Mismatch detecting method of centralized PV station

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Abstract. For the centralized PV station which uses panels constructed with by-pass diode, the mathematical model of U-I relationship is established considering mismatch. Measured values of output voltage and current are obtained by real-time measurement system. Then the equation set is formed and can be solved via Gauss-Seidel iteration method. Thus, five parameters and mismatch parameter are available, and can be used to judge the mismatch panel or panels. Moreover, database can be set up according to the relation between the environment circumstance and the five parameters, which can efficiently improve the time of mismatch detecting.

1. Introduction

When the electrical property, such as voltage, current, power, between components in the cell array is quite different, the output power of the entire PV array will be less than the sum of the individual module. This is called the mismatch of the PV array. The mismatch occurs because of internal causes and external causes. Internal causes include mixed connection of PV components with different output power, manufacturing differences, the aging problems and etc. External causes include the different orientation of sunlight, partial cover by the cloud shadow and etc [1].

When the mismatch occurs, the output power of the system will be affected. Meanwhile, the normal components will also have efficiency loss because of voltage or current constraints. If a single cell or only a minority of cells are mismatched because of shadow or other cases, the mismatched cells will get locally overheated, which will cause "hot spot effect". This phenomenon will accelerate the aging and damage of PV cells [2].

The mismatch problem is mainly alleviated by adding the bypass diode to compensate for current mismatch or adding the blocking diode to compensate for voltage mismatch. The current solution for "hot spot effect" is to connect the diode in parallel, which is called the bypass diode. When part of the cells in the same bypass diode are mismatched, current of the cells which are parallel to the same bypass diode will directly flow through the bypass diode. Thus, the voltage is limited and "hot spot effect" is eased. However, the bypass diode can only alleviate the hot spot phenomenon instead of completely eliminating its damage [3].

[4,5] study the improved method of bypass diodes. In [4], the influence of different connection modes of bypass diode is analyzed via simulation of reverse model. The application ranges of overlapping and non-overlapping are given. It should be noted that although the bypass diode isolates the mismatched cell, it isolates the other normal cells in the same parallel, resulting in a certain power loss. In [5], the clamping effect of the diode on the voltage is analyzed in detail, and the super...
A super capacitor is proposed to replace the bypass diode to make current compensation. The power of normal cells can still be transmitted to the grid, avoiding the power loss. While this super capacitor can only solve short-time mismatch.

Although the bypass diode can effectively alleviate the "hot spot effect", it also causes power loses based on the analysis above. Therefore, it is necessary to study the mismatch. However, the present researches are mostly about improving the structure of PV array. The minority of researches are on the mismatch detecting. Actually, knowing the location of the mismatch does help solve the mismatch problem and avoid the losses [6]. In [7], thermal imaging technology is introduced to identify the temperature distribution when thermal fault occurs. Thus, the drawbacks of high cost and low conversion efficiency can be addressed. While for the solar panels using bypass diodes, it is difficult to detect mismatch in this way because the thermal effect has been alleviated.

It is proposed in [8] that small signal transmission equation of Buck circuit can be used to analyze the impact of internal resistance to detect the degradation of the resistance. Also, this can only detect the mismatch circumstances when degradation of the photovoltaic panel or manufacturing failure occur. In [9], the U-I curve of the photovoltaic cell operation is checked via current scanning. The "hot spot effect" is judged by the current change in the same voltage range.

Based on the 5-parameter model of the PV cell, this paper deduces the U-I equation of the centralized PV array considering mismatch. The five parameters and mismatch parameter are solved using the measured values of current and voltage. This way of mismatch detecting is based on the mechanical modeling, and can be applied whatever external or internal causes occur.

2. Method

2.1. Mathematical model

We use the single diode model of PV cell as is shown in figure 1.

\[ I = I_{ph} - I_s \left( e^{\frac{q(U + IR_s)}{AKT}} - 1 \right) - \frac{U + IR_s}{R_{sh}} \]  

Where q is the electron charge constant, \(1.602 \times 10^{-19}\) C; k is the Boltzmann constant, \(1.381 \times 10^{-23}\) J / K; A is the diode characteristic fitting coefficient, which is variable between 1 and 2. This relationship can be seen as an equation with five parameters to be determined. Five parameters are \(I_{ph}\), \(R_{sh}\), \(A\), \(I_s\), and \(R_s\). \(I_{ph}\) is the photo-generated current. \(I_s\) is the saturation current of equivalent diode. \(R_{sh}\) is the equivalent parallel resistance. \(R_s\) is the equivalent series resistance [10].

