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Investigations into the spiral distribution of the heliostat field in solar central tower system

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ABSTRACT

The parameters and techniques involved in designing the heliostat field layout of Central Tower (CT) systems using the spiral distribution and the PSO algorithms are further investigated. The impact of extending typical domains of the shape factors on the design of the solar field and its performance are investigated and documented. Simplifications to the typical optimization procedures to design a solar field are introduced and documented. The effect of these modifications on the annual weighted efficiency of the solar field, the land required for the solar field and the computational time is documented. To quantify the effect of the introduced changes on the performance of CT, a 50 MWth CT plant is designed in Ma'an-Jordan to serve as a benchmark case for comparison purposes. Results showed that extending the domains for the shape factors "a" and "b" did not only change the optimum value of "a" and "b" but it also improved the system weighted efficiency by 0.84% and reduced the required land area by 1.8% (about 7000 m^2).

Moreover, several efforts are carried out aiming at accelerating the optimization process by reducing the two variables optimization, as the case in typical spiral algorithm optimization using PSO, into a single variable optimization, thus, eliminating the need for PSO technique. For example, a correlation between the optimal values of the shape factors "a" and "b" in the spiral distribution algorithm is established. Results of this action showed that the changes in field characteristics are less than 1%. Finally, the effect of changing the angular position constant in the spiral field pattern (the constant related to the golden ratio) on the field performance is investigated, and, it is found that the system performance is very sensitive to this constant, however, improvement of field efficiency is achieved using different values for this constant.

1. Introduction

Solar Central Tower (SCT) systems can be considered as one of the most promising energy because they can accommodate energy storage and can achieve high temperatures up to 2000 °C (Foster et al., 2010) and, thus, a high conversion efficiency. However, SCT technology is still considered to be under development stages and more improvements in finding the optimum heliostat field layout and receiver parameters are required. The values of these improvements become clearer after knowing that heliostat field is responsible for the largest cost in the SCT plant (Emes et al., 2015). However, it has been reported that distributing heliostats efficiently remains an open question since the proposal of the radially staggered distribution in the 1970s (Lipps and Vant-Hull, 1978). Since then, the radially staggered distribution is the most found in literature and the most adopted by the operated commercial plant and numerous optimizing codes, such as RCELL (Lipps and Vant-Hull). Kistler (1986). Each code develops a unique radially staggered pattern. Many other heliostat distributions were found in literature such as Fermat spiral (Noone et al., 2012), and parallel cornfield (Zhou and Zhao, 2014) distributions. A comparison of these distribution methods was done by Ramos and Ramos (Sep. 2012) and Mutuberria et al., 2015. It has been found that the Fermat spiral distribution is a promising option; it produces efficient solar fields with less field area compared to other distributions. This drew the attention of the authors of this work. The variables of the Spiral distribution for certain objective functions-namely the annual weighted efficiency-were obtained using an optimization technique. Through several papers in the literature, it is noticed that the optimum value of one of the distribution design parameters is always located at the maximum limit of its domain (Barberena et al., 2016; Piroozmand and Boroushaki, Jul. 2016). This domain is quoted from Noone et al. (2012) whom first presented the Fermat spiral distribution for heliostats. However, the limits of the domain are not explained in the literature. This paper studies the effect of relaxing parameters domains on the optimization

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Nomenclature

Symbols

a	first shape factor of spiral field
Alt	altitude above sea level (km)
AM	air mass
b	second shape factor of spiral field
c	acceleration constant
H	height dimension (meter)
I	solar radiation (W/m^2)
i	counter
it	iteration number
n	day number in a year (n = 1 at January the first)
N	normal vector
Q	particle position in the PSO algorithm
R	range
rand	a random number between 0 and 1
Rec	location of the center of a receiver in the Cartesian coordinate (m)
SLR	slat range (m)
Sun	sun vector with respect to an observer on earth
T	the vector from heliostat to tower receiver (m)
V	particle velocity in the PSO algorithm
W	width dimension (m)
w	the inertia weight

