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Economic optimal control applied to a solar seawater desalination plant

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ABSTRACT

This paper discusses the formulation of an optimal control strategy taking into account economic objectives in the fresh water production process through a solar seawater desalination plant. It contributes both a linearised model of the solar-field dynamics and a simplified model of the produced distillate as a function of the outlet solar field water temperature. Then such linear models are used to design an economic receding horizon optimal controller. In particular, it comprises incomes related to the production of fresh water and the costs dealing with the electricity. Several simulations validate the proposed models and show the performance of the proposed economic optimal control strategy. In both cases, actual disturbances from physical experiments have been included in the simulations. Notice that the AQUASOL facility available at the Plataforma Solar de Almería (Spain) has been considered in this work as testbed.

1. Introduction

Fresh water shortage constitutes a fundamental issue nowadays. One way to obtain an additional source of fresh water in coastal places is the use of seawater desalination plants. Desalination processes are intensive energy consumers, therefore, optimal control approaches dealing with economic goals are welcome. Whatever the technology of the desalination plant, there is always a single overall objective, that is, maximisation of fresh water production and minimisation of (electrical) energy usage (Al-Karaghouli and Kazmerski, 2013; Fiorenza et al., 2003; Ghaffour et al., 2013; Karagiannis and Soldatos, 2008; Mezher et al., 2011).

In the last decades, automatic controllers applied to water desalination have been developed to solve mainly operational goals (i.e. maintaining a given setpoint, tracking a desired reference, etc.) (Roca et al., 2008b; Torrico et al., 2010). In addition, optimization algorithms have been employed to design cogeneration plants with desalination processes (Hosseini et al., 2012; Salcedo et al., 2012; Shakib et al., 2012; Wu et al., 2013). The objective function includes thermodynamic and environmental issues. However, few contributions have tackled an economic objective in the daily operation of the desalination process. In this context, several strategies are found in the automatic control literature based on optimal control and that could be used to control desalination plants. For instance Kadam and Marquardt (2007) summarise several developments and applications of the dynamic real-time optimization (D-RTO) framework. It is based on the idea of a hierarchical control scheme where an upper layer solves online an economical dynamic optimization problem and determines the optimal trajectories for a lower controller. The work by Zavala et al. (2009) follows the ideas of D-RTO in order to control an energy production system using weather forecast information. In particular, authors modify the original D-RTO formulation to tackle stochastic information derived from the uncertainty in the weather prediction. The work (Engell, 2007) motivates the use of the D-RTO paradigm in the field of chemical processes. Indeed, it points out that process control should be seen as a means to optimise plant operation rather than to track pre-computed set-points. Economic Model-based Predictive Control (EMPC) constitutes a prominent strategy dealing with economic-based optimal controllers. The idea behind EMPC is to replace the quadratic function related to the distance to a desired set-point or trajectory by an economic-based performance index (Amrit et al., 2013; Diehl et al., 2009; Gopalakrishnan and Biegler, 2013; Rawlings et al., 2012; Subramanian et al., 2014).

This paper presents a receding horizon optimal control approach where economic objectives of a solar seawater desalination plant are considered. In fact, the control goals are: (i) to maximize the fresh water production; (ii) to minimize the running costs (i.e. electric energy of the pump that regulates the water entering into the solar collector field; (iii) to fulfil state (water temperature) and

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Notation

A_a	cross-section area of the absorber tubes, m^2
c_2	1.3464e-4 °C $m^2/(W\,s)$
c_3	0.0012 s^{-1}
c_{56}	−0.0055 s^{-1}
c_{6m}	0.0049 s^{-1}
c_{6F}	−0.0204 °C/kg
C	0.0591 °C/s
c_7	0.3981, €/m^3
c_8	1.53e-6, €/W
C_p	water mean heat capacity, J/(kg K)
D	storaged fresh water, m^3
$E_C(u(t))$	electricity consumption ($E_C(u(t)) = 191.4178u^2(t) - 479.4625u(t) + 663.8211$)
H	global thermal losses coefficient, J/(s K)
I, d_2	solar irradiance, W/m^2
L_{eq}	equivalent absorber tube length, m
$\dot{m}_F$, u	solar-field mass flow rate, kg/s
$\dot{m}_M$, d_1	first-effect mass flow rate, kg/s
T_{oF}, z	outlet water temperature, °C
T_a, d_3	environment temperature, °C
T_{iM}	temperature of the water entering the desalination process, °C
T_{iF}, d_4	inlet water temperature, °C
$\bar{T}$	water mean temperature in the solar field, °C
β_F	solar field parameter
β_I	Irradiance model parameter, m
ρ	water mean density, kg/m^3
λ, β	lagrange multipliers or costates dealing with the Hamiltonian formulation (optimization problem)

input (flow rate) constraints. Notice that current prices of electricity (€/W) and fresh water (€/m^3) are taken into account in the optimization problem.