2.1.1. Modified formulas

Modified formulas of \(I_{ph}\), \(R_{sh}\), \(I_s\), and \(R_s\) under different illumination and temperature circumstances are shown in Equation (2-1) to (2-4):
\[
I_{ph} = \left( \frac{S}{S_{ref}} \right) \left[ I_{phref} + C_T (T - T_{ref}) \right]
\]
\[
I_s = I_{sref} \left( \frac{T}{T_{ref}} \right)^3 \left[ \frac{q}{k} \frac{1}{T_{ref} T} \right]
\]
\[
R_s = R_{sref} \left( \frac{T}{T_{ref}} \right) \left[ 1 - \beta \ln \left( \frac{S}{S_{ref}} \right) \right]
\]
\[
R_{sh} = R_{shref} \left( \frac{S}{S_{ref}} \right)
\]

Where \(I_{phref}\) is the photo-generated current under standard condition (SC). \(S\) is the real-time illuminance (W/m\(^2\)). \(S_{ref}\) is the SC illuminance, 1000W/m\(^2\). \(C_T\) is the temperature coefficient which can be provided by the manufacturer. \(E_g\) is the forbidden band width (eV), depending on the material of the photovoltaic cell. \(T\) is the real time temperature of the diode. \(T_{ref}\) is the SC temperature, 25°C. \(\beta\) is a constant taken as 0.217. From calculation when the illuminance changes, \(R_s\) almost remains the same [11].

2.1.2. U-I relationship of a panel A PV panel consists of 60 cells, which are divided into 3 groups as shown in Figure 2. We call each group a unit. There are 20 cells in a unit and each unit has a by-pass diode connected in parallel.

Figure 2. Schematic diagram of PV panel.

Considering cloud shadow, when part of cells in a group are masked, the current will pass directly through the bypass parallel diode. The voltage of each group will be limited to the same as the voltage of the diode, which is 0.3V for the silicon diode denoted by \(U_{DD}\). Assume that there are \(N_1\) cells are unmasked and \(N_2\) masked, the sum of \(N_1\) and \(N_2\) is 60. Cell voltage considering cloud shade is shown in Equation (3):

\[
U_I = \frac{U}{N_1} - \frac{N_2 U_{DD}}{20N_1} + IR_s
\]

So, the U-I relationship considering cloud shade is shown in Equation (4):

\[
I = I_{ph} - I_s \left( \frac{U}{N_1} \frac{N_2 U_{DD}}{20N_1} + IR_s \right) - \left( \frac{U}{N_1} - \frac{N_2 U_{DD}}{20N_1} + IR_s \right) \frac{1}{R_{sh}}
\]

2.2. Solution of the parameters
The relationship of output voltage and current is non-linear and contains exponential function. The linear iteration methods are no longer suitable. Here we can use Gauss-Seidel iteration method.
2.2.1. Gauss-Seidel iteration method. Suppose that \( x^{(k)} = (x_1^{(k)}, x_2^{(k)}, \ldots, x_n^{(k)}) \) is the approximate solution of the non-linear equation set \( F(x) = 0 \). The \( i^{th} \) component of the \( (k+1)^{th} \) iteration can be achieved by the \( i^{th} \) equation of the equation set as the Equation (5) shows.

\[
f_i(x_1^{k+1}, x_2^{k+1}, \ldots, x^n_{k+1}, x_i, x_{i+1}, \ldots, x_n) = 0
\]

(5)

When \( i=1 \), \( x! \) is solved by the equation \( f_1(x_1^{(k)}, x_2^{(k)}, \ldots, x_n^{(k)}) = 0 \), denoted by \( x_1^{(k+1)} \); when \( i=2 \), \( x_2 \) is solved by the equation \( f_2(x_1^{(k+1)}, x_2^{(k)}, \ldots, x_n^{(k)}) = 0 \), denoted by \( x_2^{(k+1)} \); as a general rule, the solved \( x_i \) is denoted by \( x_i^{(k+1)} \).

The way to solve a certain \( x_i^{(k+1)} \) is actually equal to solving a single variable non-linear equation. We use Newton iteration method here.

The steps of solving the parameters is as follows.

1. Choose the initial value of the iteration \( x^{(0)} \); set the maximum number of iterations and the error precise, denoted by \( N \); \( k \) is zero.
2. Calculate \( x^{(k+1)} \)
3. Judge whether the error precise is met or not.
4. When \( k = N \), the iteration is over; otherwise, \( k = k+1 \), and return to (2).

2.2.2. The solution of parameters. Voltage value and current value can be achieved by real time measurement system. Considering the error caused by the measurement equipment and other accidental error, the data are the mean values in every 30 second duration. Six sets of \( U \) and \( I \) values are needed to solve the parameters, denoted by \( (U_i, I_i) \); \( i \) is 1, 2, 3, 4, 5 and 6. After obtaining the data, the equation set can be achieved as Equation (6):

