Influence of local shadow on output of photovoltaic array

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Abstract—This paper first deduces the engineering mathematical model of photovoltaic cells, then builds the photovoltaic cell and photovoltaic array model in Matlab / Simulink, and then simulates and compares the output of photovoltaic array under the condition of series and parallel connection, the number of shadows and shadow distribution. Finally, the different effects of shadow in series and parallel and the influence of shadow distribution on the output of photovoltaic array are analyzed.

1. Introduction
In addition to renewable energy, such as wind energy, solar energy, hydro energy and geothermal energy, low-carbon energy also includes nuclear energy and clean coal\cite{1}. Compared with other low-carbon energy sources, solar energy will not cause environmental pollution; compared with other clean energy sources, it is the most widely distributed and low-cost. For the plateau land forms in Northwest and southwest China, solar energy is more abundant\cite{2}. Therefore, this paper chooses to study photovoltaic energy, deduce the engineering mathematical model of photovoltaic cells, build the physical model in Matlab / Simulink, and analyze the impact of different shadows on the output of photovoltaic array.

2. Modeling and Simulation of photovoltaic cells

2.1 Principle of photovoltaic power generation
The basic structure of photovoltaic cell is p-n junction. When p-n junction is under light, it absorbs solar energy, which speeds up the movement of electrons and holes and produces electron transition, resulting in photogenerated current\cite{3}.

2.2 Mathematical model of photovoltaic cell
The mathematical model of photovoltaic cell is generally derived from its equivalent circuit, and the output of photovoltaic cell is expressed by formula through circuit analysis. The equivalent circuit diagram of photovoltaic cell is shown in the figure:

Fig.1 Equivalent circuit of photovoltaic cell
$I_{ph}$ is Photogenerated current; $U_D$ is Diode voltage; $I_0$ is the dark current flowing through the diode; $R_{SH}$ is the equivalent bypass resistance of photovoltaic cell; $R_S$ is the equivalent internal resistance of photovoltaic cells; $I$ is the current output from the photovoltaic cell to the load; $U_{OC}$ is the output voltage at both ends of the load.

According to Kirchhoff current theorem, it can be deduced that:

$$I = I_{ph} - I_0 - I_{sh}$$

$$U = U_D - IR_S$$

(1)  
(2)

The mathematical formula of photogenerated current can be obtained by querying the data:

$$I_D = I_0 \left[ \exp \left( \frac{qU_D}{AKT} \right) - 1 \right]$$

$$I = I_{ph} - I_0 \left[ \exp \left( \frac{qU_D}{AKT} \right) - 1 \right] - \frac{qU_D}{R_{SH}}$$

(3)  
(4)

By querying the data, the internal short-circuit current of photovoltaic cell can be obtained:

$$I_{sc} = I_0 \left[ \exp \left( \frac{qU_{OC}}{AKT} \right) - 1 \right]$$

(5)

If the load is short circuited at this time, the dark current flowing through the diode can be ignored. In the actual production of silicon wafers, the $R_{SH}$ value is 200–300 ohm, the $R_S$ value is 7.7~13.5 milliohm[3]. Therefore, when calculating the output current, the $I_{sh}$ on the $R_{SH}$ can be ignored to obtain the simplified output current and the output power:

$$I = I_{sc} - I_0 \left[ \exp \left( \frac{qU_D}{AKT} \right) - 1 \right]$$

$$P = U_L I_L = U_L I_{PH} - U_L I_0 \left[ \exp \left( \frac{qU_D}{AKT} \right) - 1 \right]$$

(6)  
(7)

$I_0$ is the reverse saturation current of p-n junction in photovoltaic cell; $q$ is the electron charge; $K$ is Boltzmann constant ($1.38 \times 10^{-23}$ J/K); $A$ is the curve constant of p-n junction in photovoltaic cell(1~2); $T$ is the absolute temperature(K); $U_L$ is the output voltage of photovoltaic cell; $I_L$ is the output current of photovoltaic cell.

