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A Reverse Osmosis Laboratory Plant for Experimenting with Fault-Tolerant Control

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Abstract— **A test bed for research and teaching in fault-tolerant control (FTC) systems is presented. The laboratory plant is based on an industrial reverse osmosis desalination plant equipped with standardized components, which introduces more realism and robustness into the experiments. This paper describes the plant, the mathematical model of the system and an illustrative experiment. Moreover, the problem of choosing the hardware/software platform for the real-time operation is addresses.**

I. INTRODUCTION

IN the last fifteen years many efforts have been carried out in order to develop methods and algorithms to obtain control systems, which are tolerant when faults occurs. The effect of component malfunction can be highly problematic for the normal operation of a control system, and consequently it is unrealistic to ignore that faults happen. 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. Several books are available for the subject (see e.g. [5], [11], [12], [19] [32] and the bibliographic review of [38]). The most frequent application areas are e.g. aviation, aerospace, nuclear power plants and other fields where safety plays an important role as for example chemical plants working in a potentially explosive environment.

A very important aspect for the research in a particular area is to have available laboratory equipment to be able to carry out experiments, which verify the theory. In the field of FTC, only little real-time laboratory experiments have been reported. Frequently used test beds are either simulation tools for aerospace applications ([15], [17]), ship propulsion systems ([13]) and sewer networks ([25], [27]) or academic special designed laboratories as the three-tank system ([16], [22], [23], [28]). In [21], the simulation of a reverse osmosis desalination plant is used as an example.

Reverse osmosis is well known as a separation process used in desalination for removing salt from sea water and brackish water, as well as to purify fresh water for medical, industrial and domestic applications. However, it is also a process, which is extensively used in the food industry. It is applied, for instance, for the concentration of 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 prevent water spotting on the vehicle.

Reverse Osmosis (RO) plants consists of sensible components, which work under high pressure. Therefore they are prone to faults. Although fault tolerance is a positive property wished for all processes, it takes particular relevance when the plant is used to obtain high purified water during medical surgeries or when fresh water is gained from brackish water by using RO plants in desertic isolated regions, where water for inhabitants and animals may not be discontinued and the plant maintenance is inaccessible in a short time.

Progress in the reverse osmosis systems has been reached in the last ten years by technological improvements of materials and components. However, control has still not considered an important issue and much research effort has to be carried out. The first multi-loop control system for RO was proposed in [2]. A simplified dynamic model for an industrial plant is reported in [3]. Dynamic models for RO plants were reviewed by [31] and in [8] a dynamic model for control purposes is proposed. Applications of advanced control design techniques are given for example in [7], [10], [29], [30] and [20]. Finally, a FDI/FTC simulation study on a RO model under actuator faults is presented in [21].

The conclusion of the above described state of the art is that on the one hand there are deficits of real application for experimenting with FTC and on the other hand reverse osmosis is a very useful process with very wide utilization in industry that has not been sufficiently studied from the control point of view. This has been the main motivation for the design of a test-bed for FTC based on a RO industrial plant.

The outline of the paper is as follows. A short description of FTC is given in Section 2, whereas the plant is described in Section 3. Section 4 discuses the real-time system architecture. A dynamic model based on physical laws is presented in Section 5. Section 6 shows an illustrative example. Moreover, a linear model for the operating point is obtained by using the subspace algorithm N4SID ([37]). Finally, conclusions are drawn in Section 7.

II. FAULT-TOLERANT CONTROL SYSTEMS

Fault tolerance is a property that 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-

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Tolerant Control System (PFTCS). Contrarily, Active Fault-Tolerant Control Systems (AFTCS) require a new controller that is obtained by using either adaptive control or switching control ([26]). Adaptive control leads to fault accommodation, whereas switching control makes possible controller reconfiguration. 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 scheme of an AFTCS is summarized in Fig. 1.

