Layout optimization of heliostat field based on genetic algorithm

Yuan LIu[1,*], Yi Tang [1], Weijie Cong [2]

[1]School of Automation, Xi'an University of Posts and Telecommunications, Xi'an 710121, China
[1]School of Automation, Xi'an University of Posts and Telecommunications, Xi'an 710121, China
[2]School of Science, Xi'an University of Posts and Telecommunications, Xi'an 710121, China

Abstract. In order to improve the annual average optical efficiency of a tower solar power plant, a simulated heliostat field layout optimization model is constructed using ray tracing method to calculate the shadow shading efficiency. is constructed using ray tracing method to calculate the shadow shading efficiency. Genetic algorithms are used to encode the variables such as solar pitch angle, solar azimuth angle, and coordinates of heliostat mirrors in chromosomal individuals in binary regions, and to find the near-optimal solutions in iterative populations through the use of ray tracing method. Simulation results show that the model can significantly optimize the layout of the tower solar power system. Simulation results show that the model can significantly optimize the layout of the tower solar power plant and improve the annual average optical efficiency. neighboring heliostats is at 0.398 times the sum of the length and width, the optical efficiency of the Khi Solar One power plant reaches 61.83%, which is an improvement of 15.74% compared to that of the Khi Solar One power plant. improvement of 15.74% compared to this engineering example.

1.Introduction

With the growing global energy demand, the development of clean energy is becoming more and more important. Solar energy, as one of the most promising clean energy sources, has become the focus of attention. Tower solar power plants produce clean energy through an efficient and sustainable way of power generation. Compared with traditional photovoltaic power generation, tower solar power generation has higher energy density, cheaper cost, more stable power generation performance, and is more energy efficient and environmentally friendly [1]. The main concentrating component of a tower solar power plant is the heliostat [2], and the layout of the heliostat field closely affects the optical efficiency of the power plant. Thus, how to optimize the layout of the heliostat field has become one of the most important factors to improve the optical efficiency of the tower solar power plant.

Codes written for heliostat fields, such as HELSOL3, appeared early in the development of tower solar power plants in the 1980s. In recent years, with the development of optimization algorithms, there are more and more studies on the optimization of fixed-sun mirror layout. Literature [3] uses an improved whale algorithm to optimize the fixed-sun mirror field layout. Literature [4] used numerical methods to optimize the layout and specifically analyzed a tower solar power (SPT) system. Literature [5] explored the effect of different sizes of heliostat mirrors on its power generation using Monte Carlo algorithm.

However, the above literature has certain shortcomings in the accurate calculation of shadow obscuration efficiency. They did not consider the interactions between heliostats and their effects on the shadow shading efficiency, resulting in the possibility of large errors between the calculation results and the actual situation. In response to this problem, we propose a heliostat field layout optimization model based on genetic algorithm. The model comprehensively considers key factors such as solar altitude angle, heliostat size, and layout height. A ray-tracing method is used to determine whether the incoming and outgoing rays are shaded or not, and the model is validated with actual engineering data. It aims to reduce the error between the shading efficiency and the actual situation, so as to obtain higher optical efficiency.

2.Fixed-heaven mirror field modeling

The optical efficiency of a heliostat is achieved by focusing the sun's rays on a single point to concentrate and utilize the energy, which is defined as the ratio of the area of the reflected beam of the heliostat to the area of the incident beam. It is mainly affected by 5 factors: shadow shading efficiency η_{sb}, cosine efficiencyη_{cos} atmospheric transmittanceη_{at}, collector truncation efficiency η_{trunc} and specular reflectivity η_{ref}.

The Optical efficiency of a fixed-heaven mirror field η is

$$\eta = \eta_{sb}\eta_{cos}\eta_{at}\eta_{trunc}\eta_{ref}$$

where the specular reflectance is usually η_{ref} is regarded as a constant

$$\eta_{ref} = 0.92$$

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[*] Corresponding author: liuyuan_2024@163.com

The calculation focuses mainly on the remaining four metrics, of which the shadow shading efficiency is more complex. Some detailed model parameters [6] are calculated as follows

Atmospheric transmittance η_{at}

$$\eta_{at}=\begin{cases} 0.99321-0.0001176d_{HR} \\ +1.97\times10^{-8}\times d_{HR}^{2}\ \ (d_{HR}\le1000) \\ e(-0.0001106)d_{HR}\ \ (d_{HR}\ge1000) \end{cases}$$

where d_{HR} is the distance from the center of the fixed-sun mirror mirror to the center of the collector.

