Solar Energy 165 (2018) 1–9

Contents lists available at ScienceDirect

Solar Energy

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

Temperature homogenization of a solar trough field for performance improvement

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ARTICLE INFO

Keywords:
Online nonlinear optimization
Model Predictive Control
Solar trough
Regression Trees

ABSTRACT

Optimal operation of solar plant is a challenge due to the multiple disturbances affecting the plant. Research in optimal temperature set-point tracking is extensive whereas research concerning optimal power production under disturbances is not.

A solar plant has to deal not only with temperature and radiation disturbances but also with dirt accumulated on the collectors which lead to a great disparity in collectors reflectivity. Cleaner collectors produce higher output temperature because of the higher reflectivity. In fact the temperature in this collector may be so high that they have to be defocused with the corresponding energy losses. The paradox is that the most efficient loops may be the one collecting less energy because of defocusing. This paper proposes a new solution based in the manipulation of the loops input valves in order to homogenize the temperatures of the different loops and avoid defocusing.

The paper presents an original non linear model based optimization to homogenize the loop temperatures by manipulating the inlet valves of the loops. The nonlinear model is based on a distributed parameters model. In order to perform the optimization, temperature profiles of the loops and its reflectivities are needed. These are obtained by means of a Classification and Regression Trees (CARTs) trained with the full distributed parameters model. Simulations are carried out using a model of the Plataforma Solar de Almería (PSA) solar trough plant to show the results of the proposed control scheme, temperature homogenization and production benefit.

1. Introduction

The use of renewable energies had a boost in the second half of the 70s after the first oil crisis although the main reason for the interest in renewable energies was economic. Currently, and driven by global warming, there is a global awareness to search for inexhaustible sources of energy. Solar is the most abundant source of renewable energy in the world.

In the last decade, several Concentrated Solar Plant (CSP) have been built around the world. Examples of commercial CSPs currently producing are: Solaben 50 MW CSPs (220 hectares, 90 loops) (Solaben 2, 2017), 50 MW Andasol solar plants (Solar Millennium AG, 2017), Solana CSP (Arizona, USA) with a gross turbine capacity of 280 MW and molten salts thermal energy storage (777 hectares, 808 loops) (Solana Generating Station, 2017) and Khi Solar One in South Africa (operational since 2016) (Khi Solar One, 2017). The possibility of using thermal energy storage is an added advantage of CSP over other renewable technologies (Wittmann et al., 2008; Gil et al., 2010; Camacho et al., 2011). Thermal energy storage is usually done using molten salts which are currently used in Solana and in Kaxu 100 MW CSP located in Pofadder, South Africa (Kaxu Solar One, 2017).

The main objective of the control systems in solar trough plants is to maintain the outlet temperature of the field around a desired set-point. While in conventional fossil fuel power generating processes the main source of energy (the fuel) can be manipulated as the main control variable. Furthermore, the main source of energy itself is considered as a disturbance since the plant controller will have to deal with radiation transients due to clouds.

Research to improve the performance of solar power plants from the control and optimization point of view has been addressed in many ways. Most of them have been implemented and tested at the ACUREX plant, a parabolic trough field plant, for research and experimentation purposes, located in Almería, Spain (Camacho et al., 1992; Silva et al., 1997; Igreja et al., 2003; Camacho et al., 2007a; Camacho et al., 2007b). Research in solar fields control is extensive and covers both linear and nonlinear control methods for tracking the outlet temperature of the field.

Within the Model Predictive Control (MPC) it can be found, inter

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https://doi.org/10.1016/j.solener.2018.03.001
Received 24 August 2017; Received in revised form 27 February 2018; Accepted 1 March 2018

alia, an adaptive MPC to control a parabolic solar trough plant in Gallego and Camacho (2012), a Gain-Scheduled Control of solar power plant is design in Johansen et al. (2000), Alsharkawi and Rossiter (2017), and in Gallego et al. (2013) an Observer-based Model Predictive Control is developed. Lima et al. (2016) presents a filtered Dynamic Matrix Control (FDMC) where a filter is used for the prediction error so that the robustness of the control strategy is ensured applied to a solar collector field and Alsharkawi and Rossiter (2016) proposes a Dual mode MPC for a concentrated solar thermal power plant based on an estimated linear time-invariant state space model around a nominal operating point. Within the nonlinear MPC, in Andrade et al. (2013) a non linear MPC with robustness of stability ensured by using a Lyapunov criterion is presented and in Gil et al. (2014) a Neural Network based MPC and Kalman Filter weighting computation is proposed for a distributed collector field.

