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Real-Time Fault Tolerant Control of a Reverse Osmosis Desalination Plant Based on a Hybrid System Approach

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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, RO plants are little studied from the control engineering point of view: modeling, design of control algorithms and real-time experiments are scarcely reported in the literature. The present work is a study on a real RO plant in order to discover possible faults, to analyze potential methods for Fault-Tolerant Control (FTC) and the real-time experimentation.**

In order to implement model based control, the plant is identified in several operating points. Model Predictive Control (MPC) is used as control law and a hybrid supervisor is proposed to combine different methods, which perform better for different kind of faults. Satisfactory results are obtained for the real-time operation.

I. INTRODUCTION

CONTROL systems should ensure in general that the controlled process behaves satisfactorily independently of component malfunctioning and faults. Conventional feedback control normally does not satisfy this requirement and therefore many efforts have been carried out (see e.g. [7], [26], [33], [34]) in order to obtain control systems, which tolerate faulty components with acceptable performance. The effect of component malfunction can be highly problematic for the normal operation, and consequently it is unrealistic to ignore that faults occur. Thus, Fault Tolerant Control (FTC) has focused on the design of controllers that tolerate possible faults while maintaining a stable behavior as well as an acceptable performance.

The application of FTC can be motivated by different reasons depending on the considered application. The most frequent application areas are e.g. aviation, aerospace and other fields where safety plays an important role as for example chemical industrial plants working in a possible explosive environment. Various approaches for FTC have been suggested in the literature but not always these methods can be applied in general. Thus, a combination of them should be carried out. On the other hand, these methods are seldom tested for the real-time operation.

RO plants require sensible components, which are also prone to faults. In some cases, it is necessary to provide FTC to RO plants. This is the case, for example, when the plant is used to obtain high purified water during medical surgeries or when desalting brackish water is gained by RO plants in deserted isolated regions, where water for inhabitants and animals may not be discontinued and the plant maintenance is inaccessible in a short time.

Although some contributions about the control of reverse osmosis plants can be found in the literature, this is a field that requires more research efforts. For example, in [23] a simple incremental on/off control system is proposed. Such a system must have a large storage system to meet demand surges. Moreover, the system design should be based on average demand value to avoid frequent on/off sequence of the membrane modules. The first multi-loop control system for RO was proposed in [3]. 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 [4]. Dynamic models for RO plants were reviewed by [29] and [10]. In [2], an overview about process control of desalination plants is given and [5] presents some advanced control techniques for RO plants. DMC (Dynamic Matrix Control) is compared with standard PID control in [28]. Decoupled control is proposed in [27]. Some ideas of using hybrid control in desalination plants are proposed in [9] and the simultaneous design of two PI controllers for a RO plant by using multiobjective optimization is the subject of [12]. A nonlinear control approach for a high recovery RO system is proposed in [20]. Finally, a FDI/FTC simulation study on a RO model under actuator faults is presented in [19].

In the present work, real-time results of a FTC system obtained on a real reverse osmosis laboratory plant are presented. The methodology consists in the combination of several FTC approaches by means of a hybrid automaton. In Section 2, approaches for the FTC are presented. Section 3 is devoted to describe the RO plant and several possible faults. In Section 4 the particular approach for the described plant is presented, so that real-time results experiments as well as results are shown and analyzed is Section 5. Finally, conclusions are drawn in Section 6.

II. 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 [18] 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.

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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 Fig. 1.

