# FAULT-TOLERANT SUPERVISORY CONTROL OF A REVERSE OSMOSIS DESALINATION PLANT POWERED BY RENEWABLE ENERGIES

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## ABSTRACT

Many applications of Reverse Osmosis desalination plants (RO plants) require a fault tolerant system, in particular when human life depends on the availability of the plant for producing fresh water. However, they have been little studied in the literature from this point of view, in particular, when the plant is powered by renewable energies. In this case, the availability of the power supply is limited and depending on weather conditions. Therefore, the plant has to be able to work at different operating point and hence, fault tolerance becomes essential.

The present work reports a study, in the framework of the European project Open Gain, on Fault-Tolerant Control (FTC) of a RO plant powered by renewable energies. The approach is based on optimized PID control loops in the lowest control level and a Model Predictive Control (MPC) as supervisory controller. The MPC provides fault tolerance by using a prioritized lexicographic algorithm.

Keywords: fault tolerant control, reverse osmosis desalination

## 1. INTRODUCTION

Reverse osmosis desalination plants use sensible components, which are also prone to parameter changes because membranes are sensitive to temperature of feed water, fouling, scaling and pressure variations. RO plants are normally controlled by using PID control laws, which are tuned but not optimized.

Although such plants are difficult to control and control is a very important aspect for the safety and economical plant operation, this subject is not much researched and only some contributions can be found in the literature. For example, the first multi-loop control system for a RO plant was proposed in Alatiqi, Ghabris, and Ebrahim (1989). It includes one pressure controller and two pH controllers. For desalination plants in general and RO in particular, only few contributions regarding model based control have been reported. A simplified dynamic model for an industrial plant is reported in Al-Bastaki and Abbas (1999). In Alatiqi, Ettouney, and El-Dessouky (1999), an overview about process control of desalination plants is given and Assef et al. (1995) presents some advanced control techniques for RO plants. DMC (Dynamic Matrix Control) is compared with standard PID control in Robertson et al. (1996). Decoupled control is proposed in Riverol and Pilipovik (2005). Some ideas of using hybrid control in desalination plants are proposed in Gambier and Bareddin (2002) and the simultaneous design of two PI controllers for a RO plant by using multi-objective optimization is the subject of Gambier, Wellenreuther, and Badreddin (2006). A nonlinear control approach for a high recovery RO system is proposed in McFall, et al. (2008). FTC (Fault Tolerant Control) approaches are presented in McFall et al. (2007) with simulation results and in Gambier,. Blümlein and Badreddin (2009) for a real-time application. Dynamic models for the control of RO plants are reviewed in Soltanieh and Gill (1981) and in Gambier, Krasnik and Badreddin (2007). Finally, different configurations for the control system are analyzed in Gambier, Wellenreuther, and Badreddin (2009), and a laboratory plant for experimenting with the real-time control of a RO process is described in Gambier, Miksch, and Badreddin (2009).

Until now, no work has proposed a fault tolerant control system, which is optimized in order to operate with renewable energies. In the present study, a supervisory control system based on a fault tolerant MPC, which optimize the set points according to the available energy is presented. The low level control is implemented by using parameter optimized PID controllers. In Section 2, the RO process is described from the control viewpoint. Section 3 is devoted to introduce the problem of fault-tolerant control. In Section 4, the proposed approach is described. Simulation results are shown and analyzed is Section 5. Finally, conclusions are drawn in Section 6.

## 2. PROCESS 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 (see Figure 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 Buros (2000) and Wilf et al. (2007) 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.

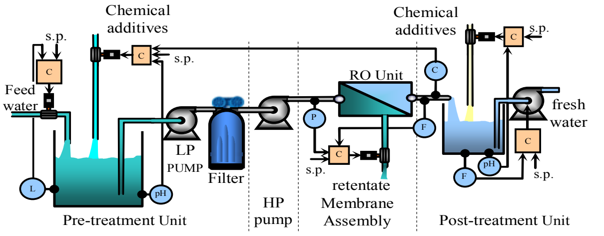

Figure 1: Schematic Diagram of a RO Plant and Its Control Loops

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 Figure 2.

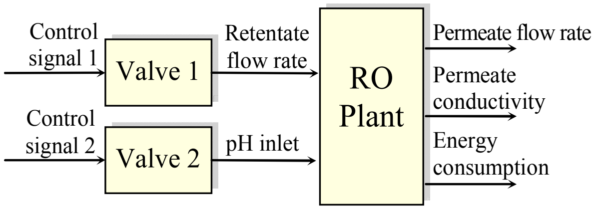

Figure 2: I/O Representation of the RO Plant

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 Figure 3.

