Fault-Tolerant Control of a Small Reverse Osmosis Desalination Plant with Feed Water Bypass

A. Gambier, T. Miksch, E. Badreddin

Abstract—Many applications of Reverse Osmosis (RO) desalination plants require fault tolerance, in particular when human life depends on the water purity. However, they have been little studied in the literature from this point of view, in particular, when small plants use a feed water bypass to modify the permeate conductivity by mixing a little amount of feed water with the permeate. Such plants have a different system configuration and different dynamic behavior from standard plants.

The present work is a study on Fault-Tolerant Control (FTC) of a small plant with feed water bypass by using Model Predictive Control (MPC). Very satisfactory results show the advantages of using a fault-tolerant control system in this kind of plants.

I. INTRODUCTION

Reverse osmosis is well known as a separation process used in desalination for removing salt from sea water and brackish water. However, it is also a process, which is extensively used in the food industry. It is applied, for instance, for concentrating milk, whey and fruit juices. In the wine industry, it is also applied to remove e.g. acetic acid, alcohol, smoke taint and brettanomyces taint. Reverse osmosis water is sometimes used in car washes during the final rinse to avoid membrane fouling. Afterward, it passes through filter cartridges (a safety device) and is sent through the membrane modules (permeators) by a high-pressure pump. Because of the high pressure, pure water permeates through the membranes and the salty water becomes concentrated (retentate or brine). The water product flows directly from the permeators into the post treatment unit, and the retentate (at high pressure) is discharged, usually, after passing through an energy recovery system (see [9] and [34] for a review of membrane processes).

Many of the plants, which are presented in the above mentioned literature, include a pre-treatment unit, where the salt concentration of permeate (or also permeate conductivity) is controlled by adjusting the pH value of the feed water. However, small plants or plants for drink water purification do not include pH control and permeate conductivity is a non-controlled variable. In order to be able to adjust the permeate conductivity, a bypass valve, which allows mixing permeate with a small amount of feed water, was installed for the present work. This construction leads to a different system topology, which has first been studied from the control point of view in [12]. In that work, it is pointed out that it is necessary to control the permeate conductivity in order to obtain better water quality. A multivariable unconstrained MPC is used as control law.

In some medical applications, for example in surgery rooms and semiconductor industry, a continuous supply of high quality water is essential. Thus, fault-tolerant control systems should be a standard for this kind of plants but this topic is still an open problem in the literature.

The description of the plant including particularities and structures is explained in Section 2. Dynamic properties, modeling and the control space are the topics of Section 3. A short introduction to FTC and the used approach are presented in Section 4. Section 6 shows the performed studies and their results. Finally, conclusions are drawn in Section 7.

II. PLANT DESCRIPTION

A. General Description

A basic RO system consists in general of a pretreatment stage, a high-pressure pump, a membrane assembly (RO unit) and a post-treatment unit (Fig. 1). Salty feed water is first pretreated to avoid membrane fouling. Afterward, it passes through filter cartridges (a safety device) and is sent through the membrane modules (permeators) by a high-pressure pump. Because of the high pressure, pure water permeates through the membranes and the salty water becomes concentrated (retentate or brine). The water product flows directly from the permeators into the post treatment unit, and the retentate (at high pressure) is discharged, usually, after passing through an energy recovery system (see [9] and [34] for a review of membrane processes).

Pretreatment is important in RO plants because suspended particles must be removed in order to maintain the membrane surfaces continuously clean. Thus, pretreatment consists of fine
filtration and the addition of chemicals to inhibit precipitation and the growth of microorganisms. The pH value of the feed water is also adjusted in this unit. The high-pressure pump supplies the pressure that is needed to allow water to pass through the membrane in order to reject salts. The pressure range is from 15 to 25 bars for drink and brackish water and from 54 to 80 bars for seawater.

The membrane assembly consists of a pressure vessel and several membrane units such that feed water is pressurized against the membrane. The membrane must be able to resist the entire pressure drop across it. The semi-permeable membranes vary in their ability to pass fresh water and reject the passage of salts. Finally, the post-treatment consists of stabilizing the water and preparing it for distribution. This post-treatment might consist of removing gases such as hydrogen sulfide, adding minerals and adjusting the pH value.

