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Gain-scheduling model predictive control of a Fresnel collector field

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ABSTRACT

Model predictive control strategies have been applied successfully when controlling solar plants. If the control algorithm uses a linear model associated only to an operating point, when the plant is working far from the design conditions, the performance of the controller may deteriorate.

In this paper, a gain scheduling model predictive control strategy is designed for the Fresnel collector field located at the Escuela Superior de Ingenieros de Sevilla. Simulation results are provided comparing the proposed strategy with another linear MPC controller showing a better performance. Furthermore, two real tests are presented showing the effectiveness of the proposed strategy.

1. Introduction

Interest in renewable energy sources such as solar energy experienced a great impulse after the Big Oil Crisis in the 70 s. Driven mainly by economic factors, this interest decreased when oil prices fell. Nowadays, there is a renewed interest in renewable energies spurred by the need to reduce the environmental impact produced by the use of fossil energy systems (Camacho & Berenguel, 2012; Goswami, Kreith, & Kreider, 2000). Solar energy is, by far, the most abundant source of renewable energy. In fact, wind and most of the hydraulic energies come from solar energy (Camacho & Gallego, 2013).

Many solar energy plants have been commissioned in the last 15 years. The three 50 MW Solnova and the two 50 MW Helioenery parabolic trough plants of Abengoa in Spain can be mentioned as examples, as well as the SOLANA and Mojave Solar parabolic trough plants constructed in Arizona and California, each of 280 MW power production (Yield, 2017). Examples of solar tower plants are plants PS10 and PS20 in Southern Spain of 10 MW and 20 MW respectively. In 2016, the 50 MW solar tower plant Khi Solar One operated by Abengoa Solar was commissioned in South Africa (Abengoa, 2017).

One of the main applications of solar energy is the production of electricity. For example, in parabolic trough plants the solar radiation coming from the sun is focused onto a metal tube where a fluid is circulating. The fluid is heated up and then used in a steam generator to produce electricity (Camacho, Berenguel, & Rubio, 1997; Camacho, Samad, Garcia-Sanz, & Hiskens, 2011). Another application of solar energy is the supply of air conditioning in buildings. The interest in solar cooling systems has been increasing for several decades, driven by the fact that the need for air conditioning is usually well correlated to solar radiation (Kima & Infante-Ferreira, 2008; Sonntag, Ding, & Engell, 2008).

This paper deals with the control of a Fresnel collector field which belongs to the solar cooling plant located on the roof of the Engineering School (ESI) of Seville (Bermejo, Pino, & Rosa, 2010). The plant was commissioned in 2008, consisting of a Fresnel collector field, a double effect LiBr+ water absorption chiller and a storage tank. The Fresnel collector delivers pressurized water at 140–170 °C to the absorption machine for producing air conditioning. If solar radiation is not high enough for heating the water up to the required temperature, the storage tank may be used. If neither the solar field nor the storage tank are able to heat up the water to the operation temperature, the absorption machine must resort to burning natural gas.

In Witheephanich, Escano, Gallego, and Camacho (2013) and Witheephanich, Escano, and Bordóns (2014) possible control approaches for this kind of plant are discussed, showing simulation results of the application of an explicit model predictive control. Similar facilities have been deployed in other places (Döll, Bentaher, & Mongerstern, 2014; Zhou, Li, Zhao, & Dai, 2017).

Regarding similar applications for buildings, in Berger et al. (2012) a prototype of a linear Fresnel collector providing the driving heat at temperatures up to 200 °C for two cascading ammonia water absorption chillers is presented, including some experimental tests defocusing collectors. In Häberle et al. (2007), a linear concentrating Fresnel collector is used to drive an NH3-H20 absorption chiller, without including control issues.

Fresnel collectors are also used to feed an Organic Rankine Cycle with storage in Rodat, Souza, Thebault, Vuillerme, and Dupassieux (2014). The solar plant is simulated using both oil and water/steam

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as heat transfer fluid. Simulations with Dymola using Modelica code are provided. Operating experiences are included in Rodat, Bruch, Dupassieux., and El-Mourchid (2015) using cascade PI control and a reference governor. An interesting application of building integration of Fresnel concentrators for solar cooling applications can be found in Chemisana, López-Villada, Coronas, Rosell, and Lodi (2013).

The control objective in this kind of plant is to maintain the outlet temperature of the solar field around a desired set-point (Berenguel et al., 2005). Many works related to the control of solar plants have been developed and published since 1980. Most of them were tested in the parabolic trough ACUREX solar collector field. This trough plant consisted of a field of solar collectors, a heat storage system and an electrical conversion unit (0.5 MW Stal Laval turbine) (Carmona, 1985). In Camacho, Rubio, Berenguel, and Valenzuela (2007a,b) and Rubio, Camacho, and Carmona (2006) a review of different control strategies applied to the ACUREX plant is presented. Moreover, the books by Camacho and co-workers (Camacho, Berenguel, Rubio, & Martínez., 2012) and Lemos and co-workers (Lemos, Neves-Silva, & Igreja, 2014) overview different approaches related to predictive and adaptive control of this kind of system. Since a solar collector field is affected by multiple disturbance sources and its dynamics change strongly with the operating conditions (Pin, Falchetta, & Fenu, 2007), conventional linear control strategies do not perform well throughout the entire range of operation, thus requiring the application of nonlinear control strategies many of them treated in Camacho et al. (2012) and Lemos et al. (2014).

