way. See figure 6.1 for a block diagram for the dilution part.

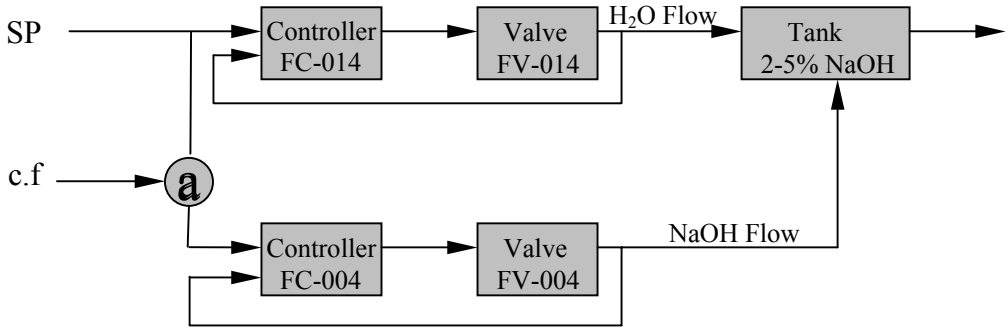

Figure 6.1 *Block diagram for the dilution part.*

Once the filling condition is fulfilled i.e. tank level is below the setting in the operator's panel, see figure I.1 in appendix I, the set point for the water flow will follow a ramp until it equals a pre chosen set point. This set point is defined as a constant, set-point-factor times the maximal water flow, see figure I.1 in appendix I.

6.2.2 Mixing ratio

Previously the NaOH dilution was based on a volume ratio between the water flow and the NaOH flow since the flow meters measure the flow in units of volume/time. To this relation the density is needed to calculate the correct mass ratio. Diluting e.g. NaOH with the concentration of 5% gives only a small difference between using the volume ratio and the mass ratio but if e.g. diluting NaOH with the concentration of 50% the difference is remarkable. The following expression should be used to calculate a, in figure 6.1 using mass ratio:

$$\frac{\left(\rho_{NaOH}(C\%)\right)*\overset{*}{V}_{NaOH}*C}{\left(\rho_{NaOH}(C\%)\right)*\overset{*}{V}_{NaOH}+\rho_{H_2O}*\overset{*}{V}_{H_2O}}=2-5\% \quad \text{and} \quad \overset{*}{V}_{H_2O}*\mathrm{a}=\overset{*}{V}_{NaOH} \qquad (6.1)$$

$$\text{giving: } \mathrm{a}=\frac{(2-5\%)*\rho_{H_2O}}{\rho_{NaOH}(C\%)*\left(C\%-(2-5\%)\right)} \qquad (6.2)$$

Where $\overset{*}{V}_{NaOH}$ & $\overset{*}{V}_{H_2O}$ is the NaOH/H_2O-flow and $\rho_{NaOH}(C\%)$ the density of NaOH with the concentration of C%.
The density is given from the following second-degree polynomial [10] with $R^2=1$:

$$\rho_{NaOH}(C\%)=-187.0*C^2+1153.57*C+996.6489 \text{ at } 20°\text{C}. \qquad (6.3)$$

6.3 The reactor

6.3.1 Feed forward

First an example on how feed forward can be used will be given [2]: imagine controlling the temperature of a house. Using only feedback control, no changes in the indoor temperature will be done until variations in the outdoor temperature are noticed indoor. But instead of waiting for the variations to affect the indoor temperature they could be used in the controller in advance. This way of controlling a process is called feed forward. Translating this to the ACU™ means reactor pressure will correspond to the indoor temperature and the flow changes will be the outdoor temperature variations.

Consider the scenario with variations in customers flow, e.g. if flow increases it is followed by the product flow which causes the pressure to drop over the reactor, see figure 6.3. The pressure drop will, when registered tell the NaOH flow to increase to adjust for the pressure drop followed by the CO_2.

If the system instead, immediately after having noticed a flow change, could tell the NaOH and CO_2 flow to either increase or decrease, it doesn't have to wait for the pressure to change. In this way the process should be able to handle such disturbances as flow changes and become more stable.

To be able to use feed forward the flow variations need to be detected. The output flow is on demand from customers signal $u_i(t)$, the sum of all the variations was expressed as:

$$\Delta u(t)=\sum_{i=1}^{3}u_i(t)-\sum_{i=1}^{3}u_i(t-1) \qquad (6.4)$$

Where $u_i(t)$ is the signal at output number i, and at time t and $u_i(t-1)$ the same but previous sampled signal. See figure 6.2.

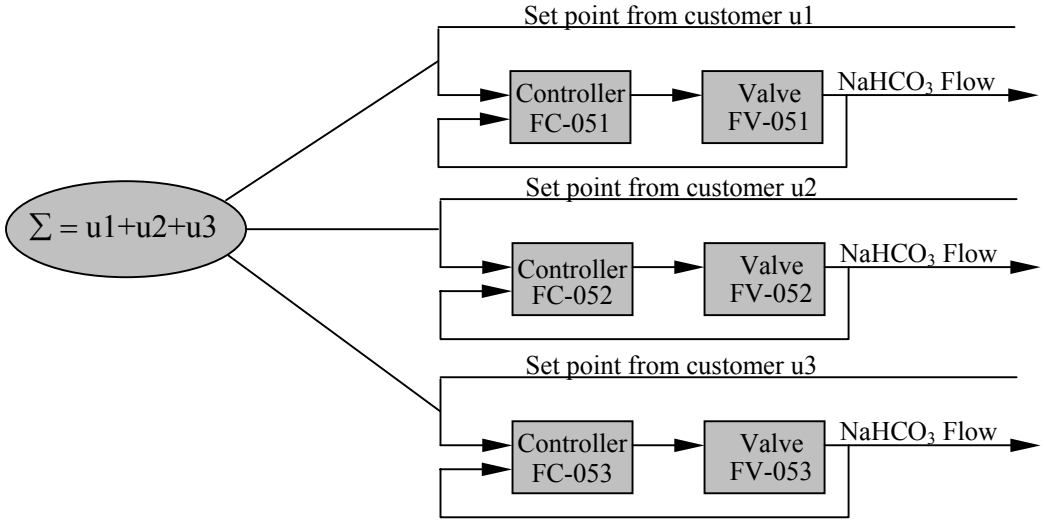

Figure 6.2 *Collecting customer's signal while controlling the ACU™.*

This signal has to be scaled, which was done experimentally before it is fed forward to PC035, see figure 6.3.

