# INTEGRATED DESIGN AND CONTROL USING THE DYNAMIC SIMULATION OF A REVERSE OSMOSIS PLANT

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## Abstract

*This document presents the optimal design of a desalination plant using the dynamic simulation of a reverse osmosis plant. Predictive control is normally used to calculate the operating point. However, this operating point, as well as the plant design, can be improved with an integrated design, mainly regarding the size of the equipment. The main purpose of this plant control is to supply the water demand (which varies throughout the day and is different throughout the year) with the least amount of energy, avoiding the draining and spillover of the tanks and taking into account a series of system restrictions, such as the need to clean the filters or membranes or the technical limitations of the pumps. This document will show how an integrated design improves the design and the control of a specific plant. The EcosimPro© modelling tool has been used to develop the dynamic simulations of the desalination plant in the study.*

**Key Words:** Integrated design, dynamic simulation, desalination plants, hybrid control, dynamic optimisation, EcosimPro©

## 1. INTRODUCTION

Reverse osmosis is a simple method to produce potable water from brackish water or sea water. This is because desalination plants that use reverse osmosis need less power, are cheaper to install and need less space and maintenance than other plants that use other desalination systems [7]. Reverse osmosis is therefore an ideal technique to produce potable water [4], [19].

Reverse osmosis plants are especially useful to supply potable water to remote areas with difficult access. In these cases, advanced control techniques are especially necessary to reduce and facilitate maintenance, supervision by qualified operators and the automatic operation of the plant as well as to avoid shutdowns due to system problems and malfunctions. On the one hand, an optimum design of operation and a correct integrated design of the plant will help reduce the size and cost of the equipment. Power consumption will therefore be reduced as well and the lifetime of the various plant elements will be extended, while meeting the variable water demands of the population. [1], [8], [11], [12], [16]

This document focuses on the integrated design of the reverse osmosis plants, minimising the size of the equipment and, especially, optimising the dimensions of the tanks. The available information on water demands, the calculation of the consumed power and the control strategy are taken into consideration. The integrated design is optimised by performing a dynamic simulation of a specific plant [13] using the EcosimPro© modelling and simulation tool and the estimates of available power and future water demands. The operation of a reverse osmosis plant mixes continuous decisions (such as the flow of treated water) and discrete decisions (such as the cleaning operations or the use of on-off valves) so that the result is a hybrid problem.

This document is organised as follows: Section 2 presents an introduction to reverse osmosis plants. Section 3 then describes the integrated design and control strategy. Finally, section 4 shows some of the results obtained.

## 2. REVERSE OSMOSIS PLANTS

Figure 1 shows a typical reverse osmosis plant. Supply pump B1 transfers the brackish water from a well to storage tank T1. From this tank, water is channelled to high pressure pump B2, which increases the pressure of the current up to a value greater than its osmotic pressure. The pressurised water current is then transferred to a reverse osmosis membrane rack. The pressure gradient on both sides of the membranes makes part of the feedwater flow through the membrane so that a flow of pure water is obtained. This treated water is stored in tank T2. From there, the water required to meet the population's demands is obtained after a series of post-treatments. A more detailed description of the components of a reverse osmosis plant is shown in [2].

