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# Optimal control applied to distributed solar collector fields with partial radiation[☆]

Sergio J. Navas[a,*], Francisco R. Rubio[a], Pedro Ollero[b], João M. Lemos[c]

[a] Departamento de Ingeniería de Sistemas y Automática, Universidad de Sevilla, Spain
[b] Departamento de Ingeniería Química y Ambiental, Universidad de Sevilla, Spain
[c] INESC-ID, Instituto Superior Técnico, University of Lisbon, Portugal

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## ABSTRACT

This paper describes and assesses two strategies to control distributed solar collector fields, especially during days with partial radiation due to the passage of clouds. The main objective of these control strategies is to maximize the electrical power generated during different situations in which different parts of the solar field receive different degrees of solar radiation. Simulations were carried out using two connected models, one for the solar field (taking into account all of its loops), that includes the passage of clouds, and another one for the power cycle. The solar field simulated is a pilot plant, in which it is assumed that all the loops have the same characteristics; and the nominal power range of the Rankine cycle is 800–2330 kW. Finally, the improvement in electrical power achieved by both strategies is compared with a typical control strategy that tries to keep constant the outlet oil temperature of the field. This improvement varies between 4% for clear days and 5.7% for cloudy days.

## 1. Introduction

The main technologies for converting solar energy into electricity are photovoltaic (PV) and concentrated solar power (CSP). Parabolic trough, solar towers, Fresnel collector, and solar dishes are the most used technologies for concentrating solar energy. This paper focuses on parabolic trough solar fields, that consist of a collector field (Fig. 1), a power cycle, and auxiliary elements such as pumps, pipes, and valves. The solar collector field collects solar radiation and focuses it onto a tube in which a heat transfer fluid, such as synthetic oil, circulates. The oil is heated up and then used by the power cycle to produce high pressure steam in a boiler, and electricity by expanding it in a turbo-generator.

The main goal of a parabolic trough solar field is to collect solar energy in order to produce as much electrical power as possible. Normally, most of the solar thermal power plants try to achieve this objective by keeping the outlet oil temperature of the field around the maximum allowable value, that in this case is 400 °C, imposed to prevent oil degradation. However, some studies like (Lippke, 1995; Camacho and Gallego, 2013) show that this way to operate the field does not produce the best results of electrical power generated. In Lippke (1995) it was suggested that the optimum strategy is based on adapting the oil outlet temperature to the incident solar radiation, keeping constant the superheating temperature of the steam, whereas in Camacho and Gallego (2013) it was proposed to change the outlet temperature set point according to the value of the solar radiation. Therefore, in Lippke (1995) the controlled variable is the superheating temperature, while in Camacho and Gallego (2013) it is the oil outlet temperature. In this paper the issue of controlling optimally a field with partial radiation is handled, and to do so an entire field model is used in order to take into account not only the total incident radiation, that is the case of Camacho and Gallego (2013) and Lippke (1995), but as well its distribution among each of the loops that constitute the solar field. With this model it is possible to simulate each loop of the field, instead of simulating only one of them and supposing that the behavior of the entire field is the same.

The use of a solar field model that individually takes into account all its loops was proposed in Abutayeh et al. (2014), but it was used to test a control strategy based on maximizing the outlet oil temperature of the field, which as said before it is not the optimal way to produce the maximum electrical power. However, in this paper this type of field model is used to compare two control strategies whose main objective is to maximize the electrical power, especially during days with partial covering. Both strategies consist of MPC controller, that uses

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[*] Corresponding author.
*E-mail addresses:* snavas1@us.es (S.J. Navas), rubio@us.es (F.R. Rubio), ollero@us.es (P. Ollero), jlml@inesc-id.pt (J.M. Lemos).