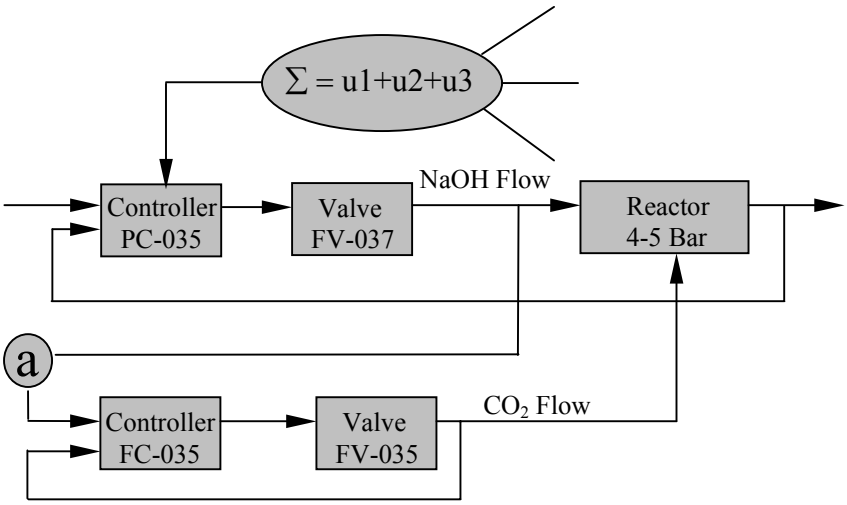

Figure 6.3 *Where to use feed forward while controlling the reactor pressure.*

6.3.2 Different pressure control

In the previous program, and also in the new version with the discussed changes the pressure has been controlled by the NaOH flow as seen in figure 6.3. With pressure variations this will cause some variations in pH since the CO_2 only follows the NaOH as the slave. Therefore a second test version with a different control philosophy was implemented and tested. This philosophy is explained from the block diagram in figure 6.4.

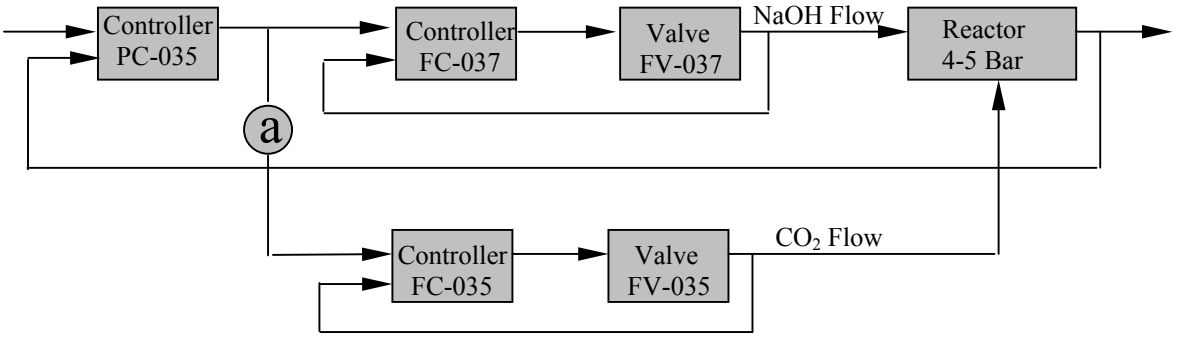

Figure 6.4 *Block diagram showing a different kind of pressure control for the reactor.*

In figure 6.4 the parallel form of ratio control is shown. The idea is to let both NaOH and CO_2 enter the reactor at the same time and by doing so increase the mixing conditions while controlling the pressure.

6.4 Configuration of the operator's panel

The only face to the world the PLC has is if there is an operator's panel (OP) configured to it. Through the OP the operator can get information about the process and also in some matter change it e.g. set points and other parameters. In order to make the process image clear the configuration of the OP therefore includes a lot of graphics. The data transferred back and forth are called tags and uses the same addresses that they are given in the data block created for the S7 program.

Most of the screens from the previous program were reused but some screens were adjusted and updated for the new program. The screens are collected in appendix I.

6.5 Evaluation of software changes

6.5.1 Start and stop sequences

In order to decrease the overshoot of gas in the reactor during the start up sequence the NaOH flow followed a ramp with the CO_2 as its slave. The slope of the ramp was experimentally determined. Adding 0.05 to the controller's output once every program cycle gave good results.

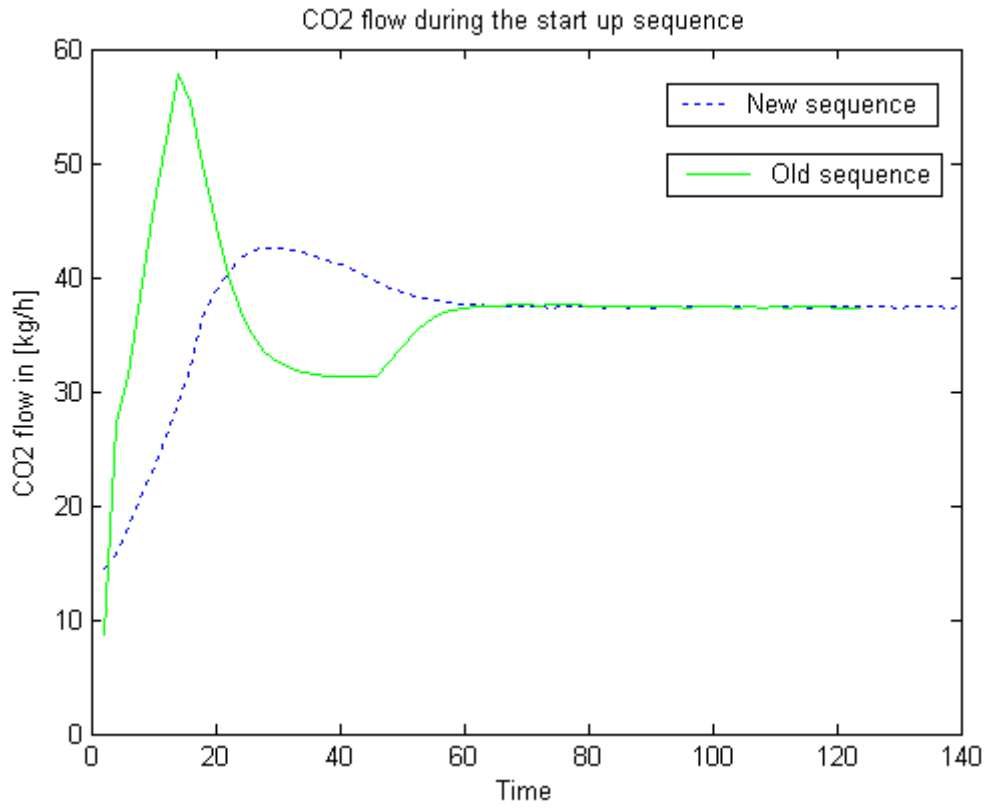

Figure 6.5 *Amount of CO_2 in the start up sequence with new control valve.*

In figure 6.5 it is seen that the big overshoot of CO_2 is gone. This could be seen both in the logger data, and in the product flow that contained less bubbles. Preventing a big overshoot gives less risk for gas accumulation in the upper parts of the reactor, see figure 2.1. Observed from the logger data was, that undissolved gas causes big pressure variations on its way through the reactor and should therefore be prevented.