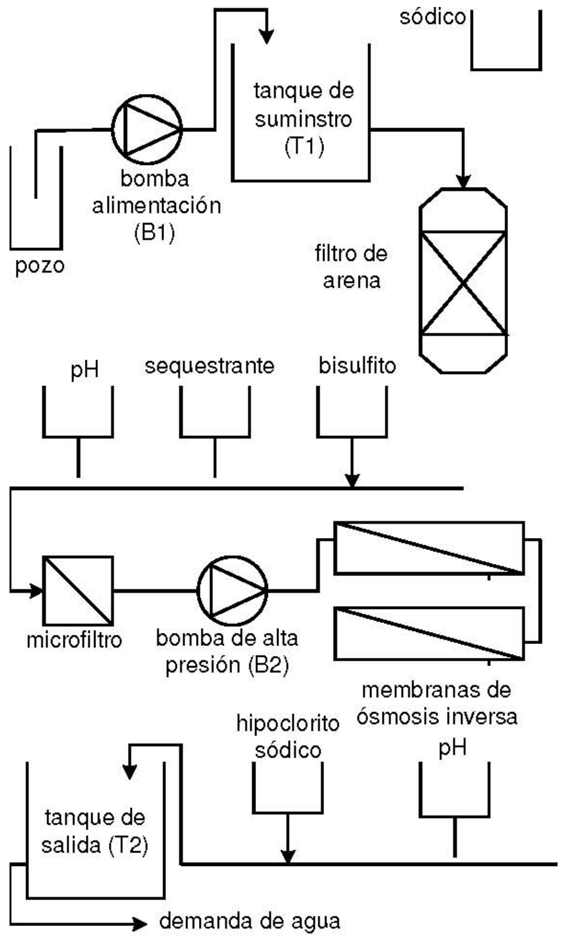


Figure 1: Typical reverse osmosis plant

### 2.1 REVERSE OSMOSIS PROCESS

Reverse osmosis is a separation process that uses pressure to force a solvent (water) through a semipermeable membrane. This membrane holds the solute (salt) on one side and allows the pure solvent through to the other side. This process therefore yields a current of pure water from a current of brackish water, that flows through the membrane, known as 'permeate' and a current of water with a higher salt concentration than the supply water that does not flow through the membrane as is known as 'waste'.

This process requires high pressure on the supply side (greater than 50 bar in the case of sea water with very high salinity). This pressure is supplied by HP pump that is responsible for most of the electrical power consumption in the plant.

The main problem during plant operation is the progressive loss of performance of the membranes due to the fouling caused by organic components that precipitate, salts that crystallise and other components that are adsorbed on the membrane surface. The supply current needs to be pretreated to avoid this situation. This pretreatment consists of filtering the water and adding chemical components that prevent the precipitation of soluble compounds and the growth of colonies of microorganisms. In addition, periodic cleaning will be done periodically to eliminate any substances that may have precipitated on the membrane.

A post-treatment is then necessary to make the pure water current from the membranes potable. This process normally consists of adjusting the pH, adding chemical compounds to eliminate the microorganisms and causing a moderate increase in the salinity of the water by making a correct mixture with part of the pretreated supply current.

## 3. INTEGRATED DESIGN

The purpose of the integrated design is to optimise the design of the plant (in this case by minimising the size of the tanks) taking into account the control strategy. The main purpose of the control is to be able to supply a water demand over a given timeframe taking into account a series of restrictions [18], [10].

### 3.1 WATER DEMAND

The water demand varies throughout the day and is approximately a periodic curve that repeats every 24 hours [3]. Estimating the shape of the curve is essential to ensure the design of the desalination plant is correct. This estimate, however, is easy based on the historical figures of water consumption in a given population.

Figure 2 shows a typical water demand curve over two days. The figure shows that water consumption reaches its minimum level during the night, whereas it reaches it daily peak in the morning. It is important to consider that, apart from the daily variations, the water demand curve also varies significantly every day of the week and, especially, every month of the year.

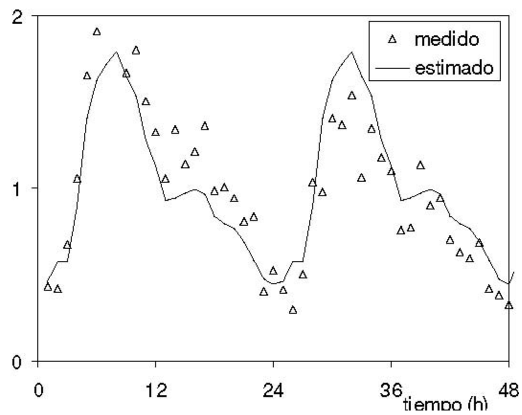


Figure 2: Water consumption: Measurement and estimated water flow (m3/h) vs time (h).

