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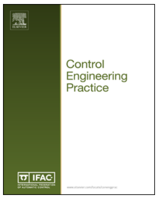

Nonlinear controllers for solar thermal plants: A comparative study

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ABSTRACT

Solar plants have nonlinear dynamics which must be taken into account when a control system is applied to them. The main purpose of the control systems is to maintain the outlet temperature in a desired reference value and, at the same time, attenuate the undesirable transients caused by the disturbances. Linear controllers, like PID ones, are not able to obtain good performance over the whole operation range of these kind of plants. To overcome these limitations two nonlinear controllers, a nonlinear model-based predictive controller and a distributed sliding mode controller, are applied to a solar plant in this work. The performance of these controllers is tested through experimental and simulation results, which show the tracking and disturbance rejection capabilities of the proposed controllers.

1. Introduction

Over the past decades, the use of renewable energy has been receiving attention of scientific community and government agencies. The increment in the greenhouse gases and industrial process emissions, and the accelerated consumption rate of fossil fuel sources are the main factors leading to the use of such kind of processes. Among the different renewable energy sources, solar energy is showing to be the most technically feasible (Graef, 1991; Krauter & Rüther, 2004). Disregarding indirect solar alternatives, there are two main classes of solar plant: (i) based on photovoltaic technology and (ii) based on solar thermal technology. Additionally, solar thermal plants have the significant advantage of being able to store the excess of thermal energy produced for future purposes, turning them more competitive against fossil fuels plants (Camacho, Berenguel, Rubio, & Martínez, 2012).

A solar thermal plant can be described as a system where the solar energy is collected, then concentrated, and transferred to a thermal fluid. The main source of power, which is the solar radiation, cannot be manipulated and its availability presents several limitations due to cloud transients. Even further, the dynamics of a solar plant is highly dependent upon the operating conditions, which can change widely. From a control point of view, these plants are characterized by distributed parameters (partial differential equations), nonlinearities and uncertainties. Therefore, PID (Proportional-Integral-Derivative) controllers are not the most appropriate to obtain a satisfactory closed-loop performance in the whole operating range of the solar plant. To this aim, the feedback control scheme implemented on such process must incorporate a nonlinear mechanism to operate effectively.

Many advanced control strategies have been developed to be applied to solar plants, the results have been summarized in Lemos, Neves-Silva, and Igreja (2014), Camacho et al. (2012), and Camacho, Rubio, Berenguel, and Valenzuela (2007a, 2007b). Simple control laws based on lower order transfer function models are used if the desirable control bandwidth is not too stringent. Whereas nonlinear controllers provide performance and robust stability improvements in the whole operation range, but at cost of increasing the controller complexity design and, consequently, the computational cost. Classical nonlinear control techniques, such as feedback linearization and sliding mode control, are difficult to be applied on solar thermal plants due to their infinite dimensional nature. Most of the results presented in literature are based on the spatial discretization of the original set of partial differential equations (PDEs) to obtain a set of ordinary differential equations (ODEs). However, spatial discretization techniques may result in loss of relevant dynamics and always raises the question on the discretization efficiency (Christofides, 2001). In this way, the resulting controller may lead to a poor control quality. On the other hand, nonlinear model-based predictive control (NMPC) algorithms have been used with success in the control of solar plants and several industrial applications (Qin & Badgwell, 2003). The main advantages of these algorithms are their constraints

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handling capability and the possibility of using accurate nonlinear models to calculate the control action, improving the overall system performance.

In this work, two nonlinear controllers with different control principles are presented to deal with the solar thermal plants control problem. The first one is the practical nonlinear model-based predictive control (PNMPC) algorithm. This control strategy allows the designer to use any kind of nonlinear model and it includes a Lyapunov function in the cost function to guarantee the closed-loop system stability and set-point tracking for the typical modeling errors present in solar thermal plants (Andrade, Pagano, Álvarez, & Berenguel, 2013). The second nonlinear control strategy is the distributed sliding mode control (DSMC), presented in Andrade, Pagano, Álvarez, and Berenguel (2014) and Sira-Ramirez and Rivero-Mendonza (1990). The main idea of this control strategy is the combination of the method of characteristics (Alinhac, 2009) with sliding mode control. The method of characteristics is used to transform the PDE model into a system of ODEs without approximation. Then, the control design is performed in this set of ODEs instead of the original distributed parameter system. Moreover, due to the fact that the actuators of solar thermal plants (mainly pumps) cannot deal with the switching action characterized by this control technique, a smooth control law is developed based on the concept of equivalent control (Hung, Gao, & Hung, 1993).