At the same time, we need to consider the situation when the photovoltaic cell works in the maximum power and open circuit state. Then the current expression can be obtained:

$$I_L = I_{sc} \left[ 1 - C_1 \left[ \exp \left( \frac{U}{C_2 U_{OC}} \right) - 1 \right] \right]$$

(8)

Based on the known information, the expressions of $C_1$ and $C_2$ can be obtained:

$$C_1 = \left( 1 - \frac{I_m}{I_{sc}} \right) \exp \left( \frac{-U_m}{C_2 U_{OC}} \right)$$

$$C_2 = \frac{U_m}{U_{OC} - 1} / \left[ \ln \left( 1 - \frac{I_m}{I_{sc}} \right) \right]$$

(9)  
(10)

There are five factors to determine the output are maximum output voltage $U_m$, maximum output current $I_m$, short circuit current of photovoltaic cell $I_{sc}$, open circuit voltage of photovoltaic cell $U_{OC}$ and Maximum output power $P_{max}$.

When the ambient light changes, the device temperature of photovoltaic cells will also change. So we have to set the reference light $S_{ref}$ as 1000 w/m$^2$, and the battery reference temperature $T_{ref}$ as 25°C, component temperature $T$ is:

$$T(°C) = T_{air}(°C) + K(°C \cdot m^2/w^2) \cdot S(w/m^2)$$

(11)

$T_{air}$ is the actual ambient temperature, $K$ is the scale factor(0.03), $S$ is the actual light intensity of the environment.

The optimized four actual reference coefficients can be obtained by the following formula:

$$\Delta T = T - T_{ref}$$

$$\Delta S = \frac{S}{S_{ref}} - 1$$

$$I_{sc}' = I_{sc} \frac{S}{S_{ref}^2(1 + \alpha \Delta T)}$$

$$U_{OC}' = U_{OC} \left[ (1 - c \Delta T) \ln \left( e + b \Delta S \right) \right]$$

$$I_m' = I_m \frac{S}{S_{ref}(1 + \alpha \Delta T)}$$

(12)  
(13)  
(14)  
(15)  
(16)
\[ V_m' = V_m[(1 - c\Delta T)\ln(e + b\Delta S)] \]  
\[ a = 0.0025, \quad b = 0.5, \quad c = 0.00288. \]

2.3 Photovoltaic cell modeling

After obtaining the output expression of photovoltaic cell, the original parameters are selected as \( U_m = 16.6V, \quad I_m = 7.5A, \quad I_{SC} = 8.32A, \quad U_{OC} = 21.6V. \) Carry out modeling and simulation in Matlab / Simulink, as shown in the following figure:

![PV cell packaging simulation diagram](image)

In order to explore the effects of ambient temperature and light intensity on the output of photovoltaic cells, two groups of control experiments will be set up, with illuminance as 1200 w/s², 1000 w/s², 800 w/s², 600 w/s², 400 w/s². The output current and power with ambient temperature of 10℃, 20℃, 30℃, 40℃, 50℃ are compared and analyzed.

![Output characteristic curve of photovoltaic cell under different illumination](image)
It is not difficult to find from Fig.3 that with the increase of illumination, the short-circuit current and maximum output power of photovoltaic cells increase significantly, but the corresponding open circuit voltage changes very little; It can be found from Fig.4 that with the increase of temperature, the open circuit voltage of photovoltaic cells gradually increases and the change of maximum power is small.

To sum up, on the premise of keeping the temperature and illumination unchanged respectively, for single module photovoltaic cells, changing the illumination will affect the maximum power and short-circuit current; Changing the temperature will affect the open circuit voltage.

3. Analysis of local shadow output characteristics

3.1 Principle of photovoltaic array

In practical application, in order to obtain higher output power, photovoltaic cells will be connected in series and parallel to form photovoltaic array. However, when the external environment or internal factors change, such as shielding, uneven light distribution and battery aging, the output power of photovoltaic cells will be greatly reduced. Local shadow is the main factor causing power mismatch. When the photovoltaic panel is blocked, it will cause the solar cell to reverse bias, no longer output power, and become the load of other solar cells, consuming power. It will even further cause hot spot effect, resulting in permanent damage to the battery [4].

Therefore, when building a photovoltaic array, a reverse diode can be connected in parallel next to each battery board, and each branch is connected with a blocking diode in series. When partial shielding occurs, the blocked battery block has a reverse voltage. At this time, the bypass diode is turned on to short circuit the battery block; The blocking diode in series prevents the photovoltaic system from charging the branch, and effectively solves the hot spot effect.

