Mismatch locating strategy of photovoltaic array

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Abstract. Single-diode model of Photovoltaic cell is adopted in this paper and is modified by adding a mismatch reflect parameter. The deduced mathematical model of serial PV is provided in this paper. The unknown parameters in the model is determined by the environment conditions including the irradiation and the temperature. With the measured data of the current and voltage values, equation set about the unknown quantities can be listed out. Then iteration method is introduced to solve them. The mismatch reflect parameter is vital to locate the mismatched series in the PV array.

1. Introduction

With the development of photovoltaic generation system, more and more researches are concentrated on it. Before, a large proportion of attention is paid on the improvements of the efficiency. Many novel MPPT strategies are proposed to increase it. Researches on the mismatch problem are quite rare in compare [1]. Mismatch occurs when the electrical property, such as voltage, current, power, between components in the cell array is quite different. Thus, the output power of the entire PV array will be less than the sum of the individual module. There are many causes leading to the phenomenon including internal causes such as mixed connection of PV components with different output power, manufacturing differences and the aging problems and external causes such as the different orientation of sunlight, partial cover by the cloud shadow [2].

The most common way to alleviate mismatch 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 [3].

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 [4].
In [5], DC resistance of the serial module instead of bypass diode is used to detect hot spot. Then "hot spots" are cut off by biostable relay. The cut-off part can be re-connected into the circuit after the temporary mismatch. However, this method will still cause power loss in the same series and the equipment cost is high. In [6], the internal conditions and external conditions of hot spot failure considering the bypass diode in parallel are obtained. The quantity of maximum cells that can be connected with the same bypass diode in series is induced via the simplified U-I model. While this method can be only applied to a small system containing one or two bypass diodes. Also, this method is based on the current and voltage values of the single PV cell and is difficult to achieve in reality.

A mismatch locating strategy is proposed in this paper. Part I is the introduction. The single-diode model of Photovoltaic cell and its modification is introduced in part II; the deduced mathematical model of serial PV is also discussed in this part. Part III introduces the approach to solving the parameters in detail and part IV is the application and result. The last part is discussion. The major contributions of this paper are:

1. It proposes an approach to locate the mismatch series of PV array. When mismatch is caused by internal causes, actions can be taken to directly find out the fault series and solve it.
2. The location algorithm is based on mechanism model. Thus, it is applicable to the mismatch circumstances whatever induced by internal or external causes.

2. Mathematical model

2.1. Mathematical model of PV cell

The single-diode model of PV cell is shown in Fig.1.

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

(1)

Where q is the electron charge constant, 1.602 × 10^{-19} C; k is the Boltzmann constant, 1.381 × 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, namely Iph, Rsh, a, Is and Rs. Iph is the photo-generated current; q/AkT is denoted by a here; Is is the saturation current of equivalent diode; Rsh is the equivalent parallel resistance; Rs is the equivalent series resistance.

2.2. Modified formulas of U-I equation

Modified formulas of Iph, Rsh, Is and Rs based on irradiation and temperature values are shown in (2):
\[
\begin{align*}
I_{ph} &= \left( \frac{S}{S_{ref}} \right) I_{p(href)} C_T (T - T_{ref}) \\
I_s &= I_{ref} \left( \frac{T}{T_{ref}} \right)^3 \left[ 1 - \frac{1}{\exp \left( \frac{1}{k T_{ref}} \right)} \right] \\
R_s &= R_{sref} \left( \frac{T}{T_{ref}} \right) \left[ 1 - \ln \left( \frac{S}{S_{ref}} \right) \right] \\
R_{sh} &= R_{shref} \left( \frac{S}{S_{ref}} \right)
\end{align*}
\]

(2)

Where $I_{p(href)}$ is the photo-generated current under standard condition (SC). $S$ is the real-time irradiation (W/m²). $S_{ref}$ is the SC irradiation, 1000W/m². $C_T$ 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.

2.3. $U$-$I$ relationship of serial modules

Suppose that a PV module consists of 3 units and each unit consists of 20 cells. Each unit is connected with a bypass diode in parallel. As is shown in Figure 2.

![Figure 2. Schematic diagram of PV module](image)

Modules in series can be seen as a module with several units. As is shown in Figure 3.