Two valves are used for the control of permeate flow rate and its conductivity, which are carried out by manipulating the flow rate of retentate and the chemicals at the pretreatment unit, respectively, as it is shown in Fig. 2.

Notice that changes in the retentate flow rate also affect the permeate conductivity. However, changes in the pH of feed water do not modify the permeate flow rate. This leads to a triangular system as given in Fig. 3.

B. Plants with feed water bypass

In the case of small plants, pre-treatment units are very simple and normally pH control of feed water is not implemented. Permeate conductivity can be changed by using a bypass pipeline, which permits to mix a small amount of feed water with the product, if the quality requirements for the product are met. Permeate conductivity can be changed by using a bypass valve and a valve in the retentate stream closed up to 100%. In this case, the conductivity is 391 < Cp < 462 μS/cm.

The maximum water purity is obtained by a completely closed bypass valve and a valve in the retentate stream closed up to 100% (10% valve opening). Notice that this valve may not be completely closed in order that the plant is able to works.

The maximum water purity is obtained by a completely closed bypass valve and a valve in the retentate stream closed up to 100% (10% valve opening). In this case, the conductivity is 391 μS/cm (i.e. 260 ppm). The maximum value for the conductivity (462 μS/cm) is obtained for both valves opened up to 100%.

Thus, the range for the conductivity is 391 < Cp < 462 μS/cm.

III. PLANT DESCRIPTION AND DYNAMIC LINEAR MODEL

A. Steady-state plant characteristics

The plant under consideration has a capacity in nominal operation of about 250 l/h (i.e. 0.25 m³/h) for a feed water of 500 l/h. The concentrate flow rate is also 250 l/h, i.e. 50% retentate and 50% permeate. The bypass flow rate is about 0.02 l/h for the nominal operation. The range for permeate flow rate is given by 21 l/h < q_p < 433 l/h for a valve opening varying between 100% > a_p > 10%. Notice that this valve may not be completely closed in order that the plant is able to works.

The maximum water purity is obtained by a completely closed bypass valve and a valve in the retentate stream closed up to 90% (10% valve opening). In this case, the conductivity is 391 μS/cm (i.e. 260 ppm). The maximum value for the conductivity (462 μS/cm) is obtained for both valves opened up to 100%.

Thus, the range for the conductivity is 391 < Cp < 462 μS/cm.
The normal operation point is 50% valve opening for both valves. Under these conditions, the permeate flow rate is 250 l/h and the permeate conductivity 425 μS/cm (283ppm). Notice that in order to put the set point, for example, at 200 l/h it is necessary to open the retentate valve up to 60% (Fig. 7, a). Once the valve is fixed to this value it is not possible to modify this flow rate by using the bypass valve. On the contrary, modifying the bypass valve, the conductivity can be adjusted to another reference value (Fig. 7, b).

B. Dynamic behavior of the plant

The open-loop step response of the plant is shown if Fig. 8, where one observes that a step change in the retentate valve produces a permanent change in the permeate flow rate and in its conductivity. On the other hand, a step change in the bypass valve produces a permanent change in the permeate conductivity but only a transitory disturbance in the permeate flow rate.

C. Dynamic model of the plant

For the controller design, a model-based predictive control approach is used. Therefore, a time-discrete state-space linear model, whose general equations are given by

\[
\dot{x}(k + 1) = A \dot{x}(k) + B u(k) + E v(k) \quad \text{and} \quad y(k) = C \dot{x}(k) + D u(k) + F e(k),
\]

is obtained offline from sampled-data for a sampling time of 0.15 s and the operating point mentioned above. The corresponding estimated model (including the dynamic of the valves) is summarized in Table I.