3.2 Photovoltaic array modeling

In order to analyze the output characteristics under different shadows in series and parallel, a 5 * 3 photovoltaic array [5] is built in this paper, as shown in Fig.5:
5.3 Influence of the number of series and parallel shadows on output under local shadow

In order to explore the influence of the number of shadows on the series branch, the number of shadows on the parallel branch and the shadow layout on the output of the photovoltaic array, three groups of control experiments will be set up for analysis. The illumination after occlusion is set to $166 \text{ W/s}^2$ [6].

1) Influence of shadow number of series branches on output of photovoltaic array

In order to explore the output difference of different shadow numbers of series branches, six groups of occlusion conditions will be set, namely no occlusion, occlusion PV1, occlusion PV1PV2, occlusion PV1PV2PV3, occlusion PV1PV2PV3PV4 and full occlusion of the first branch. The output image of photovoltaic array is shown in Fig.6:
It can be found that when the illumination is the same after occlusion, the output waveform of the photovoltaic array presents at most two peaks regardless of the number of input shadows; with the increase of the number of shadows, the maximum output power decreases gradually; the maximum output power is very close to the output power greater than one occlusion. To sum up, when the occlusion rate is close to half, the maximum output power is close to the output power of the branch under full occlusion.

(2) Influence of shadow number of parallel branches on output of photovoltaic array

In order to explore the output difference of different shadow numbers of parallel branches, six groups of occlusion conditions will be set, namely no occlusion, occlusion PV1, occlusion pv1pv6 and occlusion pv1pv6pv11. The output image of photovoltaic array is shown in Fig. 7:
As in the case of series connection, when the occlusion degree is consistent, at most two peaks will appear in different shadow numbers in parallel; the maximum power points in the four cases are far away, and the voltage value corresponding to the maximum power decreases with the increase of the number of shadows.

It can be found that when the illumination degree is the same, the influence on the maximum power point when the shadow is distributed in the parallel branch is greater than that when the shadow is distributed in the series branch.

(3) Influence of shadow layout on photovoltaic array output

In order to explore the influence of shadow distribution on the output of photovoltaic array, five working states will be set, corresponding to the number of five shadows. Because the illuminance after occlusion is set to $166 \text{ W/m}^2$ in this experiment, the arrangement and combination of shadow layout in a series branch can be ignored as long as the number of shadows in a series branch is determined. Therefore, the results of optimal shadow layout and worst shadow layout corresponding to different number of shadows will be analyzed, as shown in Tab.1:

| Number of Shadows | Optimal distribution | Output power/kW | Worst distribution | Output power/kW | D-value of power/kW |
|-------------------|----------------------|-----------------|-------------------|-----------------|---------------------|
| 1                 | [1 0 0]              | 1.61            | [1 0 0]           | 1.61            | none                |
| 2                 | [1 1 0]              | 1.52            | [0 0 2]           | 1.35            | 0.17                |
| 3                 | [1 1 1]              | 1.46            | [2 1 0]           | 1.21            | 0.25                |
| 4                 | [4 0 0]              | 1.41            | [2 0 2]           | 1.12            | 0.29                |
| 5                 | [5 0 0]              | 1.33            | [3 2 0]           | 0.85            | 0.48                |

According to the above table, when the number of shadows increases, the smaller the output power of the photovoltaic array, the greater the difference between the output power of the optimal shadow distribution and the worst shadow distribution; When the number of shadows is closer to the number of series, the larger output power can be obtained when the shadows are distributed in the same series branch; When the number of shadows is far from the number of series, the more uniform the shadow distribution in the array, the greater the output power can be obtained.
4. Conclusion
After modeling the engineering mathematics of photovoltaic cells, the models of photovoltaic cells and photovoltaic arrays are built, and the output characteristic curves and outputs of photovoltaic arrays under different shadow modes are measured, analyzed and compared. The results are as follows:

(1) When a single photovoltaic cell operates under different illumination, with the increase of illumination, it only affects the short-circuit current and maximum output power of the photovoltaic cell; When operating at different temperatures, it only affects the open circuit voltage of photovoltaic cells.

(2) When the series branch has occlusion, the occlusion rate is close to half, and the maximum output power is close to the output power of the branch under full occlusion; The influence of shadow distribution in parallel branches on the maximum power point is greater than that in series branches.

(3) When the number of shadows in the photovoltaic array increases, the total output power of the photovoltaic array decreases, and the output power difference between the optimal array and the worst array gradually increases.

(4) The influence of photovoltaic array output power not only comes from light intensity and temperature, but also is affected by the number of shadows and occlusion distribution mode.

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