## 3. FAULT-TOLERANT CONTROL

### 3.1. Overview and Definitions

There are several definitions and classifications of FTC systems (FTCS). In the following, the definitions given in Mahmoud, Jiang, and Zhang (2003) 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.

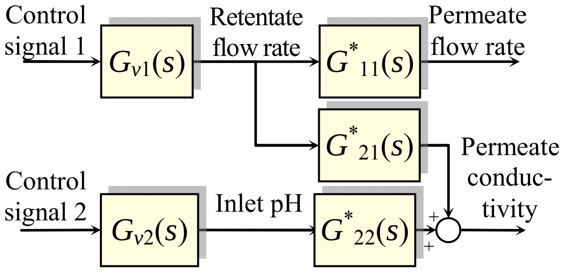

Figure 3: Block Diagram of a RO plant

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 most simply 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 of sensible components) is foreseen in the plant. AFTCS need a priori knowledge of the expected faults or a mechanism for the detection and isolation of unanticipated faults, namely a FDI scheme. A simplified classification of FTCS is summarized in Figure 4.

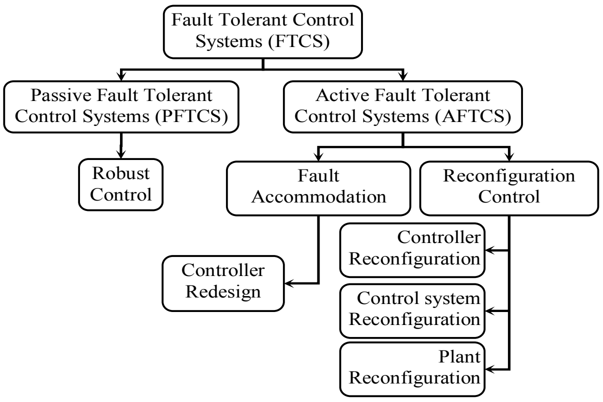

Figure 4: Classification of FTCS

### 3.2. Control Laws for FTSC

The above mentioned mechanisms for providing fault tolerance have different degree of complexity. PFTCS is the simplest case, followed by fault accommodation and finally the system reconfiguration in its different stages.

Hence, the design of FTC systems should be undertaken including this sequence, i.e. first the controller should be robust, then it has to provide 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 Abdel-Geliel, Badreddin and Gambier (2006), the Dynamic Safety Margin (DSF) 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 Staroswiecki (2006); fault tolerance based on controllers designed by using Eigenstructure Assignment (EA) has been proposed in Jiang (1994). A different approach, the Pseudo Inverse Method (PIM), is proposed in Staroswiecki (2005). 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 Maciejowski (1997) and later implemented in Ocampo-Martinez (2007). A real-time study of MPC is presented in Miksch, Gambier and Badreddin (2008a). Results of a comparison between LQ, PIM and MPC from a real-time point of view are presented in Miksch, Gambier and Badreddin (2008b), where it is shown that MPC has several advantages regarding the other ones.

## 4. FTC APPROACH FOR THE RO PROCESS

The proposed approach includes a low level control system based on parameter optimized PID controllers and a MPC, which provides supervisory control and fault tolerance.

### 4.1. Lowest Control Loops

Standard control systems of RO plants are normally based on PID controllers. A method for the join optimazation of two coupled control loops of a RO plant has been proposed in Gambier, Wellenreuther, and Badreddin (2007). Later the authors investigate in Gambier, Wellenreuther, and Badreddin (2009) other control system topologies. They found that a better topology for such kind of systems is such one as given in Figure 5. Therefore, this is the control system used in the current approach for the lowest control loops.