Collector cut-off efficiency η_{trunc}

$$\eta_{\text{trunc}}=\frac{G}{\text{W}-\text{U}}$$

where G represents the energy received by the collector, and W represents the specular total reflection energy, and U represents the shadow masking loss energy.

Energy flow density ρ_{lux} is the amount of energy absorbed per unit area. The calculation is given from literature 7

$$\rho_{lux}=\frac{1}{2\pi\sigma^2}\iint exp(-\frac{x^2+y^2}{\sigma^2})dxdy$$

where σ is the distance from the reflected light to the absorber tower.

$$\sigma=\sqrt{x^2+y^2+(H-h)^2}$$

From the definition of the collector truncation efficiency, we can see that η_{trunc} is

$$\eta_{trunc}=\frac{\rho_{lux}\cdot S_x}{\rho_s\cdot\eta_{sb}\cdot S}$$

where $\rho_s=1.367\times10^3 w/m^2$ is the average energy flow density of solar radiation at the Earth's surface, and S_x is the surface area of the heat absorber, and S is the total area of the heliostat.

Shadow obscuration loss is the loss of shadow due to the shadow of a heliostat obscuring other heliostats and the loss of shadow obscuration from absorption towers [7], both of which cast shadows related to the solar altitude angle and azimuth angle.

Solar altitude angle α_s

$$sin\,\alpha_s=cos\,\delta\,cos\,\varphi\,cos\,\omega+sin\,\delta\,sin\,\varphi \tag{1}$$

Solar azimuth γ_s

$$cos\,\gamma_s=\frac{sin\,\delta-sin\,\alpha_s\,sin\,\varphi}{cos\,\alpha_s\,cos\,\varphi} \tag{2}$$

where φ is the local latitude, with north latitude specified as the positive direction; ω is the solar time angle; δ is the solar declination angle.

To calculate the shadow shading efficiency, any one of the fixed-sun mirror field is first selected as the sample of the study object [8]. Let the sample coordinates be (x, y, h) in the coordinate system of the heliostat field, and substitute Equation (1) and (2) to obtain the unit vector $\vec{\boldsymbol{s}}$ of the incident light and the unit vector $\vec{\boldsymbol{r}}$ of the reflected light, respectively

$$\begin{cases} \vec{\boldsymbol{s}}=\begin{bmatrix} -cos\,\alpha_s\,cos\,\gamma_s \\ -cos\,\alpha_s\,sin\,\gamma_s \\ -sin\,\alpha_s \end{bmatrix} \\ \vec{\boldsymbol{r}}=\dfrac{(-x,-y,H-h)}{\sqrt{x^2+y^2+(H-h)^2}} \end{cases}$$

At this time, the normal vector of the heliostat $\vec{\boldsymbol{n}}$ can be calculated by the principle of reflection and the angular bisector theorem of vectors, or by the pitch angle of the heliostat A azimuth angle B can also be calculated by the pitch angle and azimuth angle of the heliostat

$$\begin{cases} \vec{\boldsymbol{n}}=\dfrac{-\vec{\boldsymbol{s}}+\vec{\boldsymbol{r}}}{\|-\vec{\boldsymbol{s}}+\vec{\boldsymbol{r}}\|} \\ \vec{\boldsymbol{n}}=\begin{bmatrix} \sin A\cos B \\ \sin A\sin B \\ \cos A \end{bmatrix} \end{cases}$$

The above equation can be used to find the pitch angle of the heliostat A and azimuth angle B

$$\begin{cases} A=\cos^{-1}\left(\dfrac{\sin\alpha+\dfrac{H-h}{\sqrt{x^2+y^2+(H-h)^2}}}{\|-\vec{s}+\vec{r}\|}\right) \\ B=\tan^{-1}\left(\dfrac{\cos\alpha\sin\gamma+\dfrac{y}{\sqrt{x^2+y^2+(H-h)^2}}}{\cos\alpha\cos\gamma-\dfrac{x}{\sqrt{x^2+y^2+(H-h)^2}}}\right) \end{cases}$$