| TABLE I  
| STATE-SPACE LINEAR MODEL |
|---|---|---|
| **A** | **B** |
| 0.201 0.000 0 0 0 0 0 20e-4 -001 | -3,301 -0.129 0 0 0 0 0 0.001 001 |
| 0 0.757 0 0 0 0 0 0.113 0 009 | 0 009 |
| 0 0 0.955 0 0 0 0 0.01 -0.062 | 0 0.002 -0.002 |
| 0 0 0 0 0 0 0 0.110 -0.066 | 0 -0.04 -0.041 |
| 0 0 0 0 0 0 0 0.889 0.004 | 0 0 1.7e-4 |
| 0 0 0 0 0 0 0 -1.338 0024 | 0 0 0.02 |
| 0 0 0 0 0 0 0 0.905 0 | -0.632 0 |
| 0 0 0 0 0 0 0 0.009 0 | 0 0.005 0 |
| 0 0 0 0 0 0 0 0 0.029 | 0 0.057 |

Notice that it could be possible to reduce the model from order nine to order seven with an infinity norm error bound of 3e-4. However, the obtained model does not lead to satisfactory results.

Stochastic processes are assumed to be independent and Gaussian with mean value equal to zero. Covariance matrix of output vector process is noted \( R \), Covariance matrix of states vector process \( Q \) is used as design parameter for the Kalman estimator ([6]). A diagonal matrix with all elements equal to 10 leads to satisfactory results.

It is important to remark here that some authors point out that reverse osmosis plants have a strong nonlinear behavior because of fouling. This statement could not be confirmed experimentally at least for the small plant. Fouling is a very slow process that is normally interrupted once a week by membrane washing. Thus, it is possible to observe that the plant has a quite linear behavior changing slowly its parameter in the course of a week but without affecting significantly the control.

IV. FAULT-TOLERANT CONTROL SYSTEMS

A. Overview and definitions

There are several definitions and classifications of FTC systems (FTCS). In the following, the definitions given in [20] are adopted, where a FTCS is a control system that can work stably with an acceptable degree of performance even
though in the presence of component faults. FTCS should detect and accommodate faults avoiding the occurrence of failures, i.e. irrecoverable damages at the system level.

Fault tolerance can be reached by means of different mechanisms. For example, it is possible to obtain a limited fault tolerance by using a robust control system design. This approach is sometimes named Passive Fault-Tolerant Control System (PFTCS). Contrarily, Active Fault-Tolerant Control Systems (AFTCS) require a new controller either by using adaptive control or switching control. Adaptive control leads to the faults accommodation, whereas switching control makes possible a reconfiguration of the control system. Notice that reconfiguration can take place at different levels depending on the severity of the fault and on the available system infrastructure. The simplest case of reconfiguration is given by controller switching. However, there could be other kind of reconfigurations if some redundancy is available: changes on the control system topology by using functional redundancy (redesign of the control system by using other actuators or/and other sensors) or plant reconfiguration if physical redundancy (i.e. standby backup facilities for a fault accommodation and if all these mechanisms are insufficient in order to solve the problem a reconfiguration should be attempted.

Some control laws have been modified as well as developed to manage fault accommodation: for example in [2], the Dynamic Safety Margin (DSM) is proposed to provide fault accommodation for controllers that cannot manage constraints as for example PID (Proportional, Integral and Derivative) control, LQ (Linear Quadratic) optimal control and unconstrained MPC (Model Predictive Control). Another approach for LQ controllers can be found in [29]; fault tolerance based on designing controllers by using Eigenstructure Assignment (EA) has been proposed in [15]. A different approach, the Pseudo Inverse Method (PIM), is proposed in [30]. It tries to obtain a controller for the faulty closed loop system by minimizing the distance to the nominal control system. The constrained MPC has also been studied for fault-tolerant behavior. It was first proposed in [19] and later implemented in [25]. A real-time study of fault-tolerant MPC is presented in [23]. Results of a comparison between LQ, PIM and MPC from a real-time point of view are presented in [24], where it is shown that MPC has several advantages regarding the other ones.