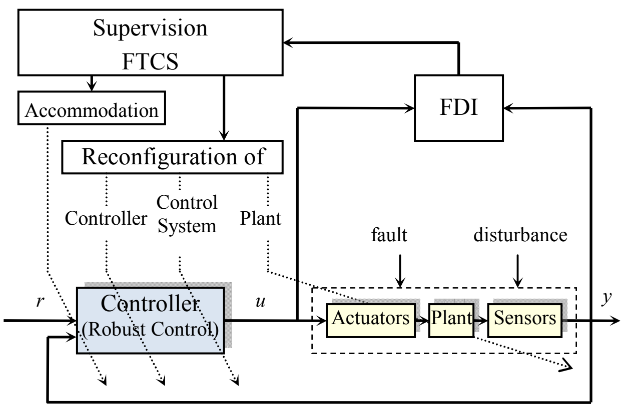

Fig. 1. Scheme of an AFTSC system

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.

In order to implement FTC systems, control laws have to be able to manage the faults. Hence, 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 [33]; fault tolerance based on controllers designed by using Eigenstructure Assignment (EA) has been proposed in [14]. A different approach, the Pseudo Inverse Method (PIM), is proposed in [34]. The constrained MPC has also been studied for fault tolerant behavior. It was first proposed in [18] and later implemented in [25]. A real-time study of 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 in front of the other ones. In this study, constrained MPC is used as control law.

III. PLANT DESCRIPTION

A. General Description

The process itself is well known and can be found in the specialized literature (see e.g. [6] for a review about different desalination processes). Here, a short description will be carried out for completeness reasons (see Fig. 4). Salty feed water is first pretreated to avoid membrane fouling. It is then 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 very concentrated (retentate). The water product flows directly from the permeators into a storage tank, where pH is adjusted and minerals are added. The retentate (at high pressure) is discharged (Fig. 4) or sent to an energy recovery device (see e.g. [36]).

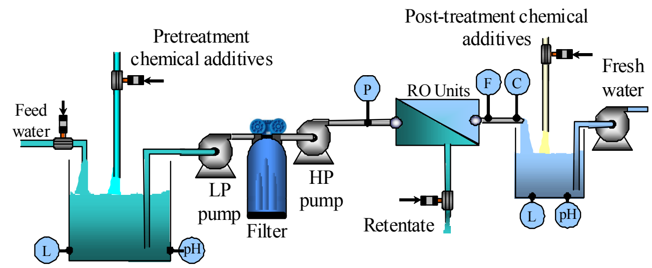

Fig. 2. General scheme of a reverse osmosis desalination plant

B. Laboratory Plant

For the laboratory, a reverse osmosis OSMO Eco plant from the Italian manufacturer OSMO Sistemi was chosen. This plant has been designed for the treatment of municipal/tap water and therefore, it does not include pre-treatment and post-treatment units. The OSMO Eco model consists essentially of a vertical centrifugal high pressure pump, an active carbon filter, a security cartridge filter and three membrane assemblies. A membrane assembly consists of a pressure vessel and several membrane units, which allow the feed water to be pressurized against the membrane.

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, the plant has been outfitted with sensors, actuators and a PC computer in order to carry out closed-loop control experiments. A schematic diagram of the supplemented plant is given in Fig. 3. Furthermore, membrane assemblies configured in a serial/parallel scheme are also shown in this figure.

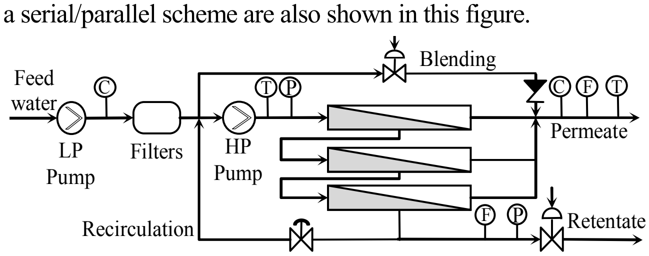

Fig. 3. Simplified schematic diagram of the RO plant

A picture of the OSMO Eco model is given in Fig. 4. The pressure for the OSMO Eco is about 16 bars for tap water. However, it should be from 18 to 25 bars in the case of brackish water. Seawater desalination plants require between 50 and 80 bars.