## 3.2 CONTROL VARIABLES

The control goal is formulated from a financial point of view: being able to supply the potable water consumption, minimising the power requirements and changing the handled variables smoothly.

The calculation of the control strategy is done for a certain control horizon. A dynamic simulation is used to predict the evolution over time of the different variables of the reverse osmosis plant during that time. In the case under study, the selected control horizon is of 48 hours.

The variables that can be changed to ensure the water supply are the following:

- The flow of the supply pump (B1)
- The flow of the high pressure pump (B2)
- The moments for the cleaning of the membranes

The specific plant studied in this document represents a typical case, and in it the supply pump (B1) is a centrifugal on/off pump that can supply a water current several times greater than the maximum level that the high pressure pump can supply (B2). Thus, pump B1 will remain off most of the time. In order to formulate the optimisation problem in practical terms, the operation of these pumps is parameterised by means of an input vector, as shown in figure 3.

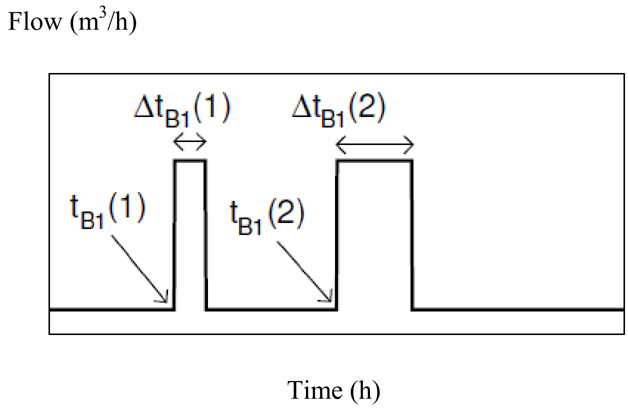


Figure 3: Parameterisation of pump B1 water flow (m3/h) vs time (h).

The high pressure pump (B2) in the case under study is a displacement pump with a speed variator. The nominal flow of the pump is 1 $m^3$/h, although its speed may be modified by approximately 30% over the nominal value. Thus, the handled variables that can be edited for pump B2 are *n* different values of the flow of that pump throughout the control horizon. Where *n* is a value set by the user. See figure 4.

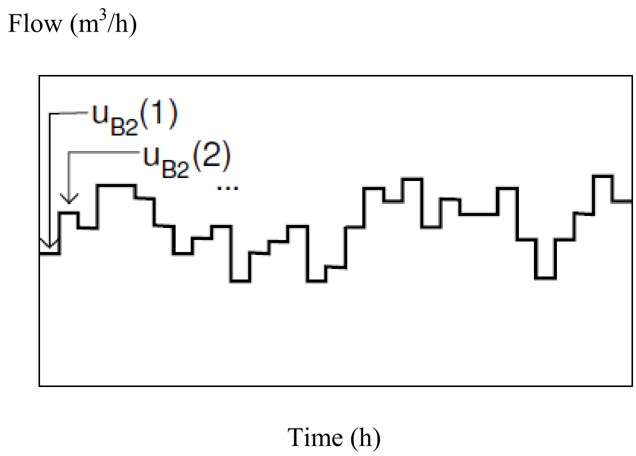


Figure 4: Parameterisation of pump B2 water flow (m3/h) vs time (h)

As set out above, the life of the membranes can be extended by performing adequate pretreatment and periodic cleaning of the membranes. Although there are several types of cleaning operations, this document only contemplates one 30-minute operation every 24 hours, using part of the generated permeate. See Figure 5.

### 3.3 RESTRICTIONS

The control strategy needs to comply with a series of constraints. The main constraint is that the water level in the tanks (T1 and T2) needs to be maintained between a certain maximum and minimum value. This will ensure that the water demands are met.

