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Optimization of multiple receivers solar power tower systems

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ABSTRACT

In this article a new procedure to optimize the design of a solar power tower system with multiple receivers is presented. The variables related to the receivers (height, aperture tilt angle, azimuth angle and aperture size) as well as the heliostat field layout are optimized seeking to minimize the levelized cost of thermal energy. This is a high dimensional optimization problem with black-box nonconvex objective function.

The proposed strategy alternatively optimizes the receivers and the heliostat field. A separate aiming region is considered for each receiver. The aiming regions, the number of heliostats and their locations are obtained with the proposed procedure. Specifically, heliostat positions are obtained through a pattern-free greedy-based location method.

1. Introduction

SPT (Solar Power Tower) systems are known as one of the most promising technologies for producing solar electricity, as claimed in the literature [1–3]. An SPT system is here considered to consist of three main components: a tower, one or several receivers and a field of heliostats comprising rectangular mirrors. Direct solar radiation is reflected and concentrated by the heliostat field onto the receivers, placed at the top of the tower. The heliostats have two-axis movement in order to reflect the direct light from the sun to fixed targets on the receivers. The thermal energy is transferred in the receivers to a heat conducting fluid and, then, electricity is produced through a conventional thermodynamic cycle.

In recent years, higher power requirements are imposed on the SPT systems calling for large-scale plants such as Gemasolar (19.9 MW and 2650 hel. [4,5]), Khi Solar One (50 MW and 4120 hel. [6]) and Ivanpah (377 MW and 1,73,500 hel. [7,8]). Using one-receiver systems, as pointed out in Refs. [9–11], the large amount of heliostats forces to locate heliostats far from the tower, increasing atmospheric and spillage losses. The use of multiple receivers systems allows to reach high temperatures required to achieve conversion efficiency of solar energy to electricity, see Ref. [12].

Regarding the spatial configurations of the multiple receivers, there are different proposals in the literature: vertical [13], circular [14,15], same focal spot [16] and horizontal, see Refs. [10,17].

In what concerns the heliostat field layout, different approaches have also been studied in the literature, see Refs. [9,10,12,13,17,18]. A common approach relies on the field separation method: for each receiver a separate region, called aiming region is identified, where the heliostats will we placed, see Ref. [18].

This method is mainly based on two facts: the varying heliostats performance regarding their position in the field [11], and the computational time reduction by implementing simplified methods to calculate shading and blocking effects [19,20]. If, for instance, we consider three aiming regions, namely North, West and East, the West region will be most efficient at the beginning of the day and the East region in the afternoon. These performances imply that the optimal number and density of heliostats will not necessarily be the same for each selected region.

Different shapes are usually imposed to the aiming regions, such as concentric circular trapezoids [13] or ellipses [10,17]. However, such aiming regions overlap, and it is not trivial how to fix a strategy to assign heliostats at the intersection of the regions.

The heliostat location problem is usually solved by applying a parameterized geometrical pattern. The pattern parameters are

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optimized and the final number of heliostats is obtained by oversizing the field, see Ref. [10]. This way, although the optimal parameters for the oversized field are obtained, there is a high risk that a strong distortion exists between the original and final configuration. The field separation strategy has already been used under radially-staggered layouts in Ref. [11].

Finally, in order to design the SPT system, it is essential to understand the performance of the subsystems formed by the receivers and the heliostat field. The field and the receivers are interdependent, as pointed out in Ref. [13], where it is shown that an increase of the height of a receiver reduces some optical losses (shading, blocking and cosine effects) in large heliostat fields. It is thus important to design both components simultaneously.

This coupled optimization problem has been addressed in the literature by different authors. In Refs. [10], a genetic-based algorithm is proposed to optimize the radial-stagger field layout parameters, the tower height and the receiver aperture size and tilt angle. In Ref. [9], 11 design variables are optimized through a variant of the Powell algorithm and a genetic-based algorithm. In a different way, in Ref. [11] the receiver is firstly selected to be as simple and cheap as possible, and then the radial-staggered field is limited to a ellipsoidal boundary which size is determined by the receiver. Finally, in Ref. [13], a reference field is fixed and the two receivers considered are placed in the best vertical arrangement found. Then, different 2-zones heliostat field configurations are evaluated and the one reaching the best plant performance is selected.

In this article a new method to design a multiple receivers SPT system is presented, where the receivers and the heliostat field layout are simultaneously optimized. The variables related to the receivers and the heliostats (number and positions) are optimized through an alternating process to obtain a multiple receivers system that minimizes the LCOE (*levelized cost of thermal energy*).

The spatial configuration selected for the multiple receivers system is the horizontal distribution, and each receiver is characterized by its own height in the tower, aperture tilt angle, azimuth angle and aperture radius, see Fig. 1.

The separation method is applied to design the field layout and each aiming region is obtained by the algorithm without imposing any particular shape. For simplicity, the heliostats are considered aiming the same receiver regardless the instant of time.