The pitch angle as well as the azimuth angle are plotted for separate heliostats at different moments of the same day as shown in figure 2 below

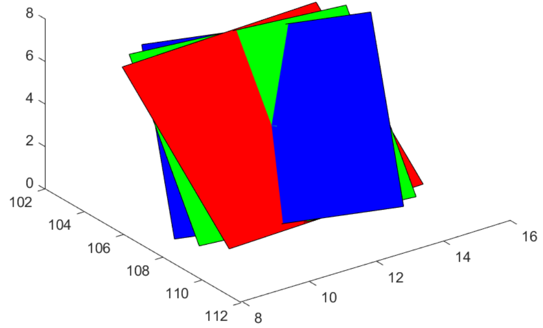

Figure 1 Pitch angle and azimuth of a single heliostat at different moments of time

Splitting each heliostat equally into $m\times n$ grid, the calculation of the shaded area is converted into the calculation of the ratio of the number of grid points falling within the shaded range to the total number of grid points. Two neighboring heliostats are arbitrarily selected as M and N (M is the shaded heliostat), and their pitch and azimuth angles are respectively A_1 , B_1 ,A_2 , and B_2 and the center of the mirror of M and the center of the mirror of N are taken as the center of the mirror of M and the center of the mirror of N respectively. O_1 and N mirror center O_2 as the origin to establish two different mirror coordinate systems, in which the transformation matrix T of the mirror field coordinate system is calculated as follows:

$$T=\begin{pmatrix} -\sin B_1 & -\sin A_1\cos B_1 & \cos A_1\cos B_1 \\ \cos B_1 & -\sin A_1\sin B_1 & \cos A_1\sin B_1 \\ 0 & \cos A_1 & \sin A_1 \end{pmatrix}$$

Transform any grid point in the M mirror coordinate system H_1 into the mirror field coordinate system with coordinates of H_1'

$$H_1'=T\cdot H_1+O_1=\begin{pmatrix} x_1' \\ y_1' \\ z_1' \end{pmatrix}$$

Transforms the mirror field coordinate system to the N-mirror coordinate system by means of the rotation matrix G to the N-mirror coordinate system

$$G = \begin{pmatrix} -\sin B_2 & -\sin A_2 \cos B_2 & \cos A_2 \cos B_2 \\ \cos B_2 & -\sin A_2 \sin B_2 & \cos A_2 \sin B_2 \\ 0 & \cos A_2 & \sin A_2 \end{pmatrix}^T$$

Get its coordinates

$$H_1'' = G \cdot (H_1' - O_2) = \begin{pmatrix} x_1'' \\ y_1'' \\ z_1'' \end{pmatrix} \tag{1}$$

Let the light ray direction vector in the mirror field coordinate system be $\overrightarrow{\boldsymbol{v_0}}$, which is also converted to N-mirror coordinates using the rotation matrix G to get its coordinates

$$\overrightarrow{\boldsymbol{v_N}} = G \cdot \overrightarrow{\boldsymbol{v_0}} = (a, b, c)$$

The couplings (3) and (4) are obtained over the H_1'' , the light rays of $\overrightarrow{\boldsymbol{v_1}}$ and $\overrightarrow{\boldsymbol{v_1}}$ The point of intersection with the plane in which the mirror N of the fixed-sun mirror is located is $H_2 = (x_2, y_2, 0)$, which is given by

$$\frac{x_2 - x_1''}{a} = \frac{y_2 - y_1''}{b} = \frac{-z_1''}{c}$$

From the above equation, we can calculate the H_2 the coordinates of the point

$$\begin{cases} x_2 = \dfrac{cx_1'' - az_1''}{c} \\ y_2 = \dfrac{cy_1'' - bz_1''}{c} \end{cases}$$

The presence or absence of occlusion can be determined from the H_2 the positional coordinates of the N mirrors can be determined whether there is occlusion or not. If occlusion exists, the shadow occlusion loss of the fixed-sun mirror can be calculated by the ratio of the number of grid points falling within the shadow to the total number of grid points to the area of the mirror.

The absorption tower shadow loss is the loss caused by the shadow of the absorption tower obscuring the heliostat. The specific location of the shadow of the absorption tower is calculated to determine whether it is obscuring the heliostat. As show in figure 2.

