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Optimized Design of Heliostat Field based on Adaptive Gravitational Search Method

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Abstract

In this paper, the optimization model of the annual average thermal power output per unit area is first established. Then the correlation analysis of the optimization parameters is carried out to obtain the conclusion that the sizing of the heliostat can determine the other optimization parameters, and thus the mirror field, when the scheduling rule is determined. Traversing the sizing of the heliostats, the width and height of each pair of heliostats corresponds to an initial mirror field through the Campo alignment rule. The optimal alignment of the initial mirror field and the annual average thermal power can be obtained through the adaptive gravitational search algorithm. The values of the optimization parameters such as heliostat coordinates, heliostat sizes, mounting heights, and the number of heliostats under this alignment are output to obtain the annual average of the heliostat field under the optimization parameters. Optical efficiency, annual average output thermal power, and annual average output thermal power per unit mirror area are obtained under the optimized parameters.

Keywords

Variable Step-size Traversal; Single-objective Optimization; Fixed Heliograph Field; Adaptive Gravitational Search Algorithm.

1. Introduction

With the progress of science and technology and the development of human society, the energy problem is becoming increasingly serious. In order to solve the problem of imbalance between world energy supply and demand, and to realize the goal of "carbon peak" and "carbon neutral", it is indispensable to develop clean new energy and promote new energy technology. As an emerging clean and renewable energy technology, the role of tower solar thermal technology in China's future energy structure should not be underestimated, so the development of tower solar thermal technology is an inevitable requirement of the national energy development strategy [1].

The solar thermal power station is mainly composed of heliostat and collector. The solar mirror is used to reflect and converge sunlight. The azimuth and horizontal angle of the mirror can be adjusted according to the position of the sun in real-time, to ensure that the light emitted from the center of the sun can be projected to the center of the collector after reflecting on the mirror surface [2].

2. Optimized Design of a Heliostat Mirror Field

2.1 Optimization Model of Annual Average Thermal Power Per Unit of Mirror for Collectors

Set the absorption tower position coordinates (0,0,0), the size of the heliostat (width×height) is p×q, the installation height of the heliostat is h, the total number of heliostat mirrors in the mirror field is N, and the position coordinates of the ith heliostat is (x_i, y_i).

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The annual average output thermal power function P_{year}/A per unit mirror area is taken as the optimization index, and a single-objective optimization model is established, which is expressed as follows.

$$\max P_{year}/A_{sum}$$
$$s.t.\begin{cases} P_{year} \geq 60 \\ p \geq q \\ 2 \leq p \leq 8 \\ 2 \leq q \leq 8 \\ 2 \leq h \leq 6 \\ h > q/2 \\ 100 \leq \sqrt{x_i^2 + y_i^2} \leq 350 \\ \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} \geq p + 5 \end{cases} \tag{1}$$

Where: A_{sum} is the total mirror area of the mirror field $A_{sum} = \sum_i^N A_i$, A_i is the area of the ith mirror, and P_{year} is the average annual thermal power output of the mirror field.

2.2 Determine the Optimal Size of the Sun-setting Mirror

(1) Determining the relationship between the size of the heliostat and the objective function

The size of the fixed-sun mirror affects the amount of light received in the mirror field and the collector truncation efficiency.

The smaller the size of the fixed-sun mirror, the higher the collector truncation efficiency, making the higher optical efficiency, thus making the higher thermal power output per unit mirror area.

At the same time, the reduction in the size of the fixed-sun mirror makes the total light-gathering area of the mirror field decrease, which makes the output thermal power of the fixed-sun mirror field decrease, but does not affect the output thermal power per unit mirror area. Specific steps are as follows:

$$\frac{E_{field}}{NA} = \frac{DNI \cdot \sum_i^N A_i \eta_i}{NA} = \frac{DNI}{N} \cdot \frac{\sum_i^N A \cos\theta_{si} \eta_i}{A} = \frac{DNI}{N} \cdot \sum_i^N \cos\theta_{si} \eta_i \tag{2}$$

Where: A is the mirror area of a single heliostat; N is the total number of fixed-sun mirrors in the mirror field.

