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Temperature control in a solar collector field using Filtered Dynamic Matrix Control

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ABSTRACT

This paper presents the output temperature control of a solar collector field of a desalinization plant using the Filtered Dynamic Matrix Control (FDMC). The FDMC is a modified controller based on the Dynamic Matrix Control (DMC), a predictive control strategy widely used in industry. In the FDMC, a filter is used in the prediction error, which allows the modification of the robustness and disturbance rejection characteristics of the original algorithm. The implementation and tuning of the FDMC are simple and maintain the advantages of DMC. Several simulation results using a validated model of the solar plant are presented considering different scenarios. The results are also compared to nonlinear control techniques, showing that FDMC, if properly tuned, can yield similar results to more complex control algorithms.

1. Introduction

The use of solar energy has increased significantly in the last years in several applications [8]. Nowadays, solar energy is being used for electricity generation by means of photovoltaic plants or solar-thermal plants in many countries [29]. Also, it is the primary energy source for other processes, such as distillation plants to produce fresh water [1], bio-reactors to produce bio-mass [10], furnaces [4] and air-conditioning systems [30], among others. In these thermal processes, solar collector fields are applied to heat water or another fluid. Then, these fluids are used to feed the main stage of the plant, as for example evaporators in distillation plants or absorption chillers in air-conditioning installations. Therefore, the temperature of the heated fluid should be controlled to allow the correct operation of these main stages. This constitutes an important control problem because of the nonlinear dynamics, the delay, and disturbances that characterizes the solar collector field system [8].

In the process analyzed in this paper, the AQUASOL plant at *Plataforma Solar de Almería* (SPAIN), fresh water is produced using a combined solar and fossil multi-effect distillation plant [1]. The plant has an evaporator feeded with hot water from a set of tanks used to accumulate the thermal fluid coming from the solar collectors or, when solar radiation is not sufficient, from a gas heater. As in other plants that use solar collector fields for the continuous production of heated water, solar radiation cannot be manipulated and aspects such as daily solar cycle, cloud level, and atmospheric conditions have to be considered as part of the control problem. This must be done in order to maximize the use of renewable energy and to avoid the use of gas [24]. Moreover, because of the fluid transportation and long distances (the solar collector field has and area of 500 m^2) the process dynamics exhibits important time delays [20]. Thus, advanced control techniques have to be applied to control this process to achieve satisfactory performance [6].

Model Predictive Control (MPC) appears as a solid candidate to control thermal processes in solar plants [7]. Several studies have demonstrated the advantages of MPC in different processes: in [21] a robust generalized predictive controller is used to control a solar air-conditioning system; in [4] a solar furnace is controlled using a constrained control strategy; in [12] a nonlinear MPC is applied to the Accurex plant at the *Plataforma Solar de Almería* (SPAIN), where parabolic collectors are used to heat oil to feed a vapor-turbine for electricity generation.

For the particular case of AQUASOL, several solutions have been presented in literature, from simple control algorithms [6] to more complex controllers, e.g., feedback linearization based controllers [24], multi-model MPC [3], or nonlinear MPC [27]. In all cases the main objectives are to force the outlet temperature to follow a

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desired reference that depends on the inlet temperature of the field and to reject disturbances caused by cloud and ambient temperature, using the water flow as manipulated variable.

In this work, the authors propose the use of the Filtered Dynamic Matrix Control (FDMC) to control the solar collector process of the AQUASOL plant. The FDMC is a modification of the classic DMC, a linear MPC algorithm. Despite the fact that industrial processes are, in general, nonlinear, most control design techniques in industrial applications are based on the use of linear models. The main reasons for this are that: (i) processes have a stable behavior in open loop and using long horizons and adequate weighting factors allows for stable closed-loop systems [26], and (ii) linear models provide good results when the plant is operating in the neighborhood of the operating point [5]. Hence, the analysis of some closed-loop properties of these controllers, like disturbance rejection and robustness, is very important for the process industry as they can be transformed in simple and useful modifications of the control algorithms to achieve better performance in real applications [20]. Particularly, in multivariable industrial processes, dead times are always used to model the plant behavior. In such models, each signal path between the inputs and outputs may show a different delay. Although these MPC formulations can include multiple delays in a straightforward manner, robustness and/or disturbance rejection can be poor because the controller does not have enough degrees of freedom to achieve a satisfactory trade-off between these two important specifications [20].

