Journal of Process Control 68 (2018) 205–217

Contents lists available at ScienceDirect

Journal of Process Control

journal homepage: www.elsevier.com/locate/jprocont

Modelling and predictive control of a recirculating cooling water system for an industrial plant

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ARTICLE INFO

Article history:
Received 5 June 2017
Received in revised form 23 April 2018
Accepted 30 April 2018

Keywords:
Industrial cooling water system
MPC
Mixed integer optimization
Industrial control

ABSTRACT

This paper deals with the design and implementation of a Model Predictive Control (MPC) algorithm for an industrial recirculating cooling water system. The plant is composed of three large reservoirs, four pumping units, three cooling towers with modulating fans, and a piezometric tower. A physical model of the system has been derived from balance equations and has been validated with experimental data. Then, a nonlinear state observer has been developed to estimate unmeasured quantities, such as the water flow rates and temperatures recirculating from the utilities. Finally, an MPC algorithm has been designed by reformulating the original nonlinear system in terms of a linear time-varying one to improve the computational efficiency of the method. The presence of on/off actuators, pumps, and fans, makes the resulting optimization problem a Mixed Integer Quadratic Programming one. Extensive simulation results and comparisons with the relay-based control scheme currently implemented witness the potentialities of the proposed solution in terms of energy savings, better control, and lifetime of the equipments. The proposed MPC algorithm is currently being tested on the real plant, its very satisfactory performance confirm the results of the simulation experiments.

1. Introduction

Many industrial plants produce a huge amount of waste heat that must be rejected with recirculating cooling water systems made by a water network, cooling towers, reservoirs, pumps. In this way, it is possible to conserve fresh water and to reduce thermal pollution to the environment. Extensive studies have been focused on the design of recirculating cooling water systems with the goal to improve their performance, see e.g. [10,17,5,6]. These systems are frequently controlled with simple Single-Input-Single-Output regulators, for instance relays controlling levels and/or temperatures by suitably actuating pumps and fans. However, this decentralized solution can lead to unsatisfactory performance and to an overall excessive use of the actuators, with a corresponding high energy consumption. This issue calls for a multivariable control synthesis approach, possibly based on an optimization criterion, like Model Predictive Control (MPC), nowadays the most widely used advanced control design method in the process industry, see [7,8,12], and with a solid theoretical background, see e.g. [4,13,15].

This paper deals with the design of an MPC algorithm for the recirculating cooling water system of an industrial steel production plant located in the northern Italy, see Fig. 1. The goal of the project has been to reduce the energy consumption due to pumps and fans and, at the same time, to improve the control performance, in particular for what concerns the regulation of the levels inside the reservoirs and the temperature of the cooled water.

The system has been first modelled with mass and energy balance equations, plus black-box relations estimated from the measured data and used to represent unknown or highly uncertain relations. Then, a nonlinear estimator of the unknown and unmeasurable quantities has been developed and an MPC regulator has been designed by resorting to a linear time varying representation of the plant according to an approach similar to the one described in [14]. The most challenging characteristics of the underlying control problem are due to the on/off nature of pumps and fans, which make the problem a Mixed Integer Quadratic Programming (MIQP) one. The overall control scheme has been tuned and validated with a large number of simulation experiments, then the MPC algorithm has been implemented and tested on the real plant. The results obtained witness the significant performance improvements, with

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https://doi.org/10.1016/j.jprocont.2018.04.009
0959-1524/

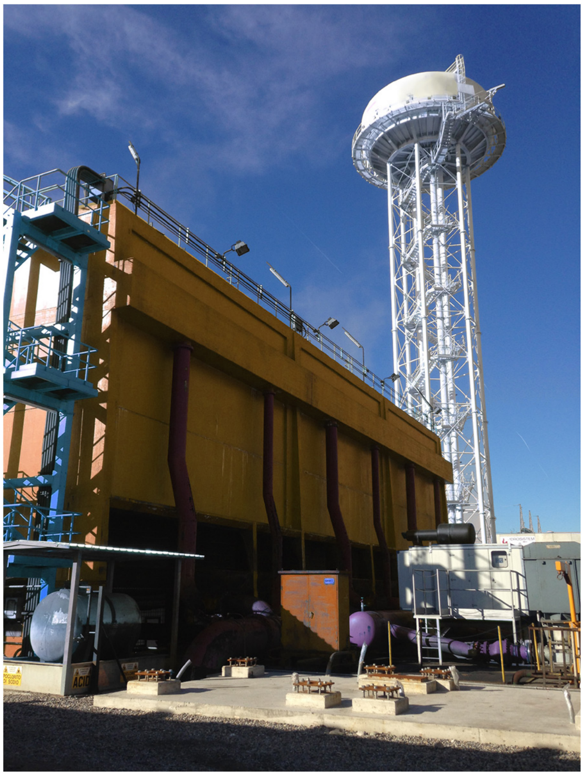

Fig. 1. Picture of the evaporative and piezometric towers.

respect to the decentralized control scheme currently in use, and based on relays, in terms of energy savings, better control action, increased lifetime of the actuators. For these reasons, the engineering of the MPC algorithm is now under development for its permanent use on the real plant.