In this paper a gain scheduling generalized model predictive control (henceforth GS-GPC) for a Fresnel plant is developed. Gain scheduling is a control technique where process dynamics can be associated to the value of some process variables related, in this case, to the operating point, so that the controller parameters can be computed from these variables. In Camacho et al. (2007b), there is a section devoted to gain scheduling summarizing the main approaches already used in the field, mainly using the actual oil flow as scheduling variable. Regarding MPC, different control approaches have also been applied in this scope and summarized in Camacho et al. (2007b), Camacho et al. (2012) and Lemos et al. (2014). As recent examples, with applications to the ACUREX field, in Limon, Alvarado, Alamo, Ruíz, and Camacho (2008) a robust MPC for tracking was designed, while in Gallego, Fele, Camacho, and Yebra (2013), an observer based MPC was developed and tested. Andrade, Pagano, Álvarez, and Berenguel (2013) developed a practical nonlinear MPC. More recently, in Khoukhi, Tadjine, and Boucherit (2015) a nonlinear continuous time generalized predictive control (GPC) is developed and tested only in simulation.

The main contribution of this paper is the development of a gain scheduling model predictive control for a Fresnel collector field. The approach is similar to that proposed in Camacho, Berenguel, and Rubio (1994) for a parabolic trough solar field. However there are some significant differences which are listed below:

1. The model developed is different because the controller is applied to a different type of plant. This plant is based on a Fresnel collector and not on a parabolic trough and uses water as heat transfer fluid instead of oil.
2. In the approach developed in Camacho et al. (1994), the unconstrained GPC problem was solved for 4 values of the flow. The controller gains were obtained for these four points and the control scheme interpolated the controller gains. In the MPC controller developed in this paper, the interpolation is done for the parameters of the linear model not for the solution of the GPC problem. Furthermore, the approach proposed in Camacho et al. (1994) does not solve a constrained GPC problem, as in this case. The main drawback of using the interpolation between the controller parameters is that it provides an approximation to the global solution of the optimization problem, but for the unconstrained case. It uses the explicit solution of the GPC problem for the four considered points and interpolates among them. The approach used here, interpolating between the linear model parameters allows constraints in the GPC optimization problem to be taken into account in an easy way, and to be solved using a QP algorithm.
   A simulation to compare the performance of the two approaches (for the unconstrained case) has been included. The one proposed here performs slightly better as is shown in Section 5.
3. Additionally, the unconstrained GPC problem has been solved for several water flow levels considering the actual linear model associated to every point (obtained by a least square identification method). The evolution of some of the optimal controller parameters is compared to the evolution obtained by the approach presented here and the one proposed in Camacho et al. (1994). The approach proposed here is closer to the optimal evolution, especially at low flow levels.
4. Moreover, in this paper an estimation of the efficiency loss produced by the miscalibrated mirrors is carried out for the real tests. This estimation is useful for the feedforward controller which uses a better optical efficiency estimation.

Table 1
List of abbreviations.

GPC	Generalized Model Predictive Control
GS-GPC	Gain-Scheduling Model Predictive Control
HTF	Heat Transfer Fluid
ISE	Integral of the Square Error
ITAE	Integral of Time multiplied by Absolute Error
MF-GPC	Medium-Flow Generalized Model Predictive Controller
MPC	Model Predictive Control
PCM	Phase Change Material
PDE	Partial Differential Equation
PRBS	Pseudo random binary sequence

The GS-GPC control strategy developed in this paper is tested using a nonlinear distributed parameter model and compared to a GPC designed for medium flow conditions (MF-GPC), showing its advantages. Two real tests carried out at the actual plant are also shown and discussed.

The paper is organized as follows: Section 2 briefly describes the solar cooling plant. Section 3 presents the mathematical model of the Fresnel collector field used in this paper. Section 4 describes the design process of the proposed control strategy. Section 5 presents the simulation results and the real tests performed at the actual plant. Finally, Section 6 draws to a close with concluding remarks.

2. Brief plant description

The solar cooling plant was commissioned in 2008 and consists of three subsystems: the double-effect LiBr+ water absorption chiller of 174 kW nominal cooling capacity. The solar Fresnel collector field which heats up the pressurized water and delivers it to the water absorption chiller. The PCM storage tank which helps to supply energy to the water to reach the required operation temperature whenever the solar field is not able to reach it. Fig. 1 shows the scheme of the whole plant.

Water absorption chiller. Normalfont this is a double-effect cycle LiBr + absorption machine with 174 kW and a theoretical COP of 1.34, which transforms the thermal energy (hot water at 140–170 °C) coming from the Fresnel solar field or the PCM storage tank, into cold water to be used by the ESI of Seville (Bermejo et al., 2010). Apart from the hot water, a cooling fluid for the condenser is needed in the absorption machine. This is obtained from the water catchment of the Guadalquivir river.

Solar field. The solar field consists of a set of Fresnel solar collectors (see Fig. 2) which concentrate solar radiation onto a line where a 64 m long absorption tube is located. The energy is transferred to a heat transfer fluid (in this case, pressurized water).