Fault Diagnosis Method and Simulation Analysis for Photovoltaic Array

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Abstract—Based on the distinguishing characteristics of the output current and voltage for photovoltaic array working in different states, a novel voltage and current detection method was proposed in this paper compared to the original current and voltage method. Of this method, the fault position can be located precisely and quickly by analyzing the current and voltage variation of each branch, according to the characteristic that the output current as well as voltage of the fault branch is less than the normal one’s of the same number modules. The feasibility of this novel method is proved by the simulation results given under the Matlab/Simulink environment.

Keywords-photovoltaic array; photovoltaic module; fault diagnosis; simulation analysis

I. INTRODUCTION

Solar energy is a kind of inexhaustible green energy which can be used by the mankind freely and fairly. Solar PV power generation, as a use form of solar energy, converts the solar energy into electrical energy through photocell photovoltaic effect. PV power generation has been applied more and more widely owing to many advantages such as free of pollution, safe, without noise, general resource, easy to install, and short construction period.

In the solar PV generation system, the output voltage of a PV cell is only 0.5V because of the limitation of the process procedure, so the PV module is constructed by connecting several PV cells in series mode, and the PV array is formed by several PV modules in series-parallel connection in order to satisfy the high-voltage high-power supply requirement [1]. However, several faults like open-circuit fault, short-circuit fault as well as shield event result in the dramatic decrease of the output voltage and power, even the normal working state is always interrupted by the serious condition of these faults. So the real-time fault diagnosis and fault resolution are very significant during the working process of the PV array.

II. COMPOSITION OF PHOTOVOLTAIC ARRAYS AND CATEGORY OF FAULTS

A. Composition of photovoltaic arrays [2]

The output characteristic curve of a PV cell is shown in Fig. 1, which presents a transition process from constant current output state to constant voltage output state with voltage increases, and there is a maximum power point at the boundary of these two states.

The PV module is generally composed of a large number of PV cells which are connected first in series with each cell and then in parallel with each large series, and then PV array is constructed by plenty of modules in the same way. There are 36 cells in a PV module connected in series-parallel mode normally.

<table>
<thead>
<tr>
<th>TABLE 1.</th>
<th>THE CATEGORY OF FAULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>types of fault</td>
<td>causes</td>
</tr>
<tr>
<td>degradation of module properties</td>
<td>1. R_s increased. 2. R_SH decreased. 3. The film of reducing the reflection degenerated.</td>
</tr>
<tr>
<td>Short circuit</td>
<td>Cell Short circuit</td>
</tr>
<tr>
<td>Module Short circuit</td>
<td>It is easy to occur in the thin-film batteries as the pinhole, localized corrosion and battery material damaged.</td>
</tr>
<tr>
<td>open circuit</td>
<td>Cell Open circuit</td>
</tr>
<tr>
<td>Module Open circuit</td>
<td>fragmentation of cell</td>
</tr>
<tr>
<td>Hot spot</td>
<td>partial shade</td>
</tr>
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</table>

![Figure 1. The characteristic curve of PV cell](image-url)
cells that have fault spot is obviously different from that of the normal working PV cells, leading to an obvious difference between the two infrared images. By the infrared image processing and analysis, the probable error area and the characteristic information of fault spot can be extracted to distinguish whether the condition of the PV cells is normal. However, this method presents some unavoidable shortcomings, such as its inferior discernment in the minor temperature differences, poor real-timeliness, hamstrung malfunction analysis and alarm online; low accuracy and efficiency at present stage [5].

B. Voltage and current measurement method

Reference [6] raises a method of judging module faults and the location of faulted module through detecting current and voltage. As shown in Fig. 2, collected signals include: current $I_i$ (i = 1 · · · M) in each series-connection branch, the overall array output voltage $U_{\text{array}}$, and the voltage $U_{ij}$ of half of cell modules in each series-connection branch.

Normal circumstance of cell components in array:

$$I_i = I_2 = \cdots = I_M$$
$$U_{ij} = U_{i\alpha}, \quad (i, j, 1 \leq j \leq M)$$

When the cell module in some series-connection branch is damaged, then

$$\begin{align*}
I_i &< I_{\text{ref}}, \quad (i \neq j, 1 \leq j \leq M) \quad (1) \\
\text{If} & \quad i \leq N/2 \\
\text{Then} & \quad U_i > U_{ij}, \quad (i \neq j, 1 \leq j \leq M) \quad (2) \\
\text{If} & \quad i \geq N/2 \\
\text{Then} & \quad U_i < U_{ij}, \quad (i \neq j, 1 \leq j \leq M) \quad (3)
\end{align*}$$

Simply calculate and analyze the measurement data according to (1), (2) and (3), then you can find the approximate location of faulted cell module. But the defect of this method is that: it is unable to locate precisely the fault position and distinguish the type of failure.