ACUREX solar field can be considered as one single collector loop, though is formed by 10 loops, to obtain an overall dynamic model of the complete system in order to design a controller for tracking a setpoint on the outlet temperature of the field (which will be the weighted average temperature of the 10 loops). In Cirre et al. (2009) a multilayer control strategy is proposed for solar trough plants which uses a lumped description of the solar field to solve the temperature tracking problem. When developing a control strategy based on an overall dynamic model, either lumped or distributed parameters model, certain parameters can be considered constant for all loops, such as reflectivity, efficiency of the receiver tubes or the shape factor of the collector. It is possible to approximate the full dynamics of the field by a single loop when considering constant these parameters. Even if these parameters are not the same in all loops, i.e. reflectivity, a well-designed controller can continue performing a good field outlet temperature tracking at the cost of having some loops at higher temperatures than others. For example in Camacho and Gallego (2013), a procedure to obtain the best working temperature is presented. In this work, the ACUREX solar field is considered a lumped model for the calculation of the optimal setpoint.

If the plant is required to work at a high average temperature, which usually happens with high levels of solar radiation, a situation where some loops work at a much higher temperature than the rest of the field may appear. This problem is produced mainly by two facts: (a) these loops are more efficient than the rest of the field and (b) the input valves of the solar field are not well balanced so that the flow is not equally distributed (loops with low flow are hotter than loops with high flow levels). If the temperature of hotter loops exceeds the safe limits of the thermal fluid, the collectors have to be defocused to reduce the fluid temperature leading to energy losses. The main motivation of this work is the research of new control strategies for performance improvement, in terms of power production, in solar trough plants under disturbances.

In this work, an online nonlinear model based optimization to control the loop's inlet valves in parallel with a linear global dynamic model based Gain-Scheduling Generalized Predictive Control (GS-GPC) for the tracking of the outlet temperature of the field is proposed. The global GS-GPC controller, manipulating the flowrate, is responsible for the control of the outlet temperature of the field while the nonlinear optimization will include a nonlinear distributed parameter simplified model of each of the loops to control the aperture of the inlet valves in order to obtain a field temperature homogenization to achieve a power production improvement when the solar field is not well balanced.

This paper is organized as follows: In Section 2 the ACUREX field and mathematical models that have been used are described. In Section 3, a GS-GPC control scheme is explained as well as a Feed-Forward in series. Temperature profiles estimations using CARTs and the proposed nonlinear optimization to obtain a temperature homogenization of the field is described in Section 4. Simulation results are presented in Section 5. Finally, in Section 6, the paper draws to a close with some concluding remarks and future work.

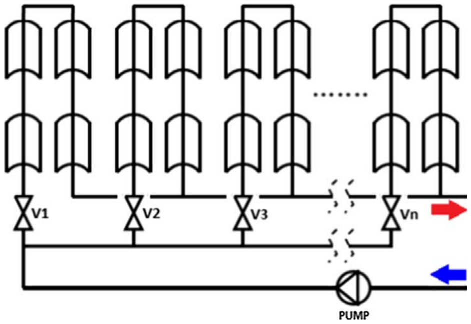

Fig. 1. Acurex field schematic.

2. ACUREX solar trough field

The ACUREX field, located at the Plataforma Solar de Almería, consists of 480 parabolic trough collectors. The collectors are arranged in 10 loops, each one composed of two rows of 12 modules. The total length of each loop is 172 m, which comprises active parts (142 m) and passive parts, i.e. joints and other parts not reached by concentrated radiation (30 m).

In this paper two types of model are proposed for the plant: a concentrated parameter model will be used in the feed-forward module of the control loop, and a distributed parameter model will be used for simulation purposes. Both models have been obtained through tests and validations conducted at the plant and have been used by many authors. A schematic of the plant is shown in Fig. 1. For a complete description of the plant and the modeling procedure, refer to Carmona (1985), Camacho et al. (1997).

2.1. Distributed parameters model

The dynamics of the distributed solar collector field are described by the following system of partial differential equations (PDE) describing the energy balance (Carmona, 1985; Camacho et al., 1997):

$$\rho_m C_m A_m \frac{\partial T_m}{\partial t} = IK_{opt} n_o G - H_l G(T_m - T_a) - LH_t(T_m - T_f) \tag{1a}$$

$$\rho_f C_f A_f \frac{\partial T_f}{\partial t} + \rho_f C_f \dot{q} \frac{\partial T_f}{\partial x} = LH_t(T_m - T_f) \tag{1b}$$

where the subindex m refers to the metal and f refers to the fluid. The model parameters and units are shown in Table 1.

The geometric efficiency depends on hourly angle, solar hour, declination, day of the year, local latitude and collector dimensions. The density ρ, specific heat C and coefficient of heat transmission H_t depend

Table 1
Parameters description.

Symbol	Description	Unit
t	Time	s
x	Space	m
ρ	Density	kg/m^3
C	Specific heat capacity	J/(kg °C)
A	Cross sectional area	m^2
$T(x,y)$	Temperature	°C
$T_a(t)$	Ambient Temperature	°C
$q(t)$	Oil flow rate	m^3/s
$I(t)$	Solar radiation	W/m^2
n_o	Geometric efficiency	Unitless
K_{opt}	Optical efficiency	Unitless
G	Collector aperture	m
H_l	Global coefficient of thermal loss	W/(m^2 °C)
H_t	Coefficient of heat transmission metal-fluid	W/(m^2 °C)
L	Length of pipeline	m