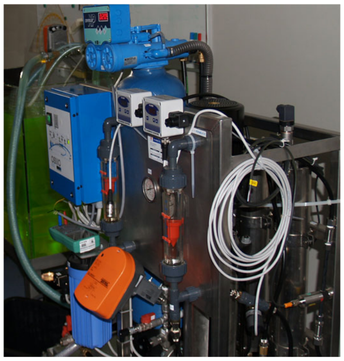

Fig. 4. Overview of the laboratory plant

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. This ability decreases with the time because of scaling and fouling. Therefore, membranes have to be washed when the permeability factor decay under a limit value. If the permeability factor after cleaning does not reach a minimum working value, membranes have to be replaced.

C. Properties for Fault Tolerant Control

The properties of the plant for FTC can be classified as follows:

RO plant: Some faults can be directly simulated in the plant as for example water leak, pressure drop and pipeline block.

Sensors: The plant has at the present time eight sensors placed according to Fig. 3. Notice, that flow rates of permeate and retentate have a fix relationship so that the permeate flow rate can also indirectly measured by using the retentate flow rate sensor. This feature is used later in the example (see Fig. 8).

Actuators: Two servo valves are available for control. Both valves provide signals that indicate the current valve opening such that its speed can be calculated. Thus, the correct valve functioning can continuously be checked simplifying the fault detection mechanism. Moreover, the pump speed could be manipulated by a cycloconverter.

Control system reconfiguration: This kind of reconfiguration takes place when control loops are changed during the operation. Traditionally, two standard control loops are defined for this plant: *i*) Control of permeate flow rate by sensing permeate flow rate and manipulating retentate flow rate and *ii*) control of permeate conductivity by sensing permeate conductivity and manipulating bypass flow rate. However, several additional control loops can be considered for reconfiguration. These possibilities are summarized in Table I.

It is important to remark here that the manipulation of pump speed and the recirculating flow rate are features that have not been implemented yet in the plant.

Plant reconfiguration: The plant has three membrane assemblies, which are configured in serial/parallel topology (serial in retentate, parallel in permeate) as shown in Fig. 3 (also Fig. 5a). This configuration has the drawback that the plant will shut down if one of the membrane assemblies is blocked since the retentate flow will completely be interrupted. The same effect appears in pure serial configuration (Fig. 5c), as well. However, a serial configuration is necessary to improve the water quality if a membrane assembly is performing with a degraded salt rejection. A pure parallel configuration (Fig. 5b) eliminates the blocking problem with the additional advantage that each membrane assembly can be cleaned online. Nevertheless, the pump will have to work at higher pressure. The configuration of Fig. 5d describes a two-stage plant, which is useful for a better water quality. Thus, it would be useful to have a mechanism for reconfiguring the plant when it is necessary according to the schemes of Fig. 5.

TABLE I
ADDITIONAL POSSIBLE CONTROL LOOPS FOR RECONFIGURATION

Type of Control	Measured Variables	Manipulated Variables	Controlled Variable
Simple control	Retentate flow rate	Retentate flow rate	Permeate flow rate
Simple control	Transmembrane pressure	Retentate flow rate	Permeate flow rate
Simple control	Permeate flow rate	Pump speed	Permeate flow rate
Simple control	Permeate flow rate or conductivity	Bypass flow rate	Permeate flow rate
Cascade control	Permeate flow rate & transmembrane pressure	Retentate flow rate	Permeate flow rate
Cascade control	Permeate conductivity & permeate flow rate	Bypass flow rate	Permeate conductivity
Cascade control	Permeate flow rate and permeate conductivity	Pump speed	Permeate flow rate