In [20], the authors showed that the DMC implicitly uses a Smith Predictor, a famous Dead-Time Compensator (DTC) structure, to compensate the dead-time of the process. Because of this, DMC presents the same properties of the SP: poor performance in the disturbance rejection of load disturbances for lag-dominant processes. Also in [20], the authors propose a modification of the classical SP, the Filtered Smith Predictor (FSP), which adds a filter to provide an extra tuning degree of freedom that can be used to improve closed-loop load disturbance rejection or robustness. The FSP modifies the SP structure including a filter acting in the error between the process output and the model output. This filter allows the FSP to be tuned in such a way that slow poles are eliminated from the closed-loop responses, improving disturbance rejection performance. Using the ideas of the FSP and the fact that DMC uses internally a SP, in [16], the authors presented a modification of the DMC algorithm, the FDMC, which have the advantages of the FSP structure listed above. Furthermore, the new controller is obtained with a minor modification of the original algorithm. Hence, it is simple to tune and implement in practice, allowing the use of existing MPC controllers in industrial applications.

Other modifications of the DMC exist that try to solve the disturbance rejection and robustness problems. The most cited is [17], where a state-space interpretation of the DMC is done, and a Kalman filter is included in the algorithm to change how the predictions are made, which affects the disturbance rejection and robustness. However, the tuning guidelines of the filter are heuristic, and their influence on the DMC properties are only qualitative. This line of modification is also present in other works, e.g., [13,14]. As will be shown later on, the FDMC tuning guidelines are much more clearer, and their effect on the DMC properties are obtained analytically. Another advantage is that existing FSP tuning methodologies already developed for MIMO dead-time compensators [11] can be used to improve robustness and disturbance rejection performance. Also, this approach uses a transfer function representation instead of state-space, as was presented in the other works.

To demonstrate the FDMC capabilities, this control algorithm will be applied to the solar collector field of the AQUASOL project. Simulation results under real operation conditions are used to show the satisfactory performance of the proposed FDMC. The disturbance data used in the simulations were obtained during experiments with the plant. The simulations also used a thoroughly validated nonlinear model of the process [22,25]. Also, the FDMC is compared with more complex nonlinear control techniques [24,9]. The simulation results include sunny and cloudy days in different seasons, and also different disturbances dynamic behavior. The presented results extends the ones analyzed in [15] where a preliminary study of FDMC robustness was discussed.

The rest of the paper is organized as follows. The modified DMC algorithm is discussed in Section 2 where the robustness and disturbance rejection properties of the controller are analyzed and compared to the original DMC. Implementation aspects of the proposed controller are given in Section 3. The AQUASOL plant characteristics and the nonlinear model of the solar collector field are presented in Section 4, along with the linearized discrete model to be used with the FDMC. The simulation study considering the different scenarios is presented in Section 5. Conclusions are given in Section 6.

2. DTC interpretation of DMC

As stated in the introduction, the DMC algorithm can be analyzed through a particular Dead-Time Compensator (DTC) structure, the Filtered Smith-Predictor (FSP). This is important because it will allow the improvement of closed-loop disturbance rejection or robustness of the DMC using many known tuning guidelines of the FSP [20].

The FSP is presented in Fig. 1, and it comprises a primary controller $C(z)$ and a predictor structure. The primary controller is tuned considering the dead-time-free nominal model of the process. The dead time is compensated by the predictor structure, which uses the process model to predict the output after the dead-time. The difference between the classical SP and the FSP is the addition of the prediction error filter $F_r(z)$, which can be tuned to change the closed-loop properties, as will be seen in Sections 2.3 and 2.4. For the sake of simplicity, and since the process model dealt with in this paper is SISO, only the monovariable case will be discussed here. The MIMO case is better described in [16]. The variables of Fig. 1 are the process output $y(t)$, the control action $u(t)$, the disturbance $n(t)$ and the set-point $r(t)$. The dynamics between the disturbance and the output is represented by $P_p(z)$. Note that if $P_p(z) = P(z)$, then $n(t)$ becomes an input disturbance. The nominal process model is $P_n(z) = G_n(z)z^{-d_n}$, where $G_n(z)$ is the dead-time-free nominal model and d_n is the nominal dead time.

The transfer functions that represent the nominal dynamics of the FSP are

$$\frac{Y(z)}{R(z)} = \frac{C(z)P_n(z)}{1 + G_n(z)C(z)}, \tag{1}$$

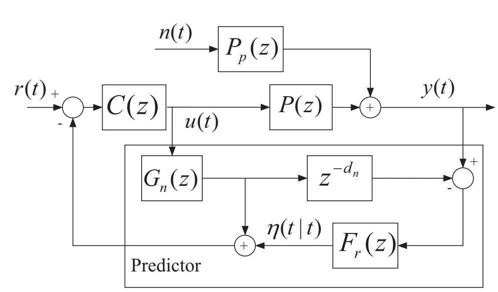

Fig. 1. Structure of the FSP.