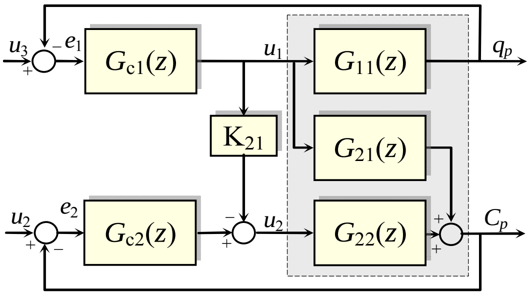

Figure 5: Control system topology for the low level control system

The transfer function for the first control loop is given by

$$e_1(z) = \frac{A_{11}\, r_{10}}{A_{11}^*}\,, \tag{1}$$

and the transfer function of the second control loop is in this case

$$e_2(z) = \frac{A_{21}A_{22}A_{11}^* r_{20} - A_{11}Q_{11}T_1^* r_{10}}{A_{21}A_{11}^* A_{22}^*}\,. \tag{2}$$

Polynomials $A_{ij}$ and $B_{ij}$ are denominator and nominator of the transfer function $G_{ij}(z)$, where the variable $z$ has been eliminated for simplicity in the notation. Constants $r_{10}$ and $r_{20}$ are the amplitude of the set points. Transfer functions for the control signals are:

$$\Delta u(z) = \frac{A_{11}Q_{11}r_{10}}{P_{11}A_{11} + Q_{11}B_{11}} = \frac{A_{11}Q_{11}r_{10}}{A_{11}^*} \text{ and} \tag{3}$$

$$\Delta u(z) = \frac{Q_{22}(A_{21}A_{22}A_{11}^* r_{20} - A_{11}Q_{11}T_1^* r_{10})}{A_{21}A_{11}^* A_{22}^*}\,. \tag{4}$$

where $A_{11}^* = P_{11}A_{11} + Q_{11}B_{11}$, $A_{22}^* = P_{22}A_{22} + Q_{22}B_{22}$ and $T_1^* = B_{21}A_{22} + B_{22}A_{21}K_{21}$.

PID controllers are obtained taking

$$u_i(z) = \frac{Q_{ij}(z)}{P_{ij}(z)} e_j(z)\,. \tag{5}$$

$$P_{ij}(z) = z(z-1) \text{ and } Q_{ij}(z) = q_{ij,0}z^2 + q_{ij,1}z + q_{ij,2}\,, \tag{6}$$

respectively. Moreover, parameters have to satisfy the constraints

$$\begin{bmatrix} -1 & 0 & 0 \\ 1 & 1 & 0 \\ -1 & -1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} q_{ij,0} \\ q_{ij,1} \\ q_{ij,2} \end{bmatrix} < \mathbf{0} \tag{7}$$

in order to show PID behavior.

The parameter optimization is carried out following Gambier, Wellenreuther, and Badreddin (2009) by using an Multi-objective Optimization method (MOO). This is not presented here in order to save space.

### 4.2. Improving the Lowest Level Controller Design

A particular control problem with RO plants consists in that plant parameters change fast because of fouling and membrane cleaning has to be carried out often (e.g. once a week). Thus, process parameters obtained after cleaning are very different from the parameters obtained one week later before cleaning. Therefore, the control performance deteriorates fast in the course of the week, when the controller was adjusted by using parametric optimization. Hence, a robust control approach should be used. The method given in Gambier (2009) extended the parameter optimization of PID controllers by using MOO when the parameter uncertainties are given in the form of intervals polynomials. Thus, it is possible to design robust control loops in the lowest level satisfying the first level of fault tolerance.

An additional problem is given by the fact that MOO optimization requires a predefined parameter space in which the controller parameters should be searched. This problem has been solved by Bajcinca and Hulin (2004). The toolbox presented in that work allows obtaining all stabilizing PID controllers in the parameter space for a given plant. This is used here in order to initialize the MOO algorithm.

### 4.3. Supervisory Control Loop

The supervisory control is implemented according to Figure **6** by using model predictive control. The MPC has two main functions. On the one hand, it provides the optimal set points for the low level control loops, such that the system works at the optimal operating point according to the energy availability. On the other hand, the MPC is responsible for providing fault tolerance.

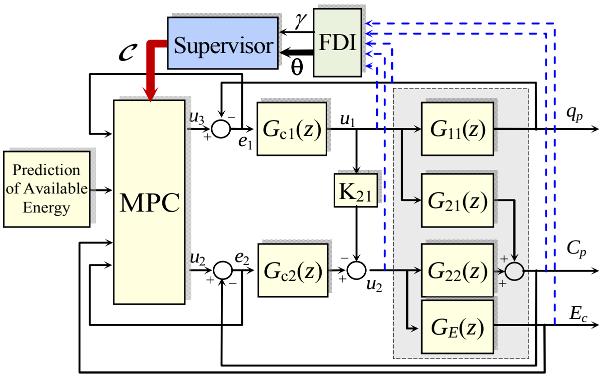

Figure 6: FT-MPC as Supervisory Controller

The MPC design for fault tolerance follows the work of Miksch, Gambier, and Badreddin (2010). It is based on the lexicographic multi-objective optimization of an $l_1$ norm by using a linear program. Constraints are given in the way of prioritized objectives, whose priorities are defined in order to satisfy the definition of performance regions as given in the example of Figure **7**.