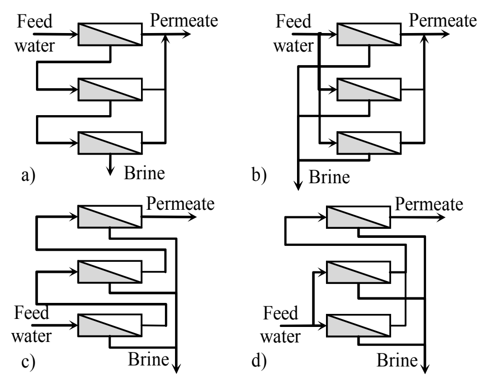

Fig. 5. Possible topologies for the organization of membrane assemblies

D. Important Faults

RO 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
FAULTS STUDIED ON THE REAL REVERSE OSMOSIS PLANT

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

IV. 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 experimentally verified. Furthermore, it is well maintained and updated. For stronger real-time requirements, a host/target system based on Windows/ QNX is planned. This configuration is also compatible with hardware and software described before (see [9] for a review on RTOS issues).

V. MODELLING THE LABORATORY PLANT

The plant topology is defined as shown in Fig. 6. Notice that the bypass flow rate affects the flow rate of permeate and therefore the system is no longer triangular as in the traditional plants ([29], [30]).

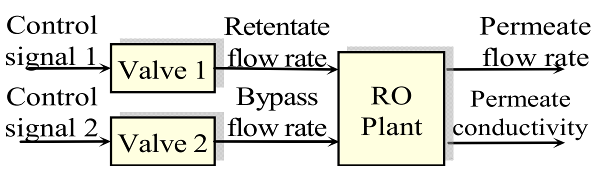

Fig. 6. Input/output block diagram of an OSMO Eco RO plant

The modeling process will be divided in several steps. The first one consists in decomposing the plant in subsystems. Hence, assumptions will be carried out. After that, subsection model equations for each subsystem are presented as follows.

A. Plant decomposition

The plant decomposition is carried out following [8]. Hence, the decomposition of a membrane assembly for a RO unit is according to Fig. 7. It consists of the retentate subsystem, the permeate subsystem and the membrane.

B. Modeling Assumptions

Nowadays, the spiral wound technology dominates the mark of membrane production. Although modeling principles and general balance equations are independent of the membrane technology, some equations will change from a technology to the other one in order to accommodate geometrical aspects and filtering procedures. In addition, following assumptions are taken for the model building:

- Membrane is assumed to be a flat surface such that the problem becomes one-dimensional.
- Inside the RO module, flow rates are assumed to be laminar.
- RO unit is completely fed with water.

C. Modeling the Retentate Side

Balance equations for mass, momentum, energy and salt of this subsystem yield

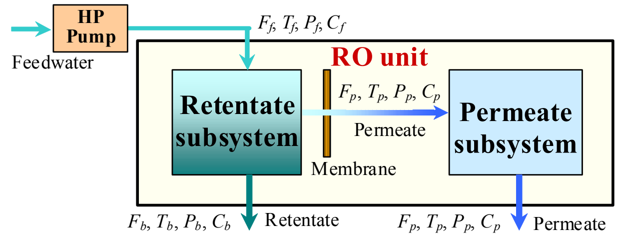

Fig. 7. Decomposition of the RO module.

