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Optimization of Reverse Osmosis Seawater Desalination Plants by Advanced Process Control

How can the operation of reverse osmosis seawater desalination plants, especially the membrane units, be optimized using the Advanced Process Control functions of SIMATIC PCS 7?

White Paper | 2016-11-29

Do you want to optimize operation of your desalination plant, especially the reverse osmosis membrane units, with respect to process stability and energy consumption, and increase the degree of automation?

Do you want an automation solution that is uniform, straightforward, and easy to adapt?

This White Paper provides an overview of the available closed-loop control concepts for this task, and how they can be implemented transparently and with minimal effort using the SIMATIC PCS 7 Advanced Process Library.

Content

"Seawater desalination generally is a very energy intensive process. In reverse osmosis most of the energy is needed for operation of high pressure pumps."

Introduction

Basic Information on Reverse Osmosis Process

The shortage of fresh water resources in dry climate zones of the earth like Australia or the Middle East has increased the need to obtain drinking water or water for irrigation of plants by desalination of sea water in regions close to the coast. Currently around 1% of world population depends on desalinated water for daily use, but this fraction is supposed to grow rapidly [2.].

In principle, there are two main alternatives for seawater desalination: thermal processes (vacuum distillation) and membrane processes. Seawater desalination generally is a very energy intensive process, but pressure driven membrane processes are typically less energy intensive than thermal processes [3.].

For sea water desalination based on reverse osmosis a semipermeable membrane is used to filter out the dissolved salt ions and obtain low-salt drinking water. Therefore, the salty water has to be pressed with high pressure through the membrane to overcome the osmotic pressure, a thermodynamic parameter driven by chemical potential differences of the solvent.

In the normal osmosis process the solvent naturally moves from an area of low solute concentration, through a membrane, to an area of high solute concentration to level out the concentration differences. If enough pressure is applied to the high solute concentration and solvent flow is in equilibrium this is equivalent to the osmotic pressure. Further increasing pressure will cause solvent flow in the reverse direction and therefore is called reverse osmosis.

The energy consumption of reverse osmosis sea water desalination plants is mainly required to generate the high pressure required in front of the membrane.

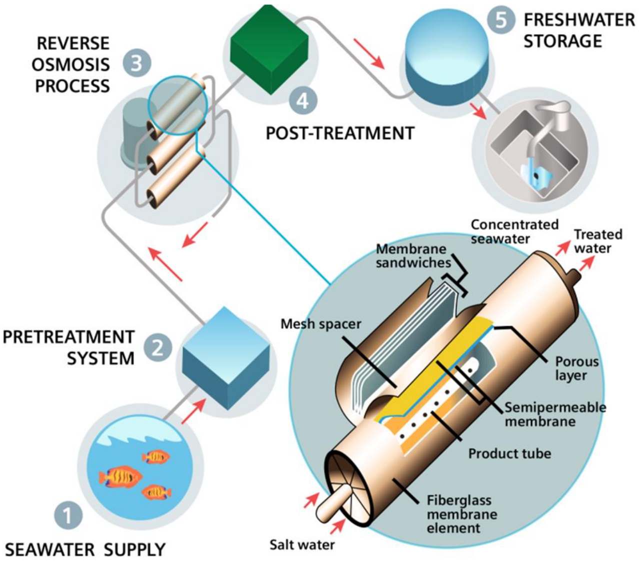

Figure 1: Overview of reverse osmosis seawater desalination process

A seawater desalination plant consists of several process steps (Figure 1):

- Pretreatment system: fresh salty water from the seawater intake is cleaned using mechanic screens and ultra-filtration. The pH value is balanced by dosing acids, and chlorine is added to kill bacteria.
- Reverse osmosis (RO): the core process consists of several membrane units, each containing large numbers of vessels.

- Post-treatment may include adjusting of pH-value, remineralization and adding lime or caustic to prevent corrosion of concrete-lined surfaces.
- Freshwater storage is a tank farm.

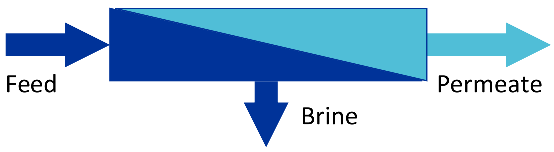

Figure 2: Schematic view of reverse osmosis membrane

The salty feed water is pushed to the high pressure level using a high pressure pump. The semipermeable membrane inside of each membrane vessel restrains most of the salt. Only desalinated water ("permeate") gets through the membrane, while the rest is rejected as "brine" with high salt concentration. The high pressure membrane unit is common to all reverse osmosis desalination plants although the details of pre- and post-processing may vary.