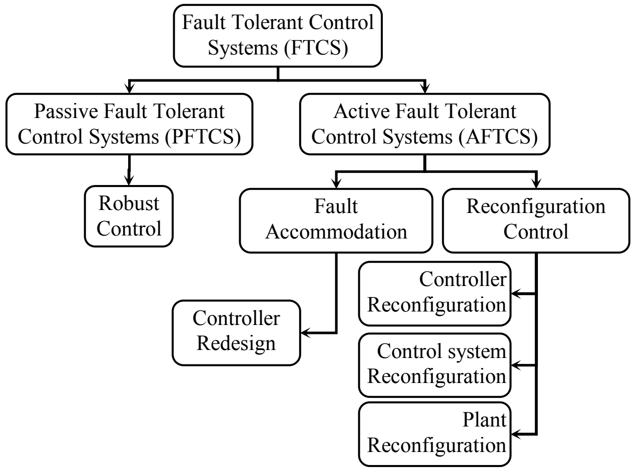

Fig. 1. Classification of FTCS

B. *Control Laws for FTCS*

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 [1], 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 [30]; fault tolerance based on controllers designed by using Eigenstructure Assignment (EA) has been proposed in [15]. A different approach, the Pseudo Inverse Method (PIM), is proposed in [31]. 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 [17] and later implemented in [24]. A real-time study of MPC is presented in [21]. Results of a comparison between LQ, PIM and MPC from a real-time point of view are presented in [22], where it is shown that MPC has several advantages regarding the other ones. In this study, constrained MPC is used as the control law.

III. REVERSE OSMOSIS DESALINATION SYSTEM

A. *Laboratory Plant*

The reverse osmosis plant is the OSMO Eco model from the Italian manufacturer OSMO Sistemi. It consists essentially of a vertical centrifugal high pressure pump of 750 W and 16 bars, an active carbon filter, a security cartridge filter and three membranes assemblies. The plant supplies in nominal operation 250 l/h permeate with a conductivity value of 7 µS/cm for 500 l/h feed water at 800 µS/cm. The system is provided with two manometers, two flowmeters and a microcontroller for the membrane cleaning control. Electronic sensing as well as feedback control was absent. Therefore, sensors, actuators and a computer have been added in the laboratory in order to obtain real-time equipment for control. An overview of the plant is given in Fig. 2.

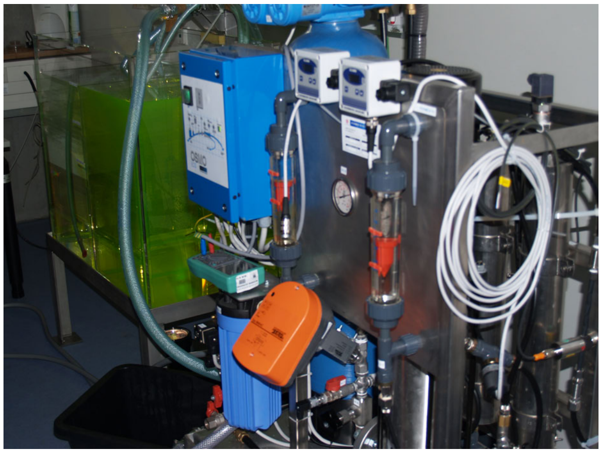

Fig. 2. Overview of the laboratory plant.

The schematic diagram of Fig. 3 shows the placement of sensors and actuators as well as the serial/parallel configuration of the pressure vessels.

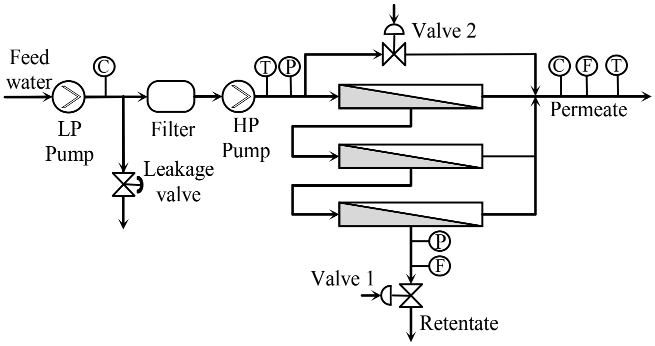

Fig. 3. Schematic representation of the RO plant

B. *Dynamic Model of the Plant*

Normally, two inputs and two outputs are defined for RO desalination plants, namely flow rate and conductivity of permeate as outputs and the transmembrane pressure and pH inlet (see [2]). However, the OSMO Eco plant does not have a pretreatment unit and hence no pH control is carried out. Consequently, the plant topology is defined here as shown in Fig. 4.