The paper is organized as follows. In Section 2 the plant is described and its dynamical model is derived. Section 3 describes the design of the control system, i.e. the state estimator and the MPC control algorithm. In Section 4 simulation experiments are first reported and discussed, and the performance obtained with MPC are compared to those provided by the control scheme currently implemented and based on relays to illustrate the benefits of the proposed solution. Some results concerning the use of the MPC algorithm for control of the real system are also reported. Finally, Section 5 closes the paper with some additional comments and hints for future work.

2. Model of the plant

The plant is composed of two reservoirs R1 and R2 collecting hot water from the plant utilities (furnaces, mills, etc.), three evaporative towers with fans, and a reservoir R3 collecting the cooled water, see Fig. 2. A small quantity of hot water can also be sent from the utilities directly to R3. Two pumping units, P1 and P4, are used to transfer hot water from R1 and R2 to the towers, while two pumping units, P5 and P7, move cooled water from R3 to the utilities. The pumping unit P5 actually pumps water to a water tower used to stabilize part of the pressure flow to the real plant. Unit P1 is made by four pumps of equal size, unit P4 has six pumps, P5 seven pumps, and P7 six pumps; all the pumps have only on/off operating modes. Along the pipe connecting the reservoir R1 to the evaporating towers there are also some filters to remove impurities; however, their presence does not influence the control problem considered in this work, so that they have been neglected in the modelling phase. Moreover, since the evaporative towers are not always able to process all the water pumped by P1 and P4, an additional direct bypass from R1 to R3 can be manually opened. This increases the temperature of water in R3, but avoids flooding from the top of the towers, that would result in water leakage.

Table 1
Nomenclature.

h_1, h_2, h_3	water levels in reservoirs R1, R2, R3 [m]
$\bar{h}_1, \bar{h}_2, \bar{h}_3$	heights of the reservoirs R1, R2, R3 [m]
T_1, T_2, T_3	water temperatures in reservoirs R1, R2, R3 [K]
T_{h1}, T_{h2}, T_{h3}	temperatures of the inlet flows of reservoirs R1, R2, R3 [K]
w_{h1}, w_{h2}, w_{h3}	inlet flow rates of reservoirs R1, R2, R3 from utilities [m^3/s]
h_p	water level in the piezometric tower [m]
T_{ei}, T_{eo}	temperatures of inlet and outlet flows of the evaporating towers [K]
T_{ex}, φ_{ex}	ambient temperature [K] and humidity [%]
A_1, A_2, A_3, A_p	areas of reservoirs R1, R2, R3, and of the piezometric tower [m^2]
$n_{p1}, n_{p4}, n_{p5}, n_{p7}$	number of activated pumps of P1, P4, P5, P7
$w_{p1}, w_{p4}, w_{p5}, w_{p7}$	flow rates of the pumping units P1, P4, P5, P7 [m^3/s]
w_b	bypass flow rate [m^3/s]
w_s	overflow from R3 to R2 [m^3/s]
w_{op}	water outlet flow rate of the piezometric tower [m^3/s]
f_p	fan position (0 = stopped, 1, 2, 3,4 = maximum speed)
α	% of water outlet flow rate from R1 to the evaporating towers [%]
c_e	evaporative coefficient at zero wind speed [m/s]
c	water specific heat [J/kg K]

For confidentiality reasons, the characteristics of all the described units cannot be reported. However, in order to give an idea of the size of the system, in standard operating conditions the total water flow to the plant utilities lies in the range [3500–4000 m^3/h], while the total water which can be stored in R1, R2, R3 is 1800 m^3. All the variables used in the equations of the following sections are described in Table 1.

2.1. Model of the reservoirs

The reservoirs have been described by means of mass and energy balance equations. According to [3], the term representing the energy exchange between the surface of a reservoir with area A and water temperature T with the external environment characterized by temperature T_{ex} and humidity φ_{ex} has been modeled as

$$\gamma(A, T, T_{ex}, \varphi_{ex}) = Ac_e \left(6.11 * 10^{\frac{7.5T}{237.7+T}} - 6.11 * 10^{\frac{7.5T_{ex}}{237.7+T_{ex}}} \varphi_{ex} \right)$$

where c_e is a coefficient that depends on wind speed, the latter assumed null in this case. This choice is motivated by the walls delimiting the reservoirs that stand for meters above the water level, hence zeroing the wind speed at the water level.

Reservoir R1

$$\begin{aligned}
\dot{h}_1(t) &= \frac{1}{A_1}(w_{h1}(t) - w_{p4}(t)) \\
\dot{T}_1(t) &= \frac{1}{cA_1 h_1(t)}(cw_{h1}(t)(T_{h1}(t) - T_1(t)) - \gamma(A_1, T_1(t), T_{ex}(t), \varphi_{ex}(t)))
\end{aligned}$$

Reservoir R2

$$\begin{aligned}
\dot{h}_2(t) &= \frac{1}{A_2}(w_s(t) + w_{h2}(t) - w_{p1}(t)) \\
\dot{T}_2(t) &= \frac{1}{cA_2 h_2(t)}(cw_s(t)(T_3(t) - T_2(t)) + cw_{h2}(t)(T_{h2}(t) - T_2(t)) \\
&\quad -\gamma(A_2, T_2(t), T_{ex}(t), \varphi_{ex}(t)))
\end{aligned}$$