To recover the energy content (high pressure) of the salty water rejected by the membrane an energy recovery device is used. It exploits the pressure content of the reject water to increase the pressure of fresh salty water coming from the ultra-filtration unit, which is afterwards further increased by the booster pump in order to reach the pressure in front of the membrane. Pelton turbines were the first energy recovery devices deployed in reverse osmosis plants. However, nowadays mostly isobaric pressure exchangers (piston pressure exchangers; or isobaric rotary devices: Figure 4) are used because they provide higher energy efficiency.

In the P&I diagram of a typical reverse osmosis unit (Figure 3), the following components are visible:

- Inflow from pretreatment unit, typically containing flow and temperature measurement.
- High pressure pump with closed loop control of pressure in front of the membrane by manipulation of pump speed.
- Membrane vessel.
- Permeate outflow with measurement of pressure and flow. Electrical conductivity is measured as an indicator of salinity, i.e. permeate quality.
- Pressure indication in brine leaving membrane vessel, in order to monitor differential pressure along membrane vessel.
- Brine outlet with flow and pressure measurement.
- Energy recovery device, e.g. isobaric rotary pressure exchanger.
- Booster pump with flow control via manipulation of pump speed.

During operation, membrane performance is affected by different types of fouling [4.]:

- Microbiological fouling, e.g. bacteria, slime, algae
- Solvable organic fouling, e.g. humic acid, fulvic acid
- Insolvable organic fouling, e.g. oil
- Metal oxide fouling, e.g. Fe, Mn, Cu, Ni, Zn
- Cationic charged materials, e.g. coagulant, detergent, biocides
- Insolvable solids, e.g. clay, salt particles

Most types of fouling will decrease permeate flow significantly and increase pressure drop along the membrane, while only slightly reducing salt rejection.

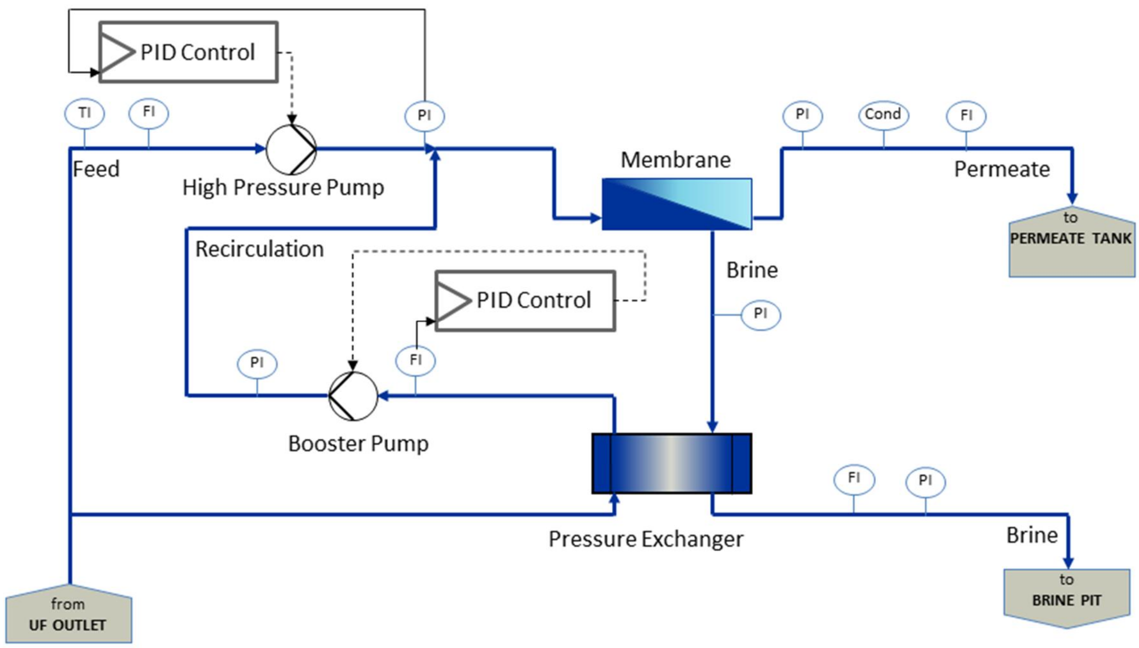

Figure 3: P&I-diagram of reverse osmosis unit with conventional automation

Challenges in the Automation of Reverse Osmosis Plants

The partially automated operation of reverse osmosis plants is considered state of the art. Compared to process engineering plants in other industries, such as the chemical industry, a desalination plant has fewer sensors and control loops. Nevertheless, reverse osmosis plant automation has its own special challenges:

- The output of the desalination plant is typically used as drinking water and thus has to be compliant with strict hygienic regulations [1.].
- The chemical and fluid mechanical processes in the membrane vessels are complex and cannot easily be modeled.
- Seawater desalination generally is a very energy intensive process. In reverse osmosis most of the energy is needed for the operation of high pressure pumps. Measures that reduce energy consumption can therefore pay for themselves after a short amount of time.
- In order to compensate for the effects of fouling, the high pressure setpoint has to be increased several times a day. This is typically done manually by plant operators.
- Membrane fouling has to be monitored in order to find the appropriate time for flushing each membrane unit. If flushing is not sufficient to return to good membrane performance, cleaning in place (CiP) using chemical detergents has to be applied.
- Engineers with relevant know-how about water-specific, biotechnological issues are usually available on-site, but not control engineers. That is why any control solution must have a clear and transparent structure so that it can be operated and maintained by the available personnel.

Advanced Process Control for Reverse Osmosis Plants

The use of I&C (instrumentation and control) technology in seawater treatment plants generally has the following objectives:

- Increased degree of automation.
- Minimization of operating costs, especially energy costs.
- Saving of investment costs through optimal use of existing infrastructures.

Sophisticated control engineering methods, which have become known under the keyword Advanced Process Control (APC) in other industry sectors, such as the chemical industry and oil refining industry, offer potential for optimization of process control in the water industry as well. Ever since these methods have been seamlessly integrated into modern distributed control systems such as SIMATIC PCS 7 [5.] and are made available at low cost as standard software blocks [6.], nothing more stands in the way of their successful application in desalination plants.

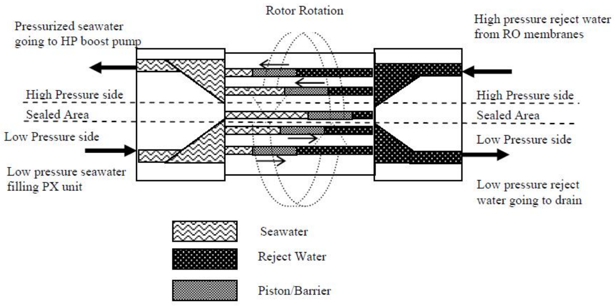

Figure 4: Schematics of rotary pressure exchanger [11.]

Model Predictive Control (MPC) is particularly attractive in this context. MPC allows "predictive operation" of the plant because it takes into consideration both the physical/chemical interactions between different variables and measurable disturbance effects. MPC is integrated as a standard function block in the SIMATIC PCS 7 Advanced Process Library with the name ModPreCon.

This paper shows, on the basis of a specific real world example, how this optimization potential can be tapped. The case study is a pilot project implemented with the same uniform approach [9.] that was already successfully applied to wastewater treatment plants:

- Configuration and parameter assignment of a simulation model of the reverse osmosis membrane unit, build on an industry-specific library of plant components [7.].
- Simulation study on the current state of automation (baseline).
- Specification of requirements for optimization of process control.
- Design and configuration of an APC solution for the existing plant type through a combination of standard function blocks and use of associated software tools for computer-aided commissioning of closed-loop control functions.
- Benchmarking simulation in order to quantify the improvement potential of the APC solution.

The goal of the pilot projects is to develop a generalizable APC solution for widespread plant types. The studies necessary for this can only be performed using a detailed simulation model. Later on, when extensive field experience will exist, APC solutions can be created for comparable reverse osmosis plants without new simulation studies. Eliminating this laborious modeling step will not only save costs but also valuable time before commissioning of the new closed-loop control concept at a desalination plant.

"Higher degree of automation, more stable process operation, higher safety of compliance with quality specifications, and reduced specific energy consumption can be expected from the MPC solution."

Optimization of Reverse Osmosis Unit

Simulation Model

The example to be examined is a membrane unit of a real world seawater desalination plant in Arabia. A model is created in a Siemens internal tool for simulation of biological and chemical process technology. The membrane model is based on [10.]. Models of both high pressure pump and booster pump use pump performance curves from pump datasheets.

Fouling is assumed to increase steadily in such a way that after 40 hours of unit operation, flushing of the membrane vessels is required.