Cleaning of the membranes (۰ - ۱)

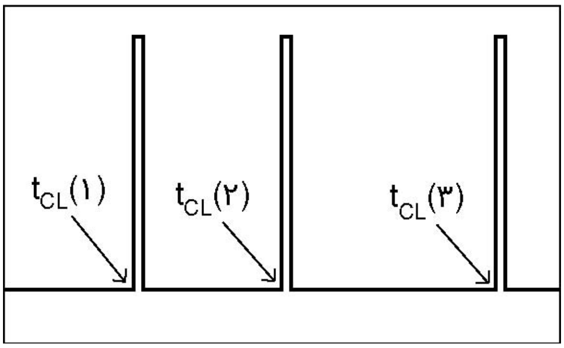


Figure 5: Parameterisation of the cleaning

In addition, several constraints related to the handled variables are taken into account. Once the supply pump is started up (B1), the following shutdown cannot be done until after a minimum delay. Similarly, there is a minimum delay between the pump shutdown and following startup.

In the high pressure pump (B2), the difference between two consecutive changes is limited by a certain maximum value so that the operation of the membranes is smooth.

Finally, the membranes need to be cleaned every 24 hours, that is, the maximum time between two cleaning operations is 24 hours. Other types of cleaning operations, such as flushing or chemical cleaning, are not considered in this document.

### 3.4 OPTIMISATION

Figure 6 shows the optimisation structure that is used in this document. The optimiser uses the estimate of the water demand and the measurements on water consumption, water level in the tanks and flows to calculate the optimum operating point at each moment [5], [15].

The hybrid dynamic optimisation has been reformulated in continuous terms with the parameterisation commented above [14]. Mathematically, the problem of the integrated design can be formulated as the minimisation of the following cost function (which takes into consideration the size of the tanks, the power consumption and the control efforts):

$$J = \beta_1 \int_0^{48h} E \cdot d\tau + \frac{\beta_2}{n_{B2}} \sum_{nB2} \Delta u_{B2}^2 + \beta_3 \sum_i h_i \cdot s_i \quad [1]$$

where: β1, β2 and β3 are weight factors
E is the power consumption (kW)
hi and si are the height and the cross-section
nB2 is the number related with the parameterisation of pump B2
ΔuB2 are the changes between two consecutive values of the flows of pump B2.

The predictive control will continue to operate at every sampling interval. The optimiser will calculate new values of the handled variables. But the integrated design, taking into account the size of the tanks, will only be done when the plan is designed.

## 4. RESULTS OF THE OPTIMISATION

A detailed description of the specific plant on which this study was performed was developed and validated in a real pilot plant [12], [13]. With the integrated design structure presented in section 4, the optimum calculated size of the tanks is:

- height of tank T1 = 2.1 m
- cross-section of tank T1 = 1.5 $m^2$
- height of tank T2 = 2.9 m
- cross-section of tank T2 = 2 $m^2$

When the tanks were designed without taking into account the integrated design, that is, considering only the water demand predictions and not the control strategy, the dimensions of tank T1 were similar, but the calculated dimensions for tank T2 were:

- height of tank T2 = 3.0 m
- cross -section of tank T2 = 10 $m^2$

That is, several times larger than the tank that was calculated with the integrated design.