The methodology presented to solve the heliostat location problem is a greedy-based algorithm which does not impose geometric patterns for the heliostats locations and does not fix in advance the number of heliostats. In a greedy algorithm, solutions are progressively built by incorporating at each iteration a new element (heliostat) until a complete feasible solution is obtained. The selection of the new element follows a greediness criterion seeking improvement of the objective function at each individual step. Although optimization based on a pure greedy heuristic may not necessarily be optimal, e.g. Ref. [21], it is frequently used in combinatorial optimization theory and practice. Its common use may be due to its simplicity, and, as stated in such paper, due to the fact that it is widely assumed that it often provides solutions that are significantly better than the worst ones. See e.g. Ref. [22–25], for results of the greedy algorithm on a bunch of combinatorial optimization problems.

The spatial configuration selected for the multiple receivers system is the horizontal distribution, and each receiver is characterized by its own height in the tower, aperture tilt angle, azimuth angle and aperture radius, see Fig. 1. As far as the authors are aware of, these are novel issues in the literature.

The rest of the paper is organized as follows. In Section 2, the SPT system is presented. Section 3 explains the optimization problem and our methodology to solve it. We apply the proposed algorithms to a given configuration and discuss the main results in Section 4. The last section is devoted to summarize our results and to present some perspectives for further work.

2. Decision variables and functions

The optimal design of a multiple receivers SPT system consists of determining the apertures dimensions and receivers positions in the tower and the location of the heliostats so as to minimize the LCOE. In the following subsections, the variables, the feasible sets and the functions involved in the optimization problem will be presented.

2.1. Decision variables

In the chosen system of coordinates, the positive x axis is the North direction, the positive y axis is the West direction and the z axis is orthogonal to the ground. We deal with cavity receivers with circular aperture, see Fig. 1(a) and [1] for further details. Although our approach is valid for any number of receivers, we consider for simplicity three receivers, called North, West and East, and numbered as receiver 1, 2 and 3 respectively.

The four most relevant variables associated to each receiver design are considered, namely the *height* h in the tower, the aperture *tilt* angle ξ (which measures the separation from the vertical line), the *azimuth* angle α (which measures the separation from the North axis) and the aperture *radius* r, see Fig. 1(a),(b). From now on we will denote by Θ_i the optimization variables related to receiver i and by Θ the full collection of decision variables concerning the receivers:

$$\begin{aligned} \Theta &= (\Theta_1, \Theta_2, \Theta_3) \in \mathcal{M}_{4\times 3} \\ &\text{with } \Theta_i = (h_i, \xi_i, \alpha_i, r_i)^t \in \mathbb{R}^4 \quad \forall\, i = 1,2,3\,. \end{aligned} \tag{1}$$

Some constraints, influenced by technical and legal regulations, determine the feasible region $\boldsymbol{\Theta}$. They are written as follows:

$$\boldsymbol{\Theta} := \left\{ \begin{array}{ll} \Theta \in \mathcal{M}_{4\times 3}: & r_{min} \le r_i \le \min(h_i, r_{max}) \le h_{max} \quad \forall\, i \\ & \xi_i \in [0, \pi/2] \\ & \alpha_i \in [\underline{\alpha}_i, \overline{\alpha}_i] \end{array} \right\}. \tag{2}$$

Here, r_{min} and r_{max} denote the minimum and maximum receiver radius and h_{max} is the maximum value for the tower height. The ranges for the variables α_i are calculated as follows:

$$\begin{aligned} \underline{\alpha}_1 &= \max\{-\pi/2, \alpha_3 + \varsigma_3 + \varsigma_1\}\,, \\ \overline{\alpha}_1 &= \min\{\pi/2, \alpha_2 - \varsigma_2 - \varsigma_1\}\,, \\ \underline{\alpha}_2 &= \max\{0, \alpha_1 + \varsigma_1 + \varsigma_2\}\,, \\ \overline{\alpha}_2 &= \min\{\pi, \alpha_3 - \varsigma_3 - \varsigma_2\}\,, \\ \underline{\alpha}_3 &= \max\{-\pi, 2\pi + \alpha_2 + \varsigma_2 + \varsigma_3\}\,, \\ \overline{\alpha}_3 &= \min\{0, \alpha_1 - \varsigma_1 - \varsigma_3\}\,, \end{aligned} \tag{3}$$

where the angles ς_i are obtained through the following equations:

$$\varsigma_i = \arcsin\left(\frac{r_i}{\sqrt{r_i^2 + d_{\text{ap}}^2}}\right) \quad \forall\, i = 1,2,3\,. \tag{4}$$

The fixed parameter d_{ap} denotes the distance between each aperture and the center of coordinates, see Fig. 1(a)–(c).

In what concerns the field, the heliostat locations, given by the coordinates (x,y) of their centers, are the variables to be used. All heliostats are assumed to be rectangular, to have the same dimensions and to be composed of rectangular facets; see Refs. [26,27] for approaches where heliostats of different sizes are allowed. The finite collection of coordinates of the centers of the