$$dm_b/dt = F_f - F_b - F_m - F_{bp} \tag{1}$$

$$dC_b/dt = 1/m_b\left[(F_f - F_{bp})(C_f - C_b) - F_m(C_p - (C_b + C_f)\right] \tag{2}$$

$$dT_b/dt = 1/m_b\left[(F_f - F_{bp})(T_f - T_b) - F_m(T_m - T_b) - \dot{Q}_b/C^*_{p,b}\right], \tag{3}$$

$$\begin{aligned} d^2p_b/dt^2 = \alpha[&-dp_b/dt + \alpha_1 p_b + \alpha_2 p_f + \alpha_3 p_{be} \\ &+\alpha_4(F_f - F_{bp})^2 - \alpha_5(F_f - F_{bp} + F_b)]F_b \end{aligned} \tag{4}$$

with $\alpha = 2/(\rho_b A_b l)$, $\alpha_1 = (a_0^2 + a_b^2)/(a_0^2 - a_b^2)$, $\alpha_3 = a_b^2/(a_0^2 - a_b^2)$, $a_0^2 = (1+\zeta)A_b^2$, $\alpha_4 = 2/(\rho_f a_f A_b)$, $\alpha_5 = 4\pi\nu_b l/A_b^2$, $A_b = \pi(R_i^2 - NR_{OF}^2)$. $C^*_{p,b}$ is the average value of $C_{p,b}$ between T_f and T_b. The retentate flow rate is obtained from

$$F_b^2 = 2\rho_b a_b^2 A_b^2/(a_0^2 - a_b^2)(p_b - p_{bo}). \tag{5}$$

K_{bo} and p_{bo} are defined by the external valve. The heat flow rate $\dot{Q}_b(t)$ represents heat losses in the system and is calculated from

$$\dot{Q}_b = \alpha_t A_{pv} \Delta T_x, \tag{6}$$

where A_{pv} is the internal area of the pressure vessel, α_t is the overall heat transfer coefficient and ΔT_{xb} is given by

$$\Delta T_{xb} = (T_f - T_b)/\ln\left[(T_a - T_b)/(T_a - T_f)\right], \tag{7}$$

where T_a is the ambient temperature outside the unit.

D. Modeling the permeate side

For the permeate side, following equations are obtained:

$$dm_p/dt = F_m + F_{bp} - F_p, \tag{8}$$

$$dC_p/dt = [F_{bp}(C_f - C_p) - F_m C_f]/m_p, \tag{9}$$

$$dT_p/dt = 1/m_p\left[F_m(T_m - T_p) + F_{bp}(T_f - T_p) + \dot{Q}_p/C^*_{p,p}\right], \tag{10}$$

$$d^2p_p/dt^2 = \beta[-dp_p/dt + \beta_1(p_m - p_p - \beta_2 F_p)]F_p \tag{11}$$

with $\beta = 64\nu_p/(\rho_p A_p l_p d_p^2)$, $\beta_1 = 32\upsilon_p/d_p^2$, $\beta_2 = 32\nu_p^2 l_p/(A_p^2 d_p^2)$ and $A_b = N\pi r_i^2$. $C^*_{p,p}$ is the average specific heat capacity of permeate. The heat flow rate $\dot{Q}_p(t)$ represents heat changes in the permeate side and it is calculated according to

$$\dot{Q}_p = \alpha_t A_{pt} \Delta T_{xp}, \tag{12}$$

where A_{pt} is the heat transfer area, α_t is the overall heat transfer coefficient and ΔT_{xp} is given by

$$\Delta T_{xp} = (T_m - T_p)/\ln\left[(T_a - T_p)/(T_a - T_m)\right]. \tag{13}$$

T_a has been defined above.

E. Modeling the membrane

A pressure vessel contains several membrane units. Each unit contributes with F_{p_i} to the whole permeate flow rate such that

$$F_p = \sum_{i=1}^{N_m} F_{p_i} + F_{bp} , \quad (14)$$

where N_m is the number of membrane units in the pressure vessel. The calculation of F_{p_i} is carried out from the solution-diffusion model porous model for spiral-wound modules, namely

$$F_{p_i} = K_m (p_{b_i} - p_p - \Delta\pi_o^{*}) + B(C_f - C_p) . \quad (15)$$

Pressures p_{p_i} are calculated by using the formula

$$p_{p_i} = (1-\gamma_i) p_f + \gamma_i \, p_b , \quad (16)$$

where $\gamma_i = n_i/(N_m+1)$, with n_i as index for the position of the considered unit in the sequence. Constant K_m is obtained from