The simulation, when compared with measured data from the real plant, describes the essential dynamic processes of the seawater desalination plant effectively.

Limitations of Classic Control

The current control solution, which is referred to hereinafter as classic control, is depicted in Figure 3 and mainly consists of PI controllers for high pressure in front of the membrane and booster pump flow.

Plant operators need to increase the high pressure setpoint manually several times a day to compensate for fouling and to bring the permeate output back to an acceptable level. Each of these setpoint steps leads to a steep gradient in both pump speeds, permeate flow and permeate salinity.

Neither permeate flow nor permeate salinity is controlled directly. Although decline of permeate flow due to fouling is compensated manually in a rough way, adjustments in permeate salinity cannot be performed by the operator at all.

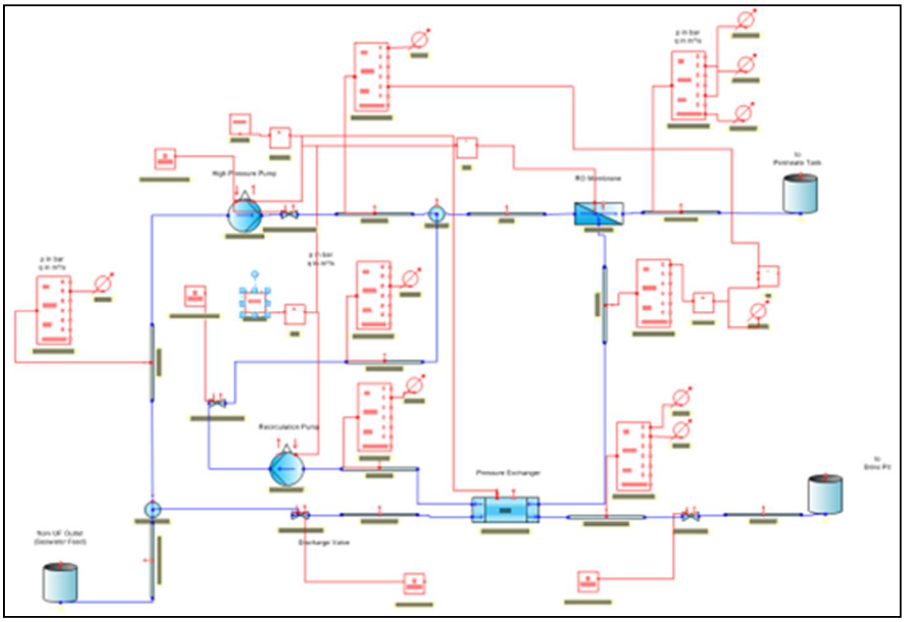

Figure 5: Simulation model of reverse osmosis unit

Solution Concept

The design of a control concept starts from a hierarchical order of requirements for typical plant operation as defined by the company operating the plant:

- Highest priority: keep permeate quality inside specifications for desired utilization as drinking water, i.e. keep permeate salinity in a range of 0...0.48 g/L.
- Medium priority: achieve desired plant throughput, i.e. track setpoint of permeate flow.
- Low priority: minimize specific energy consumption (SEC) per amount of desalinated water, i.e. run both pumps as close as possible to their optimal operating point, and stay below an upper limit for high pressure setpoint, which is related to energy consumption (This limit is lower than the absolute high constraint of the pump.).

It is desired to control salinity and permeate flow independently of each other, i.e. the controller is supposed to decouple the two interacting loops.

In order to achieve these control targets, two manipulated variables can be used:

- High pressure pump pressure setpoint.
- Booster pump flow setpoint.

The resulting 4x2x0 MPC structure with 4 controlled variables (CV), two manipulated variables (MV) and zero disturbance variables (DV) is shown in Table 1. In each column, the effect of the respective manipulated variable to all controlled variables is marked. "++" means a strong positive effect, "-" a weak effect with negative sign.

Table 1: MPC structure

	MV1 in bar HP Pump pressure setpoint	**MV2 in m3/h** Booster Pump flow setpoint
CV1 in g/L Permeate Salinity	-	-
CV2 in m3/h Permeate Flow	++	+
CV3 in kW Electrical Power HP Pump	++	+
CV4 in kW Electrical Power Booster Pump	+	++

Permeate salinity has a very high weighting (highest priority) but will stay inside its large dead zone during normal operation. Therefore the MPC will focus on permeate flow. Electrical power values of the pumps have much smaller weightings (lowest priority). The setpoints for electrical powers are the optimal efficiency operating points of the respective pumps.