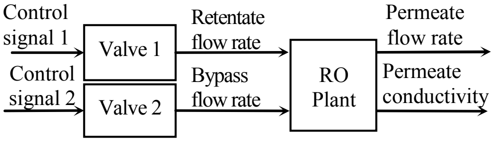

Fig. 4. Input/output block diagram of a OSMO Eco RO plant

Finally, it was necessary for this first study to simplify the plant to the simplest case. Thus, the plant is considered as a SISO system, where the input is the retentate flow rate and the output the permeate flow rate. The retentate flow rate is manipulated by the valve at the end of the retentate pipeline. The valve on the bypass pipeline is maintained closed all the time. Fig. 5 shows the open-loop step response of the plant for the permeate flow rate as well as for the conductivity.

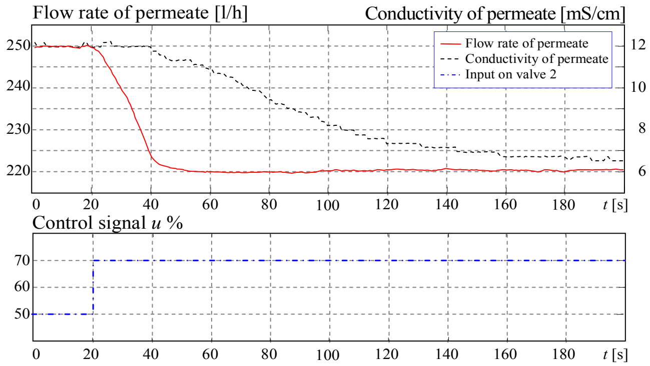

Fig. 5. Step response of the plant for a step applied on the valve 1

The plant was identified in open loop by using the N4SID algorithm ([25]). The operating point was set at 250 l/h permeate flow rate for a 50% of valve opening. A second operating point is 30% valve opening and 270 l/h. Models are summarized in Table I.

TABLE I
FAULTS STUDIED ON THE REAL REVERSE OSMOSIS PLANT

Nominal model	Second Operating Point
$\mathbf{A}=\begin{bmatrix}0.963 & -0.06 & 0.04\\ 0.136 & 0.89 & 0.24\\ 0.071 & -0.21 & 0.42\end{bmatrix}$	$\mathbf{A}=\begin{bmatrix}0.967 & -0.10 & 0.02\\ 0.156 & 0.88 & 0.15\\ 0.039 & -0.19 & 0.48\end{bmatrix}$
$\mathbf{B}=\begin{bmatrix}-2.9e{-6} & 1.e{-3} & 2e{-3}\end{bmatrix}^{\mathrm{T}}$	$\mathbf{B}=\begin{bmatrix}-9e{-5} & 1.e{-3} & -4e{-3}\end{bmatrix}^{\mathrm{T}}$
$\mathbf{C}=\begin{bmatrix}445.7 & -34.44 & 1.39\end{bmatrix};\ \mathbf{D}=0$	$\mathbf{C}=\begin{bmatrix}308.5 & -53.30 & -7.53\end{bmatrix};\ \mathbf{D}=0$

A detailed mathematical model of the plant is given in [11].

C. *Important Faults*

RO desalination plants can suffer a varied amount of faults. However, not all faults can be simulated in the real plant without causing permanent damage. Thus, possible faults are selected such that they are useful for the experiments and in addition, they can repeatedly be simulated. Such faults are described in Table II.

TABLE II
ADDITIONAL FAULTS STUDIED ON THE REAL REVERSE OSMOSIS PLANT

System component	Faults
Sensors	Disturbed measurement (e.g. offset) Sensor breakdown
Actuators	Disturbance on the control signal Reduction of the valve excursion Reduction of the valve speed Valve breakdown
Pump	Reduction of the pumping power Transitory pump breakdown
RO Unit	Leak Block of a pipeline Air in the system Scaling/Fouling

IV. FTC APPROACH FOR THE RO PROCESS

Preliminary real-time studies showed that no fault tolerant mechanism offer an acceptable response to all studied faults ([8]). Therefore, a FTCS based on a hybrid system is proposed for this RO plant. In the following, this approach is described.

A. *General Considerations and FTC Strategy*

From all faults listed in Table II, five will be studied in this work. A summary of these faults and which method performs better for overcoming it is given in Table III.