The MPC control law is well known and details of it can be found in the specialized literature (e.g. [17]). In the following, only the main idea is given for the sake of completeness. The MPC control is obtained by the numerical optimization of the performance index

\[ J = \| e(n + N) \| _2^2 + \sum_{i=1}^{k-N-1} \| e(i) \| _Q^2 + \sum_{i=1}^{k-N-1} \| \Delta u(i) \| _R^2 + \rho \| z \| _\infty^2 \]  

subject to the constraints

\[ y(k) = C x(k), \]
\[ x(k + 1) = A x(k) + B u(k), \]
\[ u_{\text{min}} \leq u_i \leq u_{\text{max}} \quad \text{for } i = 1, L, m, \]
\[ \Delta u_{\text{min}} \leq \Delta u_i \leq \Delta u_{\text{max}} \quad \text{for } i = 1, L, m \quad \text{and} \]
\[ \epsilon x_{\text{min}} \leq x_i \leq \epsilon x_{\text{max}} \quad \text{for } i = 1, L, n. \]

\( N \) and \( N_0 \) are the prediction horizon and the control horizon, respectively. The term \( \| v(\cdot) \| _M \) denotes \( v(\cdot)Mv(\cdot) \) and variable \( \epsilon(\cdot) \) is the control error defined by

\[ \epsilon(\cdot) = r(\cdot) - y(\cdot). \]  

Matrices \( Q = Q^T \in \mathbb{R}^{m \times m} \) and \( S = S^T \in \mathbb{R}^{m \times m} \) are positive semi definite and \( R = R^T \in \mathbb{R}^{l \times l} \) is positive definite. Variables \( y \in \mathbb{R}^m, u \in \mathbb{R}^l \) and \( x \in \mathbb{R}^l \) are the output vector, the input vector and state vector, respectively. \( \Delta u(\cdot) \) is defined as first difference \( u(i) - u(i-1) \). Model matrices \( A, B \) and \( C \) are of adequate dimension. \( \epsilon \) is a slack variable used to relax the constraints and \( \rho \) a weighting factor.

The fault-tolerant MPC approach, which is implemented in this work, is obtained by changing on-line the constraints according to the fault case. It is detailed described in [23].

C. The FDI unit

For this study no FDI unit has been implemented because it is assumed that all faults are known. Thus, a FDI unit consists

\[ J = \| e(n + N) \| _2^2 + \sum_{i=1}^{k-N-1} \| e(i) \| _Q^2 + \sum_{i=1}^{k-N-1} \| \Delta u(i) \| _R^2 + \rho \| z \| _\infty^2 \]  

subject to the constraints

\[ y(k) = C x(k), \]
\[ x(k + 1) = A x(k) + B u(k), \]
\[ u_{\text{min}} \leq u_i \leq u_{\text{max}} \quad \text{for } i = 1, L, m, \]
\[ \Delta u_{\text{min}} \leq \Delta u_i \leq \Delta u_{\text{max}} \quad \text{for } i = 1, L, m \quad \text{and} \]
\[ \epsilon x_{\text{min}} \leq x_i \leq \epsilon x_{\text{max}} \quad \text{for } i = 1, L, n. \]

\( N \) and \( N_0 \) are the prediction horizon and the control horizon, respectively. The term \( \| v(\cdot) \| _M \) denotes \( v(\cdot)Mv(\cdot) \) and variable \( \epsilon(\cdot) \) is the control error defined by

\[ \epsilon(\cdot) = r(\cdot) - y(\cdot). \]  

Matrices \( Q = Q^T \in \mathbb{R}^{m \times m} \) and \( S = S^T \in \mathbb{R}^{m \times m} \) are positive semi definite and \( R = R^T \in \mathbb{R}^{l \times l} \) is positive definite. Variables \( y \in \mathbb{R}^m, u \in \mathbb{R}^l \) and \( x \in \mathbb{R}^l \) are the output vector, the input vector and state vector, respectively. \( \Delta u(\cdot) \) is defined as first difference \( u(i) - u(i-1) \). Model matrices \( A, B \) and \( C \) are of adequate dimension. \( \epsilon \) is a slack variable used to relax the constraints and \( \rho \) a weighting factor.

The fault-tolerant MPC approach, which is implemented in this work, is obtained by changing on-line the constraints according to the fault case. It is detailed described in [23].

C. The FDI unit

For this study no FDI unit has been implemented because it is assumed that all faults are known. Thus, a FDI unit consists
here only of a signal, which announces the fault after a delay in order to emulate the elapsed time between the fault occurrence and its detection. A more sophisticated FDI will be implemented in the future by using the FDI toolbox described in [33].