The ModPreCon function block of PCS 7 Advanced Process Library block is ideally suited for the described tasks. The MPC Configurator provides automatic MPC design, using a few transparent parameters for adjustment of the dynamic behavior

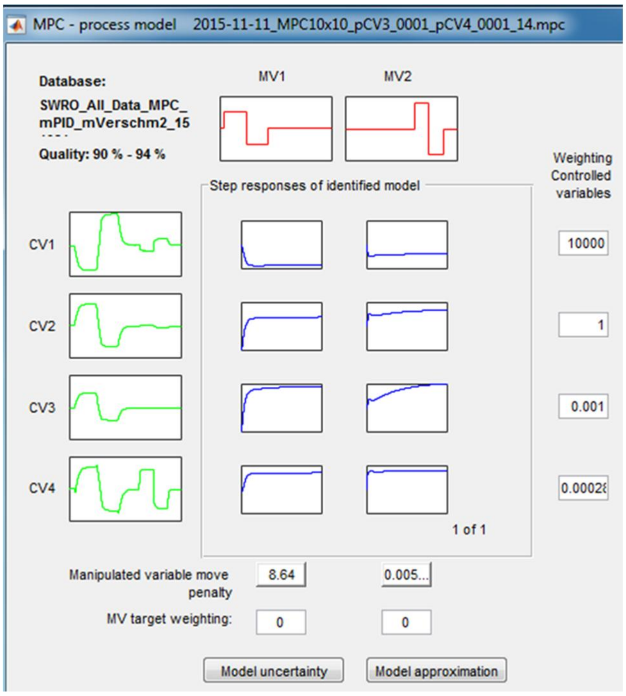

Figure 6: MPC configurator session with process model and weightings

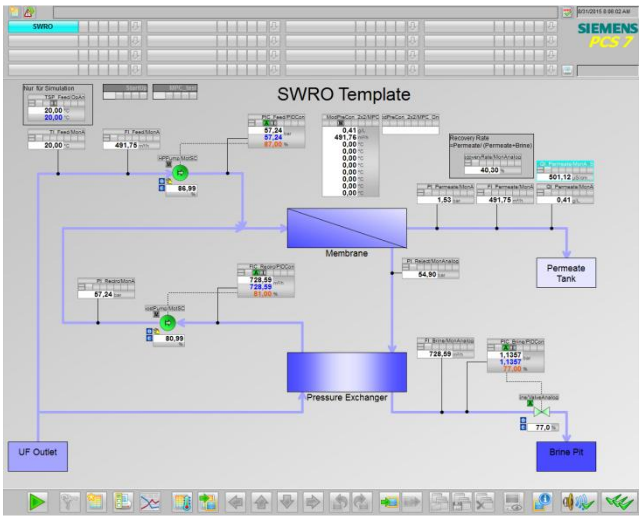

Figure 7: Simatic PCS 7 OS picture of membrane unit template

Simulation Results

The conventional PID controllers and the MPC automation are implemented in SIMATIC PCS 7 and connected to the simulator software. First, in a simulation without fouling the ability of the MPC to cope with the multivariable control problem and achieve stable feedback control is checked.

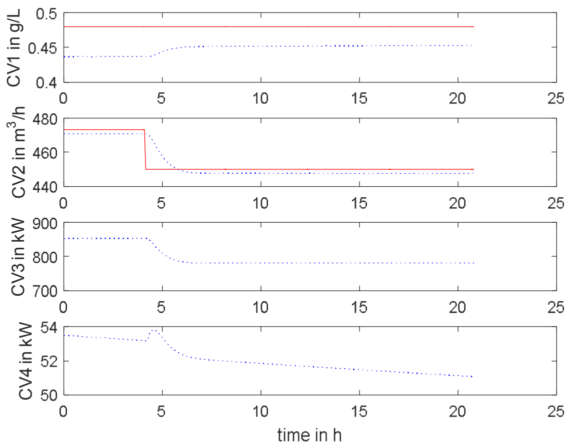

Figure 9: Setpoint step in permeate flow (CV2) – trend of controlled variables. For CV1 the red line shows the upper limit of salinity i.e. salinity is inside its control zone all the time. For CV2 the red line is the permeate flow setpoint. CV3 and CV4 have setpoints below the axis limits and low priority.