6.5.2 Tank dilution

In figure 6.6 the difference between mixing NaOH with water, based on mass and volume ratio is shown. The set point at the time for the trials was 1.7%. Dilution based on mass ratio finds the set point almost immediately. The mixing based on volume will first go up and then go down because of control circuit QC037, which adjusts the ratio. The dead time for QC037 is very long the action takes time.

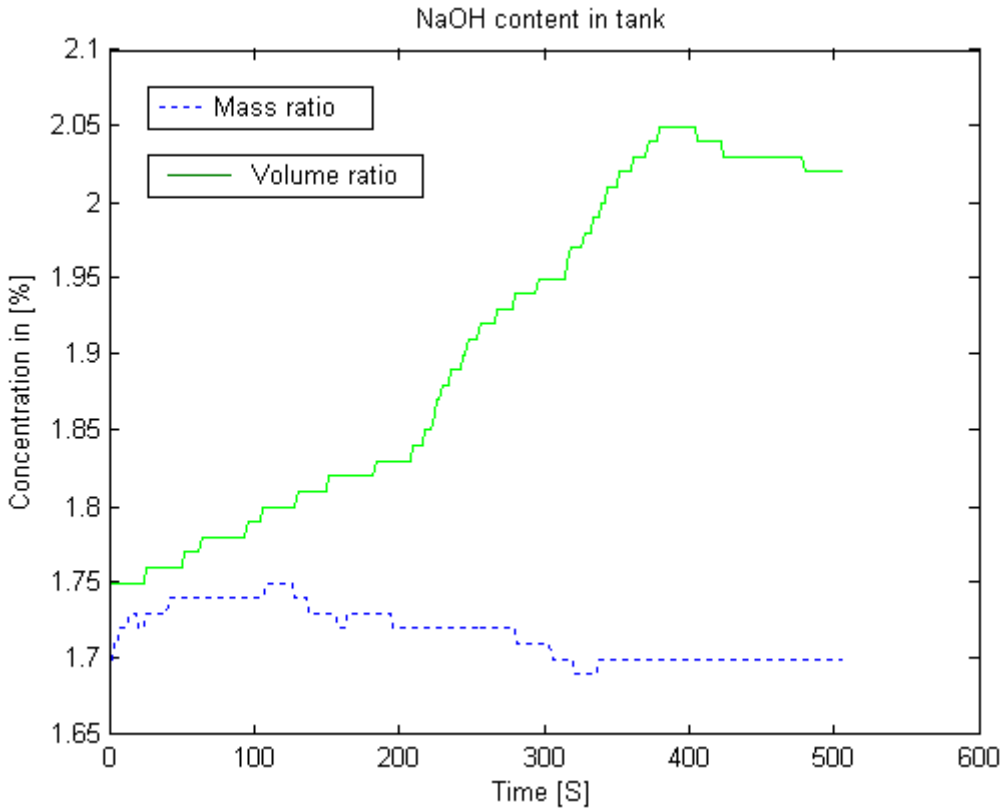

Figure 6.6 *Dilution of the tank based on mass and volume ratio, set point is 1.7%.*

This is just a small change that doesn't change the way the reactor operates since it is made for diluted NaOH up to 5%. But as discussed before the NaOH provided from the Kangas mill is as much as 12% and with higher concentrations the declination from the set point will be even bigger.

6.5.3 The reactor

6.5.3.1 Feed forward

In figure 6.7 the use of feed forward while controlling the reactor pressure can be seen. The same flow change in the output flow was done twice, once with the influence of the disturbance and once without.