V. STUDIES AND RESULTS

For the studies, the plant is set to a permeate flow rate of 250 l/h and a valve opening of 50%. Permeate flow rate and the conductivity are the controlled variables. Then, the reference signal for the permeate flow rate is changed first to 350 l/h and afterward to 300 l/h. The conductivity is set at the operating point of 425 μS/cm. This conductivity is assumed to be an index for the water quality, which in most applications of such small plants is a very important property and normally also the reason for using this kind of equipments. Therefore, this variable is considered of highest priority in the fault-tolerant control system. This means that in case of faults, the permeate flow rate can freely change within a defined range in order to maintain the conductivity as close as possible to its set point.

The conductivity is normally controlled by Valve 2. However, the conductivity can be modified by both control signals as it is apparent from Fig. 7. This provides some redundancy that can be used for obtaining fault tolerance. The performed studies are summarized in TABLE II.

<table>
<thead>
<tr>
<th>Description</th>
<th>u_{min,1}</th>
<th>u_{max,1}</th>
<th>u_{min,2}</th>
<th>u_{max,2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Case 1</td>
<td>0</td>
<td>50</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Case 2</td>
<td>50</td>
<td>50</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Case 3</td>
<td>0</td>
<td>100</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

The design parameters for the MPC are given in Table III. The sampling time and the prediction horizon are optimally chosen according to [12].

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>NUMERICAL VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>diag(1.0, 0.01)</td>
</tr>
<tr>
<td>Q_1 (Q = C’Q’C)</td>
<td>diag(100, 0.1)</td>
</tr>
<tr>
<td>S_1 (S = C’S’C)</td>
<td>Q_1</td>
</tr>
<tr>
<td>ρ</td>
<td>0</td>
</tr>
<tr>
<td>T_o</td>
<td>0.15 s</td>
</tr>
<tr>
<td>Horizons</td>
<td>N = 14</td>
</tr>
</tbody>
</table>

The delay of the FDI to find the fault has been assumed to be 5s and the adaption of the fault-tolerant MPC for accommodating faults has been supposed to take 1s.

Results are presented in Fig. 10, Fig. 11 and Fig. 12, respectively. For all figures, results for nominal MPC are presented with solid red lines and results for the fault-tolerant MPC are shown with dashed black lines. The first fault case is presented in Fig. 10. It consists of limiting the range of valve two between 0 and 50%. After the fault, the nominal MPC tries the continue maintaining the outputs at the set points but the conductivity cannot be controlled any more. The fault-tolerant MPC abandon the set-point control of the flow rate (but maintained it in a pre-defined band) in order to improve the conductivity control, since this is the most important variable.

In the second fault case, Valve 2 goes to an opening of 100% and it stays permanently at this value. The standard MPC recovers the fault returning the conductivity to its set point at the expense of an acceptable steady-state error. This is shown in Fig. 11.

Finally, Case 3 (Valve 1 is maintained fix at 30%) is the most difficult because it is not possible control the flow rate only with Valve 2. The standard MPC shows a similar behavior as the first case. The fault-tolerant MPC recovers the fault maintaining the outputs at the set points for the conductivity, whereas the fault-tolerant MPC recover the fault without steady-state error.

VI. CONCLUSIONS

In this contribution, the control problem of a small-sized reverse osmosis desalination plant with feed water bypass is studied. In order to guarantee an acceptable water quality along
Fig. 12. Control system behavior for Case 3 ($u_1 = 30\%$ for $t \geq 18\ s$)

the complete operation time even in case of faults, a fault-tolerant MPC based on adjusting its constraints is proposed.

In this first study only actuators constraints are considered. Obtained results are very satisfactory and this motivates the extension of the work in order to include other faults, additional fault-tolerant mechanisms, which introduce, for example, multi-objective optimization. Finally, the approach has to be combined with a robust fault-detection approach.

ACKNOWLEDGMENT

This work has been supported by the European Commission by means of the project Open-Gain under contract No. 032535.

REFERENCES