![Figure 3. Schematic diagram of PV modules in series](image)

When part of units in a module series 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 $U_d$. Considering a PV array with $n$ modules in each series, and totally $m$ series in parallel. As is shown in Figure 4.
Figure 4. Sketch map of PV array

Assume that there are \( n_1 \) cells are unmismatched and \( n_2 \) mismatched, the sum of \( n_1 \) and \( n_2 \) is 3n. Cell voltage considering mismatch is shown in Equation (3):

\[
U_D = \frac{U}{n_1} - \frac{n_2}{20n_1} U_d + IR_s
\]

So, the equation of the output voltage and current of the module series considering mismatch is shown in (4). The relationship of output voltage and current is non-linear and contains exponential function.

\[
I = I_{ph} - I_s \left( e^{aU_d} - 1 \right) - \frac{U_d}{R_{sh}}
\]

3. Solution of the parameters

3.1. The solution of parameters

For a series of PV module, there are 6 quantities to be solved, including \( I_{ph} \), \( R_{sh} \), \( a \), \( I_s \), \( R_s \) and the mismatch reflecting parameter \( n_2 \). Voltage value and current value can be achieved by real time measurement system. Six sets of voltage and current values are needed to solve all the parameters, denoted by:

\[(U_1, I_1), (U_2, I_2), (U_3, I_3), (U_4, I_4), (U_5, I_5), (U_6, I_6)\]

After obtaining the data, the equation set can be achieved as (5):

\[
\begin{align*}
I_i &= I_{ph} - I_s \left( e^{aU_{di}} - 1 \right) - \frac{U_{di}}{R_{sh}} \\
U_{di} &= \frac{U}{n_i} - \frac{n_2}{20n_1} U_d + I_i R_s
\end{align*}
\]

It can be seen as a equation set with six varieties, namely \( I_{ph} \), \( R_{sh} \), \( a \), \( I_s \), \( R_s \) and \( n_2 \). Different environment circumstances correspond to different parameter values. In a short duration, the five parameters can be seen as constants. Since the parameters have the upper and lower limits, it is easy to choose the initial value. Thus, it can be solved via Newton iteration method. The zero function corresponding to the six equations is \( F_i \), as is shown in (6).

\[
\begin{align*}
F_i &= I_{ph} - I_s \left( e^{aU_{di}} - 1 \right) - \frac{U_{di}}{R_{sh}} - I_i \\
U_{di} &= \frac{U}{n_i} - \frac{n_2}{20n_1} U_d + I_i R_s
\end{align*}
\]

The Jacobi matrix is denoted by \( J \), and is as follows:
The elements in the matrix is unfolded as (7-1) to (7-6); i is integers from 1 to 6. Udi is as the same as (6).

\[
\frac{\partial F_i}{\partial I_{ph}} = 1 \tag{7-1}
\]

\[
\frac{\partial F_i}{\partial I} = 1 - e^{a U_{Di}} \tag{7-2}
\]

\[
\frac{\partial F_i}{\partial a} = -I_i e^{a U_{Di}} U_{Di} \tag{7-3}
\]

\[
\frac{\partial F_i}{\partial R_s} = -I_i e^{a U_{Di}} a I_i - \frac{I_i}{R_{sh}} \tag{7-4}
\]

\[
\frac{\partial F_i}{\partial R_{sh}} = U_{Di} \frac{1}{R_{sh}^2} \tag{7-5}
\]

\[
\frac{\partial F_i}{\partial n_2} = -I_i e^{a U_{Di}} \frac{20U_i - n_2 U_d}{20(3n - n_2)^2} - \frac{20U_i - n_2 U_d}{(3n - n_2)^2 R_{sh}} \tag{7-6}
\]

Denote that:

\[x = \left(I_{ph}, R_{sh}, a, I_s, R_s, n_2\right)^t\]

\[F_z = \left(F_1, F_2, F_3, F_4, F_5, F_6\right)^t\]

Then the iteration equation can be written as (8):

\[x(n + 1) = x(n) - A_n^{-1} F_z\]

The mismatch parameter n2 reflects the number of mismatched units. As is displayed in Figure 4, the PV array contains m module series in parallel. When we solve the mismatch reflecting parameter of every certain series, we can know the overall mismatch state of the whole PV array. Moreover, we can take actions to find out the mismatched series and solve the mismatch problem.