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**Fig. 1.** ACUREX distributed solar collector field.

predictions of the future clouds together with the collector field and power cycle models, although they differ in their number of manipulated variables. While one of the strategies proposed manipulates the total oil flow, which is then equally distributed among the loops, the other manipulates individually the oil flow circulating through each loop. With both strategies, an improvement of the electrical power generated is achieved, compared to the strategy of keeping constant the outlet oil temperature; however, it will be seen that the strategy that manipulates individually the flow of each loop does not produce a remarkable improvement compared to the one that manipulates the total flow.

The paper is organized as follows: Section 2 describes the models of the solar field, passing clouds and power cycle used for simulation purposes. Section 3 describes both control strategies tested: the global strategy, that consists of an MPC controller with only one manipulated variable (total oil flow) and the distributed strategy, that consists of an MPC controller with 24 manipulated variables (oil flow through each loop). Section 4 shows the results obtained by simulations made in MATLAB. Finally, the paper draws to a close with some concluding remarks.

## 2. System modeling

The model of each of the parts that have been used to simulate the operation of a solar field during days with partial covering is presented hereafter. These parts are: the solar collector field, the passage of the clouds, and the power cycle.

### 2.1. Solar collector field model

The model of the solar collector field is the same used in Navas et al. (2016, 2017), being at the same time a slight modification of the model proposed by Camacho et al. (1997, 2007a,b, 2012), Carmona (1985) for the ACUREX field (Fig. 1). Basically, this model can be used to simulate parabolic trough solar fields by selecting parameters like the number of active (the parts where the solar radiation reaches the tube) and passive (joints and other parts not reached by concentrated solar radiation) zones, the length of each zone, or the collector aperture. The solar field simulated in this paper is modeled using solar radiation data that correspond to the site of the Escuela Técnica Superior de Ingeniería de Sevilla. It is composed of 24 loops and has dimensions of 144 × 240 m. Each loop is modeled by the following system of partial differential equations that describe the energy balance:

Active zones

$$\rho_m C_m A_m \frac{\partial T_m}{\partial t} = I n_0 G - H_l G (T_m - T_a) - d H_t (T_m - T_f), \tag{1}$$

Fluid element

$$\rho_f C_f A_f \frac{\partial T_f}{\partial t} + \rho_f C_f \dot{q} \frac{\partial T_f}{\partial x} = d H_t (T_m - T_f), \tag{2}$$

Passive zones

$$\rho_m C_m A_m \frac{\partial T_m}{\partial t} = -G H_p (T_m - T_a) - d H_t (T_m - T_f), \tag{3}$$

where the sub-index $m$ refers to metal and $f$ refers to the fluid. The model parameters and their units are shown in Table 1.

The density $\rho$ and specific heat $C$ depend on the fluid temperature (Camacho et al., 1997). The coefficient of heat transmission $H_t$ depends on temperature and oil flow (Camacho et al., 1997). The incident solar radiation $I$, that includes the cosine and incident angle modifier effects, depends on hourly angle, solar hour, declination, Julianne day, and local latitude Camacho et al. (1997, 2007a,b, 2012), Carmona (1985). The pipe has a length of 480 m (432 m of active zones and 48 m of

**Table 1**
Solar field model parameters and variables description.

| Symbol | Description | Units |
|---|---|---|
| $t$ | Time | s |
| $x$ | Space measured along the tube | m |
| $\rho$ | Density | kg/m$^3$ |
| $C$ | Specific heat capacity | J/(K kg) |
| $A$ | Cross sectional area | m$^2$ |
| $T$ | Temperature | °C |
| $\dot{q}$ | Oil flow rate | m$^3$/s |
| $I$ | Solar radiation | W/m$^2$ |
| $n_0$ | Optical efficiency | Unit-less |
| $G$ | Collector aperture | m |
| $T_a$ | Ambient Temperature | °C |
| $H_l$ | Global coefficient of thermal losses for active zones | W/(m$^2$ °C) |
| $H_t$ | Coefficient of heat transmission metal-fluid | W/(m$^2$ °C) |
| $H_p$ | Global coefficient of thermal losses for passive zones | W/(m$^2$ °C) |
| $d$ | Pipe diameter | m |