To evaluate a quantitative study on the performance of the two proposed controllers, experimental tests were conducted on a solar collector field installed on a building and also, simulation studies considering several scenarios together with performance indexes are presented. Thus, the main contribution of this paper is a comparative study, through experimental and simulation results, of the two nonlinear controllers proposed in this work operating on a solar thermal plant.

The paper is organized as follows: Section 2 briefly explains the solar thermal plant, the control problem and the mathematical model of the system. The theory used for the synthesis of the PNMPC and DSMC controllers is presented in Sections 3 and 4, respectively. A comparative study, based on simulation results and experimental tests, is presented in Section 5 and the discussion of the obtained results is shown in Section 6. The concluding remarks are summarized in Section 7.

2. Solar collector field

The solar collector field used to test the automatic control strategies is located at the CIESOL (Centro de Investigación de la Energia Solar, in Spanish) building, a Solar Energy Research Center in the University of Almería, Spain. The CIESOL building is shown in Fig. 1.

Basically, the solar energy facility is composed of a solar flat collector field installed in the roof of the building, two tanks used for hot water storage, and a gas heater as auxiliary heat source. These elements are connected by a net of pipes, including three-way valves to modify the operation mode and a variable radial pump setting the flow rate. The energy generated by the heat generation process is applied to an absorption cooling unit in order to obtain chilled water (Pasamontes, Álvarez, Guzmán, Lemos, & Berenguel, 2011). Since the focus of this paper is the control of the outlet temperature of the solar collector field, just such subsystem is considered to be described in this work. The interested reader can find more details of the whole plant in Pasamontes, Álvarez, Guzmán, Berenguel, and Camacho (2013). A diagram representing the solar energy facility is shown in Fig. 2.

The solar collector field has total surface of 160.2 m^2. Its main purpose is to increase the temperature of the fluid to provide the desired outlet temperature in an operating range between 50 °C and 100 °C. The main disturbances are the inlet and ambient temperature variations, and abrupt changes of the solar irradiance. The controlled variable is the mean outlet temperature of the solar collector field and the control variable is the fluid velocity/flow provided by a pump which flow range goes from 2.5 to 11 $\mathrm{m}^3\,\mathrm{h}^{-1}$.

2.1. Dynamic model

The modeling of the solar thermal system of the CIESOL building was firstly presented in Pasamontes et al. (2013). The subsystem of the solar collector field has been modeled by two coupled hyperbolic PDEs, one for the collector plate and one for the thermal fluid (water).

The equations for collector plate and for the thermal fluid are defined respectively as

$$\rho_m C_m A_m \frac{\partial T_m}{\partial t}(t,x) = \eta_o G I(t) - D_0 \pi h_l (T_m(t,x) - T_a(t)) - D_i \pi h_t (T_m(t,x) - T_f(t,x)), \tag{1}$$

$$\rho_f C_f A_f \frac{\partial T_f}{\partial t}(t,x) + \rho_f C_f u(t) \frac{\partial T_f}{\partial x}(t,x) = D_i \pi h_t (T_m(t,x) - T_f(t,x)). \tag{2}$$

Since the objective in solar thermal plants is to maintain the outlet temperature in a desired reference value, the system output is defined as

$$y(t) = T_f(t, L). \tag{3}$$

All the parameters and variables are described in Table 1.

For numerical simulation of system (1)–(2), the space was divided in N sections and the space derivative was written using a finite difference scheme. An ODE solver is used to obtain the system solution. The model calibration was performed by comparison of the real data with the simulation responses obtained using estimated parameter values. These parameter values were determined by a genetic algorithm fitting the integral of squared error (ISE) criterion. For more details about the model calibration and validation procedure the interested reader is referred to Pasamontes et al. (2013).

Fig. 3 shows the outlet temperature of the model compared to real experimental data. The model was simulated with data of the real closed-loop system. The model tends to the real system temperature with a maximum discrepancy of ±2 °C. The reader can notice that the behavior of the nonlinear distributed parameter model is very similar to that of the plant in different situations.

Fig. 1. The CIESOL building (Camacho et al., 2012) showing two pictures corresponding to the accumulation tanks and solar collector field.