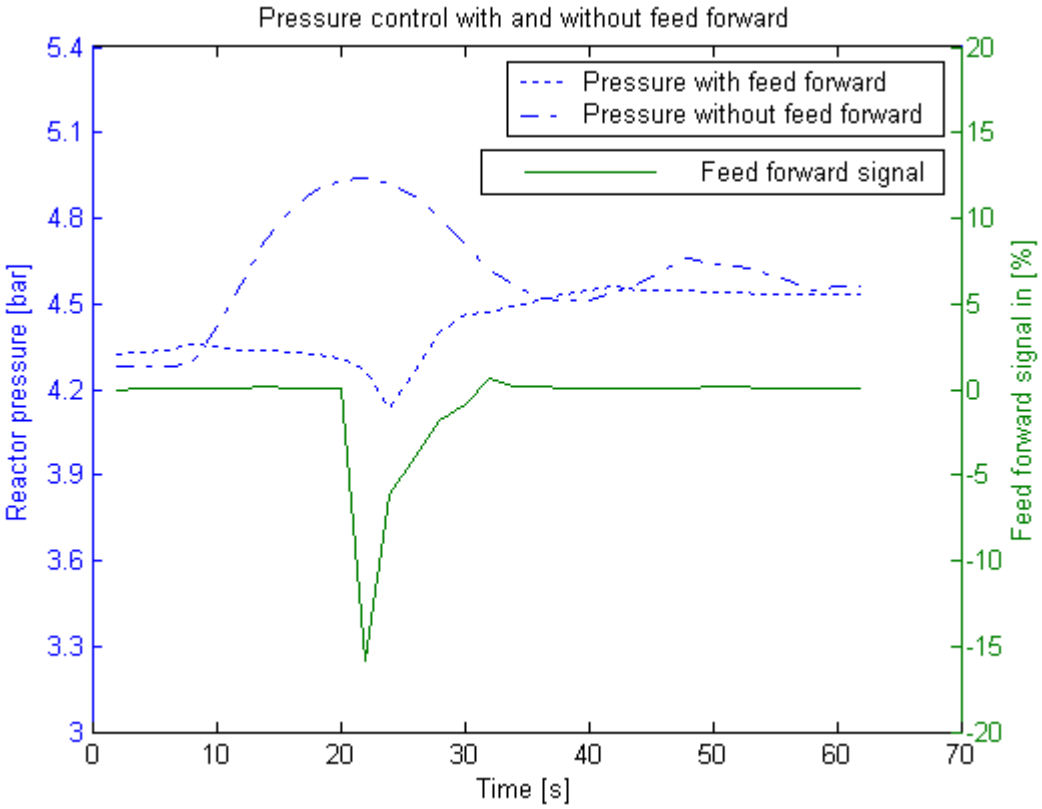

Figure 6.7 *Pressure control with and without using feed forward.*

The set point for the reactor pressure was 4.3 bar at the time for the trial. The solid line in the picture represents the scaled flow variation that was fed forward to PC035. The situation here was a negative flow change i.e. output valves were closing. A similar situation but inverted can also happen when output valves open. As seen in figure 6.7 the big pressure top is avoided, but it is not known why the pressure goes up to 4.5 bar just after the change.

6.5.3.2 Different pressure control

The different pressure control that was discussed in section 6.3.2 was tested without good results. The idea of letting the NaOH and the CO_2 enter the reactor at the same time is good but not realistic. The pressure control became very unstable because of the faster CO_2 entering the reactor at a higher pressure. Since the CO_2 is so voluminous it prevents the NaOH to enter the reactor. In the process image this was seen as the NaOH valve was completely open without any NaOH entering the reactor. Trying to slow down the CO_2 by tuning didn't change the process image and the trial was interrupted.

7 Tuning

In this chapter a certain method for tuning the PID parameters is described and how it was used to tune the two circuits controlling the reactor pressure.

7.1 Lambda tuning

The controller's task is, to via the signal to the actuator (OUT) minimize the difference between the set point (SP) and the process value (PV). In order to do so it has to be tuned for that specific process which it is controlling. By tuning a control circuit means to choose suitable values for the controllers gain (K), integral time Ti and derivative time Td. There are many different kind of tuning methods and procedures and among these the so-called lambda method was chosen to tune some of the control circuits of the ACU™. Since the process dynamics only could be determined at a low resolution, because of limitations in the sampling period of the logger only PI control was used.

7.1.1 The lambda method

What is unique with this method is that one in advance can determine how the circuit should behave while control [11]. The method uses a variable called lambda, which is the same as the time constant of the closed loop. The smaller lambda the faster becomes the controlling. The choice of lambda requires knowledge about the process and its step response. As flow processes are self-regulating we only consider this case here.

Using PI control the T_i and K_c parameters are, according to the lambda method calculated from the following relations:

$$T_i = T \qquad (7.1)$$

$$K_c = \frac{I}{K_p * (\lambda + L)} \qquad (7.2)$$

Where:
T = Time for CO_2 flow to reach 63% of its final value.
Kp = Process amplification.
L = Delay time from that the signal is changed until the flow starts to change.
λ = 3*T if (T > L) otherwise λ = 3*L.

7.1.2 Tuning the ACU™

Two of the control circuits of the ACU™ were tuned because of their significance, the one controlling the CO_2 flow and the one controlling the reactor pressure. Prior to this work the two controllers weren't tuned and used the default settings: K, Ti, Td = 3, 20, 0. Since those two circuits are interacting, the NaOH flow determines the set point to the CO_2 flow (see figure 6.3) they have to be tuned in a specific way explained as follows [7]:

- Make sure the process is stable
- Put both controllers in manual mode
- Apply a step in the signal to the CO_2 valve and register how the flow changes
- Tune controller for CO_2 flow
- Put CO_2 controller in auto mode
- Apply a step in the signal to the NaOH valve and register how the pressure changes
- Tune controller for the reactor pressure

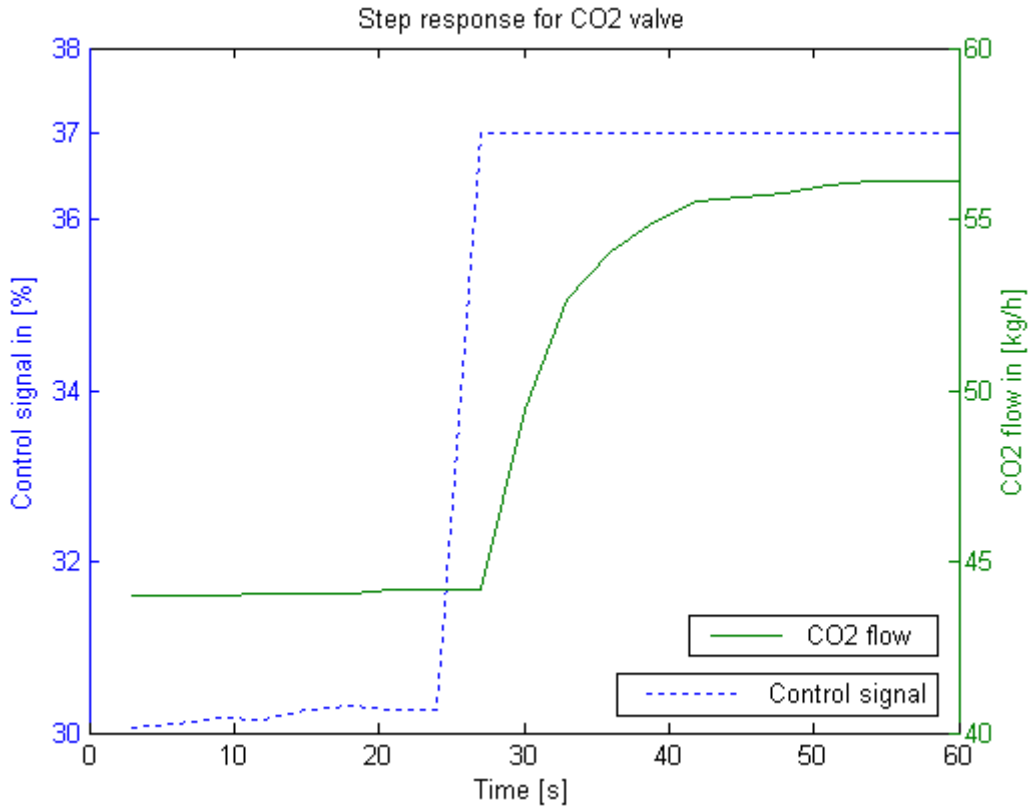

Figure 6.1 *Step response for the CO2 valve.*

The new parameters where calculated from a better-scaled graph and not from the two figures shown here. Using the lambda factor 3 (robust tuning) gave the parameter setting: K_c, T_i, T_d = 0.15, 4.2, 0.