\[
\begin{align*}
i_1 &= I_{ph} - I_1 - \left( e^{\frac{U_1 N_1 I_{ph}}{20N_1 R_1}} - 1 \right) - \left( \frac{U_1 - N_1 U_{en} + I_1 R_1}{R_{ph}} \right) \frac{1}{R_1} \\
i_2 &= I_{ph} - I_2 - \left( e^{\frac{U_2 N_2 I_{ph}}{20N_2 R_2}} - 1 \right) - \left( \frac{U_2 - N_2 U_{en} + I_2 R_2}{R_{ph}} \right) \frac{1}{R_2} \\
i_3 &= I_{ph} - I_3 - \left( e^{\frac{U_3 N_3 I_{ph}}{20N_3 R_3}} - 1 \right) - \left( \frac{U_3 - N_3 U_{en} + I_3 R_3}{R_{ph}} \right) \frac{1}{R_3} \\
i_4 &= I_{ph} - I_4 - \left( e^{\frac{U_4 N_4 I_{ph}}{20N_4 R_4}} - 1 \right) - \left( \frac{U_4 - N_4 U_{en} + I_4 R_4}{R_{ph}} \right) \frac{1}{R_4} \\
i_5 &= I_{ph} - I_5 - \left( e^{\frac{U_5 N_5 I_{ph}}{20N_5 R_5}} - 1 \right) - \left( \frac{U_5 - N_5 U_{en} + I_5 R_5}{R_{ph}} \right) \frac{1}{R_5} \\
i_6 &= I_{ph} - I_6 - \left( e^{\frac{U_6 N_6 I_{ph}}{20N_6 R_6}} - 1 \right) - \left( \frac{U_6 - N_6 U_{en} + I_6 R_6}{R_{ph}} \right) \frac{1}{R_6}
\end{align*}
\]

(6)

It can be seen as a equation set with six varieties, namely \( I_{ph}, R_{ph}, A, I_i, R_i \) and \( N_2 \). They can be solved using Gauss-Seidel iteration method. Different environment circumstances correspond to different parameter values. In a short duration, the five parameters can be seen as constants, and can be solved in this way. The mismatch parameter \( N_2 \) reflects the mismatch circumstance. There are three states of \( N_2 \), namely \( N_2=0 \), when no cells are mismatched; \( N_2=20 \), one third of cells in a panel are isolated to the main circuit; \( N_2=40 \), two thirds of cells in a panel are isolated to the main circuit; \( N_2=60 \), the whole panel is mismatched. As is displayed in Figure 3, the PV array consist of thousands of PV panels. When we know mismatch state of every certain panel, we know the overall mismatch state of the whole centralized PV station. Thus, we can take actions to find out the causes and solve the mismatch problem.
Then we conclude the flowchart of the whole mismatch detecting process as is shown in Figure 4.

We use the data acquisition unit to detect the voltage and current value of photovoltaic value. Then the data is transmitted to the chip. The data is averaged every 30 second to reduce the measurement error and other accidental error. Then 5 parameters and the mismatch parameter can be solved via Gauss-Seidel iteration method. According to the mismatch parameter the mismatch circumstance can be analyzed.

3. Results

We use the measurement system and data acquisition unit and receive the measurement value of voltage and current from the upper computer. We simulate the cloud shade by artificial barrier and induce the mismatch. There are three units in a panel, three mismatching circumstances are simulated, with one or two or three units mismatched respectively. We obtain the voltage and current values as is shown in Table 1.

| $N_2/20$ | $U_1$, $I_1$ | $U_2$, $I_2$ | $U_3$, $I_3$ | $U_4$, $I_4$ | $U_5$, $I_5$ | $U_6$, $I_6$ |
|----------|--------------|--------------|--------------|--------------|--------------|--------------|
| 0        | 17.083       | 21.492       | 27.083       | 29.152       | 30.068       | 31.423       |
| 1        | 6.278        | 6.246        | 5.879        | 5.311        | 4.463        | 3.825        |
| 2        | 4.954        | 6.549        | 8.504        | 9.406        | 9.904        | 10.432       |

Parameters can be calculated using Gauss-Seidel iteration method via the data in Table 1. The values are displayed in Table 2.
Table 2. Parameter value.

| No. | $I_{ph}(A)$ | $I_{s}$$\mu$(A) | $q/4kT$ | $R_s$(m$\Omega$) | $R_d$(Ω) | $N_2$ |
|-----|-------------|-----------------|---------|-----------------|----------|-------|
| 1   | 6.2836      | 3.4582          | 25.623  | 7.2392          | 5682     | 0.2003 |
| 2   | 6.2230      | 3.3343          | 25.5325 | 6.2355          | 5993     | 0.9235 |
| 3   | 6.1860      | 3.0828          | 25.3486 | 6.8274          | 6334     | 1.8321 |

The 5 parameters values under different mismatch circumstances are very close because the temperature and illumination conditions remains nearly unchanged. The mismatch parameter can basically reflect the mismatch circumstances if ignoring the error.

4. Conclusions

The mismatch parameter $N_2$ can determine whether the PV panel is mismatched. Thus, the mismatch location can be detected in the array. If the mismatch is caused by the cloud shade it will disappear when the shade moves; if it is caused by internal causes, the mismatch parameter will always exist, and actions should be taken to mend the mismatched panels.

Compared with thermal imaging method, it is difficult for thermal imaging method to detect mismatch because the thermal effect has been alleviated by bypass diodes which most of the panels are constructed; Compared with degradation detecting of the resistance, this can only detect the mismatch circumstances when degradation of the photovoltaic panel or manufacturing failure occur. The way to quantify mismatch gets rid of the limitation. It is dependent of the mismatch causes, and quantization makes the detection more direct.

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