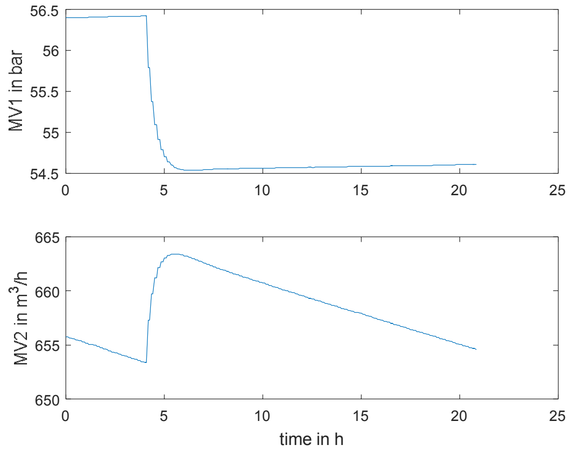

Figure 10: Setpoint step in permeate flow (CV2). The trend of manipulated variables shows that the MPC uses both of them in a coordinated way to reach the new setpoint

A setpoint step in throughput (Figure 9 and Figure 10) shows good tracking performance of the MPC.

The effect of prioritized control will be shown in a situation where salinity is at its limit and a load change is demanded (Figure 11 and Figure 12). In this situation, the MPC moves salinity back into the control zone, tolerating some deviation in permeate flow.