IV. NOVEL VOLTAGE AND CURRENT MEASUREMENT METHOD

A. Photovoltaic array model for fault detection

The novel voltage and current measurement method proposed in this paper will be illustrated using the model shown in Fig. 3. In this model, each black box is a detection unit, which can represent a module, can also indicate a number of modules or modules. If you represent a module, you can accurately locate faulty modules; if a panel that, you can determine the fault panels. Each detection unit if the number of cells containing more, the entire PV array of sensors needed less. In actual detection, it can be determined according to the specific needs of a module or a solar panel for the detecting unit. In this paper, we will take a module as detection unit.

Suppose that there are M branches in the PV array, and each branch consists of N PV modules. The number of voltage sensor for each branch is determined according to the number of PV modules covered by one sensor. If each PV module is
equipped with a dedicated voltage sensor, the number of required sensor can be obtained by

\[ S = \frac{N-1}{5} \times 1 \]  

(4)

If three successive three PV module covered by only one sensor, the corresponding sensor number is

\[ S = \frac{N-1}{2} \times n \]  

(5)

So the general situation of n PV modules covered by one sensor, the required sensors for each branch is given by

\[ S = \frac{N-1}{2n-1} \times n \]  

(6)

Where S must be rounded to the nearest integer towards positive infinity. Consider that the number of PV module covered by one sensor is the same, \( n \leq N/2 \) can be obtained easily, and then the relationship between S and n is given by

\[ S = f(n) = \frac{N-1}{2n-1}(N-1)(n+1) = (N-1)(n+1) - \frac{N}{2} \times \frac{n}{n-1} \]  

(7)

In which, \( f(n) \) is a decreasing function, the increase of n lead to the decrease of S, and the minimum value is obtained when \( n = N/2 \), so the least sensor required while one voltage sensor covers N/2 PV modules.

Arrange a current sensor and N/2 (integer(N/2)+1 when N is odd number)voltage sensors for each branch, and then the current of each branch \( I_{ij} \), the global output voltage \( U \), as well as the half voltage of each branch \( U/2 \), can be obtained. So the fault branch can be detected by the current analysis of each branch, and the concrete fault point of that branch can be located according to \( U_{ij} \).

**B. Principle of fault diagnosis**

The output current and voltage of each branch with the same number of PV modules must be approximate the same in normal operation state, so the fault point can be found in accordance with this characteristic.

The fault branch can be determined based on the output current state. Generally, the PV array works in the maximum power point with the MPPT (Maximum Power Point Tracking) function [7]. If a short-circuit fault of a PV module occurs in a branch, the output current of this branch will decrease apparently; the current of the corresponding branch will be zero when a open-circuit fault occurs at any PV module connected in series of this branch; there is hot spot phenomenon of a PV module, the current of this branch will decrease because of the current dissipation of the fault module. So the fault branch can be located according to the decreased current compared to other normal branches.

The fault category can be determined based on the aforementioned phenomena. Open-circuit fault of the branch can be confirmed when the current is zero; if the current drops a litter (like less than 10% of the rated current), and the PV array can not work normally any more, then the short-circuit fault can be confirmed except for the hot spot phenomenon; if the current drops dramatically (like more than 40% of the rated), the hot spot phenomenon can be determined. The limitation of these three cases can be set according to the concrete situation.

<table>
<thead>
<tr>
<th>TABLE II. OPEN-CIRCUIT FAULT</th>
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<tbody>
<tr>
<td>( I_{(A)} )</td>
</tr>
<tr>
<td>Open-circuit</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE III. SHORT-CIRCUIT FAULT</th>
</tr>
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<tbody>
<tr>
<td>( I_{(A)} )</td>
</tr>
<tr>
<td>One cell short-circuit</td>
</tr>
<tr>
<td>One module short-circuit</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>TABLE IV. HOT SPOT PHENOMENON</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_{(A)} )</td>
</tr>
<tr>
<td>10% of a cell is shaded</td>
</tr>
<tr>
<td>30% of a cell is shaded</td>
</tr>
<tr>
<td>50% of a cell is shaded</td>
</tr>
<tr>
<td>The cell is totally shaded</td>
</tr>
</tbody>
</table>
V. SIMULATION RESULTS

The simulation model is developed in Matlab/Simulink. First, the PV cell is constructed based on the equivalent circuit [2], and then the PV module is formed by several cells which are connected in series-parallel model. The 6×3 PV array is established using 18 PV modules finally. The output voltage and power of the PV array can be simulated in various fault conditions, and the corresponding fault module can be located using the aforementioned fault diagnosis method. The simulation parameters are specified as the value tested in standard condition, the illumination is 1kW/m², the temperature is 25 degree centigrade, the short-circuit current $I_{SC}=7.34A$, the open-circuit voltage $Uoc=0.6V$, and the equivalent resistor $R_s=0\,\Omega$, $R_p=200\,\Omega$. The simulation model is shown in Fig. 4.