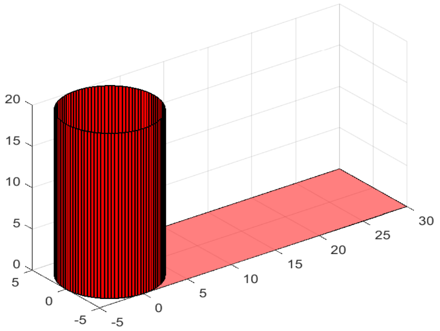

Figure 2 Schematic diagram of absorption tower shadow

From the center of the absorber tower and the radius r of the absorber tower, the position coordinates of the absorber tower shadow in the mirror field coordinate system can be determined. In the same way as the calculation of the heliostat shadow, the absorption tower shadow is analyzed for shadow loss to the heliostat.

The cosine efficiency of a heliostat is a measure of how efficiently a heliostat reflects the sun's rays.η_{cos} The cosine efficiency is calculated as follows

$$\eta_{cos} = cos\,\theta$$

where θ is the angle between the incident light of the sun and the normal of the heliostat.

The output thermal power of the heliostat field E_{field} is

$$E_{field} = DNI \cdot \sum_{i}^{N} A_i \eta_i$$

where N is the total number of heliostats in the heliostat field; DNI is the normal direct radiation angle; A_i is the surface area of the i-th heliostat; η_i is the optical efficiency of the i-th mirror. Normal direct radiation illuminance DNI is the solar radiation energy received per unit time and per unit area of the plane perpendicular to the sun's rays on the earth, which is given by

$$\begin{cases} DNI = G_0 \left[a + bexp\left(-\dfrac{c}{\sin \alpha_s} \right) \right] \\ a = 0.4237 - 0.00821(6 - H)^2 \\ b = 0.5055 + 0.00595(6.5 - H)^2 \\ c = 0.2711 + 0.01858(2.5 - H)^2 \end{cases}$$

where G_0 is the solar constant, the $G_0 = 1.366KW/m^2$; H is the altitude.

3.Genetic algorithm based model implementation

In this section, a genetic algorithm is used to solve the model and the average annual optical efficiency $\overrightarrow{E_{fieldy}}$ of the tower solar is chosen as the fitness function

$$\overrightarrow{E_{fieldy}} = \frac{\sum_{k=1}^{Q} \sum_{i=1}^{Z} E_{field}}{Z \cdot Q \cdot S}$$

where Z is the number of local time points per month, take Z = 5; Q is the total number of months per year, take Q = 12; S is the total area of the heliostat mirror. And set some constraints: solar azimuth angle $0 < \gamma_s \leq 360$, solar altitude angle$0 < \alpha_s \leq 90$, heliostat coordinates

-667.5<X<667.5, -667.5<Y<667, local time 0:00-23:59.

The optimization variables were transformed into gene combinations using binary coding and a bit string of L=5 was used to represent the initial population $p(t)$ with an initial population size N_p of 500.

According to the roulette wheel selection method, the size of the proportion of an individual's fitness is used to determine whether its offspring are retained or not, thus selecting good individuals from the t-th generation population $p(t)$ to be inherited into the next generation population $p(t + 1)$. The following equation

$$p_i = \frac{\overrightarrow{E_{fieldy}}}{\sum_{i=1}^{N_p} \overrightarrow{E_{fieldy}}}$$

In order to select the good individuals, multiple rounds of selection were performed based on the above selection method. Each round of selection generates a random number within [0, 1], which is used as an indicator to select the final crossed individuals.

In order to increase the diversity of the population and solve the problem of dimensional explosion caused by large-scale data, the infeasible solution is iteratively removed when the computer capacity is limited. Set the number of variables as chromosome length and the number of iterations as 500, when the number of iterations exceeds 200 times without evolution then the algorithm stops.

4.Experimental results and analysis

After optimizing the heliostat field layout by genetic algorithm, the annual average optical efficiency reached 61.83%, which is higher than the highest optical efficiency of 53.42% in Khi Solar One power station. The average spacing of the heliostats was stabilized at 4.38 m, 0.398 times the sum of the length and width.

The solar thermal map of the solar energy received by the mirrors of the heliostat field is visualized by simulation, as shown in Fig. 3.