Since the default setting for the D-action is off for the controllers used it was turned on in the new program. It wasn't used here as written before because of the bad resolution in the logger.

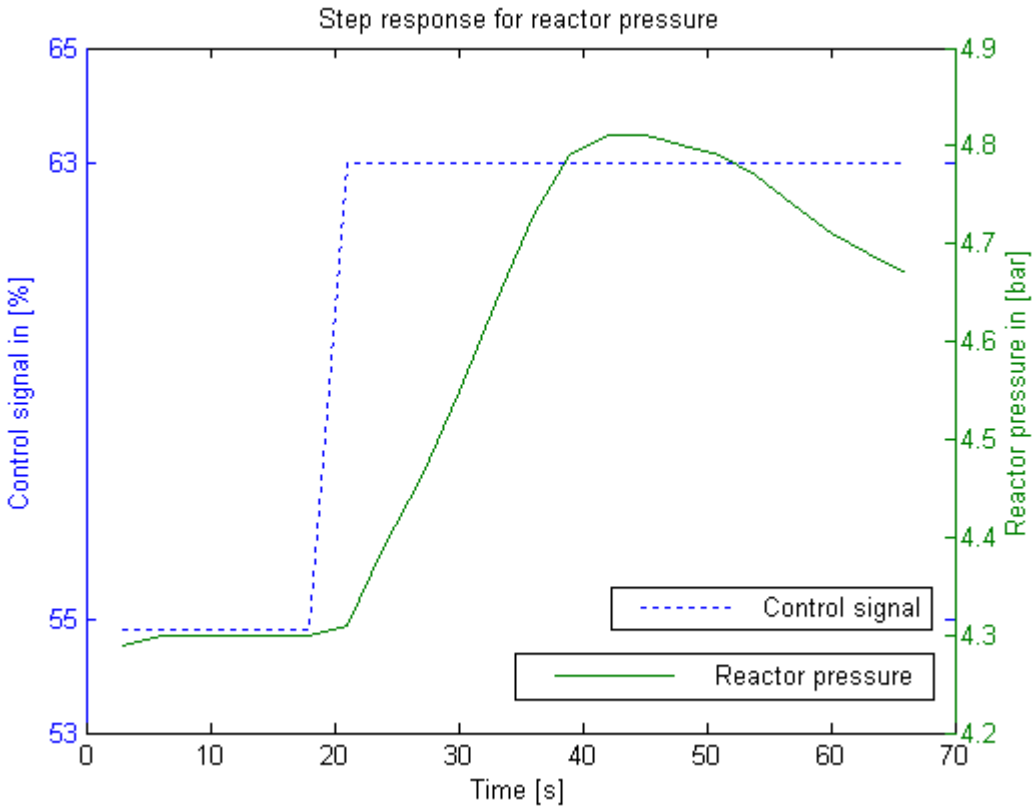

Figure 6.2 *Step response for the reactor pressure.*

Parameter calculation for the pressure control PC035 gave: K_c, T_i, T_d = 4.8, 10.0, 0.

8 Conclusions

In this master thesis several different ideas on how to improve the logics and control of the ACU™ have been investigated.

Since the ACU™ is operating at many different levels of capacity it requires equipment with a big working area. Therefore the decision to change the type of valve controlling the CO_2 was successful. Changing the valve resulted in better mixing conditions as well as less pressure variations in the reactor. These two were the most significant factors when trying to get a stable pH of the product. The problems with undissolved gas during the start up sequence of the reactor were reduced, by letting the reactor be pressurized successive and in that way prevent a big overshoot of CO_2.

To let the reactor have the best working conditions no re-circulations should be performed in the start-up sequence and both the content and pH will remain the expected in the tank. Diluting the tank should be done with respect to mass ratio in order to reach the set point in less time.

Trying to reduce pressure variations by feed forward was successful and worked well at major disturbances. The influence on the process image at other times was not required since the pressure variations were too small.

Controlling the reactor pressure by letting NaOH and CO_2 enter the reactor at the same time was tested but did not work in practice.

Since the pressure now is controlled by the NaOH flow and this obviously causes pH variations at flow changes, it is important that the CO_2 circuit is tuned to be able to adjust fast to these set point changes.

9 Future work

During the work it was learned more about the process. This knowledge did not result in any changes but the most important things will be discussed in this chapter.

9.1 Density conversion of NaOH

The mass flow meter for the NaOH flow into the reactor, measures the flow in [kg/s], the density in [kg/m^3] and the temperature in [ºC]. This density measurement and the ratio between NaOH and CO_2 determine the amount of CO_2 that will be dissolved in the reactor. Knowing the density and the temperature, the concentration could be interpolated from the following table [10]:

Concentration [kg NaOH / kg]	Temperature [ºC]						
		0	10	20	30	40	50
	0	999,9	999,8	998,2	995,7	992,2	988,1
	0,01	1012,4	1011,5	1009,5	1006,9	1003,3	999
	0,02	1024,4	1023	1020,7	1017,7	1013,9	1009,5
	0,03	1036,4	1034,5	1031,8	1028,5	1024,6	1020,1
	0,04	1048,2	1045,9	1042,8	1039,3	1035,2	1030,5
	0,05	1059,8	1057,1	1053,8	1050,1	1045,8	1041,2

Table 9.1 *The concentration of NaOH is both depending on the density and the temperature.*

Previously the conversion between the NaOH density and the concentration was done without respect to temperature. Maybe a not realistic example but easy to verify is e.g. at 20ºC a density measurement of 1020 kg/m^3 is equivalent to 2% NaOH but the same measurement done with NaOH at 50ºC corresponds to 3%.

At the trials done at the Kangas mill the temperature of the NaOH was 14ºC and the analog density measurement gave 1017.8 kg/m^3 this without regard to temperature corresponds to 1.7% NaOH and with 1.6% NaOH. Hence we were trying to dissolve too much CO_2, instead of the NaOH / CO_2 ratio of 0.8 a more accurate value is 0.75.

9.2 CO_2 Mass flow meter

The mass flow meter currently used for measuring the CO_2 flow has the range 0-400 [kg/h], and is over dimensioned. Running the ACU™ at normal production the CO_2 flow never exceed 200 [kg/h]. For coming units the dimension could be decreased which would increase the accuracy in the A/D conversion.