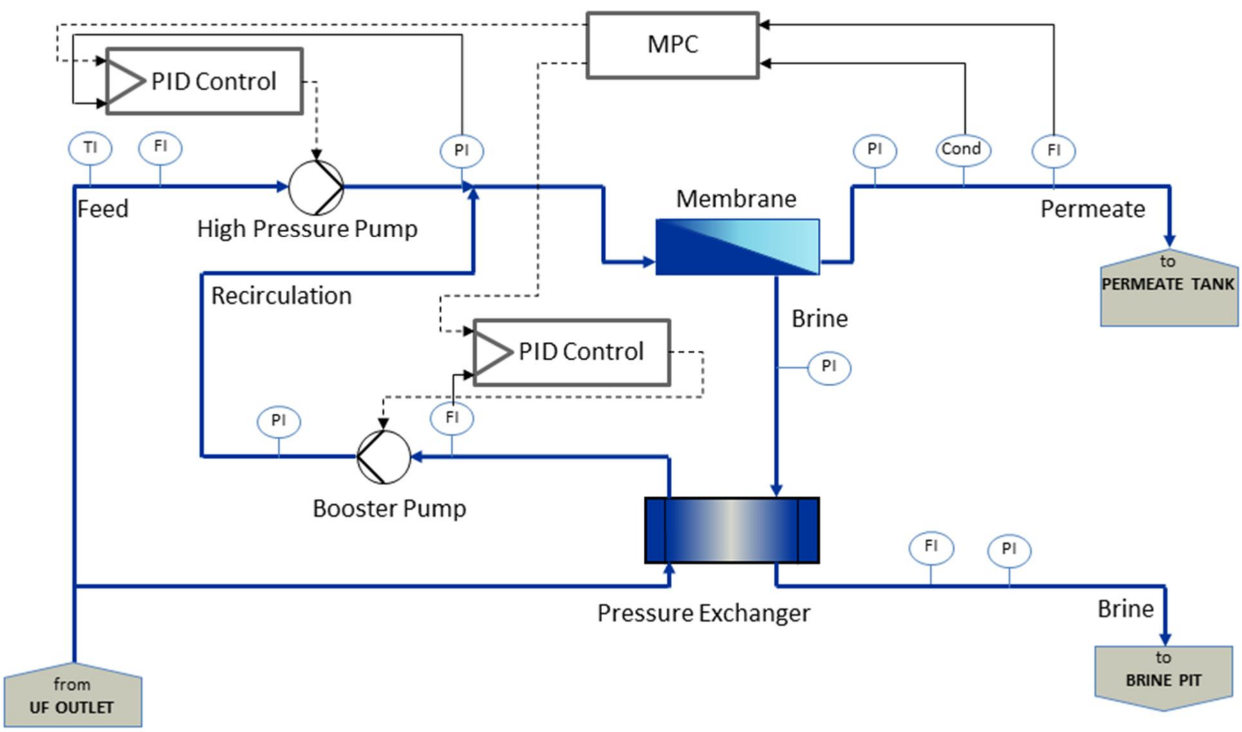

Figure 8: P&I diagram of reverse osmosis unit with MPC

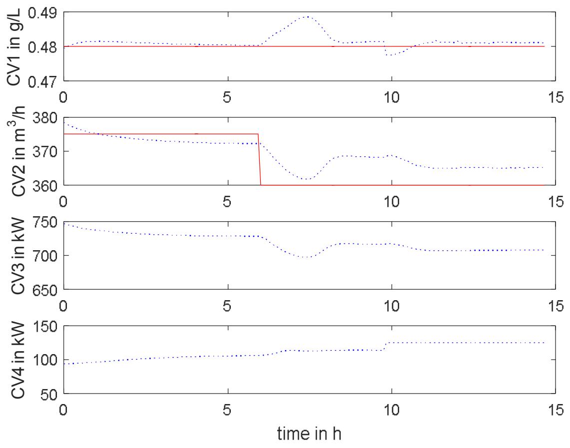

Figure 11: Setpoint step in permeate flow while salinity is at its limit – trend of controlled variables. CV1 salinity has higher priority than CV2 permeate flow. Therefore the limit violation of salinity is compensated while some deviation in permeate flow is tolerated.

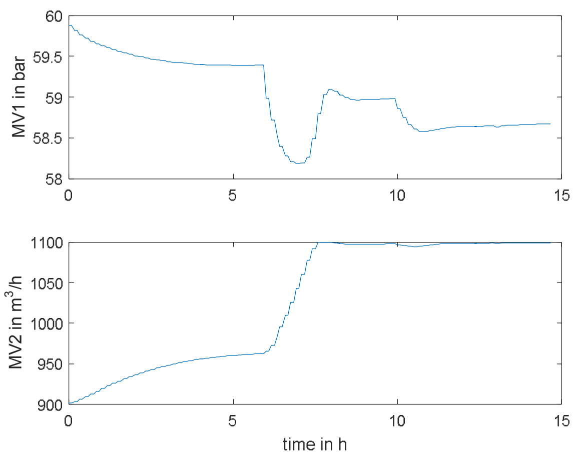

Figure 12: Setpoint step in permeate flow while salinity is at its limit – trend of manipulated variables

Benchmarking

The benchmarking scenario to compare classic PID control and MPC spans a time period of 40 hours, i.e. one complete continuous operating cycle in between two flushing events.

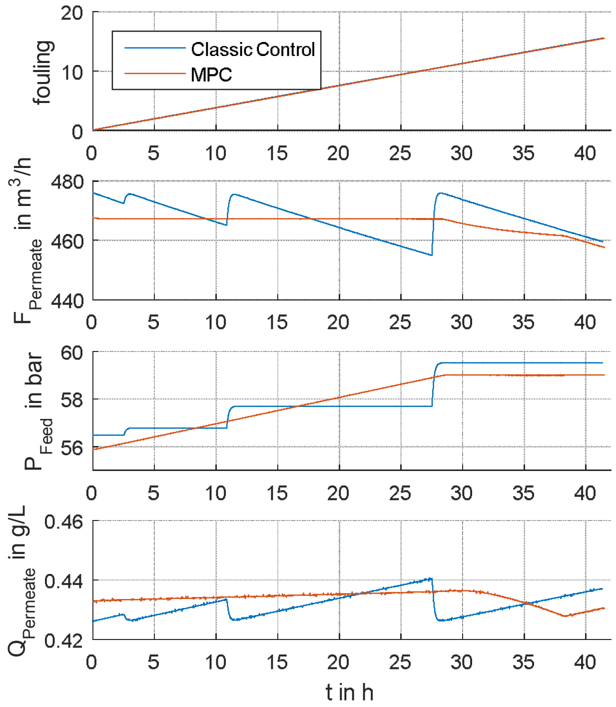

Figure 13: Benchmarking simulation, blue: classic control, red: MPC. From top to bottom: fouling, permeate flow (CV2), feed pressure (MV1), permeate salinity (CV1)