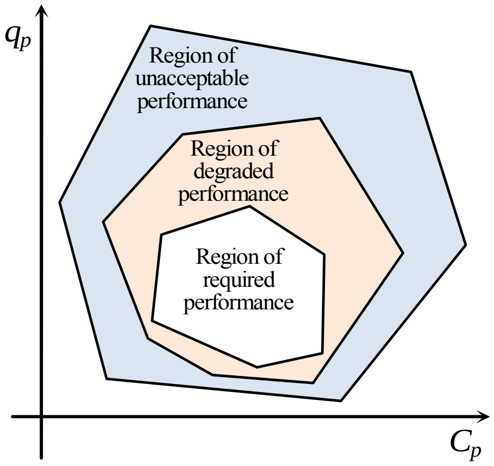

Figure 7: Example of performance regions for the outputs ($C_p$, $q_p$)

Constraints are adjusted according to the information supplied by a FDI unit (Fault Detection and Identification). However, the FDI block of Figure 6 is for the current work only simple logic that gives as output the corresponding value for $\gamma$, according to a predefined known fault. A general FDI unit has still to be implemented. The supervisor implements a logic that builds the constraints set $\mathcal{C}$ depending on $\gamma=\{0, 1, \ldots, n_\gamma\}$ and the fault parameters $\boldsymbol{\theta}$, i.e.

$$\mathcal{C} = \vartheta(\gamma, \boldsymbol{\theta}) . \tag{8}$$

For example, if the valve opening of valve 1 is limited now until a maximum value of 70%, the FDI unit yields $\gamma = 3$ and $\theta(\gamma) = 0.7$. Thus, the supervisor will deliver at the output $\mathcal{C}(\gamma) = 0.7$ (this is the new constraint for $u_1$).

### 4.4. Predictor for the Available Energy

An experimental model of the energy consumption and a prediction of the available energy from the PV and wind subsystems are used to determine the set points for the PID controllers.

The predictor of the available energy is carried out according a simple charging model for the lead-acid battery pack. This model is obtained from Huang et al. (2010) as a linear perturbed model. Model parameters are experimentally obtained for satisfy a real laboratory system.

## 5. STUDIES AND RESULTS

The control system proposed in this work is being implemented at the present time. Some results of the low level control system can be found in Gambier, Wellenreuther, and Badreddin (2009). Some results about using the MPC as a fault tolerant controller are presented in the following.

For the studies, the plant is set to a permeate flow rate of 250 l/h and a valve openings 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 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. This provides some redundancy that can be used for obtaining fault tolerance. The performed studies are summarized in Table 1.

Table 1: Studies of Fault-tolerance for the Water Conductivity

| | *Description* | *umi* n,1 | *uma* x,1 | *umi* n,2 | *uma* x,2 |
|---|---|---|---|---|---|
| Nominal | | 0 | 100 | 0 | 100 |
| Case 1 | Valve 2 limited to 0-50% | 0 | 50 | 0 | 100 |
| Case 2 | Valve 2 stuck at 100% | 50 | 50 | 0 | 100 |
| Case 3 | Valve 1 stuck at 30% | 0 | 100 | 30 | 30 |

The design parameters for the MPC are given in Table 2. The sampling time and the prediction horizon are optimally chosen according to Gambier and Badreddin (2009).

Table 2: Design Parameters for the MPC

| PARAMETERS | NUMERICAL VALUES |
|---|---|
| $\mathbf{R}$ | $diag(1.0, 0.01)$ |
| $\mathbf{Q}_1$ ($\mathbf{Q} = \mathbf{C}^T\mathbf{Q}_1\mathbf{C}$) | $diag(100, 0.1)$ |
| $\mathbf{S}_1$ ($\mathbf{S} = \mathbf{C}^T\mathbf{S}_1\mathbf{C}$) | $\mathbf{Q}_1$ |
| $\rho$ | 0 |
| $T_0$ | 0.15 s |
| Horizons | $N = 14$     $N_u = 14$ |

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 Figure 8, 9 and 10, 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 Figure 8. 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 predefined band) in order to improve the conductivity control, since this is the most important variable.