Greek symbols

∅	latitude angle
ϕ_{acc}	receiver acceptance angle
α	altitude angle
β	angle between heliostat, receiver and the east direction
γ	azimuth angle
Λ	angular position constant
ξ	a variable
τ	transmittance
φ	golden ratio $(1+\sqrt{5})/2$
ω	hour angle

Subscripts

B	direct beam
cos	cosine factor
in	interest
int	interception factor
N	north direction
s	sun
W	west direction
Z	zenith direction
att	atmospheric attenuation factor
sh&b	shading and blocking
r	mirror reflectivity factor
tot	total
h	heliostat
rec	receiver
t	target point
tr	tracking
ref	reflected
sl	slop
ast	astigmatic
im	image
T	tangent
sag	sagittal
i	counter
Loc	local
G	global
c	center
sh	shade
sor	source
atm	atmospheric
ex	extraterrestrial

results. This paper also investigates a method of reducing the computational time of the optimization process by linking field design parameters. If an appropriate correlation among different variables is found, that means that the optimization variables are reduced, and consequently the required computational time.

A 50 MW thermal CT system will be designed using the Spiral distribution in Maa'n, Jordan. This location is considered as one of the places on earth that has the highest DNI. This plant will serve as a benchmark to study the effect of the different modifications and adjustment suggested in this work.

2. Modeling

The instantaneous efficiency of a heliostat in a heliostat field is determined using:

$$\eta_h = \eta_{cos} * \eta_{att} * \eta_r * \eta_{int} * \eta_{sh\&b} \tag{1}$$

where η_{cos} is the cosine efficiency, η_{att} is the atmospheric attenuation efficiency, η_r is the mirror reflectivity, η_{int} is the interception efficiency, $\eta_{sh\&b}$ is the shading and blocking efficiency.

Typically, the annual performance of a heliostat is presented by either the annual unweighted efficiency, (η_{huw}), or, the annual weighted efficiency, (η_{hw}) which takes into account the solar beam radiation of the specific location.

$$\eta_{huw} = \frac{\sum_{n=1}^{365} \int_{sunrise}^{sunset} \eta_{\mathrm{h}}(t)dt}{\sum_{n=1}^{365} \int_{sunrise}^{sunset} dt} \tag{2}$$

$$\eta_{hw} = \frac{\sum_{n=1}^{365} \int_{sunrise}^{sunset} \eta_{\mathrm{h}}(t)\mathrm{I_B}(t)dt}{\sum_{n=1}^{365} \int_{sunrise}^{sunset} \mathrm{I_B}(t)dt} \tag{3}$$

Following the steps of Barberena et al. (2016), Besarati and Yogi Goswami (Sep. 2014), Mustafa et al. (2012), only the 21st of each month is considered to represent the month. Thus, the whole year is presented by 12 days. The integration of Eqs. (2) and (3) is obtained using Riemann sums. A step of one hour is considered for the summation.

To describe positions and directions, a right hand Cartesian coordinate system is adopted. The coordinate system origin is at the point of interception of the receiver center with the horizontal. The north direction is represented by the x-axis, west is represented by the y-axis and the zenith direction is represented by z-axis. Within this paper, vectors are presented by an arrow $\vec{v} = \langle v_x, v_y, v_z \rangle$. Thus, the sun position can be represented by a vector from the earth to the sun ($\overrightarrow{Sun}$) as:

$$\overrightarrow{Sun} = \langle \cos\alpha_s * \cos\gamma_s, \cos\alpha_s * \sin\gamma_s, -sin\alpha_s \rangle \tag{4}$$

where α_s is the solar altitude angle, γ_s is the solar azimuth angle measured from the south. Both the solar altitude and azimuth angles are determined based on Eqs. (5) and (6), respectively.