TABLE III
STUDIED FAULTS IN THE REAL REVERSE OSMOSIS PLANT

Case	Fault	Best Method for FTC
1	Transitory pump breakdown	Robust control
2	Reduction of the valve speed	Robust control
3	Disturbed measurement (e.g. offset)	Use of a faulty model
4	Disturbance on the control signal	Constraints adjustment
5	Leak in the feed pipeline	Controller switching

The proposed FTC scheme is described in Fig. 6. It consists of a FDI unit, which deliveres the signal γ that indicates the occurring fault, a switching logic implemented by a discrete automaton and a bank of controllers/Kalman filters that can be switched on if it is necessary. The saturation block is a simple model of the actuator in order to provide an anti-windup mechanism. Since the plant is stable and all control loops are also designed to be stables, a slow switching by including a *dwell time* guarantees the stability during the switching. In order to obtain bumpless transfer between the controllers, a simplified scheme of the Hanus conditioning technique ([14]) is used.

B. *Design of the Supervisor*

The supervisor has here the function of assigning values to the 2-tuple $(\sigma, \mathcal{C})$, where σ is the switching signal that assign the corresponding controller and $\mathcal{C}$ is the set of constraints that the MPC algorithm has into account during the optimization. Variable $\gamma=\{0, 1, \ldots, n_\gamma\}$ is the discrete input coming from the FDI unit. It indicates which fault has occurred, where zero is the nominal case. Thus, the supervisor is defined in general as

$$(\sigma,\mathcal{C}) = \vartheta(q) \text{ and } \tag{1}$$

$$q^{+} = \varphi(q,\gamma)\,. \tag{2}$$

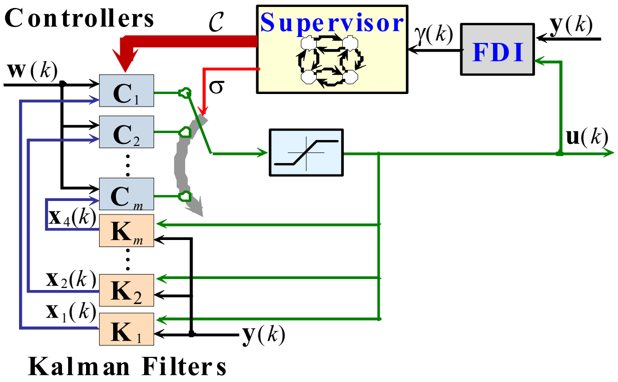

Fig. 6. Scheme for the FTCS based on the hybrid supervisor

Variable $q \in \mathcal{Q}$ is a discrete-valued state trajectory taking values in the discrete set $\mathcal{Q} = \{1, 2, 3, \dots, p\}$. ϑ is a Boolean function, which defines the output and φ represents the function of the state machine that determines the next state. Notice that this approach assumes that only one fault takes places at each time. The problem of simultaneous occurring faults can also be formulated in this way but the final automaton will considerably be more complicated.

For the studied case, the switching logic can be described by the automaton of Fig. 7. In the nominal case (i.e. normal operation), the controller 1 and constraints $\mathcal{C}_1$ are used. Nothing changes for Case 1 and 2 since a PFTC is applied. In Case 3, the controller is the same but other model is used. The controller continues being the same for Case 4 but constraints change to $\mathcal{C}_2$. The controller could become infeasible in this state. Hence, the controller is temporary changed to other one (e.g. PID) if the infeasibility occurs. Finally, Case 5 requires a switching to controller 2 with constraints $\mathcal{C}_3$ due to changes in the operating point.

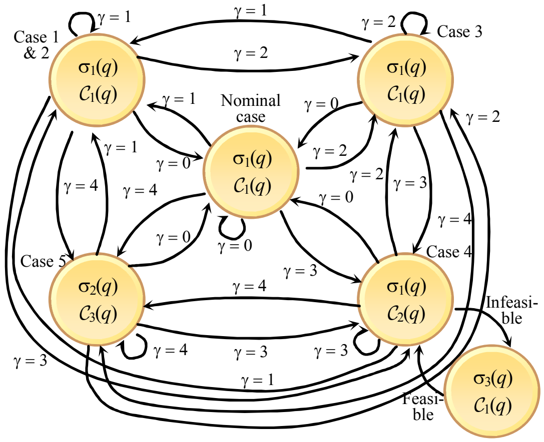

Fig. 7. Automaton that select the method for fault tolerance

Notice the simplicity of the diagram because the MPC is used. MPC provides a wide flexibility such that only few switches are necessary.

