Solar Energy 160 (2018) 117–129

Contents lists available at ScienceDirect

Solar Energy

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

On the optimization of flux distribution with flat receivers: A distributed approach

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ARTICLE INFO

Keywords:
Solar energy
Solar flux
Distributed optimization
Solar tower

ABSTRACT

One of the most important problems in the operation of solar power towers is to achieve a uniform flux density distribution at the receiver in order to avoid hot spots. The problem can be solved by computing the aim points of the heliostats by optimizing a function which measures the uniformity of the flux density over the receiver.

Due to the high number of heliostats of current commercial plants (more than 900), the number of decision variables (1800) makes the centralized approach very difficult to be implemented in real time.

In this paper, a distributed optimization algorithm that computes the aim points for the heliostat field to obtain a uniform flux density distribution and maximize the solar irradiation collected by the receiver is presented. The algorithm is tested using a model of the heliostat field of the CESA-1 solar tower plant at the Plataforma Solar de Almería (PSA) in southern Spain. Simulation results show that substantial reduction of the computational time is achieved while similar performance to that obtained with the centralized approach is attained.

1. Introduction

Interest in renewable energy sources such as solar energy experienced a great impulse after the Big Oil Crisis in the 70s. 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 (Goswami et al., 2000; Camacho and Berenguel, 2012). 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 and Gallego, 2013).

This paper deals with the operation of solar tower plants. A solar tower plant consists of a field of mirrors (*heliostats*) arranged around a tower equipped with a solar irradiation receiver. By tracking the sun, the heliostats focus the solar irradiance onto the receiver. The field can be composed of a large number of heliostats (more than 900 in recent commercial plants (AbengoaSolar, 2011), each of which is independently controlled (Gallego et al., 2014).

Solar power towers operate at higher temperatures at the receiver (700–800 °C with metal receivers and higher than 1000 °C with ceramic receivers) than parabolic trough plants (ranging from 400 °C to 550 °C depending on the fluid used). In general, operation at higher temperatures results in larger throughputs and cheaper thermal energy storage (Romero et al., 2002).

One of the most important problems when operating solar tower plants is to achieve a uniform flux distribution on the receiver. The simplest strategy is to point all the heliostats at the center of the receiver to minimize energy loss by spillage of uncalibrated heliostats (Camacho et al., 2012). However, this strategy may cause an improper flux distribution, producing undesirable thermal gradients, and leading to a fast degradation or even the destruction of the solar receiver (Spirkl et al., 1997).

Several works proposing methods for obtaining better flux distributions of solar receivers can be found in literature. For example, in García-Martín et al. (1999) a heuristic method for the optimization of the temperature distribution was developed for a volumetric receiver. Real tests showed that the proposed strategy provides a more uniform heat distribution in the receiver. A method based on a genetic algorithm is proposed in Hamza et al. (2011) for adjusting the aim targets of parabolic heliostats in a small-scale tower plant, showing a reduction of undesired peaks in the flux distribution.

In Belhomme et al. (2014) a procedure for the optimization of the aiming point is presented, based on the ant colony metaheuristic, whose effectiveness is demonstrated on a concentrated photovoltaic receiver test case. In the recent work of Besarati et al. (2014), a new optimization algorithm which works based on the principles of genetic algorithm is developed to find the optimal flux distribution on the receiver surface. The well-known HFLCAL model was used.

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https://doi.org/10.1016/j.solener.2017.12.008
Received 20 February 2017; Received in revised form 7 November 2017; Accepted 3 December 2017

Nomenclature

A_h	total mirror area (m^2)
A_m	effective mirror area (m^2)
a_h,a_w	limits of convolution integral
$azimut_{sun}$	solar azimut (rad)
C	concentration function due to the reflection law on the receiver plane
$cosrec$	incidence cosine of the reflected central ray from the heliostat on the receiver surface
D	actual distance between the heliostat surface center and the aim point
DNI	direct normal solar radiation (W/m^2)
f	focal distance (m)
f_{at}	attenuation factor
$f_i\,(x_r,y_r;\bar{x}_i,\bar{y}_i)$	flux produced by heliostat i by pointing to $(\bar{x}_i,\bar{y}_i)$ over the square centered at (x_r,y_r) (W)
$Fagent\,(x_r,y_r)_k$	flux produced over the square centered at (x_r,y_r) by agent k (W)
$\bar{F}_r$	total flux on the receiver (kW)
$F_r\,(x_r,y_r)$	flux density collected at each square of the receiver (W)
H_t	image dimensions in the tangential plane
P_h	total power reflected by a heliostat on the receiver surface (W)
r_m	mirrors' reflectivity
SLR	slant range
W_s	image dimension in the sagittal plane
$\bar{x}_i$,$\bar{y}_i$	coordinates of the aiming point for heliostat i
x_r,y_r	coordinates of the center of the squares in which the receiver plane is discretized.