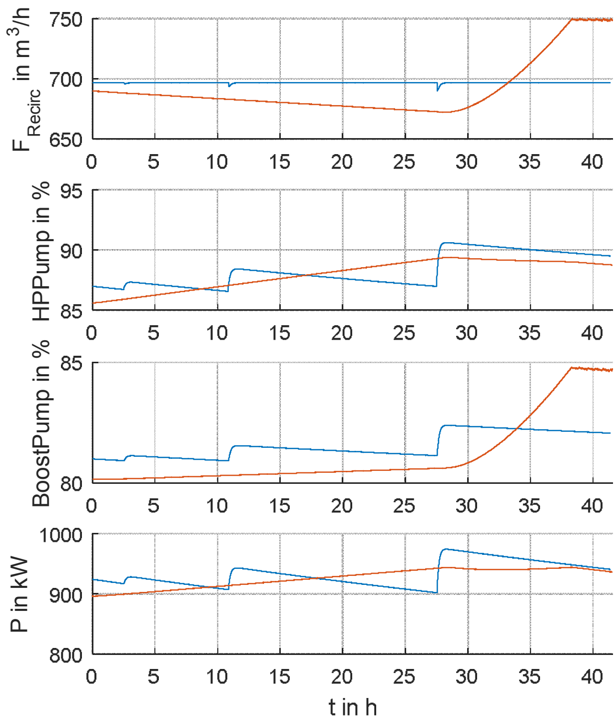

Figure 14: Benchmarking simulation, further variables from top to bottom: recirculation flow (MV2), high pressure pump speed (CV3), booster pump speed (CV4), overall electric power consumption of both pumps

In the benchmarking scenario (Figure 13 and Figure 14) membrane fouling is increasing constantly, which leads to decreasing permeate flow and increasing permeate salinity. To keep the throughput close to its setpoint with the existing classic control concept, the operator adjusts the feed pressure setpoint manually in several steps, resulting in "sawtooth" trend curves of permeate flow and permeate salinity. Controller actions caused by each setpoint step induce perturbations into plant operation every time.

Using the MPC with a lower permeate flow setpoint of 467.68 m^3/h shows a very interesting result. In nearly the same time, the same amount of water can be desalinated with a much more steady process operation. As long as the manipulated variables of the MPC are not bounded, permeate flow is constant and feed pressure is increased steadily by the MPC. As soon as the first manipulated variable (feed pressure) is bounded, the MPC tries to reduce the decrease in permeate flow with the help of the second manipulated variable booster pump flow. As soon as both manipulated variables are bounded, the MPC cannot prevent permeate flow decreasing any more, similar to PID control.

For quantitative comparison, the following key performance indicators are evaluated:

- Overall energy needed to desalinate the same amount of sea water
- Specific energy consumption (SEC)
- Time needed to produce the same amount of desalinated water
- Value range of recovery rate
- Value range of salinity
- Value range of feed pressure
- Value range of permeate flow
- Value range of high pressure pump speed
- Value range of booster pump speed

Table 2: Comparison of both control concepts

	PID	MPC
Energy in kWh	38627	38517
Production in m^3	19362	19363
SEC in kWh/m^3	1.9950	1.9892
Operation time	41h 23min 36s	41h 34min 24s
Recovery rate in %	39.5-40.6	37.9-41
Salinity in g/L	0.426-0.441	0.428-0.437
PI_Feed in bar	56.5-59.5	55.9-59.0
FI_Permeate in m^3/h	455-477	458-468
HP pump in %	86.6-90.6	85.6-89.4
Booster pump in %	80.9-82.9	80.1-84.8

The benchmarking scenario shows the advantages of the MPC concept:

- Permeate flow is kept constant at its setpoint, as long as manipulated variables are not bounded.
- Salinity variations are reduced.
- Salinity will be kept automatically in its range.
- No controller actions with steep gradients e.g. in feed pressure are necessary.
- Reduced gradients in pump speed, which might reduce pump wear out.
- Reduction of specific energy consumption per amount of desalinated sea water.
- Higher degree of automation: no manual operator action during production is necessary to compensate for fouling.

The moderate benefits in energy consumption are due to the fact that in the benchmarking simulation the pumps are operated close to their optimal operating points in the classic control scenario already. Most of the energy is consumed by the high pressure pump anyway, such that slight load shifts between both pumps that can be commanded by the MPC do not have a large effect on overall energy consumption.

Nevertheless, the large advantages in the higher automation level, the reduced strain due to steep gradients, the constant permeate flow, and the controlled salinity are accessible even with a slightly reduced energy consumption.

Outlook

The simulation results are promising. Higher degree of automation, more stable process operation with smaller variations in all characteristic values, higher safety of compliance with quality specifications, i.e. salinity will stay in its range, and reduced specific energy consumption can be expected from the MPC solution. In another requirement context, the MPC could be used to obtain higher average throughput.

In this case, the value of the quantifiable benefits (energy savings) might well be exceeded by the non-quantifiable benefits. For example a higher degree of automation of each reverse osmosis unit in a plant might be the prerequisite for a systematic optimization at plant level, e.g. load balancing of all units in such a way that more load is distributed to those units that are currently in a more clean state with respect to fouling and therefore currently provide higher efficiency. Similarly, a higher degree of automation might be exploited for adaptation of plant throughput to varying energy prices (e.g. day and night) in conjunction with the capacity of tank farms.

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