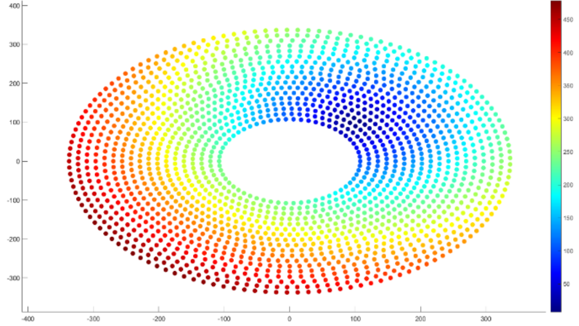

Figure 3 Thermal map of solar energy received by mirrors

Fig. 3 shows that the overall layout is close to the optimization results, and there are some areas with low solar energy utilization, which should reduce the density of heliostats in this area and increase the density in other areas.

In order to check the performance of the algorithm, the results are simulated and analyzed to obtain a visualization picture of the layout of all the heliostats around the absorption tower as shown in Fig. 4.

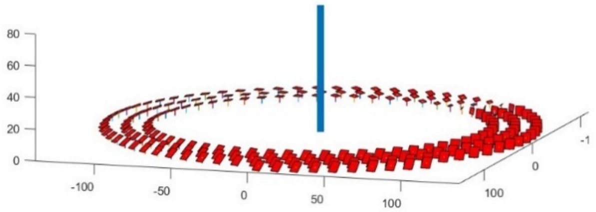

Figure 4 The case of part heliostats around the absorption tower

The simulated heliostat field in Fig. 4 is the optimal heliostat field array layout method. The optimization results show a significant increase in the annual average optical efficiency compared with the engineering example, which verifies the accuracy of the model.

5.Conclusions

The factors affecting the optical efficiency of tower solar power plants are studied and analyzed in detail. A simulated fixed-sun mirror field optimization model was developed with the optical efficiency expression as a fitness function. A genetic algorithm was used for model solving and the results were evaluated and analyzed using parameters from engineering examples. It is shown that the optical efficiency of Khi Solar One power plant reaches 61.83% when the average spacing of neighboring heliostats is at 0.398 times the sum of the length and width, which is an improvement of 15.74% compared to the engineering example.

The significant improvement in optical efficiency indicates that the optical efficiency of the tower solar power plant is mainly affected by the shadow shading efficiency. However, how to select the time period with significant influence for the study is still a difficult problem to solve. Meanwhile, the sunlight reflected from the fixed-sun mirror is in the form of light spots on the heat-absorbing tower. Therefore, how to design the heat-absorbing tower so that as little spot energy as possible is wasted is also a direction for future research.

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References

1. J. HUANG, Z.G. YAN, B. DENG, et al. Research progress on the software of the heliostat field layout of the solar tower thermal power plant. Dongfang Electric Review, 37(2):41-47 (2023)
2. Q. GUO, C. FANG, J.W. WANG, et al. Research on solar tower power plant heliostat. Mechanical & Electrical Engineering Technology, 51(4):115-118 (2022)
3. B. GAO, H. SUN, S. LIU, Heliostat field layout optimization of solar tower power station based on improved whale algorithm. Acta Energiae Solaris Sinica, 44(10): 209-217 (2023)
4. F.J. COLLADO, J. GUALLAR, Two-stages optimized design of the collector field of solar power tower plants. Solar Energy, 135(10):884-896 (2016)
5. L.Z. HAN, Z.H. ZHANG, F.Y. YAO, et al. Optimization of Heliostat Field Layout Based on Particle Swarm Optimization Algorithm. Advances in Applied Mathematics, 13(4): 1607-1617 (2024)
6. P. ZHANG, Z.W. XI, W.H. HUA, et al. The calculation method of the optical efficiency of the solar power tower heliostat field. Technology and Market, 28(6):5-8 (2021)
7. J.X. LIU, Research on modeling simulation and optimal layout of heliostat field optical efficiency for Solar Power Tower. Lanzhou Jiaotong University (2023)
8. Q. DING, Z.Y. ZENG, W.Z. CHEN, et al. An evaluation method for effective mirror area of heliostat field. Acta Energiae Solaris Sinica, 42(9): 184-189 (2021)