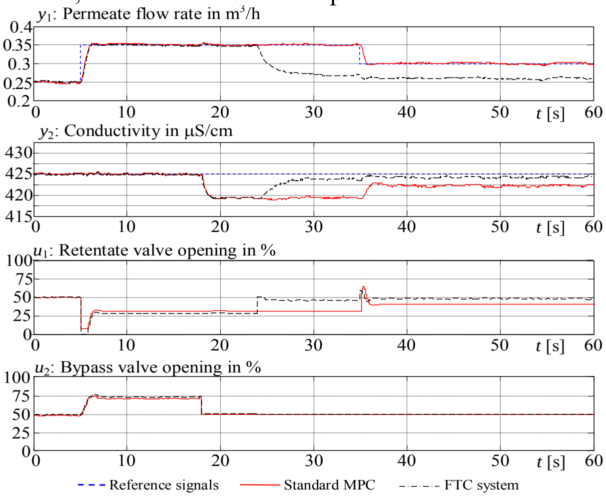

Figure 8: Control system behavior for Case 1 ( $0 \leq u_2 \leq 50$ % for $t \geq 18$ s)

In the second fault case, Valve 2 goes to an opening of 100% and it stays permanently at this value. The standard MPC shows a similar behavior as the first case. The fault-tolerant MPC recovers the fault returning the conductivity to its set point at the expense of an acceptable steady-state error. This is shown in Figure 9.

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 (Figure **10**). The standard MPC introduces a major deviation from the set point for the conductivity, whereas the fault-tolerant MPC recover the fault without steady-state error.

Notice that the concurring nature of the two outputs in the fault case, i.e. producing as much water as possible but keeping the right range of salinity, is a multi-objective optimization problem. This will be undertaken in a future work.

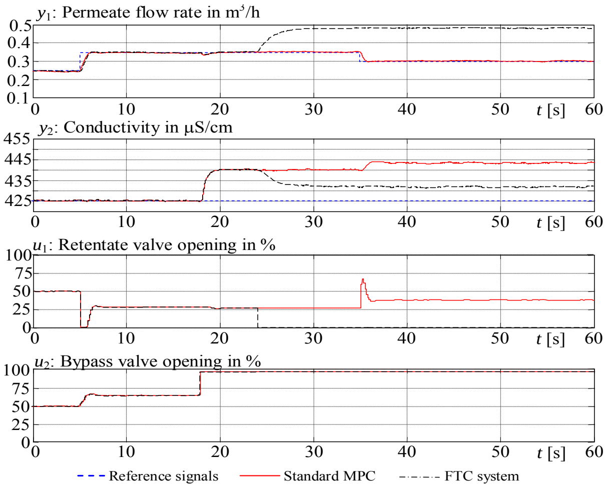

Figure 9: Control system behavior for Case 2 ($u_2 = 100$ % for $t \geq 18$ s)

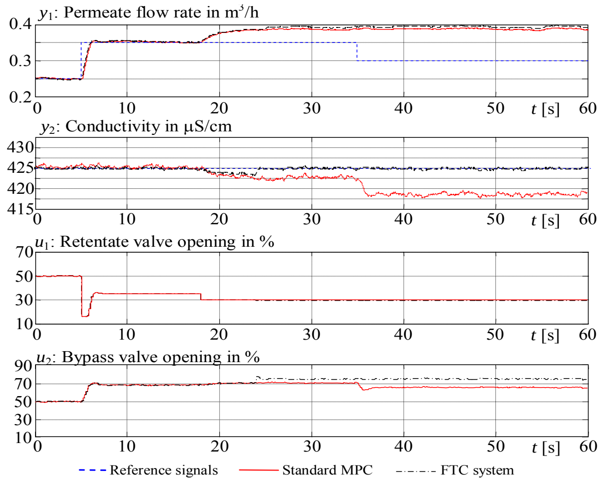

Figure 10: Control system behavior for Case 3 ($u_1 = 30$ % for $t \geq 18$ s)

## 6. CONCLUSIONS AND FUTURE WORK

In this contribution, the control problem of a reverse osmosis desalination plant is studied. In order to guarantee an acceptable water quality along the complete operation time even in case of faults, a fault-tolerant MPC based on adjusting its constraints in the supervisory level 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. Moreover, the whole control system of Figure 6 has still to be implemented since it has only been tested partially. Finally, the approach has to be combined with a robust fault-detection approach.

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