3.2. Simplification of calculation

From modification formulas we know that Is, a and Rs are impregnability when irradiation changes. As the influence of temperature change in a short duration on parameters can be neglected, and the irradiation remains almost unchanged in a short duration, Is, a and Rs can be regarded as the fixed value in a short duration; and Ip, Rsh change as the irradiation changes. At a certain time, the irradiation and temperature are determined, so the U-I curve is also determined. Thus, the five parameters are also deterministic. In order to simplify the calculation, Is, A and Rs can be replaced by the values at the nearest integral time; only the values of Ip, Rsh are required to be calculated. At integral time, all the five parameters are required to be calculated. Thus, we need only 3 sets of values of voltage and current, denoted by:

\[(U_1, I_1), (U_2, I_2), (U_3, I_3)\]
The equation is as same as (6) while i is 1, 2 and 3. Using Newton iteration method and Jacobi matrix is as follows:

\[
J = \begin{bmatrix}
\frac{\partial F_1}{\partial I_{ph}} & \frac{\partial F_2}{\partial I_{ph}} & \frac{\partial F_3}{\partial I_{ph}} \\
\frac{\partial F_1}{\partial R_{sh}} & \frac{\partial F_2}{\partial R_{sh}} & \frac{\partial F_3}{\partial R_{sh}} \\
\frac{\partial F_1}{\partial n_2} & \frac{\partial F_2}{\partial n_2} & \frac{\partial F_3}{\partial n_2}
\end{bmatrix}
\]

The elements in the matrix is unfolded as (9-1) to (9-3); i is integers from 1 to 3. Udi is as the same as (6).

4. Result
We use the measurement system and data acquisition unit and receive the measurement value of voltage and current from the upper computer. Considering the error caused by the measurement equipment and other accidental error, the data gathering system measure the data every second and transmit the mean values in every 30 second duration to the upper computer. The cloud shade is simulated by artificial barrier.

The data is acquired from a serial PV system. This can be used to confirm the method in this paper. There are three units in a module, 20 modules in series in these case. Four mismatching circumstances are simulated, with zero or one or two or three modules masked respectively. We obtain the voltage and current values as is shown in Tab.1.

Table 1. Database of current and voltage of PV module

| n2 | Measurements values of voltage and current |
|----|------------------------------------------|
| 0  | U  | 234.1 | 393.2 | 473.3 | 564.6 | 594.5 | 615.2 |
|    | I  | 6.500 | 6.495 | 6.462 | 6.112 | 5.708 | 5.196 |
| 3  | U  | 254.3 | 368.5 | 495.6 | 586.9 | 608.9 | 618.1 |
|    | I  | 6.499 | 6.485 | 6.395 | 5.118 | 4.172 | 3.625 |
| 6  | U  | 291.2 | 405.2 | 517.5 | 566.1 | 579.9 | 592.4 |
|    | I  | 6.497 | 6.475 | 5.997 | 4.715 | 3.991 | 3.127 |
| 9  | U  | 145.4 | 249.5 | 392.4 | 502.7 | 536.1 | 552.5 |
|    | I  | 6.497 | 6.497 | 6.468 | 5.756 | 4.646 | 3.660 |

Parameters can be solved via the method above based on the data in Tab.1. The unit of I is A, and the unit of U is V. The results are displayed in Tab. 2.

Table 2. Parameter value

| No. | Iph (A) | Is (μA) | q/kt | Rs (mΩ) | Rsh (mΩ) | n2 |
|-----|---------|---------|------|---------|----------|----|
| 1   | 6.52    | 3.45    | 25.6 | 10.23   | 8273     | 0.17|
| 2   | 6.49    | 4.33    | 26.5 | 9.23    | 9234     | 2.93|
| 3   | 6.50    | 3.08    | 26.3 | 12.82   | 7263     | 6.08|
| 4   | 6.49    | 2.90    | 25.9 | 7.52    | 10239    | 9.14|

The 5 parameters values under different mismatch circumstances are very close because the temperature and irradiation conditions remains nearly unchanged. The mismatch parameter can basically reflect the mismatch circumstances if ignoring the error.
5. Conclusion
The mismatch parameter $n_2$ can determine whether the serial modules are mismatched. In reality, $n$ is comparatively smaller than $m$. When the PV array is very large, which is widely used in centralized PV station, to find out the mismatched series is meaningful. 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 can be taken to find out the mismatched modules and mend them.

6. References
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