9.3 Gain scheduling

Another thing that was implemented to the ACU™'s control program was gain scheduling for the reactor pressure. Gain scheduling means that the controller's OUT (0-100%) interval is divided into subinterval where different parameter settings hold. In Kangas the process became stable only by changing the CO_2 control valve and this feature was never used and the pressure was only tuned at one capacity.

Just recently modifications where done to another ACU™ at the paper mill in Anjalankoski where adjustment of the concentration of NaOH entering the reactor needed different gain and integral time for the pressure to become stable. Gain scheduling is a solution to this problem but the intervals should, from this experience depend on the NaOH concentration and not on the capacity.

10 Bibliography

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[10] **http://www.solvaycausticsoda.com/docroot/caustic/static_files/attachments/faq___dilution.pdf**

[11] **Swedish Pulp and Paper Industries.** SSG document 5253 Regleroptimering (1997).

Appendix I Operator's panel

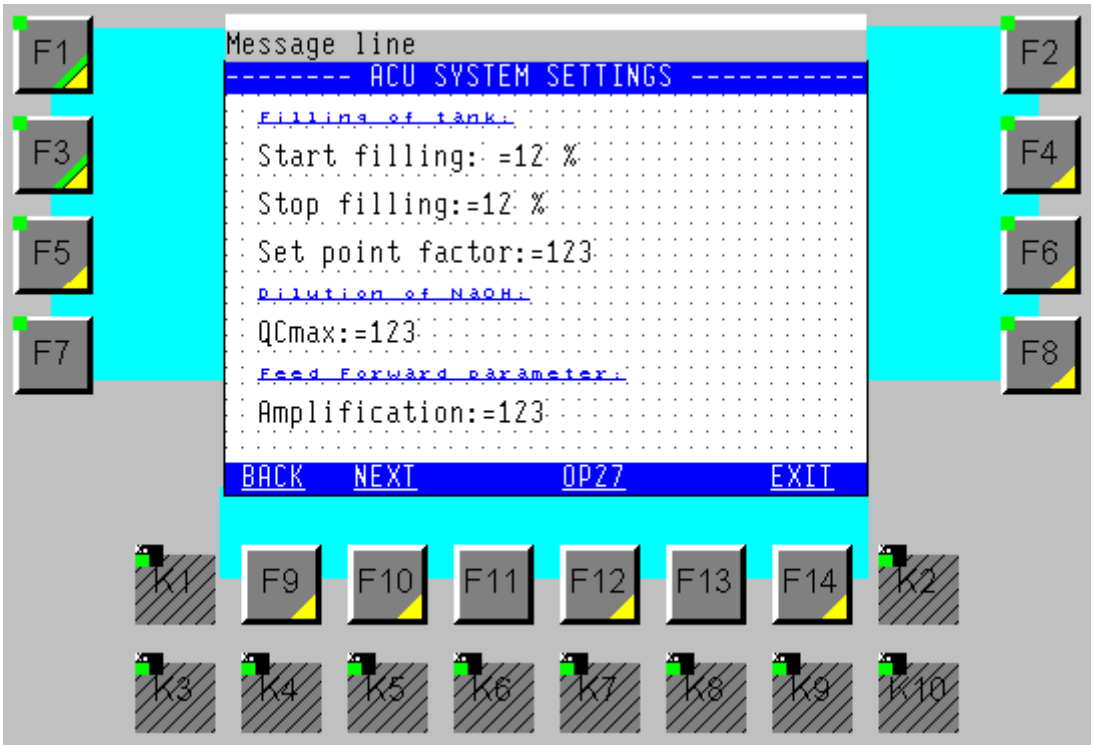

Figure I.1 *Settings for the ACU™, screen 1.*

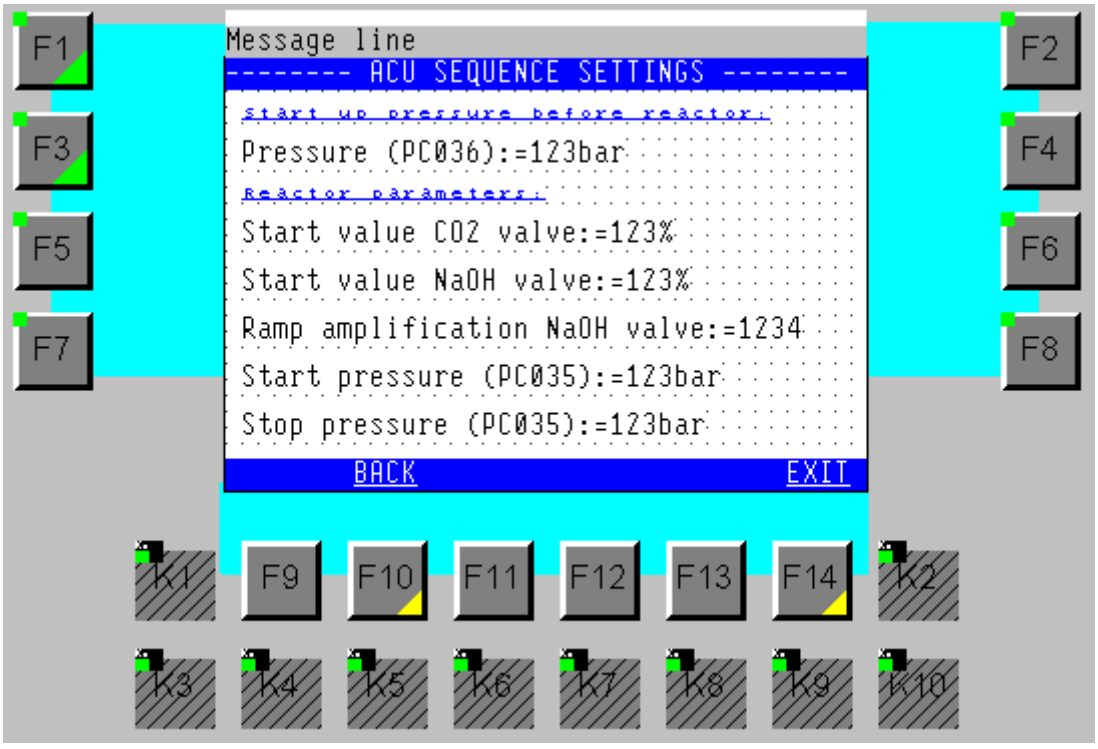

Figure I.2 *Settings for the ACU™, screen 2.*

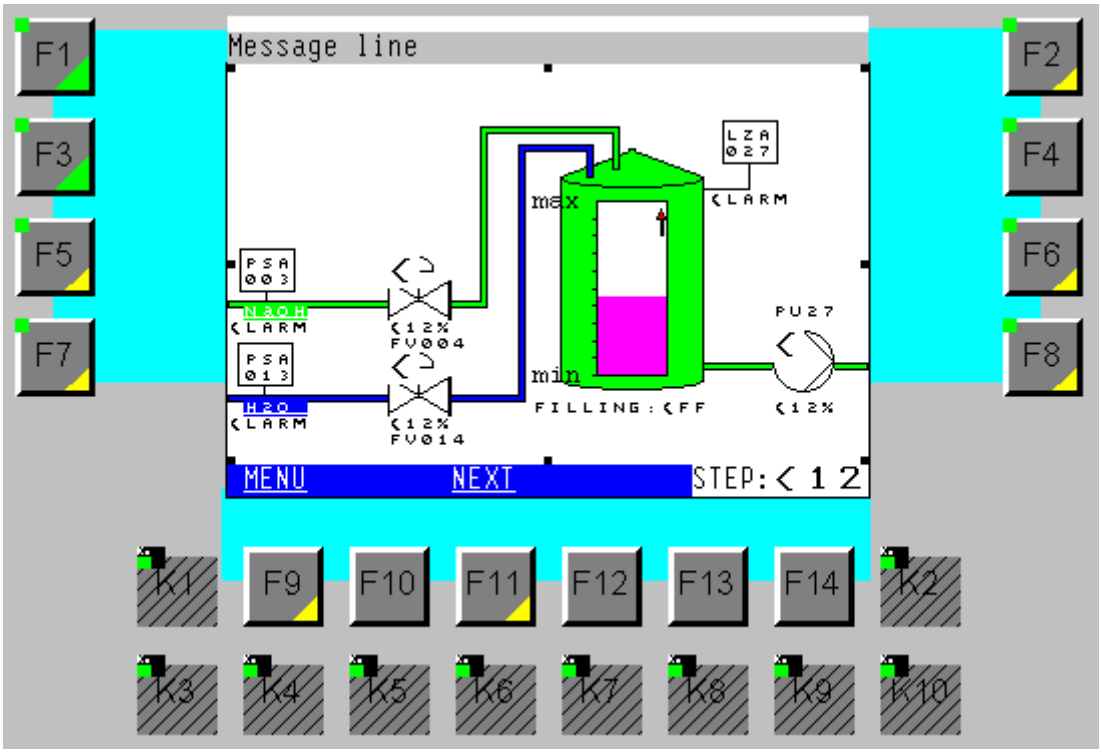

Figure I.3 *Process image for the dilution part, screen 3.*

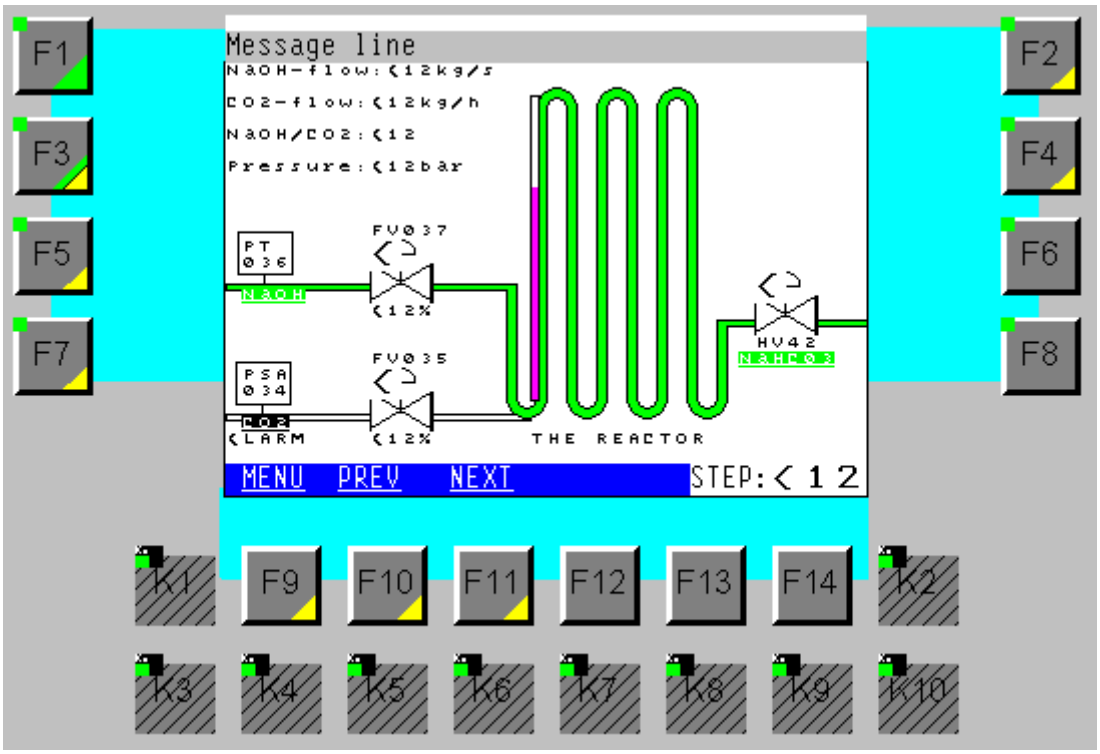

Figure I.4 *Process image for the reactor part, screen 4.*

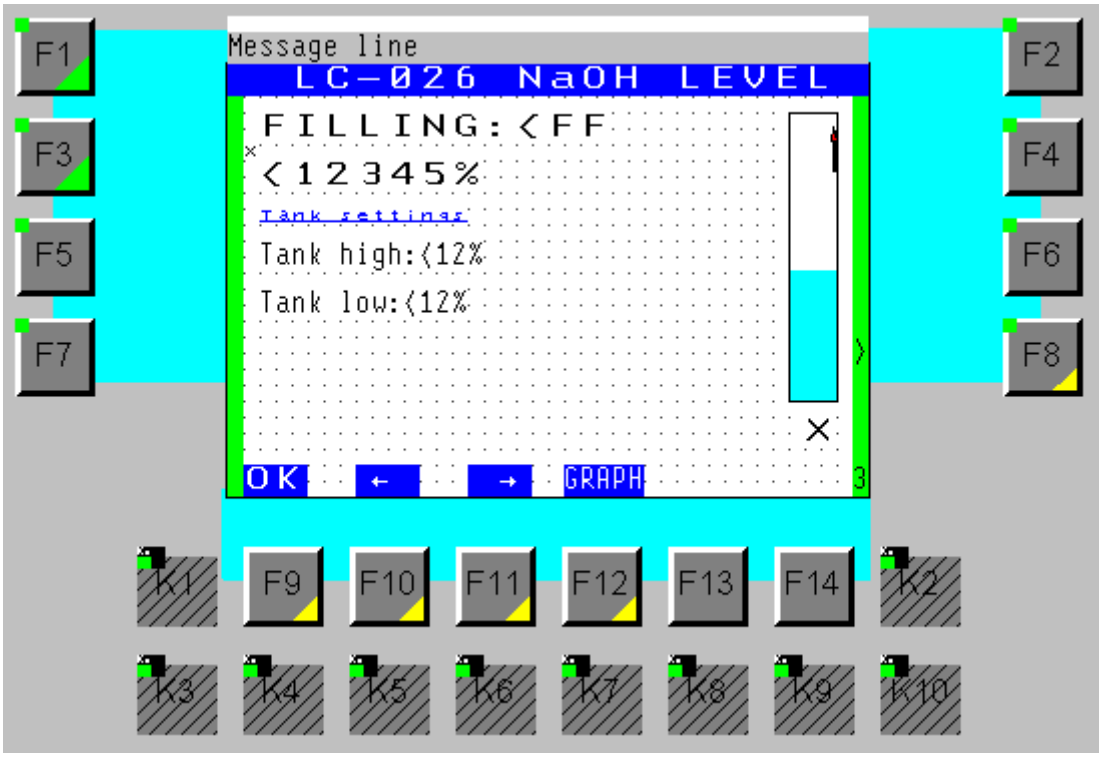

Figure I.5 *Level control of tank, screen 5.*

Appendix II The start and stop sequences

In this appendix the start and stop sequences will be described in detail. Information about the different valves and control circuits is found in the system description in chapter 2 and appendix IV.

The start sequence contains 5 (1-5) steps and the stop sequence 4 (50-53), which all have to be completed before moving on to the next. A certain parameter, "seq_step" determines where in the sequence the program is executing. While ACU™ is not running "seq_step" = 0 and while running, either manual or towards the process "seq_step" = 10. The operator's panel is updated with information about which step is currently executing.