Therefore, the smaller the size of the fixed-sun mirror, the larger the annual average output thermal power per unit mirror area.

(2) Constraints on mirror size

Due to the mirror side length between 2m and 8m, the annual average output thermal power of the mirror field must reach 60MW, so the size constraints of the heliostat mirror can be written as:

$$s.t.\begin{cases} 2 \leq p \leq 8 \\ 2 \leq q \leq 8 \\ P_{year} \geq 60 \end{cases} \tag{3}$$

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2.3 Determine the Optimal Mounting Height of the Heliostat

(1) Determine the relationship between the installation height of the heliostat and the objective function

As the installation height of the fixed-sun mirror affects the pitch angle of the fixed-sun mirror, thus affecting the direction of the incident light, so that the fixed-sun mirror lighting area, shadow shading efficiency, cosine efficiency, collector truncation efficiency have a large change, so the analytical solution is more difficult to obtain, the numerical solution is used here, and the search for the optimal mounting height is traversed using a variable-step traversal method [3].

The specific steps are as follows:

Step1: discretize the height of the heliostat, the discretized form is:

$$\begin{cases} h_k = h_0 + km \quad k = 1,2,3\cdots \\ h_k \in (2,6) \end{cases} \tag{4}$$

Step2: According to the rules of the variable step size traversal method, substituting h_k into the problem one can get the corresponding annual average output thermal power function per unit mirror area as

$$P_k = P_{year}^k / A \tag{5}$$

Where: P_{year}^k is the annual average thermal power output of the mirror field when the mounting height of the heliostat is h_k.

Step3: Plot the graph of P_k about h_k.

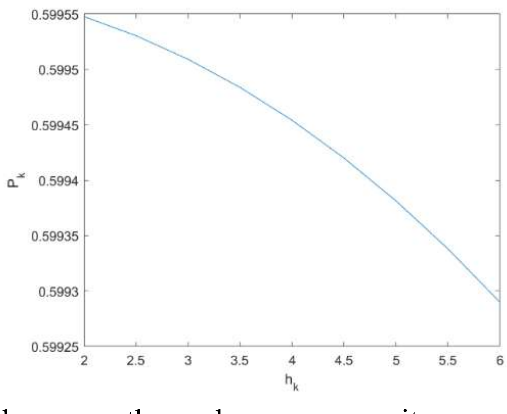

Fig. 1 Plot of annual average thermal power per unit area versus installation height

Step4: Observe Fig. 1 to see that P_k decreases monotonically as h_k increases.

(2) Constraints on the installation height of the heliostat

The installation height of the heliostat is between 2m and 6m, and it is necessary to ensure that the heliostat will not touch the ground when rotating around the horizontal axis, so the constraints can be written as:

$$s.t.\begin{cases} 2 \le h \le 6 \\ h > q/2 \end{cases} \tag{6}$$

2.4 Campo Layout Method

Due to the large number of heliostats in the mirror field, it is difficult to use every heliostat as an input variable. Therefore, it is necessary to encode the fixation mirrors in a uniform way to reduce the computational effort and to adapt to the rules. The Campo arrangement method [7] is adopted as it combines flexibility and simplicity.

The Campo arrangement starts from the first row of the first region (i.e., the first circle around the absorber tower from inside to outside). The first heliostat is placed in the north direction, and the rest of the heliostats are arranged uniformly in the circumferential direction on the principle of no mechanical collision. The second line of heliostats and the first line of staggered arrangement, the same area between successive rows of mirror spacing remains unchanged, the most intensive arrangement as shown in Figure 2 [4].

The angle between the first row of heliostats is:

$$\alpha_1 = 2\arcsin[DM/(2R_1)] \tag{7}$$

The diameter of the characteristic circle of the heliostat is:

$$DM = DH + d_{safe} \tag{8}$$

Where: DH is the angular distance between the tops of the heliostats, and the expression $DH = \sqrt{p^2 + q^2}$, d_{safe} is the safe distance between two heliostats.