This paper is organized as follows. Section 2 describes the desalination pilot-plant. Section 3 deals with the model of the solar seawater desalination plant. Section 4 focuses on the economic optimal control strategy applied to the desalination plant. Simulations are discussed in Section 5. Finally, conclusions are detailed in Section 6. Notation table summarising the most important symbols used along this paper is included.

2. The AQUASOL facility

The AQUASOL plant available at the Plataforma Solar de Almería (Spain) has been considered as testbed (Alarcón-Padilla et al., 2008; Roca et al., 2008a, 2008c). It consists of a Multi-Effect Distillation (MED) plant, a stationary CPC (Compound Parabolic Concentrator) solar collector field, a thermal storage system based on water (24 m^3 of total volume), a Double Effect Absorption Heat Pump (DEAHP) (LiBr-H_2O) and a smoke-tube gas boiler. Fig. 1 shows the configuration and interconnection of the main subsystems.

The system operates with water as heat-transfer fluid, which is heated through the solar collectors and a heat pump. The solar energy is converted into thermal energy in the form of hot water and is then stored in the tanks. An on-off valve, V1, is used to flow water in the solar field through the secondary tank until the nominal temperature is reached. The desalination plant is a forward-feed MED unit, see (Zarza, 1995), with 14 cells or effects. The seawater is preheated and pumped to the first cell, or heater, where the brine falls by gravity to the following effect. At the same time, part of the water is evaporated. The thermal energy required by the MED plant is provided by the hot water from the storage system. A three-way regulation valve, V2, is used to reach the inlet first-effect nominal temperature by mixing water from the primary tank with that one returned from the heater.

The overall system was designed to make feasible the following three operating modes depending on the energy source:

- Solar. In the solar mode, the desired temperature in the heater is reached exclusively with the energy supplied from the solar field. This operating mode is useful in periods with good irradiance or with temporary passing clouds in which the storage system can damp sporadic energy falls.
- Fossil. When thermal power delivered by the solar field is not enough due to low radiation conditions or during night operation, the system must be operated with the DEAHP, using the 35 °C saturated steam produced in the last effect of the MED plant as the low temperature source and 180 °C saturated steam from the boiler as the high temperature source.
- Hybrid. In this mode, the energy supplied by the solar field is not enough to maintain the desalination plant in the nominal operating point. For this reason, solar and fossil energies are combined in order to keep the distillation production rate. As part of the thermal energy is obtained by means of the solar field, the DEAHP must work at the minimum possible load.

The economic optimal control strategy explained in this paper is applied to the solar mode.

3. Modelling

When the MED unit is working under nominal operating conditions, the distillate production mainly depends on the thermal energy delivered to the MED heater. In solar model, the MED inlet temperature, T_{iM}, is reached with the solar field, which is connected to the storage system. Therefore, to predict the distillate production, a whole model of the plant is needed.

Fig. 2 shows a diagram with the main variables involved in the non-linear model of the plant (Roca et al., 2008c). The inputs are the solar-field water mass flow rate, $\dot{m}_F$, valve positions, V_1, V_2, irradiance, I, and ambient temperature, T_a. The storaged distillate, D, is the output of the model. This model joins three non-linear subsystems: the solar field, the storage system and the MED unit.

3.1. Solar-field linear model

Consider the following mathematical non-linear dynamic model of the outlet solar-field temperature (Roca et al., 2008b)

$$\rho \cdot C_p \cdot A_a \cdot \frac{dT_{oF}(t)}{dt} = \beta_I \cdot I(t) - \frac{H}{L_{eq}} \cdot (\bar{T}(t) - T_a(t)) - C_p \cdot \beta_F \cdot \dot{m}_F(t) \cdot \frac{T_{oF}(t) - T_{iF}(t)}{L_{eq}}, \quad (1)$$

where ρ is the water mean density, C_p the water heat capacity, A_a the cross-section area of the absorber tubes, T_{oF} the outlet solar-field temperature, β_I an irradiance model parameter, H the global thermal losses coefficient, L_{eq} the equivalent absorber tube length, β_F a solar field parameter which includes the number of operative CPC's in the solar field, $\dot{m}_F$ the water mass flow rate, T_{iF} the inlet solar field temperature and $\bar{T}$ the water mean temperature between outlet and inlet water temperatures, $T(T_{oF}\,|T_{oF})/2$.

In order to avoid the non-linearity in the term $T_{OF}(t)\dot{m}_F(t)$, the previous model is linearised with Taylor series leading to

$$\dot{T}_{oF}(t) = c_2 I(t) + c_3 T_a(t) + c_{56} T_{oF}(t) + c_{6m} T_{iF}(t) + c_{6F} \dot{m}_F(t) + C, \quad (2)$$