I.1 The start sequence

Step 1.
The level in the tank is checked and the controlling of valves FV004 and FV014 is turned to auto mode. Execution remains here until the level in the tank is below the Tank-low-setting, which is set in the operator's panel, see figure I.1 appendix I.

Step 2.
Controlling of the tank is running implying there is enough diluted NaOH in the tank to start the pump. PC036 is turned into automatic mode and the program will wait for the pump to pressurize before the reactor. Execution remains here until the pressure reaches Before-reactor-pressure, see figure I.2 appendix I. This step takes approximately 20 seconds according to logger data.

Step 3.
Now the pressure control before the reactor is turned on, and the $NaHCO_3$ production can start. Both FV035 and FV037 are given a start value because they open at different OUT-signals, see figure I.2 appendix I. FC035 is put in automatic mode. The signal from the pressure controller (signal to FV037) will manually follow a ramp in the beginning so this phase doesn't go to fast. The slope of the ramp is set in the panel, see figure I.2 appendix I. When the pressure reaches Reactor-pressure, see figure I.2 appendix I, PC035 is put in automatic mode and the execution will continue to the next step.

Step 4.
Now the reactor is pressurized and HV42 is opened. Since the NaOH has started to flow also the diluted NaOH concentration controller QC037 is put into automatic mode, given its last stored OUT value from before the stop.

Step 5.
By now the whole ACU™ is pressurized and there are two possibilities, either the $NaHCO_3$ goes to the customer or it goes through HV45, if it is open. Controllers FC051-FC053 are put in automatic mode and the valves FV051-FV053 are given a start signal, same as to FV037 so that the product starts to flow in case of signal from customer.

I.2 The stop sequence

Step 50.
Means ACU™ is stopped either by a shut down alarm, no signal from customer or it is stopped manually from the panel. Controllers FC004, FC014 and PC036 are put in manual mode with OUT = 0%.