Due to the constraints in the single-objective optimization model of Eq. (29), the interval between the neighboring sides of adjacent heliostats in the same row is not less than 5 m. Therefore, $h_{clear} = 5$, the safe distance between two heliostats can be obtained as:

$$d_{safe} = p + 5 - \sqrt{p^2 + q^2} \tag{9}$$

Where: p is the width of the heliostat mirror and q is the height of the heliostat mirror. The radius of the characteristic circle of the first row of the heliostat in the mirror field is.

$$R_1 = (DM \times N_{inr1})/2\pi \tag{10}$$

Where: N_{inr1} is the number of fixed-sun mirrors per row in the 1st region.

The minimum increment in radius of neighboring rows in the same region is:

$$\Delta R_{\min} = DM\cos 30° - h \tag{11}$$

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$$h = R_1 - \sqrt{R_1^2 - (DM^2/4)} \tag{12}$$

The number of heliostats in each row of the same region is constant, so as the diameter of the feature circle increases, the distance between neighboring heliostats in each row of heliostats increases. When the distance between neighboring heliostats in the nth row increases to the point where a heliostat can be placed in compliance with the constraints, the next region is entered, and the number of heliostats in the next region is twice that of the previous region. From this relation, the number of heliostats per row for the nth region is obtained as:

$$N_{inrn} = 2^{n-1} N_{inr1} \tag{13}$$

The maximum number of rows allowed to be laid out in the nth region (all rows included in the last feature circle at the end of the nth region) is:

$$row_n = \frac{2^{n-1} R_1}{\Delta R_{\min}} = \frac{2^{n-1}(DM \times N_{inr1})/2\pi}{DM\cos 30° - h} \tag{14}$$

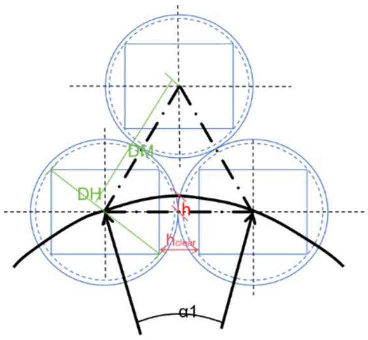

Fig. 2 Geometric relations for the densest arrangement of Campo

From the Campo arrangement process, it can be seen that all other covariates in the densely arranged mirror field can be viewed as dependent variables of the number of first row fixed-sun mirrors, N_{inr1}. By choosing the appropriate N_{inr1} and calculating the number of mirrors in a single row per region, the number of rows per region, and the row radius of each row of the expected mirror field, the dense heliostat mirror field of the Campo arrangement can be generated.

2.5 Creating the Initial Mirror Field

Fixed solar mirror width p through the traversal method from small to large traversal, the initial value of p = 2m, to determine the optimal layout of the fixed solar mirror field under the annual average output thermal power value whether to reach 60MW, if reached, the optimal width of the mirror for this p value, the output of $p_{best} = p$; if not reached, then make $p = p +$ step, to find a new value of thermal power compared with the 60MW, repeat the above steps. If p =8m, the program stops running and outputs "not found".

The installation height of the heliostat is greater than the minimum value of $q/2$. The value of h in this question is:

ISSN: 2414-1895 DOI: 10.6919/ICJE.202401_10(1).0055

$$\begin{cases} h = q/2 + 0.1 & q < 8 \\ h = 4.1 & q = 8 \end{cases} \tag{15}$$

Determination of the height q of the heliostat is traversed from small to large by the traversal method, and the process is the same as the traversal process of the heliostat described above. q=8m, the traversal about q stops, q takes the value of 8, and h takes the value of 4.1.