C. Selection of the Control Law

Several control laws have been studied for the implementation of FTCS. For this project, MPC was selected because of several reasons. The MPC law shows some robustness, which can be used for PFTC. If the inherent robustness of MPC is not sufficient for the requirements, it is also possible to apply the robust MPC algorithm proposed in [16]. This algorithm provides robust properties without a significant increase of the computational burden. Moreover, MPC provide satisfactory facilities for fault accommodation by redefining constraints, since the controller is continuously redesigned online. Finally, The MPC can also be used here in the context of switching control as it is proposed in [13].

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

$$J = \| e(k+N) \|_{\mathbf{S}}^2 + \sum_{i=k}^{k+N-1} \| e(i) \|_{\mathbf{Q}}^2 + \sum_{i=k}^{k+N_u-1} \| \Delta \mathbf{u}(i) \|_{\mathbf{R}}^2 + \rho \varepsilon^2 \qquad (3)$$

subject to the constraints

$$\begin{aligned} &\mathbf{y}(k) = \mathbf{C}\,\mathbf{x}(k), \\ &\mathbf{x}(k+1) = \mathbf{A}\,\mathbf{x}(k) + \mathbf{B}\,\mathbf{u}(k), \\ &u_{i_{\min}} \le u_i \le u_{i_{\max}} \quad \text{for } i = 1, \cdots, m, \\ &\Delta u_{i_{\min}} \le \Delta u_i \le \Delta u_{i_{\max}} \quad \text{for } i = 1, \cdots, m \quad \text{and} \\ &\varepsilon\, x_{i_{\min}} \le x_i \le \varepsilon\, x_{i_{\max}} \quad \text{for } i = 1, \cdots, n. \end{aligned} \qquad (4)$$

N and N_u are the prediction horizon and the control horizon, respectively. The term $\| v(\cdot) \|_{\mathbf{M}}^2$ denotes $\mathbf{v}^{\mathrm{T}}(\cdot)\mathbf{M}\mathbf{v}(\cdot)$ and variable $\mathbf{e}(\cdot)$ is the control error defined by

$$\mathbf{e}(\cdot) = \mathbf{r}(\cdot) - \mathbf{y}(\cdot)\,. \qquad (5)$$

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

TABLE IV

DESIGN PARAMETERS FOR THE MPC

	N	N_u	Q	R	u_{nin}	u_{nax}	y_{nin}	y_{nax}	ρ
Nominal Controller (Cases 1, 2 & 3)	25	5	10	1	-30	30	-30	30	1e4
Case 4	25	5	10	1	-20	40	-35	35	1e4
Case 5	25	5	10	1	-20	20	-20	15	1e2

The constraints for the control signal first difference were in all cases set to -3.4 ≤ Δu ≤ 3.4. Matrix $\mathbf{Q}$ is defined in all cases as $\mathbf{Q}$ = diag(Q). Because only one input is considered the matrix $\mathbf{R}$ is of dimension 1.

D. The FDI Unit

For this study no FDI unit has been implemented because it is assumed that all faults are known. Current technology for sensors and actuators provides nowadays not only standard signals but also additional information about their present operational states. Thus, the FDI unit could be simplified to the analysis of sensor/actuator signals, which indicate the local presence of a fault. Thus, a FDI unit for the treated case would be simpler. The FDI block of Fig. 6 is a simple logic that gives as output the corresponding value for γ, which in turn determines the current state of the hybrid automaton. Faults in the sensor of permeate flow rate can be detected by using a comparison with the retentate flow rate sensor. A more sophisticated FDI can be implemented by using the FDI toolbox described in [32].

V. REAL-TIME EXPERIMENTS AND RESULTS

The approach described above has been implemented for real-time operation. Aspects related to this implementation are presented in the following.