Symbols

α_{sun}	solar height (rad)
ΔF_r	difference between the maximum and the minimum flux values at the receiver
ρ_1	tuning parameter penalizing the uniformity of the flux distribution at the receiver
	tuning parameter penalizing the energy collected at the receiver
σ_{ast}	standard deviation of errors associated with astigmatic effects (mrad)
σ_{bq}	standard deviation of mirrors slope errors (mrad)
σ_{HF}	total standard deviation of the HFLCAL model
σ_{sun}	standard deviation of the sunshape model (mrad)
σ_{slp}	mirror slope error (mrad)
σ_t	tracking error (mrad)
σ_{UZ}	total standard deviation of the UNIZAR model (mrad)
ξ,ζ	coordinates in the receiver plane coordinate system
ω	incidence angle between the Sun beam and the normal vector of the heliostat plane

The heuristic approach presented in García-Martín et al. (1999), has the advantage of simplicity and low computational burden: a more uniform flux distribution is obtained by moving heliostats from hotter to colder focuses. The disadvantage is that the heliostats can only be pointed to 5 predefined focuses, thus, the flux obtained by this method is not evenly distributed over the receiver.

The other three methods mentioned above optimize the flux distribution by pointing the heliostat field at a predefined set of aiming points. The resulting optimization problem consists of finding which heliostat has to point to a given aiming point. It can be solved as an integer optimization problem, which genetic algorithms solve well (Souar and Mouffok, 2014). This method has the disadvantage that the matrix of aiming points has to be defined previously leading to a loss of degrees of freedom of the optimization problem. Thus, the obtained solution is not the global optimum (which is attained when continuous optimization is carried out) and hot spots may appear as stated in (Besarati et al., 2014). To overcome this drawback the number of the aiming points has to be increased at the cost of a higher computational burden.

In this paper, the solution is computed in a continuous way. Solving a centralized nonlinear programming with a high number of decision variables can be computationally expensive. In the case described here, considering 33 aiming points, it has been found that the centralized way of solving the optimization problem is usually slower than a multi-aiming point strategy solved by genetic algorithms, although better performances are obtained. However, using the distributed approach, the problem is solved faster than the genetic algorithm while similar performance to the centralized way is achieved. To reduce the computational time of the multi-aiming strategy, a smaller number of aiming points has to be used at the cost of worse performance indexes.

The main contribution of this paper is a distributed optimization algorithm. The procedure proposed in this paper is based on the work described in Gallego et al. (2014), where an elliptic Gaussian model was used. The method seeks two main goals:

- Shave flux peaks on the receiver by computing the appropriate aiming point for each heliostat, thus reducing the thermal stress on its components.
- Maximize the incident solar irradiance over the receiver.

In the aforementioned paper, the optimization problem was solved in a centralized way for 180 heliostats. It was shown that, when the number of heliostat increases, the computational time increases rapidly. For this reason, in this paper a distributed way of solving the optimization problem is proposed. Simulation results show that substantial reduction of the computational time is achieved while similar performance to that obtained with the centralized approach is attained.

The paper is organized as follows: In Section 2, the CESA-1 tower plant is described. In Section 3, the model used for simulation purposes is explained. In Section 4, the optimization algorithm is presented. In Section 5, the distributed approach to solve the optimization algorithm is developed. In Section 6, the results obtained and their comparison to the centralized approach are discussed. Finally, the paper ends with some concluding remarks.

2. CESA-1 tower plant

The plant model used in this paper is based on the CESA-1 solar thermal tower plant (Fig. 1), which is part of the Plataforma Solar de Almería (PSA).

The CESA-1 solar thermal tower plant consists of a field of 300 heliostats, each one providing a reflecting area of 39.6 m^2, a volumetric receiver, a steam generator, an energy storage system and a power conversion system (Yu et al., 2012). Fig. 2 shows the layout of the CESA-1 solar tower plant considered in this section, where the position of the tower is considered to be at the origin of the global system of coordinates.

The volumetric receiver is located on top of the tower, at a height of 86 m. It consists of a series of thin metal wire meshes (porous media) (Ávila-Marín, 2001), with 2500/3000 kW of nominal/maximum absorbed power and a mean air temperature of 700 °C. Solar radiation is concentrated by the heliostat field on the volumetric receiver surface, heating up the wire mesh. The heat is then transferred to the air circulating through the porous media. In this paper, a flat receiver of