Since no heliostat mirrors are installed within 100 m around the absorption tower, the radius of the characteristic circle of the first row of heliostat mirrors in the mirror field is taken as $R_1 = 100m$. Then the number of heliostat mirrors in the first row is taken as $N_{inr1} = \frac{2\pi R_1}{p+5}$. The number of mirrors in a single row in each region of the expected mirror field, the number of rows in each region, the radius of the rows in each row, and the total number of heliostat mirrors can be determined from N_{inr1}.

The total number of mirrors in the initial mirror field is expanded to 150% of the expected mirror field, and the initial mirror field is encoded by the Campo arrangement rule.

2.6 Optimal Arrangement Process of Heliostat Field based on Adaptive Gravitational Search Algorithm

Step1: Calculate the total number of heliostats in the expected mirror field, and set the number of heliostats in the initial mirror field to be 1.5 times the number in the expected mirror field to reserve enough space for the final arrangement scheme.

Step2: Encode the initial mirror field by Campo arrangement rule. Assuming the number of populations is N, the initial population will be an N×R matrix. The number of rows, N, represents the number of mirror field arrangement schemes, and the number of columns, R, represents the number of rows of heliostats in the mirror field (the direction of the rows of heliostats is along the radius of the mirror field, i.e., a circle around the absorber tower is one row).

When the spacing between neighboring fixed-heaven mirrors in the same row is large enough that a fixed-heaven mirror can be inserted between them in compliance with the constraints, the fixed-heaven mirror arrangement rule of this row changes, and the spacing between this row and the previous row (ΔR) also changes, $\Delta R = \Delta R_{\min} + rand \times \Delta R_{\min}$.

Step3: The particles of the initial population are decoded to form N mirror fields, and then each mirror field is substituted into the collector unit mirror annual average thermal power optimization model to obtain the fitness function with the unit mirror annual average thermal power as the standard, and generate the fitness matrix. The individual with higher fitness is more optimal, and the one with the highest fitness is the global optimal solution.

Step4: Iterate to get the new population. The particles may go beyond the search space boundary or overlap each other with other rows every time they update their position, so it is necessary to check whether there are particles that do not meet the constraints at the beginning of each iteration, and initialize the particles that do not meet the conditions.

Step5: Decode the updated population and perform adaptation calculation. The optimal fitness value of the updated population is compared with that of the pre-update, and if the post-update is greater than the pre-update, the global optimal solution is replaced with the current particle; if the post-update is less than the pre-update, the global optimal solution remains unchanged.

Step6: Repeat the above steps until the algorithm converges or the calculation results reach a certain accuracy.

Step7: Output the position and fitness of the optimal individual corresponding to the current population and decode it to obtain the desired arrangement scheme [5].

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The optimal arrangement is shown in Table 1.

Table 1. Optimal parameters for heliostats

No.	Widths (m)	Heights (m)	x-coordinate (m)	y-coordinate (m)	z-coordinate(m)
1	4.5	6	99.395	10.983	6
2	4.5	6	97.587	21.834	6
3	4.5	6	94.599	32.420	6
4	4.5	6	90.466	42.614	6
5	4.5	6	85.238	52.292	6
6	4.5	6	78.979	61.338	6
7	4.5	6	71.764	69.641	6
8	4.5	6	63.681	77.102	6
9	4.5	6	54.827	83.630	6
10	4.5	6	45.310	89.146	6

3. Summary

In this paper, the adaptive gravity search method is used to optimize the model, and the solution results have the advantages of fast speed and high accuracy compared with other optimization algorithms. The modeling and solving process flexibly selects a suitable coordinate system, which reduces the difficulty of thinking and the amount of calculation to a certain extent.

The optimal design model of heliostat field gives the solution of the design size, arrangement and absorption tower position of heliostat under the optimal focusing situation, which can be widely applied to the construction of space solar power station, and can be used to optimize the total energy of solar rays focused by the solar power station as well as the solar energy focused by the solar power station received by the antenna on the earth's surface, so as to achieve a more reasonable distribution of the solar power station and the terrestrial receivers. The problem of more rational distribution of space solar power stations and ground receivers can be generalized and applied to the construction of space solar power stations.

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