$$K_m = n_m \; A \, \rho_p l_f \; \tanh(2\psi l_p)/\psi , \quad (17)$$

where ψ is given by $\psi^2 = A\mu(1-\varepsilon)^2 s_v \eta_p/(\varepsilon^3 h_p)$. Parameters l_f, l_p, h_p, ε, μ, n_m and s_v are membrane's parameters. η_p and ρ_p are the density and viscosity of permeate. Constants A and B are known as water and salt permeability constants, respectively, and they are calculated according to

$$A = A_0 \, e^{a_T (T-T_0)/T} , \; B = B_0 \, e^{b_T (T-T_0)/T} , \quad (18)$$

where A_0 and B_0 are membrane coefficients at the reference temperature T_0 = 291K. a_T and b_T are dimensionless empirical membrane constants. Finally, $\Delta\pi^*$ is the average osmotic pressure, which is given by $\Delta\pi^* = \pi_b^* - \pi_p^*$, where

$$\pi_i^* = 0.5RC_iT_i[2 - PRR]/[1 - PRR] . \quad (19)$$

R is the universal gas constant and PRR (*Permeate Recovery Rate*) is computed as the quotient between permeate and retentate volumetric flow rates in percent (100% q_b/q_p).

VI. EXAMPLE

In order to illustrate the operation of the laboratory plant in the context of FTC, following example is formulated: The system is assumed to be SISO (i.e. u_2 = 0). The controlled as well as measured variable is the permeate flow rate q_p. The manipulated variable is the retentate flow rate by means of the valve at the end of the retentate pipeline. The operating point is set to a valve opening of 50% for a permeate flow rate of 250 l/h.

The controller used is a MPC whose control law is obtained by numeric optimization of the performance index

$$J = \| e(k+N) \|_{\mathbf{S}}^2 + \sum_{i=k}^{k+N-1} \| e(i) \|_{\mathbf{Q}}^2 + \sum_{i=k}^{k+N_u-1} \| \Delta\mathbf{u}(i) \|_{\mathbf{R}}^2 + \rho\,\varepsilon^2 \quad (20)$$

subject to the constraints

$$\begin{aligned} &\mathbf{y}(k) = \mathbf{C}\,\mathbf{x}(k), \\ &\mathbf{x}(k+1) = \mathbf{A}\,\mathbf{x}(k) + \mathbf{B}\,\mathbf{u}(k), \\ &u_{i_{\min}} \le u_i \le u_{i_{\max}} \quad \text{for } i = 1,\cdots,m, \\ &\Delta u_{i_{\min}} \le \Delta u_i \le \Delta u_{i_{\max}} \quad \text{for } i = 1,\cdots,m \quad \text{and} \\ &\varepsilon\, x_{i_{\min}} \le x_i \le \varepsilon\, x_{i_{\max}} \quad \text{for } i = 1,\cdots,n. \end{aligned} \quad (21)$$

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

$$\mathbf{e}(\cdot) = \mathbf{r}(\cdot) - \mathbf{y}(\cdot) . \quad (22)$$

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. The design parameters for the controller related to the operating point (50%, 250 l/h) are given in Table III (the constraints for the control signal first difference is set to $-3.4 \le \Delta u \le 3.4$). The sample time was set to 0.5 s.