Step 51.
The pump is turned off and the density controller QC037 is put in manual mode. Its last OUT value is stored for the next start.

Step 52.
$NaHCO_3$ production is stopped, both PC035 and FC035 are put into manual mode with OUT = 0%. HV43 is opened in order to depressurise the reactor less than a certain limit, Reactor-pressure, see figure I.2 appendix I.

Step 53.
HV42 and HV43 are closed, the three output controllers FC051-FC053 are put in manual mode with OUT = 0%. After step 53 the execution will return to step 0.

Appendix III Notation in the thesis

The notation used in the thesis is in accordance with the SSG-document 5253 [11] which is the standard notation used in the Swedish paper industry. This standard is also widely spread outside of this branch. The notation is as follows:

- Gain K_p
- Time constant T
- Dead time L
- Process value PV
- Set point SP
- Error e
- Controller output OUT
- Proportional gain K_c
- Integral time T_i
- Derivative time T_d
- Filter T_f
- Lambda λ
- Time t
- Sampling time T_s

Appendix IV Control loops

Beneath is a table of the different abbreviations for the control loops used to control the ACU™.

- FC004 Concentrated NaOH flow into the tank
- FC014 Water flow into the tank
- LC026 Tank level
- PC036 Diluted NaOH pressure before the reactor
- QC037 Density control
- FC035 CO_2 flow into the reactor
- PC035 Reactor pressure
- FC051 Product flow one
- FC052 Product flow two
- FC053 Product flow three

For the feedback in the system different measuring devices are used. Beneath is a list of the abbreviations of the devices and what they measure:

- FT004 Raw NaOH flow [l/s]
- FT014 Water flow [l/s]
- LT026 Level in tank [%]
- PT036 Pressure transmitter before reactor [bar]
- QT037 Density output from mass flow meter FT037 [kg/m^3]
- FT037 Mass flow meter for diluted NaOH flow [kg/s]
- FT035 Mass flow meter for CO_2 flow [kg/h]
- PT035 Pressure transmitter on the reactor [bar]
- FT051 Flow meter for product flow one [l/s]
- FT052 Flow meter for product flow two [l/s]
- FT053 Flow meter for product flow three [l/s]