A. Real-time Platform

The main requisite for the configuration of the real-time equipment was to obtain a low cost fast prototyping system that allows using Matlab/Simulink as development software. The system should also provide real-time services. The final decision was an integrated environment that includes the Real-Time Workshop (RTW) and the Windows Target together with the low cost card 626 manufactured by Sensoray. The Sensoray 626 is a PCI card that provided 16 A/D channels, 4 D/A channels and 48 bidirectional digital I/O. The system does not provide hard real time services, but the obtained package is solid enough for the considered laboratory application as it was practically verified in the laboratory. Furthermore, it is well maintained and updated. Stateflow can be used for the implementation of the switching logic. For stronger real-time requirements, a host/target system based on Windows/QNX is planned. This configuration is also compatible with the hardware and software described before.

B. Description of the Experiments

In order to evaluate the performance of the system in real-time, five experiments have been designed. The first two cases of Table III have been solved by robust control. A transitory break down of the low pressure pump is achieved by a pump power-off of 5 s. A longer power interrupt leads to an automatic shut down of the plant and therefore it is impossible to be implemented. On the other hand, a power supply under the pump minimum needs for 3-5 second is not infrequently, since the complete system is powered by wind and photovoltaic energies, which availability depends on the climatic conditions. Case 2 is simulated by a *Rate Limiter* block, which leads to a reduction of the valve speed from ±3.4 %/s to ±0.34 %/s.

Case 3 is simulated by adding to the measured flow rate a constant offset of –10 l/h (i.e. 50% of the used step change for the set point). In a similar way, Case 4 is obtained, where the control signal is modified in order to obtain a negative shift of the valve 1 opening in a value of 10%. Case 5 is a leak in the feed water. It has been implemented by opening a manual actuated valve such that the permeate flow rate is reduced in about 25 l/s. A detailed description of each single experiment is given in [8].

C. Real-time Results

Real-time results for Cases 1 and 2 are shown together in Fig. 8. The valve speed is limited the first 80s. In order to remark the effect of the fault, the system is taken out from its steady state by means of a change of 20 l/s in the set point of permeate flow rate 20s after the steady state is reached. Then, the valve is set again to normal condition and pump power-off experiments are carried out. As it is possible to observe, the MPC algorithm is robust enough to accommodate a reduction of the valve speed as well as transitory break-downs in the low pressure pump. Because of the faulty valve, the transient to the new set point lasts 15 s longer than the nominal case (normally about 20 s). On the other hand, the system requires about 8 s to be recovered from a power down of 5 s. Both results are very satisfactory for the considered plant.

If the sensor of the permeate flow rate is affected by constant offset, the nominal MPC (the same used for Cases 1 and 2) cannot recover the system and therefore an active FTC is necessary. The best result is achieved by augmenting the plant model with the model of the perturbing signal and computing the MPC for it. In this case, no switching is carried out since the controller is simply recalculated with this new model.

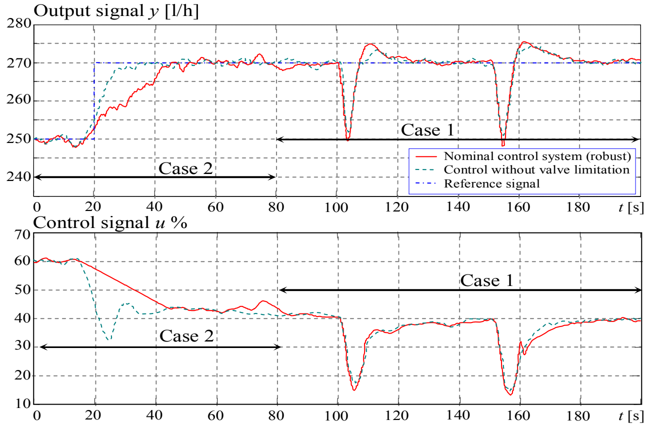

Fig. 8. Control system affected by a short pump break down and for a reduction in the valve speed (Case 1 and 2).

Real-time results for Case 3 are given in Fig. 9. The fault is applied at time 40 s and 10 s later a change in set point is applied. The nominal MPC presents an important steady-state error, whereas the new designed controller provided an excellent performance.