TABLE III
DESIGN PARAMETERS FOR THE MPC

	N	N_u	Q	R	$u_{\min}$	$u_{\max}$	$\Delta u_{\min}$	$\Delta u_{\max}$	$y_{\min}$	$y_{\max}$	ρ
Nominal Controller	25	5	10	1	-20	20	-3.4	3.4	-30	30	1e4

Matrix $\mathbf{Q}$ is defined as $\mathbf{Q}$ = diag(Q). The implementation of the MPC algorithm requires a linear model for each operating point. A model for the operating point was identified by using the N4SID algorithm ([37]). The order of the system was estimated as three. The model is

$$\mathbf{A} = \begin{bmatrix} 0.947 & -0.046 & 0.071 \\ 0.127 & 0.692 & 0.322 \\ 0.031 & -0.461 & 0.364 \end{bmatrix}; \quad \begin{aligned} &\mathbf{B} = [-3.4e{-2} \;\; 1.31 \;\; 1.721]^{\mathrm{T}}; \\ &\mathbf{C} = [445.7 \;\; -34.44 \;\; 1.39]; \; \mathbf{D} = 0 \end{aligned}.$$

Two experiments are planned for the example: *i*) the valve speed is limited after 133s and *ii*) a constant offset of -10 l/h appears in the permeate flow rate sensor. The first experiment shows that the MPC is robust for this kind of faults, although the system's reaction is slower. For the second faults, a control system reconfiguration is undertaken. Because flow rate sensors for permeate and retentate are related by

$$q_p = q_f - q_b , \quad (23)$$

where q_f = 500 l/h is the flow rate feed water fixed by the pump. Thus, q_b can be used as an indirect measurement of q_p. Hence, the following equation

$$\sigma = \begin{cases} 0 & \text{if } |q_f - q_b - q_p| < tol \\ 1 & \text{if } |q_f - q_b - q_p| \ge tol \end{cases} \quad (24)$$

is used for controller switching, where σ is the switching signal for the reconfiguration of the control loop. The conceptual block diagram is given in Fig. 8.

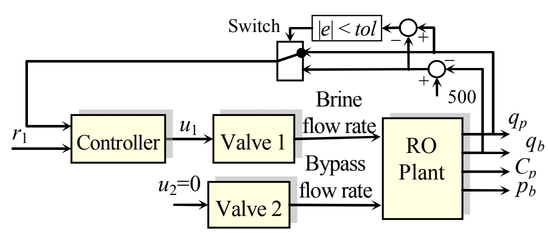

Fig. 8. Block diagram for the implementation of the example for FTCS

Real-time results are given in Fig. 9 for a nominal control system as well as for the FTCS. Notice, that both control systems can overcome the problem of limited valve speed. The sensor offset cannot be solved by the nominal controller. After the control loop reconfiguration and by using indirect measurement of the permeate flow rate, the problem created by the fault is solved.

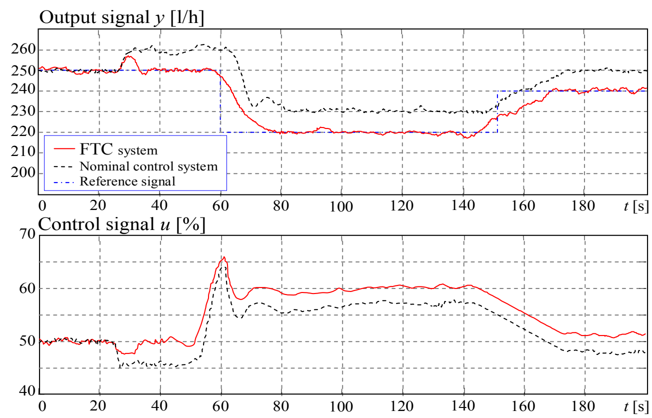

Fig. 9. Real-time control results for the FTC example

VII. CONCLUSIONS

In this contribution, an experimental pilot plant built on the basis of a small-sized industrial reverse osmosis plant is presented. The plant shows to have excellent properties for experimenting with dynamical system in particular regarding aspects of FTC and reconfiguration. The purpose of the laboratory plant is to evaluate new algorithms in a plant, where real industrial control problems can appear. The plant allows investigating several typical problems in the area of control as for example modeling, advanced control, fault detection, supervisory control and system reconfiguration. An example was presented as motivation but investigations are in an initial phase and the whole potential of the plant is open to be discovered jet.

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