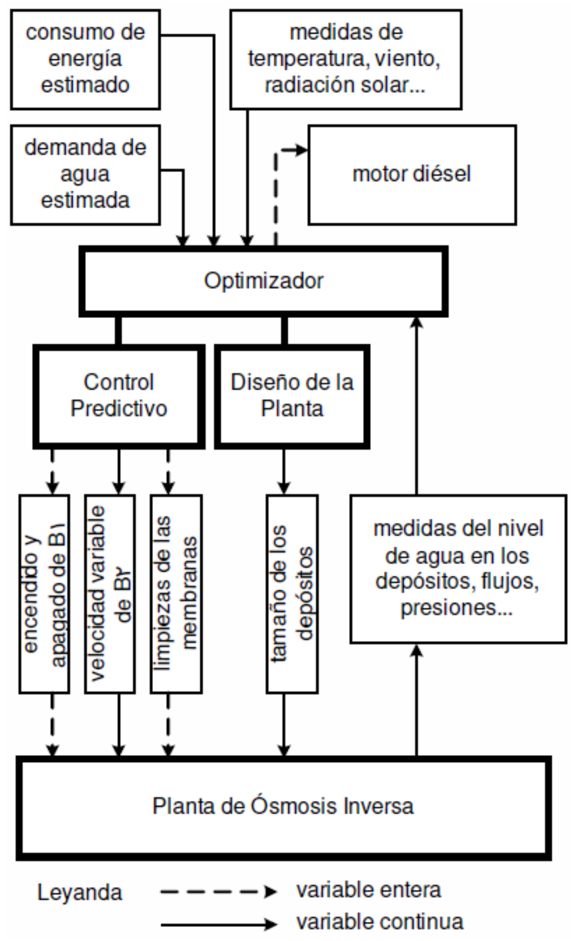


Figure 6: Structure of the reverse osmosis plant optimisation

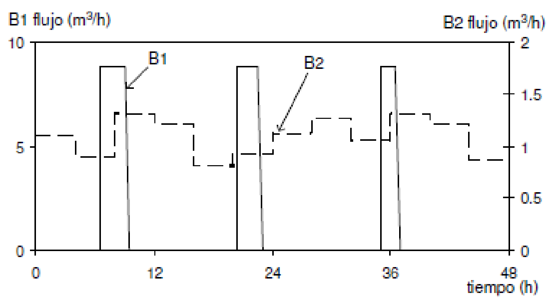


Figure 7: Pump operation Water flow (m3/h) vs time (h).

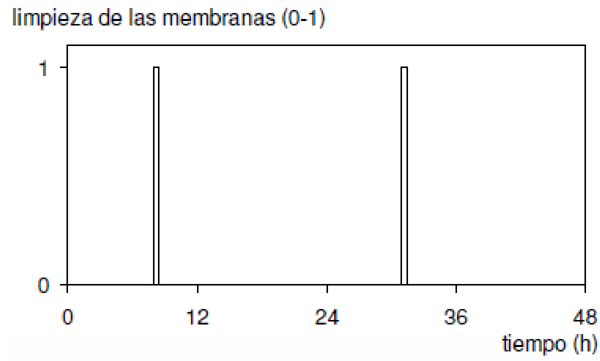


Figure 8: Moments of the cleaning of the membranes

The calculated flows of the supply pump (B1) and of the high pressure pump (B2) are shown in figure 7. In addition, the moments when the cleaning of the membranes are performed are shown in figure 8.

Finally, figure 9 shows the level of liquid in the output tank (T2) with and without control strategy. It can be seen that the liquid level exceeds the restrictions and that the water demands are not met if there is no control strategy (constant speed of the high pressure pump).

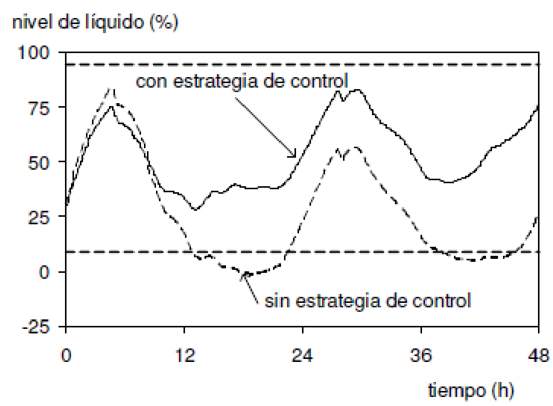


Figure 9: Water level in tank T2 water level (%) vs time (h).

## 5. CONCLUSIONS

This document shows the integrated design of a specific reverse osmosis plant, as well as the predictive control and the dynamic simulation. Its main purpose is to increase the plat efficiency, increase the useful lifetime of the components and reduce the installation and maintenance costs. The use of the optimisation is based on the reformulation of the control problem in terms of continuous variables that prevents a mixed integer optimisation and integrates the process from a financial point of view. The initial results are promising because an adequate control strategy, which meets the control targets without using too much energy, is obtained.

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