A. open-circuit fault

The current of each branch and the voltage of the fault branch are listed in Table 2 when a open-circuit fault occurs. From the Table 2, the open-circuit fault can be confirmed because of the zero value of $I_1$; the fault number of PV module is one of 1 to 3 because $U_{11}<U/2$, however the modules numbered 2 to 6 can be confirmed with no fault because both the value of $U_{21}$ and $U_{31}$ are higher than $U/2$. So the conclusion of this case is that there is an open-circuit fault at NO.1 module.

B. short-circuit fault

The current of each branch and the voltage of the fault branch are listed in Table 3 when a short-circuit fault occurs. According to Table 3, the output voltage and current decreased more or less because of the short-circuit fault, the more number of the fault cells the more serious of the voltage and current decrease situation. However, if the short-circuit fault occurs at only one cell, the working state is approximate the same to the normal because of the tiny decrease of current and voltage. So, a criterion of the decrease must be specified in order to confirm the fault state, like 10% of the working current. According to the 10% criterion, the short-circuit fault can be determined when short-circuit occurs at all 36 cells of a module simultaneously. From Table 3, $I_1<90\% I_2$, and both the value of $U_{21}$ and $U_{31}$ are higher than $U/2$, thus, the fault module can be located at NO.1 module.

C. hot pot phenomenon

The current of each branch and the voltage of the fault branch are listed in Table 4 when a hot spot phenomenon occurs. The shield of the PV cell affect the output power dramatically in accordance with Table 4, the output power has been reduced 67% of the normal value while a whole PV cell is be shielded, the harmful effect of this shield event is serious to the PV system. In the PV array, a 40% reduction of current can be set as a criterion to determine whether the hot spot phenomenon occurs or not. The hot spot phenomenon can be confirmed if the current is less than the criterion, and if the current is 60% to 90% of the normal working current, the short-circuit fault can be confirmed if there is no hot spot phenomenon.

According to the Table 4 and the aforementioned fault determination principles, the current relationship is $I_1>90\% I_2$ when the 10% area of the PV cell is be shielded, the hot spot phenomenon cannot be confirmed of this situation; if the area...
to be shield increase to 30%, the current $I_1=77\% I_2$, the hot spot phenomenon occurs, the location is NO.2 module because both the value of $U_{11}$ and $U_{21}$ are less than $U/2$ while $U_{11}$ is higher than $U/2$; if the area to be shield increase to 50%, $I_1=56\% I_2$, the hot spot phenomenon of NO.2 module can be confirmed; if the whole PV cell is shielded, $I_1=1.6\% I_2$, the hot spot phenomenon occurs, and the location is NO.6 module because the value of $U_{11}, U_{21}$ and $U_{31}$ are higher than $U/2$.

**VI. THE DESIGN OF THE FAULT DIAGNOSIS PROGRAM**

**A. Fault branch determination**

As aforementioned, the fault is confirmed if the current of one branch has been reduced compared to the normal branch. A criterion is specified in order to distinguish the real fault and the litter disturbance, the 90% value of the maximum current through the normal branch is specified as the fault criterion, in the PV array of $6 \times 3$, the criterion is given by $I_S=90\% \text{Imax}$, where $\text{Imax}=\max\{I_1,I_2,\ldots,I_M\}$. According to this criterion, the fault branch can be located if the current of this branch is less than $I_S$, otherwise the fault state cannot be confirmed. In actual detection process, the criterion value must be specified based on the working efficiency of the PV array.

**B. Fault point location**

The fault point location must be done according to the voltage of $U_{ij}$ ($1 \leq i \leq N/2$, $1 \leq j \leq M$) after the determination of the fault branch. The criterion is $U_S=U/2$, where $U$ represents the output voltage of the PV array. If the voltage of $U_{ij}$ is higher than $U/2$, thus there is no fault of these $N/2$ modules covered by this voltage sensor, otherwise the fault point is located in these $N/2$ modules, finally, the fault point can be found after the comparison of each voltage of $U_{ij}$ to $U/2$ using this method. The flowchart of the proposed diagnosis method is shown in Fig. 5.

**VII. CONCLUSION**

A novel fault diagnosis model and corresponding method are proposed in this paper, the fault point can be located precisely and quickly through the comparison of each voltage sensor value to the criterion specified in various cases. The quantity of the required sensor as well as the cost are reduced considerably of this novel method compared to the traditional current and voltage method.

**REFERENCES**