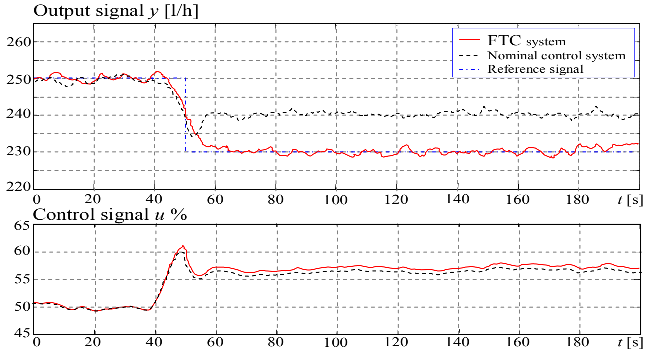

Fig. 9. Control system affected by a sensor disturbance (Case 3)

Fig. 10 shows real-time results for Case 4, where the control signal is affected by a constant offset. Here, the fault accommodation is accomplished by the relaxation of the constraints applied to the valve 1, which are modified after the fault occurrence from (-30, 30) to (-20, 40). The fault occurs again 40 s and the set point is changed 10 s later. The MPC with relaxed constraints performs clearly better.

Finally, results for Case 5 are shown in Fig. 11. The nominal MPC leads to an inacceptable control so that accommodation or reconfiguration should be used. Here, both methods are evaluated: *i*) controller redesign with changes of the operating point and *ii*) constraint relaxation. In order to maintain the set point, it is necessary to close the valve until about 20 %. This can be reached for example by relaxation of the control signal constraint. However, in this range the nominal model is not valid and therefore the flow rate presents a steady-state error. Thus, a controller for the new operating point is needed. The switching to the new controller yields a better performance. The fault is introduced after 100s by opening a manual valve until producing a leak of 30 l/s. The controller switching gives a better performance.

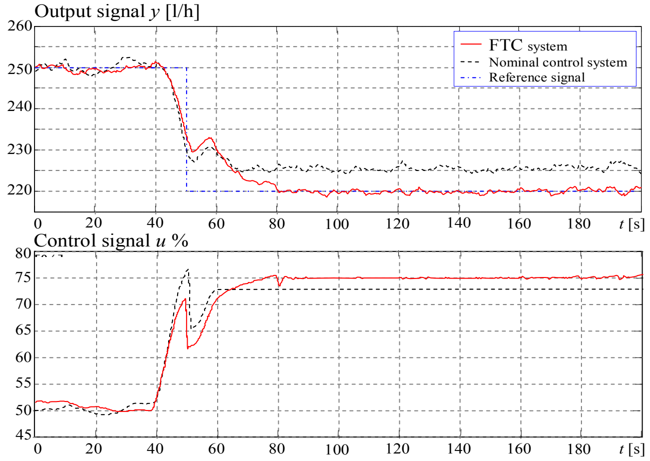

Fig. 10. Control system affected by a control signal disturbance (Case 4)

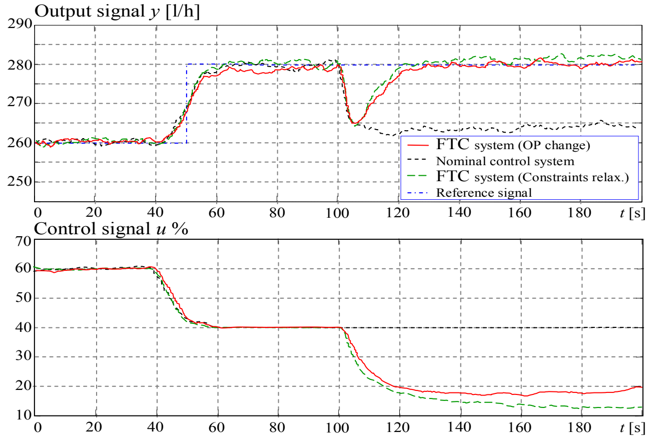

Fig. 11. Leak at feed water inlet (Case 5)

VI. CONCLUSION

In this work, a reverse osmosis plant is studied from the viewpoint of fault-tolerant control. Real-time experiments showed that no method can be applied in general. Therefore, a hybrid automaton is proposed as supervisor in order to orchestre methods according to the occurring faults. Experimental results confirm that MPC performs very well as control strategy, since it can contemplate several fault cases by changing its design parameters. In other cases, switching control has to be considered in particular when the MPC becomes infeasible. Finally, a FDI unit has still to be designed and it is the next research step in this project.

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